Iceland
Liechtenstein
Norway grants

Study Visits' Report

Geothermal energy – a basis for low-emission heating, improving living conditions and sustainable development – preliminary studies for selected areas in Poland

AGH
AGH University of Science and Technology

Wroclaw University of Science and Technology

cmr
Christian Michelsen Research AS

ORKUSTOFNUN
National Energy Authority

EGEC GEOTHERMAL

November 2017

Geothermal energy –
a basis for low-emission space heating,
improving living conditions and sustainable development
– preliminary studies for selected areas in Poland

Study Visits' Report

Programme Operators

MINISTERSTWO ŚRODOWISKA

Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej

Project Partners and Performers

AGH Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie

Politechnika Wrocławska

cmr Christian Michelsen Research AS

ORKUSTOFNUN National Energy Authority

EGEC Geothermal

Konstantynów Łódzki

Lądek Zdrój

Sochaczew

Poddębice

November 2017

Study Visits' Report

elaborated in the framework of the Project

"Geothermal energy – a basis for low-emission heating, improving living conditions and sustainable development – preliminary studies for selected areas in Poland"

co-funded by the Financial Mechanism of the European Economic Area (EEA) 2009–2014 as part of the Bilateral Cooperation Fund, PL04 Programme "Energy saving and promotion of renewable energy sources" (Agreement No. 173/2017/Wn50/OA-XN-05/D dated 09.10.2017 between National Fund for Environment Protection and Water Management (PL04 Programme Operator) and Mineral and Energy Economy Research Institute (Project beneficiary and leader)

Project Partners:

Mineral and Energy Economy Research Institute, Polish Academy of Sciences (Poland)
AGH University of Science and Technology, Kraków (Poland)
Wrocław University of Science and Technology (Poland)
Christian Michelsen Research AS (Norway)
National Energy Authority (Iceland)
European Geothermal Energy Council (reg. Belgium)

Cooperation:

Towns: Lądek-Zdrój, Konstantynów Łódzki, Poddębice, Sochaczew (Poland)
Experts, Geotermia Poddębice Ltd., Uzdrowisko Lądek-Długopole SA (Poland)

Authors and performers:

Mineral and Energy Economy Research Institute, Polish Academy of Sciences (Poland):
B. Kępińska (Project manager), A.P. Barbacki, B. Bielec, W. Bujakowski, M. Dendys, G. Hołojuch, K. Galos,
A. Kasztelewicz, W. Kęsek, L. Lankof, M. Miecznik, L. Pająk, R. Skrzypczak, B. Tomaszewska
AGH University of Science and Technology, Kraków (Poland):
M. Stefaniuk, A. Cygal, M. Hajto, E. Hałaj, M. Królikowski, K. Mitan, C. Ostrowski, B. Papiernik, M. Sada, A. Sowiżdżał,
R. Wiśniowski, S. Nagy, A, Sapińska-Śliwa, T. Śliwa
Wrocław University of Science and Technology (Poland):
B. Kiełczawa, E. Liber-Makowska, J. Blachowski
Christian Michelsen Research AS (Norway):
K. Midttømme, U.L. Dar, Ø. K. Aall, A. Birkeland, Ch. Gannefors Krafft, I. Henne, J. Kocbach, R. K. Ramstad, J.B. Skauge,
S. H. Stavland, E.S. Talhaug
National Energy Authority (Iceland):
B. Petursson, F.Ó.P. Einarsson, H. F.K. Danielsson, H. Tulinius, I. Gałeczka, K. Geirsson, J. Björnsson, S. Björnsson,
S.I. Friðleifsson, B. Guðmundsson, J.R. Guðmundsson, M. Guðmundsdóttir, S.E. Hjaltason, J. Ketilsson, J.Á.H. Þorvaldsson,
Þ.E. Sighvats
European Geothermal Energy Council (reg. Belgium):
P. Dumas, T. Garabetian, V. Pinzuti
Towns' representatives:
H. Brzyszcz, P. Krygier, S. Turkowski (Konstantynów Łódzki), R. Kaczmarczyk, G. Szczygieł (Lądek-Zdrój), P. Sęczkowski,
M. Srogosz (Poddębice), P. Osiecki, D. Dobrowolski (Sochaczew)
Experts:
M. Balcer, Z. Bociek, S. Jankowski, A. Karska, A. Ogórek, A. Peraj

Scientific editor: B. Kępińska (MEERI PAS)
Computer editor: A. Kasztelewicz (MEERI PAS)

November 2017

Contents

The term "geothermal water" was used as a synonym of the term „thermal water" sensu Geological and Mining Law (consolidated text Dz. U. 2017, item 2621)

PART I

GENERAL INFORMATION ON PROJECT, REALISATION OF TASKS 1–8 AND MAIN OUTCOMES

1. Basis for Report preparation

The Report was elaborated in a framework of the Project "Geothermal energy – a basis for low-emission heating, improving living conditions and sustainable development – preliminary studies for selected areas in Poland" cofinanced by the European Economic Area Financial Mechanism 2009–2014, Bilateral Cooperation Fund, Operational Programme PL04 "Energy saving and promotion of renewable energy sources". The Project acronim was GeoHeatPol.
The Project activities were performed on a basis of Agreement No. 173/2017/Wn50/OA-XN-05/D dated 09.10.2017 between National Fund for Environment Protection and Water Management (PL04 Programme Operator) and Mineral and Energy Economy Research Institute PAS (Project beneficiary and leader) and Annex No. 1/746 dated 21.11. 2017.

The estimated maximum Project budget was 3 543 871,91 PLN.
The Project activities were realized between 7 July and 30 November 2017.

2. Project parties

- Project Promoter: Mineral and Energy Economy Research Institute of the Polish Academy of Sciences, MEERI PAS (Project Leader) in consortium with AGH University of Science and Technology in Kraków, AGH UST and Wrocław University of Science and Technology, WUST,
- Project Partners from Donor countries: Christian Michelsen Research AS, CMR (Norway), National Energy Authority, OS (Iceland),
- Project Partner: European Geothermal Energy Council, EGEC (registered in Belgium),
- Cooperation: representatives of selected towns (mayors, employees of municipal town councils and municipal companies): Konstantynów Łódzki, Ledek-Zdrój, Poddębice, Sochaczew; experts. Among othe cooperating bodies were Geotermia Poddębice Ltd. and Uzdrowisko Lądek-Długopole SA.

Cooperation between MEERI PAS, AGH University of Science and Technology and Wrocław University of Technology took place in accordance with the Consortium Agreement dated .18.05.2017 and the Annex to the Agreement dated 17.08.2017, while between MEERI PAS and the foreign partners in accordance with the Partnership Agreements: with Christian Michelsen Research AS (Norway) dated 3.08.2017, with the National Agency for Energy (Iceland) dated 28.07.2017 and with the European Geothermal Energy Council dated 3.08.2017.

3. Project objectives and scope

The main objectives of the Project included the transfer of knowledge, know-how, and replication of good practices developed in the application of geothermal energy (renewable energy source) from Norway and Iceland to Poland. Those Donor countries are leaders in geothermal installations: Norway, owing to the common use of geothermal heat pumps, and Iceland, owing to the use of their geothermal water and steam resources. Such energy sources supply zero-emission district-heating facilities, improve living conditions, support sustainable development, and allow for efficient energy management. EGEC was used as a European platform to assess the regulatory and financial conditions to support geothermal energy all around Europe.

Geothermal district heating is at an early stage of development in Poland: presently, six geothermal plants have been operating. There can and should be more of them, owing to the prospective resources indentified in various regions, as well as the existence of ca. 500 district heating distribution networks. Some of them can be supplied from geothermal energy sources, at least to a certain extent. However, there is a barrier in the form of the shortage of knowledge and awareness among a number of stakeholders, together with a limited access to good practices and modern technologies.
The Project has contributed to the expansion of knowledge and an increase of acceptance and awareness on the part of stakeholders, in respect of a broader use of geothermal resources, low-emission energy generation, improvement of living conditions, and building of bilateral co-operation. Contacts and co-operation was started, forming good foundations for subsequent joint projects.

The Project Partners from the Donor countries also expanded their knowledge and competence on geothermal district heating operations in the conditions that are typical for Poland and other countries. And that should also contribute to the increase of possibilities and competitiveness in the case of their participation in other projects or on European markets.

4. Project background

The Project was initiated by the Polish Ministry of the Environment, specially by the State Plenipotentiary for Raw-Material Policy and Chief Geologist of Poland. The Operators of the PL04 Programme “Energy Saving and the Promotion of Renewable Energy Sources”, under which this Project was performed, were the Polish Ministry of the Environment and the National Fund of Environmental Protection and Water Management (NFEP&WM). The results of the Project works will contribute to the proper development of geothermal district heating in Poland, strengthening the applicable initiatives of the Polish government in that area.

Three towns selected for the Project: Konstantynów Łódzki, Poddębice, Sochaczew are located in the Polish Lowlands. In terms of geological and geothermal conditions they are representative of many other localities situated within this main geostructural unit of Poland, where proespects for geothermal energy development for space heating are mainly related to sandstone reservoirs of Lower Jurassic or Lower Cretaceous. Lądek-Zdrój is an example of a spa – one of many, where there is an urgent need to switch heating systems into clean ecological ones. The location of this town within the Sudety region implies different geological, tectonic, hydrogeological and geothermal conditions than the Polish Lowlands. The study of this case was very informative and paying attention on the conditions for a stable, long-term sustainable use of geothermal water both for medicinal purposes (as it has been so far) and for planned heating (thanks to geothermal water expected to be discharged by planned deep well).

5. Project Tasks

The Project activities were included into the following Tasks:

Task 1. Study Visit to Poland,
Task 2. Study Visit to Norway,
Task 3. Study Visit to Iceland
Task 4. Technical reports from Study Visits,
Task 5. Study Visits’ Report,
Task 6. Project Dissemination,
Task 7. Project Management and Promotion,
Task 8. Indirect costs.
These activities are presented in more details below.

Task 1. Study Visit to Poland, 17–23.09.2017

This task included e.g. the evaluation of the potentials and conditions of geothermal sources and energy effective district heating in the prospective regions of Poland, using the examples of the selected Polish towns, visited during the Project performance: Konstantynów Łódzki, Poddębice, Sochaczew, and Lądek-Zdrój; obtaining information for preliminary feasibility studies on the use of geothermal energy and efficient energy management in the selected towns. Starting contacts between the Project Partners and performers.

The Visit included the following:

- Opening Conference in Łódź, 18.09.2017,
- Technical Visits in four selected Project towns, 19–23.09.2017,
- International working Kick-off-Meeting (KoM) on 18.09.2017 (reported under Task 7).

The Study Visit to Poland and its events (given above) were participated by the Project partners representatives (MEERI PAS, AGH UST, WUST, CMR, OS, EGEC), representatives of selected towns, experts. Altogether there were about 50 persons. The Opening Conference and technical visits were attended also by the representatives of the Ministry of the Environment and NFEP&WM – co-Operators of PL04 Programme.

Opening Conference, 18.09.2017

The Conference took place in Łódź (Holiday Inn Hotel) on 18.09.2017. The main objectives and assumptions of the Project were presented, with an introduction to geothermal district heating in Europe, in the Donor Countries in particular. That was a background for the description of e.g. the present status of the sector, pubic support instruments available since 2016, development prospects of the sector in Poland, conditions and development plans of geothermal energy in the selected towns, objectives and programmes of the technical visits to particular sites. About 70 persons participated the Conference. They were the representatives of the Project performers, interested local governments, district-heating companies, consulting offices, investors, research workers, doctoral students, undergraduates and general public. 19 papers were presented (available at www.eeagrants.agh.edu.pl).

The Conference represented high organisational and substantive standards which were attained owing to a considerable involvement of all the partners and project performers, as well as very professional and competent simultaneous interpreting.

Technical Visits in four selected towns, 19–23.09.2017

Technical visits to the four selected Project towns took place on 19-23.09.2017: Konstantynów Łódzki, Poddębice (19.09.2017), Sochaczew (20.09.2017), and Lądek-Zdrój (21–23.09.2017). The first three towns are situated in the Polish Lowlands, and the fourth in the Sudety Mountains. When travelling from Łódź to Lądek-Zdrój (21.09.2017) the delegation stopped shortly at the Bełchatów open-pit lignite mine and power plant.

Similarly to the Opening Conference, the technical visits attained their objectives and fulfilled their assumptions. They were very well prepared in both organisation and substance, owing to considerable involvement of the Project partners and performers, as well the co-operating agencies and corporations. again, we wish to emphasise the role of professional and competent interpreting.

More detailed observations and recommendations of the Study Visit to Poland and the proposals to be taken into account in the Report on the Study Visits (T. 5) are contained in the Technical Reports drafted by the Partners, experts and town representatives. The Reports were prepared under separate Task 4 (also concerning similar Technical Reports on the Study Visits to Norway T. 2 and Iceland T. 3).

Task 2. Study Visit to Norway, 9–13.10.2017

The Study Visit to Norway (Bergen) was intended to learn the examples of good practice and experiences of heat pump operation in the selected Norwegian heating installations and included: visits to selected plants; initiation of bilateral contacts directed at co-operation under this Project; possibilities of future bilateral co-operation and projects; collection of information and observations for the needs of the Project performance. The group of participants was composed of the representatives of the Polish partners, towns, and experts (21 persons), together with the partners from Iceland (3 persons), EGEC (1 person), and Norwegian organisers. The programme contained the Introductory Seminar, with working meetings between the Project Partner's representatives from Norway; visits to the selected district-heating plants and grid heated buildings, as the examples of good practice in geothermal district heating, with the application of heat pumps and efficient energy management principles.

The program of the Study visit included the following:

- Introductory Seminar, 10.10.2017,
- Technical visits to the selected facilities in Bergen that use geothermal energy for heating purposes, with the application of heat pumps, as well as modern energy-saving and energy efficient solutions,
- Working discussions and meetings relating to the specific joint topics under this Project,
- International Interim Meeting of Partners (IM), 11–12.10.2017 (reported under T.7).

Introductory Seminar

The Seminar took place in Bergen on 10.10.2017. It was opened by Dr. Kirsti Midtomme (Coordinator, representing CMR) and the Chairman of the Bergen City Council. Next, the Project Partners were introduced and the main Project objectives and Project assumptions were discussed; an introduction was made to the issues relating to geothermal district heating in Europe and Poland, and primarily in Norway, with particular attention paid to heating systems and solutions, using geothermal heat pumps (including high-power pumps) that would be suitable for the Polish conditions, together with relevant economic, ecological, and social benefits. A lot of time was devoted to the issues of underground energy storage systems

(ATES and UTES), as well as low-emission, energy-saving strategies of development adopted in Bergen and Norway, using geothermal energy and other prospective renewable energy sources existing in Norway and Poland. Particular topics were presented by the CMR specialists and their co-operating institutions and companies, while some of the papers were read by other Partners, representing OS, EGEC, and IGSMiE. The Seminar made a good introduction to the Technical Visits and opportunity for starting contacts and co-operation, in connection with both the Project and possible future projects.

Electronic versions of selected presentations from the Seminar are on Project website (www.eeagrants.agh.edu.pl).

Technical visits in the selected plants in Bergen using geothermal energy for space heating and cooling, with heat pumps and modern energy-saving and energy efficient solutions

The technical visits to the selected plants in Bergen (Sweco Norge, NTNU, Høyteknologisenteret University and other) took place on 11–12.10.2017. The delegates paid attention to the care for the introduction of the relevant solutions and their application in the local conditions. The group also learned the geothermal and geological conditions of Norway, especially those of Bergen and the region.

The visit programme was very rich. A number of instructive observations were made and essential data collected, since the plants and installations were selected in the way to be the most useful for the Polish towns and the Polish conditions.

The Technical Visit to Norway fulfilled its goal and assumptions. Similarly to Poland and Iceland (T. 1 and T. 3, respectively), the visit was very well prepared organisationally and substantively.

More information on the Study Visit to Norway and the consequential observations and conclusions are placed in the Technical Reports drafted by the respective Partners, experts, and town representatives, as part of separate Task 4 (also relating to similar Study Visit Report to Poland T.1 and Iceland T.3).

Working discussions and meetings concerning the jointly studied topics under the Project

During the visit, discussions were held and opinions were exchanged between the participants, in reference to the plants being visited and the works conducted under the Project. Further methods of work were arranged to attain the assumed objectives, especially in view of the short time of Project performance and rich scope of topics. The participants also listed initial conclusions, being important for the Project performers, especially the Partners and the Polish local governments.

Interim Meeting (IM)

The international working Interim Meeting took place on 11–12.10.2017 (the meeting is reported separately under Task 7).

Task 3. Study Visit to Iceland, 2–7.10.2019

Study Visit to Iceland was intended to learn the examples of practice in grid geothermal district heating and initiate bilateral contacts between the representatives from Poland and Iceland, aimed at co-operation under the Project, as well as possibilities of future bilateral co-operation and projects. The goal was attained by holding a Seminar, Technical Visits to the selected plants; working discussions; initiation of bilateral contacts; and collection of information for the needs of the Project performance. The participants represented the Partners from Poland, Polish towns an experts (20 persons), and EGEC (1 person), as well as experts and observers themselves (from the Polish Ministry of the Environment and the NFEP&WM – 3 persons), as well as the organisers, representing the Icelandic partner.

The visit took place on 2–7.10.2017 r. and included the following:

- Introductory Seminar held at the National Energy Authority of Iceland (OS) in Reykjavik, 3.10.2017,

  Technical Visits in the selected plants in Reykjavik and southern Iceland using geothermal energy for space heating, power generation and other geothermal companies, 4–6.10.2017,

- Working discussions and meetings relating to the jointly considered topics under the Project.

Introductory Seminar

The Seminar took place at the Office of the National Energy Authority of Iceland (OS) in Reykjavik on 3.10.2017. The main objectives and assumptions of the Project were presented, with an introduction to geothermal district heating in Europe, Poland, and primarily in Iceland, with the description of the technical solutions suitable for Poland, together with relevant economic, ecological, and social benefits, associated with the general use of geothermal energy in district heating and many other applications in the Donor Country, geothermal initiatives, and the conception of energy clusters, including geothermal ones. Especially invited representatives of companies operating in the geothermal sector described their activities and the possibilities of bilateral co-operation, also in innovative areas.

The Seminar made an excellent introduction to visiting technical facilities and substantive discussions among the participants on subsequent days, especially in the context of joint work under the Project.

The Seminar represented high organisational and substantive levels thanks to a considerable involvement of all the Partners and Project performers, as well as very professional and competent simultaneous interpreting.

Selected presentations delivered during the Seminar are available at www.eeagrants.agh.edu.pl.

Technical visits in the selected facilities using geothermal energy in district heating and for other versatile purposes in Iceland

Technical Visits took place on 4–5.10.2017. The group observed selected facilities, using geothermal energy in district heating (Seltjarnarnes town and the Reykjavik agglomeration), a greenhouse farm, a snow melting system on roads and footpaths, facilities designed for recreation, balneotherapy, advanced cosmetics and biologically active article production, and geothermal power and district heating plants. Holistic approach to energy and energy saving was emphasised. Geothermal and geological conditions of Iceland were described.

The visit programme was very rich, and the plants and installations were selected in the way to be the most useful for the Polish towns.

The Study Visit to Iceland fulfilled its goal and assumptions. Similarly to Poland and Norway (T. 1 and T. 2, respectively) the visit was very well prepared organisationally and substantively, owing to the considerable dedication of the Partners and Project performers, as well as the co-operating institutions and companies. What was essential for full comprehension of the contents was very professional and competent simultaneous interpreting.

More detailed observations of the Study Visit to Iceland and the proposals to be taken into account in the Report on the Study Visits (T. 5) are contained in the Technical Reports drafted by the Partners, experts and town representatives, as part of separate Task 4 (also concerning similar Technical Reports on the Study Visits to Poland T. 1 and Norway T. 2).

Working discussions and meetings concerning the jointly studied topics under the Project, exchange of observations and opinions on the Visit

During each day of the visit, lively discussions were held and opinions were exchanged between the participants, also in small teams and among individuals, in respect of the Projects works and with the intention to arrange a further course of works on the issues planned to be completed under the Project. On the last day of the visit, the group shared their observations and conclusions, being important for the Project Partners, especially the local governments of the Project towns.

Task 4. Technical Reports on Study Visits

Technical Reports on Study Visits (T.1, T.2, and T.3) were concise and drafted by the Project partner teams, experts, and town representatives, participating in the particular Study Visits. The Reports concentrated on passing observations and remarks, as well as indication of proposed solutions, technologies etc., relating to good practices available in the Partners' countries that can be transferred to the selected areas of the Polish towns and taken into account in the Study Visits' Report (T. 5). Particular Study Visit Reports related to Poland, Norway, and Iceland contain very useful observations, recommendations, and proposals that have been included in the the Study Visits' Report to a large extent.

Task 5. Study Visits' Report

Study Visits' Report form a main outcome of the described Project. It is based on data, observations and knowledge obtained during the Study Visits, as well as multi-aspectual specialist analyses and studies completed by the Project Partners, experts, and town representatives during the Project works.

The Report has a broad scope and contains, e.g. preliminary feasibility studies of the use of geothermal energy in district heating and efficient energy management on the example of four towns situated on the selected areas of Poland, as well as e.g. the proposals of pilot installations to be provided in district heating plants, with the use of geothermal energy in the Project towns (it is expected that the proposals will be ready for implementation in a subsequent period of EEA funding). The Report also discusses basic aspects of geological, geothermal, drilling, technological, and energy generation matters, as well as economic, legal and other instruments that are indispensable for an optimum development of geothermal district heating in the selected towns (the instruments that will be in fact applicable to the whole country), so that the relevant projects could contribute to low-emission economy, improvement of the quality of life, and sustainable development. The Report is very important for the Partners and other stakeholders.

Task 5 contained 15 subtasks (5.1–5.15) listed below:

5.1. Review of geothermal conditions in Poland
5.2. Current state of geothermal uses and development prospects in Poland (focus on study areas)
5.3. Analysis of geological and hydrogeothermal parameters and evaluation of geothermal resources of Lower Cretaceous and Lower Jurassic reservoirs of the Mogilno–Łódź basin aimed to location of new heating installations

5.4 – 5.7 Pre-feasibility studies on geothermal energy uses in selected towns:

5.4. Poddębice study case
5.5. Sochaczew study case
5.6. Konstantynów Łódzki study case
5.7. Lądek-Zdrój study case
5.8. A review and lessons learnt from the so-far experiences in applying geothermal drilling technologies, well equipment, borehole research and logging – conclusions for selected areas in Poland
5.9. Best practices in geothermal drillings in Iceland suitable for Poland
5.10. Heat pumps in geothermal heating in Norway and Iceland – recommendations for Poland
5.11. ATES and UTES technologies in Norway and Europe – recommendations for Poland
5.12. Regulatory and financial incentive measures for geothermal development in Europe
5.13. General conditions for geothermal energy development in Poland and proposed actions
5.14. Proposals of pilot projects in Poland based on Project results
5.15. Final elaboration and consultations of the Report on the Study Visits

Particular topics elaborated in the framework of Task 5 are given in Part II of this Report.

Task 6. Project Dissemination

Task 6 contained the following activities:

- Project Summary Conference,
- Presentation of Project and its selected results during selected national conference organised by other entities (Kraków, Poland),
- Project website, flyer, roll'up, poster,
- Articles summarinsing the Study Visits' Report and Project results.

The scope of the activities completed under Task 6 was wider than had been planned initially. It entailed both tasks contemplated at the stage of the Project application and other activities that were completed in connection with the newly appearing opportunities of disseminating the Project during several other high-ranking national and international events to which the Project Leader's representatives were invited.

Project Summary Conference

The Conference was held at the Ministry of the Environment in Warszawa on 24.10.2017. The Ministry was a Conference co-organiser. Invitations were issued jointly by Prof. Mariusz O. Jędrysek – Secretary of State, the State Plenipotentiary for Raw-Material Policy, and Prof. Krzysztof Galos – Director of MEERI PAS (Project Leader). More than 80 persons participated. What indicated the interest and importance of the Conference topic was e.g. the participation and contributions from the Ministry of the Environment, the Ministry of Energy, the Office of the Polish Prime Minister, the NFEP&WM, and the Embassy of the Kingdom of Norway in Poland (a Donor Country).

Other participants represented the Project Partners, the Polish towns, and experts themselves, as well as other ministries and government agencies, local governments, investors, district heating companies, geothermal facilities, consulting companies, the Polish Geothermal Society, and the Polish Geological Institute-National Research Institute (conducting the complementary EEA Project, Geothermal 4PL).

The main Project results were presented during the Conference, including e.g. preliminary feasibility studies of the use of geothermal energy in district heating, in the selected towns, the proposals of pilot projects, implementation of indispensable financial instruments etc. Five addresses were read (by the directors from the Polish Ministry of the Environment, Ministry of Energy, the Office of the Polish Prime Minister, the NFEP&WM, and the Embassy of the Kingdom of Norway in Poland), members of Polish Parliament. 19 papers were presented on the key Project issues. In the participants' opinions, the Conference represented high organisational and substantive standards and indicated the importance for the Project activities for a further development of geothermal energy projects in Poland. The Conference presentations are available at Project website (www.eeagrants.agh.edu.pl).

Project dissemination during selected conference in Poland

The event selected for the Project dissemination was the IX Scientific Conference on the "Environmental Protection and Engineering – Sustainable Development" on the 25th Anniversary of the Walery Goetel School of Environmental Protection and Engineering (the School patron was the conceiver of sozology and a pioneer of the principles of sustainable development and natural resource protection). That prestigious Conference took place on 7-8.09.2017. It was organised by the AGH University of Science and Technology (with sessions taking place in Kraków and Kocierz). The Project Partners were represented by five persons from MEERI PAS, AGH UST, WUST.

Our representatives presented five papers, with the purpose of our Project dissemination.

Those papers were published in the reviewed periodical "AGH Monographs of the Faculty of Mechanical Engineering and Robotics," entitled "Geothermal energy – opportunities for low-emission district heating, improvement of the quality of life and sustainable development in the selected areas of Poland" (No. 4, 2017, ISBN 83-922535-1-8, SOiIS Publishers, AGH Kraków). The Monograph copies were distributed among all the Conference participants (ca. 100 persons), as well as the Project Partners, experts, Town Office representatives participating in our Project, co-operating entities, as well as some participants of the Opening (18.09.2017) and Summary Conferences (24.10.2017).

In addition to the above-mentioned activities planned while application for project funding, dissemination of Project and its role for the development of geothermal district heating in Poland was fulfilled during the following important and high-ranking conferences:

International Conference of the cycle "Carpathian Europe" under the auspices of the Polish Parliament Speaker, as part of the XXVII Economic Forum in Krynica Zdrój

The Conference took place on 5–-7.09.2017. The Project Partner was represented by its leader (MEERI PAS) who was invited to join a panel discussions on 6.09.2017 (with the participation of the Chief Geologist of Poland, Vice Minister of the Environment from Slovakia, the Executive Director of IGA, and a representative of the Hungarian Mining and Geological Service). During the discussions, the reference was made and showed sections of the Project being reported, as a good example of the activities for the development of geothermal energy in local district heating in Poland and other Central European countries, emphasising e.g. the need of further co-operation in the sector, as part of EEA mechanisms, and in a wider context, with the participation of the Donor Countries and the countries of this part of Europe, including Poland, Hungary, Slovakia, or Romania which have prospective geothermal resources and are fortunate to benefit from EEA grants.

Expert Panel Discussion on geothermal energy held during the POL-ECO SYSTEM 2017 Fair in Poznań

The Expert Panel discussion took place on 17.10.2017 as part of the cycle on the National Raw-Material Strategy promotion organised by the Polish Ministry of the Environment. The Project leader, accompanied by the Deputy President of the NFEP&WM, the President of the PEC Geotermia Podhalańska SA, and a representative of the Polish Geological Institute-National Research Institute participated in the panel discussion on "Heat of the Earth: geothermal energy and geothermics" by invitation of the Government's Plenipotentiary for the National Raw-Material Policy. During the panel the Project works and their importance were highlighted.

Summary Conference, complementary EEA Project “Geotermal4PL” in Warszawa

The EEA Geotermal4PL Project Partners were Polish Geological Institute and CMR from Norway. The Conference took place in Warszawa on 25.10.2017 (during the “Renexpo” Fair and Conference). The Project Manager (MEERI PAS) presented the main objectives, activities and results of the Project being reported.

Side event on geothermal in Poland organized by the Ministry of the Environment at COP23 in Bonn

The event was held at COP23 in Bonn, on 16.11.2017. The topics were the current state, prospects, examples of good geothermal heating practices in Poland, as well as selected research topics, national and international projects. The side event was attended by the Project Manager (MEERI PAS) who presented objectives, assumptions and results of the EEA Project and proposals for further bilateral projects under the EEA mechanism.

Project website

The Project website was designed, opened, and maintained at www.eeagrants.agh.edu.pl. It contains basic Project data, current activities and works, and pictures, with updates. The website fulfilled the Project’s information and promotional functions. The links to the Project website were also published by the other Project Partners. The website contains links to the EEA Funds and Norway Grants.

Flyer

The flyer texts were written in Polish and English, with graphic design. The flyer was printed in 1,000 copies in each language. The flyer was distributed among Conference participants and during other events frequented by our Partners and experts, among the representatives of the Project towns, potential investors, contractors, other stakeholders and individuals interested in the use of geothermal energy in district heating in Poland, as well as media. Brochure copies were also submitted to the Project Partners and performers, the Programme Operator, and other institutions for further promotion. The printed brochure is available in the Partners’ offices.

The electronic version of the brochure is also available on the Project website and the websites of the Project Partners.

Information and promotional roll-up and poster

A roll-up and posters were designed and printed. They were displayed for Project promotion purposes at the Opening and Summary Conferences, study visits. They are also displayed in visible places in our Project Partners’ offices.

Scientific articles and popular science articles

- Five articles presenting the Project and its selected results were published in the issue of the publication series “AGH Monographs of the Faculty of Mechanical Engineering and Robotics” entitled “Geothermal energy – opportunities for low-emission district heating, improvement of the quality of life and sustainable development in the selected areas of Poland”, as mentioned before,
- Article about the Project published in the “GlobEnergia” – one of main magazines on RES in Poland (No. 4, 2017),
- An abstract of the paper on “Developing geothermal district heating solutions for 4 towns in Poland“ was drafted and sent to the Nordic Geological Winter Meeting in Denmark,
- Elaboration, editing, and printing 15 articles, summary papers on the Study Visits’ Report and several ones presenting selected Project topics – published in the Magazine “Geological Exploration Technology. Geothermics. Sustainable Development (No 2/2017),
- Elaboration and recording of CD the main contents of the Study Visits’ Report (Polish, English).

Task 7. Project Management and Promotion

This Task included Project works management, Project working meetings, Project promotion. Under management, working meetings were organized, conference materials were prepared, press releases were prepared and published, information was disseminated in the media and electronic media. Some activitiesa are listed below.

Preparation of conference materials

That activity concentrated on drafting the content, designing graphic presentation, and printing the Conference and study Visits’ programmes, graphic design and CD recording with conference presentations, purchase of files (with designing file labels), pens, and notebooks, and preparation of name tags for Conference participants.

Project Partners' working meetings

All planned Project Partners' international working meetings took place:

- Kick-off-Meeting, KoM, in Łódź, Poland, on 18.09.2017,
- Interim Meeting, IM, in Bergen, Norway, on 11-12.10.2017,
- Final Meeting, FM, in Warsaw, Poland, on 25.10.2017.

The working meetings of the Polish partners and performers took place on the following dates: 20.07.2017, 22.08.2017, and 31.08.2017.

Project promotion activities included:

- Press releases,
- Information in press, TV, electronic media.

Press releases

Press releases promoting the Project activities were drafted in Polish and English. They were sent to selected newspapers, journals specialising in renewable energy sources, the Project Partners in Poland and abroad, the Polish Ministry of the Environment, the NFEP&WM, Polish local media during the Opening and Summary Conferences, Study Visits, Project town representatives, and co-operating institutions.

Information in press and TV stations

Project details were published in the following media (present status):

- Press: several local titles of the Project towns; "Morgunbladid", one of the main dailies in Iceland,
- TV: e.g. TVP3 Łódź regional public TV station: report on the Project recorded during the study visit to Poddębice; Icelandic TV channel: interview with the Project Manager (from MEERI PAS) and Icelandic Coordinator, OS, 4-5.09.2017.

Information in electronic media

Project details were published on Internet portals and websites of the Project Partners and the selected Project towns. Details were also displayed on the official portal and Facebook sites of the Polish Ministry of the Environment, in connection with the Project Opening and Summary Conferences.

Task 8. Indirect Costs

Indirect costs were calculated and structured according to respectibe EEA guidelines.

6. Main substantive outcomes of the Project works

The main studies developed owing to the Project performance include the following:

- Updating geothermal data of the Mogilno-Łódź Trough (in respect of future prospects for geothermal district heating),
- Preliminary feasibility studies on the use of geothermal energy in the selected towns,
- Develop innovative financial models for geothermal projects including e.g. the Geological Risk Insurance Fund,
- Proper drilling technologies and borehole research in geothermal applications,
- Heat pumps in geothermal district heating,
- General conditions and proposals for geothermal space heating in Poland,
- Proposals of pilot district heating installations, with the use of geothermal energy (to be implemented under the subsequent period of financing from EEA/Norway Grants).

The Project works contributed to achieving several important objectives and pointed out several indispensable factors and further actions for successful geothermal heating development in Poland:

- Increase the awareness of regional and local decision-makers on geothermal potential and its advantages,
- Train technicians and decision makers from regional and local authorities in order to provide the technical background necessary to approve and support projects, including ccapacity building, training and educational activities,

- Modernize the district heating systems,
- Improve the role of independent regulators,
- Improve the role of district heating companies,
- Establish a level playing field between geothermal, coal and gas price and taxing greenhouse gas emissions in the heat sector appropriately,
- Consider additional elements of public authorities, energy efficiency etc.,
- Consider, what international financing institutions can do to help,
- Geothermal utilisation is important for economic benefits and development, mitigation climate change and quality of life,
- Simplify the administrative procedures general framework conditions and proposals for the development of the concept and stratefgy to develop geothermal district heating systems in Polish towns.

7. The role of the Project in supporting geothermal district heating development in Poland

Poland is only initiating a long-awaited general development of geothermal district heating. That option has presently become realistic, mainly owing to the implementation of the government support system for exploration drilling and other types of drilling operations, as well as other services relating to that sector of ecological heating (with cogeneration) in 2016. There are many indications of good geothermal practice, with energy efficient facilities, to attain the level similar to that of the leading European countries. To that end, it is necessary to use the experiences of e.g. the best technologies and solutions available, in co-operation with the best foreign specialists, including the teams from Norway, Iceland, and EGEC, being the main European organisation in the geothermal sector.

The presented Project has contributed to the fulfilment of our intentions and its results, outputs, and outcomes will be useful for the Polish local governments in the towns that have participated in this Projects and many other locations, as well as researchers, practitioners of a number of specialties associated with district heating and geo-district heating in particular, and decision makers at various administration levels.

The use of the Project outcomes, studies, and recommendations will increase the chances of designing energy efficient and economic geothermal installations, together with the optimisation of the currently operated ones. That role of the predefined Project has been strengthened by the fact that it has been performed by initiative of the Polish State Plenipotentiary for the National Raw-Material Policy, supported by the Polish Ministry of the Environment and the Polish National Fund of Environment Protection and Water Management, both showing a great interest in the Project outcomes.

8. Good examples, specific models, observations, and recommendations for selected towns and Poland resulting from the Project performance

Joint works and discussions, information exchange, study visits, and meetings under this Project resulted e.g. in the collection of the following observations and recommendations for the selected towns and on a national scale. The Project outcomes concentrate on geothermal energy and energy efficiency, although they often contain a wider scope of issues and outreach. The Project outcomes will become inspiration and justification for starting a number of more comprehensive and advanced activities by local governments, in co-operation with researchers, practitioners, and decision makers. The Project results can be presented briefly as follows:

- There is a growing need in Poland to adopt a comprehensive and holistic approach to energy and its role,
- Geothermal energy can become an axis of modern and innovative, local and regional economic development, economic savings, mitigating climate change by lowering CO2 and increasing the quality of life,
- It is necessary to increase energy efficiency in district heating (including geothermal district heating) in Poland, implement low-temperature heating systems, improve heat reception, and assure an active participation of the final customers in those processes, in order to develop smart thermal grids: the new generation of district heating for this country,
- Geothermal energy + energy efficiency + energy storage = the tasks and recommendations for the Project towns and other areas of Poland,
- Low-temperature geothermal water (e.g. after cooling in heat exchangers) should not be treated as waste, but as a resource and motivation for further practical applications (of “each drop”),

- Proper geothermal resource management, research, modelling, and monitoring are essential for long-term and stable operation of a geothermal district heating system (involving production and injection wells, corrosion prevention, and clogging issues),
- Proper drilling technologies, borehole testing, and geothermal maintenance services are of key importance to flawless operation of geothermal wells and systems; a lot of respective solutions are waiting to be updated or applied in Poland,
- Heat pumps in geothermal installations: heat pumps should be properly selected for the Polish conditions, taking into account e.g. investment and operating costs. It will also be necessary to determine the pumps' annual operating periods in the specific, individual cases, with the expected economic effects,
- It is necessary to improve general and specialist knowledge, as well as awareness of a number of social groups regarding geothermal installations and energy efficiency,
- Energy clusters: proven initiatives of Iceland and Norway, encouraging us to apply them in Poland.

9. Possibilities, areas and forms of further co-operation on geothermal aspects and energy efficiency within the subsequent EEA/Norway Grants perspective

The course of co-operation under the present Project and the Project outcomes have convinced all Partners and performers that it will be well justified and recommended to co-operate in the future. A base fo such co-operation is as follows:

- Good mutual professional and individual contacts,
- Essential values of meetings and initiated co-operation between the leading teams in the respective countries and on an international scale, which requires continuation and expansion,
- Versatile knowledge, experience, and creative skills of teams and individuals that will be able to develop subsequent advanced and innovative topics and projects (in research, implementation, and capital investment projects).

The above-mentioned aspects present considerable chances for success in joint expansion of the present scope of topics, studied under the EEA/Norway Grants Financial Mechanisms, to be implemented in the subsequent periods in Poland and with the participation with the foreign Partner teams.

Our co-operation can be conducted successfully in several areas, including professional training, research works, pilot projects, and capital investment projects in the area of geothermal energy and energy efficiency (specific details are described in the Report on Study Visits (www.eeagrants.agh.edu.pl), as well as to some extent in the separate papers presenting selected Project results, published in this volume).

Diverse forms of co-operation in the areas of geothermal energy and energy efficiency, within the EEA/Norway Grants Financial Mechanisms should include the following, e.g.:

- Study visits, transfer of knowledge and good practice, and starting contacts,
- Advanced research and (R+D+I projects,
- Specialist training and consulting sessions,
- Demonstration, pilot, and capital investment projects,
- Transfer and exchange of experiences, technologies, and good practice in drilling, measurement methods, equipment, well stimulation, correct borehole operation, resource modelling, and practical applications,

In that way, the Project partners would jointly contribute e.g. to the implementation of the objectives of the EEA/Norway Grants Financial Mechanisms intended to limit climatic changes, fulfilment of sustainable development principles, improvement of the standard of life, and provide low-emission district heating systems.

To indicate more distant areas of geothermal development in Poland and further co-operation, within EEA/Norway Grants Financial Mechanisms, we can mention here the main issues as follows:

- District heating: central heating systems (locally with cogeneration),
- Ecological agriculture, acqua cultures and fish farming, and advanced biotechnology,
- Balneotherapy and recreation,
- Potable and mineral water production from geothermal fluids,
- Geothermal heat pumps (for heating and cooling),
- Underground thermal energy storage systems.

Final remarks

When indicating the prospects of a broader use of geothermal energy in Poland and the co-operation between Poland Norway and Iceland, we need to emphasise that the use of that specific energy source in the Donor countries, in association with energy efficiency and the holistic approach to energy in Iceland and Norway, has brought about positive ecological, economic, and social effects, including improved quality of life and other benefits.

In the case of Poland, however (despite the fact that power generation is based and will be based on fossil fuels here) there are many opportunities to use geothermal energy and to continue international co-operation in that sector, also with Norway, Iceland, and EGEC, and within EEA/Norway Grants.

One can conclude by saying that the EEA/Norway Financial Mechanisms should become for Norway, Iceland, and Poland a platform of co-operation and investment in a reliable and lasting geothermal infrastructure designed for increasing energy security, assuring independence of external energy sources, and limitation of gas emissions generated by the traditional heating systems.

Positive examples and outcomes of similar co-operation projects have been attained e.g. in Hungary and Romania. The time has come to include Poland in “geothermal” co-operation under EEA/Norway Grants. The outcomes of this GeoHeatPol Project convince us that there are great opportunities in Poland for such activities, which can be valuable for concerning regions for economic development and savings, mitigating climate change and improving quality of life.

PART II

T. 5. STUDY VISITS' REPORT

Part II contains full texts of a wide spectrum of topics elaborated by the Project Partners and performers in a framework of Task 5. Study Visits' Report. They are presented in a following sub-chapters 5.1 – 5.14:

5.1. Review of geothermal conditions in Poland
5.2. Current state of geothermal uses and development prospects in Poland (focus on study areas)
5.3. Analysis of geological and hydrogeothermal parameters and evaluation of geothermal resources of Lower Cretaceous and Lower Jurassic reservoirs of the Mogilno-Łódź basin aimed to location of new heating installations
5.4 – 5.7 Pre-feasibility studies on geothermal energy uses in selected towns:
5.4. Poddębice study case
5.5. Sochaczew study case
5.6. Konstantynów Łódzki study case
5.7. Lądek-Zdrój study case
5.8. A review and lessons learnt from the so-far experiences in applying geothermal drilling technologies, well equipment, borehole research and logging – conclusions for selected areas in Poland
5.9. Best practices in geothermal drillings in Iceland suitable for Poland
5.10. Heat pumps in geothermal heating in Norway and Iceland – recommendations for Poland
5.11. ATES and UTES technologies in Norway and Europe – recommendations for Poland
5.12. Regulatory and financial incentive measures for geothermal development in Europe
5.13. General conditions for geothermal energy development in Poland and proposed actions
5.14. Proposals for pilot projects in Poland based on Project results

5.1. Review of geothermal conditions in Poland

Distribution of geothermal resources is uneven in the world. Particularly favourable conditions for the creation of high-energy geothermal systems, which are potentially the best for industrial applications, occur in the area of lithospheric plates in rift and subduction zones. Poland is located outside of those zones, which means that there are no high temperature geothermal resources on its area. Poland is located in the zone of low temperature resources, for which heating is the key sector. Water temperatures documented with geothermal wells do not exceed 100°C. Presently, the highest temperature of geothermal water, where water reserves were identified, was reported in Konin (the area of Mogilno-Łódź Syncline). The temperature of geothermal water in the reservoir (Lower Jurassic reservoir) at the end depth of 2660 metres was 97.5°C, with mineralisation of 150 g/dm^{3}and high capacity of around 150 m^3/h (www.geotermiakonin.pl).

Geothermal conditions in Poland are relatively well recognised. Geothermal studies have been conducted in Poland since 1980's. Comprehensive information about Poland's geothermal resources is provided by a series of Geothermal Atlases, covering the areas of the Polish Lowland, Carpathians and the Carpathian Foredeep (Górecki (ed.) et al., 2006a,b, 2011, 2012, 2013). Those works indicate the possibilities of using hydrogeothermal resources (gathered in groundwater) for utility purposes, mainly heating, but also balneotherapy, recreation and the like. They have been supplemented by Atlas of geothermal water use in energy cogeneration in binary systems in Poland (Bujakowski, Tomaszewska (eds.) et al., 2014) published in 2014, indicating the opportunities of using the existing low-temperature resources in the selected regions of Poland for the production of electricity, which are not fulfilled in Poland at the moment.

In recent years, also research works were conducted in order to evaluate the energy potential with regard to using Hot Dry Rocks (HDR) in EGS systems (Wójcicki, Sowiżdżał, Bujakowski (eds.) et al., 2013; Sowiżdżał et al., 2013, Sowiżdżał, Kaczmarczyk, 2016).

Poland is located at the contact of three main tectonic European structures: Precambrian East European platform, young Palaeozoic platform of the Western and Central Europe as well as the zone of Alpine folding of Southern Europe, with a very well developed foreland basin (Stupnicka, 1997) (Fig.5.1.1). Each of those structures is characterised by different geological conditions, both in Europe and in Poland.

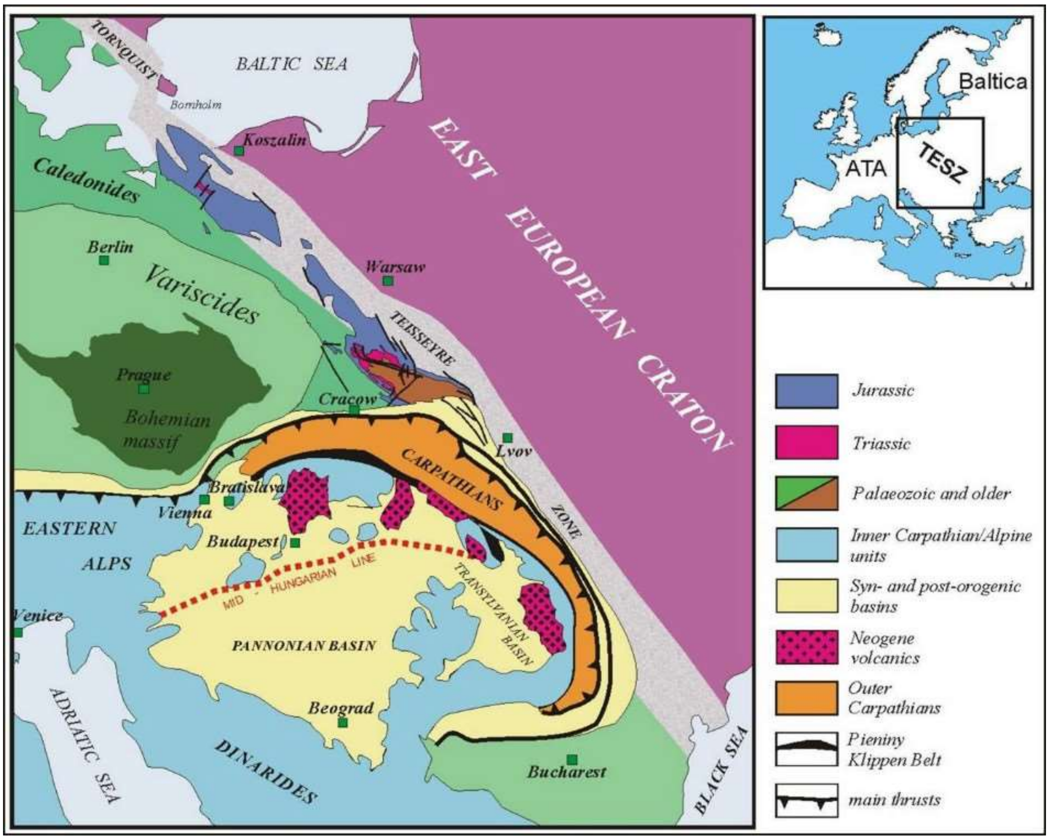


Fig. 5.1.1. Tectonic map of Central Europe showing the main tectonic components of this part of Europe, formed by three mega-units: East European Platform, Western and Eastern European Platform and the Carpathians. The three major tectonic systems of the European continent meet in the south-eastern Poland (Source: Institute of Geophysics PAS)

In Poland geothermal resources are accumulated in 4 main hydrogeothermal provinces (Fig.5.1.2):

- Polish Lowland
- Carpathians
- Carpathian Foredeep
- Sudetes

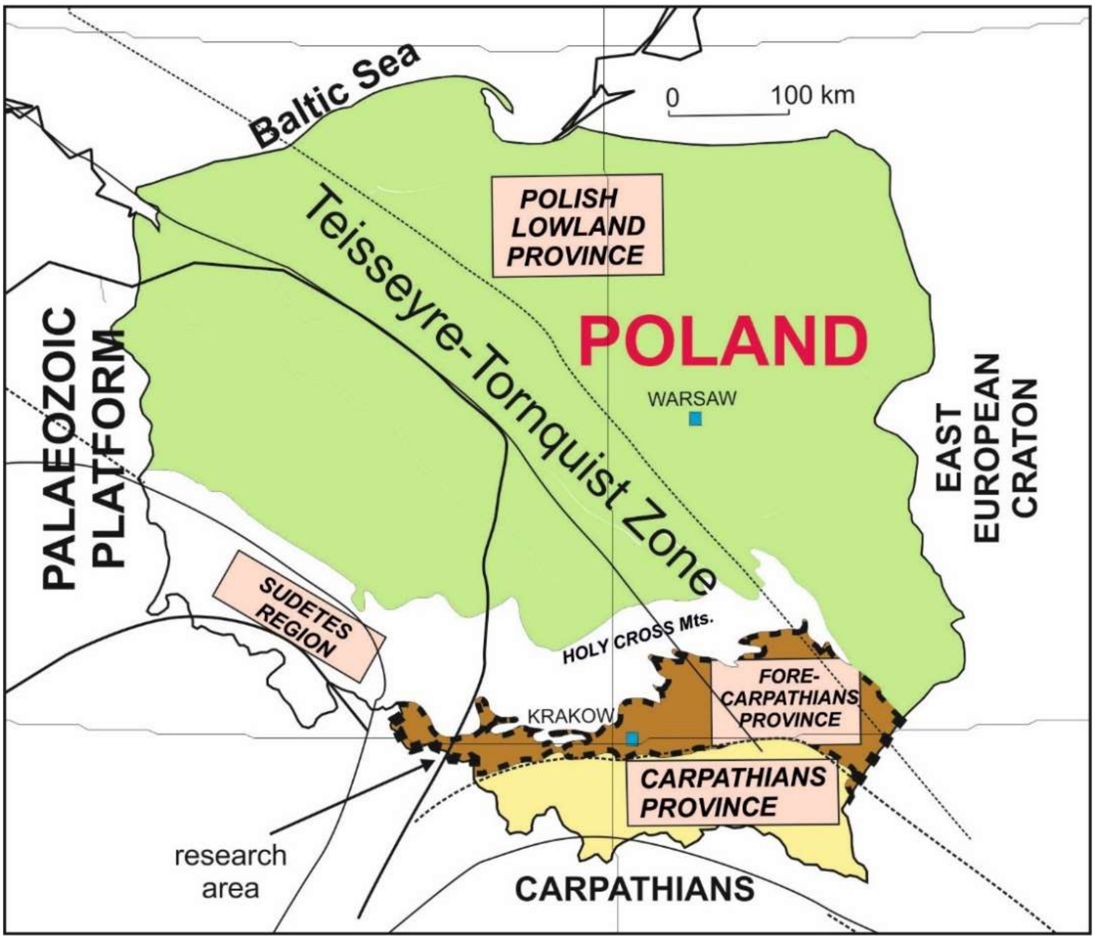


Fig. 5.1.2. Main hydrogeothermal provinces in Poland

The highest energy potential in Poland relates to the Polish Lowland and Podhale (Fig.5.1.3).

In the Polish Lowland, special attention should be drawn to the area of Mogilno-Łódź Syncline, where there are perspectives for the effective use of geothermal resources for energy purposes (both heating and electricity production in binary systems) and building of EGS installations in sedimentary rocks. In the remaining parts of Poland, the effective use of geothermal resources for heating purposes is limited due to low well capacities. The characteristics of four geothermal provinces in Poland has been presented in the chapters below.

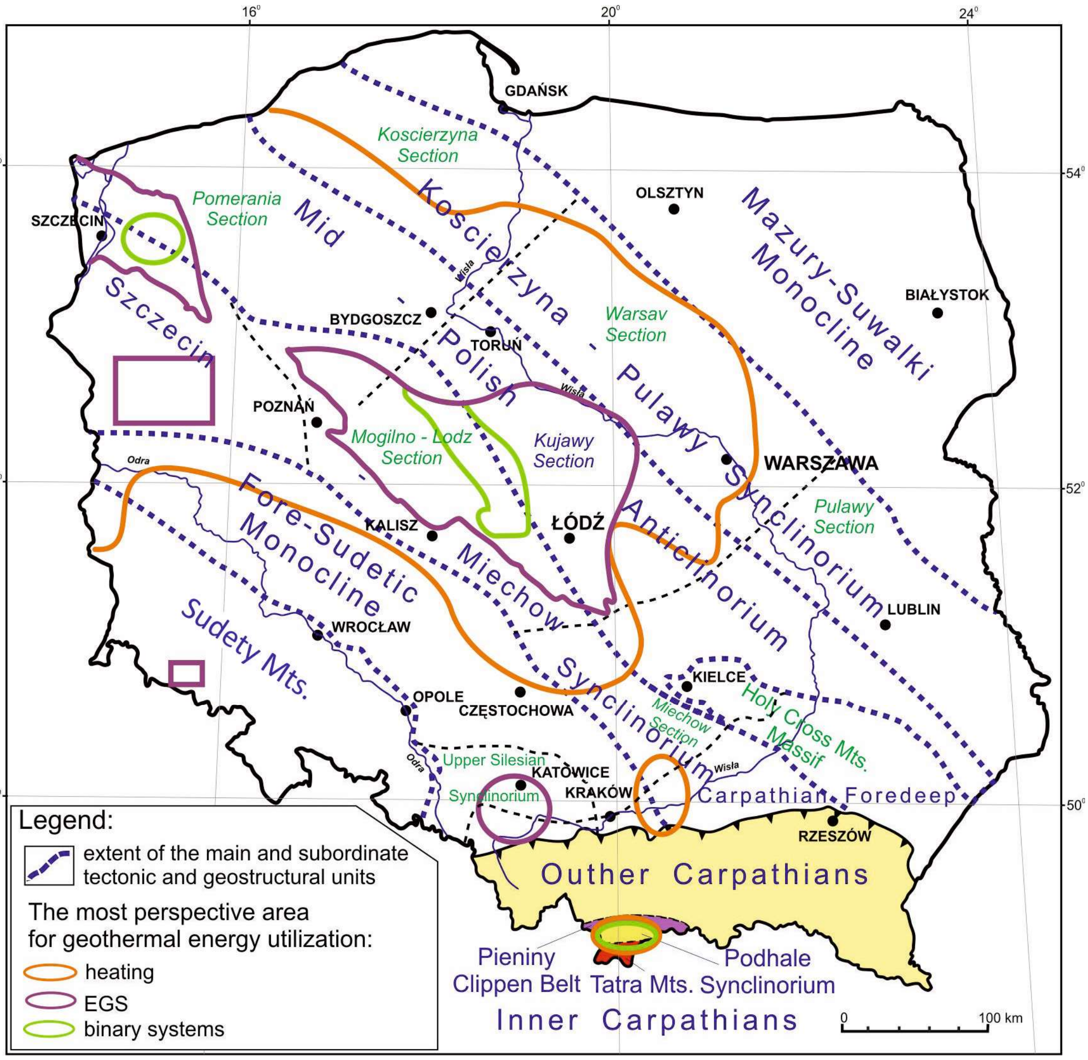


Fig. 5.1.3. Prospective regions in the area of using geothermal resources in Poland(based on the results of numerous scientific studies, including e.g. *Górecki (ed.) et al., 2006a,b, 2011, 2012, 2013)* against the map of tectonic units in Poland under the Cenozoic cover (Żelaźniewicz et al., 2011 – modified by M. Hajto)

5.1.1. Polish Lowland

The area of the Polish Lowland is the largest geothermal region in Poland. Geothermal resources there relate to Mesozoic formations (Fig. 5.1.4). A regional analysis of geothermal reservoirs on the Polish Lowland indicates that energy use for heating, technological, balneological and recreational purposes should be based on Lower-Jurassic and Lower Cretaceous hydrogeothermal reservoirs. Aquifers in Lower-Jurassic and Lower Cretaceous formations constitute sandstone complexes with high reservoir parameters. It is conducive to using high capacities, which affects economically viable constructions of geothermal plants in a positive way (Górecki et al., 2003; Górecki, Hajto (eds.) et al., 2006a; Górecki et al., 2010; Hajto, 2013).It is confirmed by the parameters of geothermal currently operating in Poland geothermal heating plant using geothermal water from the Lower-Jurassic (Pyrzyce, Stargard) or Lower Cretaceous (Uniejów, Mszczonów, Poddębice) level for energy purposes.

Significant geothermal energy resources on the Polish Lowland are also collected locally in the Upper Jurassic, Middle Jurassic, Upper Triassic and Lower Triassic formations. Geothermal waters from Devonian, Carboniferous, Lower and Upper Triassic as well as Lower and Middle Jurassic reservoirs can be used for recreational purposes, bathing and balneotherapy (Górecki, Hajto (eds.), et al., 2006b).

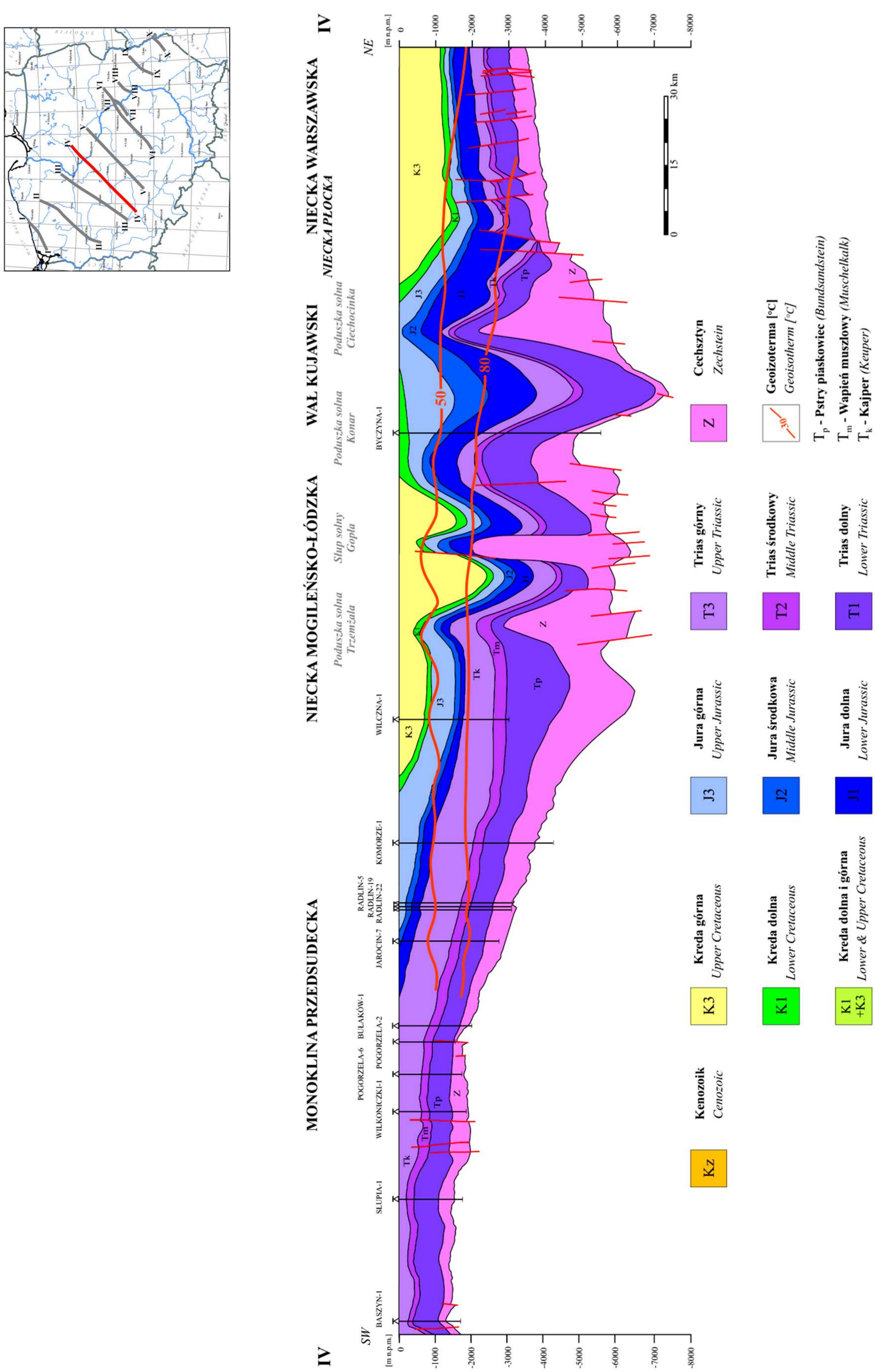


Fig. 5.1.4. Geological cross-section through the area of Polish Lowland (Górecki, Hajto (eds.), 2006a)

Lower Cretaceous reservoir

Main Lower Cretaceous aquifers are reservoir sandstones of Bodzanów Formation of the Lower Valanginian sealed with clay-mudstone formations and Włocławek Formation (Upper Valanginian–Hauterivian), and even more so sandstones of Pagórki Member (Aptianian), and, first of all, Kruszwica Member sandstones (Lower and Middle Albian) of the most upper part of Mogilno formation sealed marl-carbonate Upper Albian formations.

Lower Cretaceous formation roof is at variable depths from ca. 250 m above sea level in the area of Częstochowa and Kalisz, to over -2500 m above sea level in the area north–east of Konin. The highest depths where the roof of these formations occurs are recorded in central parts of Szczecin and Mogilno-Łódź Syncline (ordinate below -1000m above sea level). At similar ordinates the roof surface of Lower Cretaceous formations are arranged in Warszawa and Lublin Syncline. In all above-listed structural units the roof of Lower Cretaceous formations raises towards marginal zones to ordinates above -500 m above sea level and it even reaches 270 m above sea level. The roof surface is the highest on Łuków– Hrubieszów elevation (-500 ÷200 m above sea level) and in the northern part of Pomerania Syncline (-750 ÷ -200 m above sea level).

The total thickness of Lower Cretaceous formations ranges from several up to, locally, over 400 m (Mogilno Syncline). In all structural units thicknesses from 20 to 200 m prevail. The thickness of Lower Cretaceous formations usually has the highest values (over 200 m) in axial parts of syncline structures, decreasing down to several or a dozen metres in peripheral parts. The structural thickness distribution is locally distorted in the area of salt diapirs and tectonic planes. The lowest total thickness of those formations has been reported in Lublin Syncline, Łuków – Hrubieszów elevation, Mazuria – Suwałki elevation and Baltic syneclise (max. up to ca. 50 m) and in Szczecin Syncline, as well as on the area of the Fore-Sudetes.

General distribution of the total thickness of aquifers occurring in Lower Cretaceous formations is similar to the distribution of the total thickness of that age formations. The thickness of aquifers reported in the profile of Lower Cretaceous formations varies from several up to 150–300 m. The highest thickness occurs in Mogilno Syncline and in the north-eastern part of Łódź Syncline, slightly lower in the south-western Warszawa Syncline. In all structural units there is a tendency of declining aquifer thickness from the central part to peripheral zones. The lowest thicknesses of those formations are reported in Lublin Syncline, a north-eastern part of Warszawa Syncline, in Podlasie dip, Łuków – Hrubieszów elevation, Pomerania and Szczecin Syncline as well as on Fore-Sudetic area and in Miechów Syncline.

Temperature distribution in the Lower Cretaceous formations roof points to the occurrence of area dominant temperature ranges from 20–40°C. Only in the area of Skierniewice – Płock, north-western part of Mogilno-Łódź Syncline (the area of Konin) and in the north-western part of Szczecin Syncline, temperatures raise up to over 50°C and they are related to the highest structural dips of the central part of the aforementioned units. The occurrence of the highest temperatures in the Lower Cretaceous formations roof is reported in the area of Konin (particularly towards the north and north-west of Konin), where the values exceed 90°C.

Mineralisation of groundwaters occurring in the Lower Cretaceous roof layers changes from the borders of structural units (outcrop zones) towards their central parts. In outcrop zones of water mineralization units, it drops below 2 g/dm^3, it increases with water flow direction and it increases with depth up to 20, and, locally, even above 50 (in the area of Konin and Mogilno) and over 100 g/dm^3 (Szczecin Syncline). The freshest Cretaceous groundwaters occur within Kujawy anticlinorium (from ca. 1 do 10 g/dm^3), south-eastern part of Warszawa Syncline and Miechów Syncline as well as the south-eastern and western part of Mogilno-Łódź Syncline.

Geothermal waters occurring in Lower Cretaceous formations, due to mineralisation and flow conditions contain, or may contain, bromine and iodine ions concentrations enabling to use them for balneology or recreational purposes (once thermal energy is given away). Geothermal waters occurring in Szczecin Syncline and in the north-western part of Mogilno-Łódź Syncline (north of Konin) can be used for treatment purposes, whereas waters occurring in all other structural units can be used for recreational purposes. Within those reservoirs some areas of structural units were distinguished, where such data as mineralisation, Br and J concentration and temperature were documented with drilling and studies, together with prospective areas.

Capacities of potential wells very:low (below 25 m^3/h) in Lublin Syncline, on Łuków– Hrubieszów elevation, Podlasie Dip, Mazuria – Suwałki Elevation, Szczecin Syncline and peripheral zones of the other structural units. High capacities of potential doublets (above 100 m^3/h) can be expected within Kujawy and Pomerania anticlinorium (locally up to 200 m^3/h), and particularly in Łódź Syncline (locally over 300 m^3/h) and in Mogilno Syncline (locally up to 200 m^3/h).

Lower Jurassic reservoir

Lower Jurassic formations sedimentation took place interchangeably in the land and shallow-sea environment. In transgressive phases, heterolytic sandstones of a shallower shelf deposited most frequently, while in regressive phases, delta, fluvial and swampy formations with varied lithology were deposited. Only in the Pliensbachian transgressive phase occur clay-mudstone formations of a deeper clastic shelf. In terms of lithology, in the Lower Jurassic profile prevail thick complexes of sandstone formations, from fine to coarse grain, and complexes of alternating mudstones, sandstones and heterolytic beds. Thick sandstone complexes relate to Hettangian, Sinemurian, Upper Pliensbachian and Upper Toarcian sediments.

Thick claystone complexes, which can be correlated on large areas of the Polish Lowland, occur in two basic stratigraphic ranges. The older complex dates back to Early Pliensbachian, whereas the younger one to Upper Toarcian. The younger clay complex occurs throughout the area of the current scope of Lower Jurassic sediments. In most of the area, it is a compact complex of grey-green claystones and mudstones with constant thickness of 70–90 m (Górecki (ed.), 2006).

Lower Jurassic sediments are located on different Triassic members, mainly on non-aquifer Rhaetian rocks. They are covered mainly with non-aquifer Dogger, sometimes Cretaceous, Tertiary and Quaternary sediments (Górecki (ed.), 1995).

Thus, aquifers in Lower Jurassic sediments of the area under analysis are sandstone complexes of Hettangian, Sinemurian, Upper Pliensbachian and Upper Toarcian separated by discontinued series of poorly permeable and hardly permeable sediments, developed in the form of compacted fine-grain sandstones and mudstones as well as claystones. An insulating complex with the largest area is claystone-mudstone, in places, interbedded with sandstones, complex of Lower Toarcian sediments. Such formations are absent in the central part of Mogilno-Łódź synclinorium.

The location of Lower Jurassic formations roof ranges from over +350 (in the areas of outcrop to the surface) to over -350 m above sea level in the axial part of Mogilno-Łódź and Szczecin synclines. The depth of those formations roof is -1000 m above sea level on a large area of their spread, and the highest values can be found in Mogilno-Łódź Syncline (from 1500 to -3900 m above sea level), Szczecin Syncline (from -1500 to -2800 m above sea level), Warszawa Syncline (from -1500 to -2900 m above sea level) and Pomerania (in south-east, from -1500 to -1900 m above sea level).

The Lower Jurassic formations roof raises towards peripheral parts of syncline structures and in anticlinary structures (Pomerania anticlinorium, Fore-Sudetic area, Śląsk–Kraków monocline, Mazuria–Suwałki elevation and Świętokrzyski massif dip (depth from below -1000 m even up to +350 m above sea level).

The total thickness of Lower Jurassic formations changes from several to over 100 m in peripheral zones of the reservoir and in central parts of Mogilno-Łódź Syncline, and from 400 to over 1200 m in Kujawy anticlinorium. Within the Pomerania anticlinorium the reported thickness of those formations is 400-800 m, in Szczecin Syncline 200-800 m, in Warszawa Syncline 300–800 m, and in Pomerania Syncline 0–200 m. In the remaining sub-reservoirs (structural units) the total thickness of Lower Jurassic formations does not usually exceed 300 m.

It stems from the aquifers thickness map that it varies strongly from 0to over 800 m. The lowest thicknesses (below 100 m) occur in border zones of the Lower Jurassic reservoir and in the axial part of Mogilno-Łódź Syncline, in Miechów Syncline and within Śląsk-Kraków Monocline. The largest thicknesses have been reported within Kujawy anticlinorium and Pomerania anticlinorium; prevailing thicknesses there are 400–800 m. Locally, aquifers thickness in those structures is as high as nearly 900 m.

Variability in the field of the Lower-Jurassic reservoir temperatures is considerable and it achieves in extreme ranges of surface water temperatures (aquifer rock outcrop zones, direct supply areas); on the other hand, at largest depths it is as high as over 120°C in the axial part of Mogilno-Łódź Syncline (north and north–east of Konin). The area with temperatures over 50°C covers such structural units as Warszawa Syncline, Mogilno-Łódź Syncline and Szczecin Syncline. In other units waters have temperature below that value.

Mineralisation of waters related to Lower Jurassic formation schanges depending closely on the depth of their occurrence. In supply zones (outcrops of layers in peripheral parts of structural units) mineralization does not exceed 2 g/dm^3. The highest mineralisations have been reported in axial parts of Mogilno–Łódź Syncline (up to over 200 g/dm^3), Szczecin Syncline (up to over 100 g/dm^3) and Warszawa Syncline (over 100 g/dm^3). Throughout the reservoir, waters with mineralization ranging from 10–100 g/dm^3 prevail.

Geothermal waters in a major part of the Lower-Jurassic reservoir can be used also for balneological purposes, mainly due to bromide and iodide ion concentrations and for recreational purposes.

Potential outflows of wells producing waters from Lower-Jurassic reservoirs are strongly correlated with aquifers conductivity and their thickness. In most areas of reservoir rocks occurrence one can expect well outflow in excess of 100 m^3/h. The highest outflows (ca. 300–450 m^3/h) can be expected in the north–eastern part of Mogilno-Łódź Syncline. In Szczecin, Warszawa and Mogilno–Łódź synclines, as well as on Kujawy anticlinorium potential well outflows range from 250-350 m^3/h. The lowest outflows (under 100 m^3/h) could be expected in the wells located in peripheral zones of the Lower-Jurassic reservoir.

5.1.2. The Carpathians

The Polish Carpathians occupy the area of ca. 20 thousand km^2, which constitutes almost 6.5% of Poland's surface (Hajto, 2014). In 1988, Kuźmina-1 well was drilled there, with the depth of 7541 m, which has been the deepest well in Poland so far. In this well, the highest rock mass temperature in the area of the Polish Carpathians was measured and it is **178.5°C**. On the other hand, the highest **geothermal water temperature** in the area of Polish Eastern Carpathians was reported in Brzegi Dolne IG-1 well (Ustrzyki Dolne Municipality), where from the level of inoceramian beds of the Skole Unit, occurring at the depth of ca. 4300 m, water flow with the temperature of 105°C was acquired (Chowaniec et al., 2001). In the area of the Polish Western Carpathians the highest temperature, 127.5°C, was measured at the depth of 4790 m in Bańska IG-1 well, within Mesozoic series, below the main level of rocks of geothermal water Podhale reservoir (Sokołowski, 1992).

Carpathians are characterised with exceptionally diversified geological structure, developed from lithologically different geological-structural units (Fig.5.1.5, Fig. 5.1.6), which causes significant diversification of hydrogeological conditions, both in the horizontal and vertical profile of the Carpathian area. Carpathians include Inner Carpathians with the Tatra Mountains, Podhale Syncline and Pieniny Klippen Belt (being a border zone between Inner Carpathians and Outer Carpathians) and Outer Carpathians are often referred to as flysch Carpathians (Książkiewicz, 1972). Outer Carpathians are built mainly of sandstone-shale rock originating from Cretaceous-Oligocene deformed tectonically in the form of a series of nappes, overthrusts, scales and furrows mutually overthrusting northwards. Lithostratigraphic successions of main tectonic units (nappes) differ both in terms of facial development and thickness. The thickest succession, from 3000 m in the western part up to 5000 m, in the eastern part belongs to Śląsk Nappe. Flysch formations slid on indigenous earlier Miocene formations in Carpathians Foredeep (Fig. 5.1.5).

South of Pieniny Klippen Belt, within the Inner Carpathians, the area of Podhale Syncline was distinguished, which is made of Paleogene sandstone-shale formations, with the thickness up to 3 km (Podhale Flysch), lying on Mesozoic Tatra units.

Along the northern border of the Carpathian Overthrust, in the substratum of flysch and/or Miocene formations in the Carpathian Foredeep occur epivariscan platform rocks and Permian-Mesozoic cover formations (Oszczypko et al., 1989; Oszczypko, 2006a; Oszczypko et al., 2006). The depth of platform substratum in the part of Outer Carpathians explored with drillings ranges from 500 to 4500 m in the western part (Zawoja 1 well) and from 2000 m to 7000 m in the eastern part of Carpathians (well Kuźmina-1).

Geothermal waters in Carpathians have been reported in the area of Inner Carpathians (Podhale Syncline) and in some spots in flysch formations and Outer Carpathians rock substratum. The Podhale geothermal system is particularly important for the use of Carpathian geothermal resources (Górecki, Hajto (eds.) et al., 2011, Chowaniec, 2009). It is definitively the most prospective area in Carpathians. It is where the oldest and the largest geothermal heating plant in Poland has been in operation since 1990's.

Geothermal water is currently exploited by means of three production wells with the total approved outflow of 960 m^3/h of water with the temperature of 80–86°C (Kępińska, 2016). The main geothermal level of the Podhale system relates to Middle Triassic limestones and dolomites, in places with Jurassic sandstones of the Krížna unit, and in its roof part there are Middle Eocene carbonate formations (Kępińska, Wieczorek, 2011).

Outer Carpathians rocks have entirely different hydrogeological parameters. Due to the complex geological structure, translating into low intake outflows and problems with renewability of geothermal resources, there is a high geological risk in locating of a geothermal heating plant in this area, although in some locations it is justified to take such risk. Possibilities of obtaining relatively large geothermal water flows from flysch formations in the Outer Carpathian region are confirmed by results obtained during drilling of Wiśniowa-1 well, where from the depth of 3793 m considerable water flow was acquired (180 m^3/h),with relatively low mineralisation, ca. 7 g/dm^3,and the temperature of 84^{o}C, with pressure at the well head being 76 atmospheres (Karnkowski, Jastrząb, 1994).

Geothermal waters in Outer Carpathians are characterised by usually small and non-renewable resources as well as high mineralisations, which excludes their wider use. Those waters occur in small closed structures. Complex geological structure reduces obtaining higher outflows (Chowaniec, 2009; Hajto, 2011; 2012; 2013; 2014). Geothermal waters in Outer Carpathians are poorly documented, and they have been explored only in some spots (Górecki, Hajto (eds.) et al., 2011; Górecki, Hajto (eds.) et al., 2013).

A dominant direction in deep water use in this area of the Carpathians is balneotherapy and hydrotherapy. In flysch formations the occurrence of geothermal waters with different temperatures at the outflow was documented in the area of the following localities: Sól, Rabka-Zdrój, Poręba Wielka, Skomielna Biała and Lubatówka near Iwonicz-Zdrój (Fig.5.1.6). Geothermal waters characterised with temperatures at the outflow from 23 to 32°C were reported in the Carpathians substratums. Those waters were tapped in the area of Ustroń, Jaworze and Sucha Beskidzka (together with Potrójna IG-1 well) (Chowaniec et al., 2001; Chowaniec, 2009).

For balneotherapeutic purposes, in Outer Carpathians, geothermal brines are currently used only in Ustroń, Rabka-Zdrój and in Lubatówka near Iwonicz-Zdrój (Rajchel, 2011a,b).

So-far exploration of the conditions of geothermal water occurrence in the Carpathian region, including extensive regional studies carried out in recent years (Górecki (ed.)et al., 2011; 2013) point to a relatively low geothermal potential of that area. It regards particularly flysch formations in Outer Carpathians, where low values of basic hydrogeological parameters translate into low values of expected water intake outflows.

Better geothermal water parameters in flysch formations can occur in zones of different tectonic unit overthrusts. In such tectonic conditions, in the zone of Magura and Dukielsko-Grybowska unit overthrusts, geothermal waters were reported in the area of Skomielna Biała, Rabka-Zdrój and Poręba Wielka.

In areas with slightly better hydrogeological parameters, one may possibly consider possibilities of using geothermal water heat for heating purposes, with the support from other heat sources, e.g. a heat pump, biomass-fired boiler, etc. A prospective, well-explored and documented area for using carbonic geothermal water resources in balneotherapy is Lubatówka. Geothermal waters are abstracted by means of two wells: Lubatówka 12 and Lubatówka 14, and they are used only partially.

In substratum formations of flysch Carpathians, prospective areas for locating potential geothermal water intakes have been reported locally in the area of a Miocene, Cenomanian, Middle Jurassic and carbonate Devonian-Carboniferous reservoir (particularly in the area of Western Carpathians). Prospective zones occur mainly in the area of the front part of Carpathian Overthrust, south of Bochnia and Brzesko, Tarnów and Rzeszów, as well as south-west of Rzeszów (Miocene). Favourable hydrothermal conditions were also confirmed in the area of Ustroń, where geothermal waters from the carbonates of the Devonian-Carboniferous age are used.

Anticipated, usually small intake outflows (maximum up to 60 m^3/h) indicate that those waters are particularly fit for use for recreational and/or balneotherapeutic purposes (for such purposes, even relatively small water quantities will be sufficient).

In the area of Carpathians, the Podhale region (being a Polish part of Inner Carpathians) has the best reservoir and exploitation conditions for geothermal water.

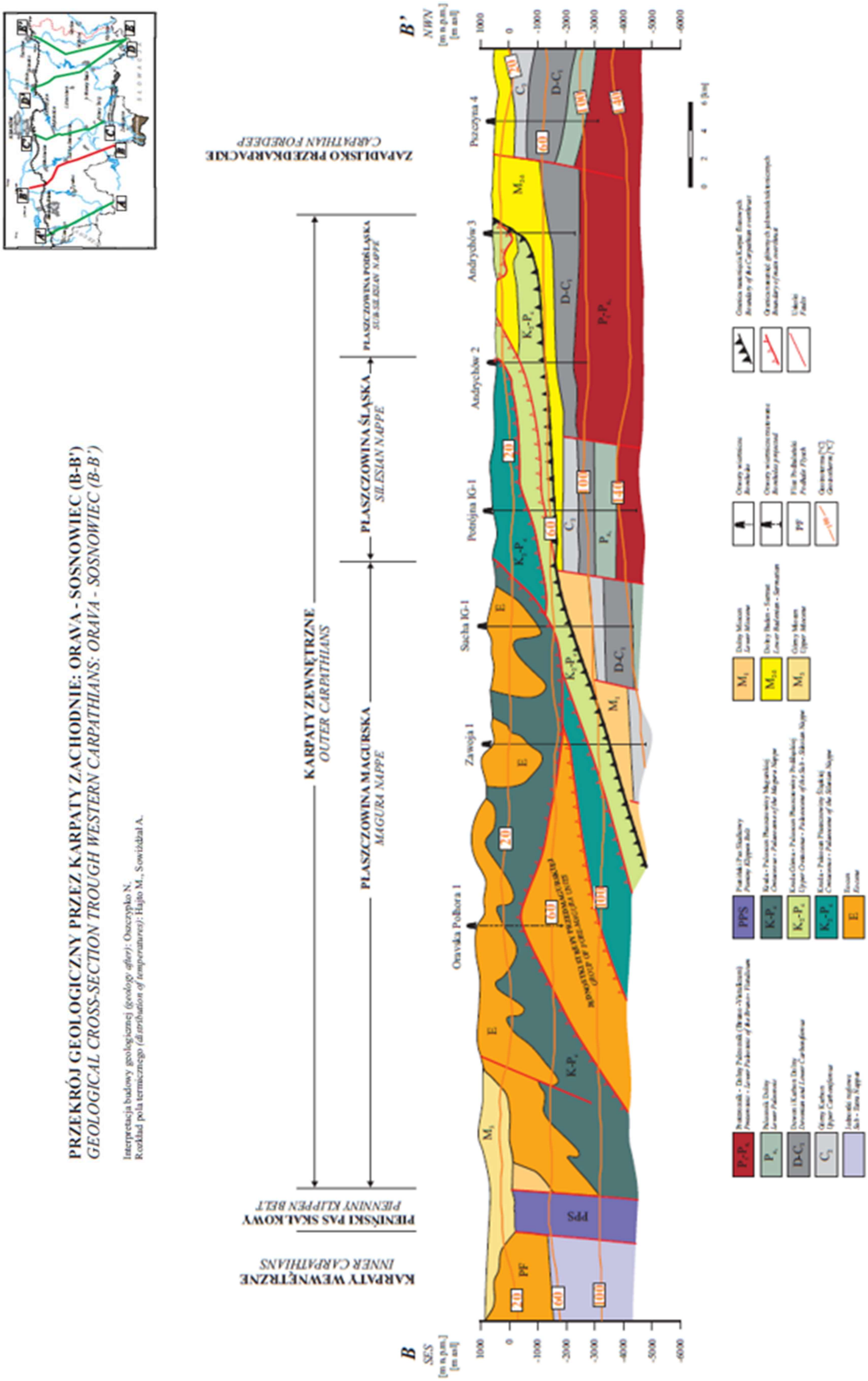


Fig.5.1.5. Geological cross-section through the Polish part of Carpathians (Oszczypko, [in: Górecki, Hajto (eds.)], 2013)

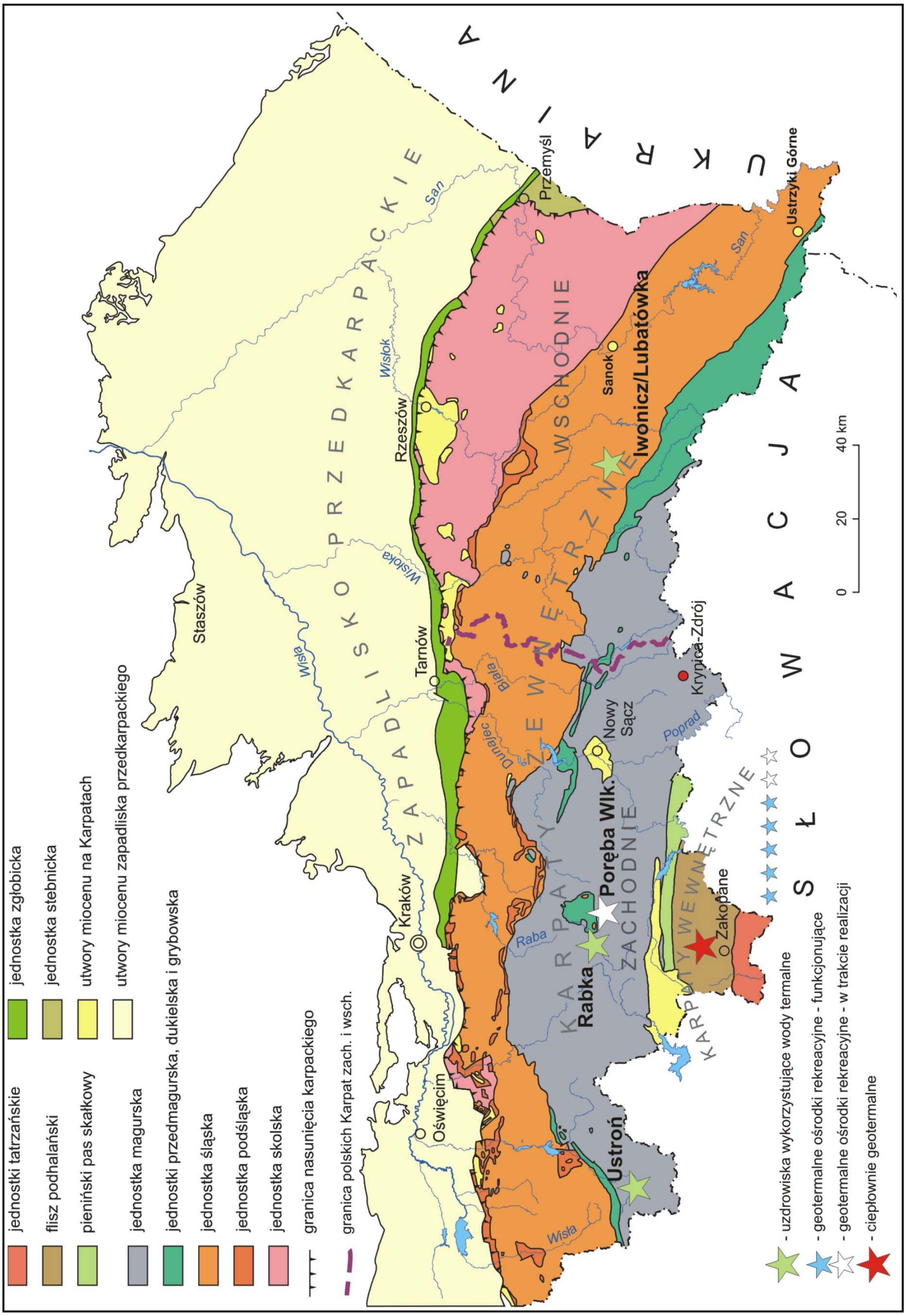


Fig.5.1.6. Geothermal water use in the area of Polish Carpathians (Górecki, Hajto (eds.), 2013) against a simplified geological and structural map (based on: Żytko et al., 1989; Jankowski et al., 2004)

5.1.2. The Carpathian Foredeep

Carpathian Foredeep, genetically related to the youngest geological unit of Poland: flysch Carpathians, is an asymmetric structure, filled with Miocene molasses sediments with the thickness from several hundred up to ca. 3 000 metres, in the form of a sequence of shales, mudstones and sandstones. That complex is referred to as the so-called indigenous Miocene, and its sediments come from the erosion of folded Carpathian flysch sediments. A clear southern Carpathian Foredeep border is indicated by the Carpathian Overthrust margin, although different Miocene thicknesses occur also under the Carpathian Overthrust.

In Poland, longitudinal extent of the Carpathian Foredeep is over 300 km long, and the maximum width does not exceed 100 km. Assymetric nature of the foredeep structure can be observed both in its cross-section (latitudinal) – maximum thicknesses of Miocene formations occur in the south, in front of the Carpathian Overthrust and they decrease northwards, and in longitudinal section, where the raise of the Precambrian-Palaeozoic substratum, the so-called Kraków rock mass divides them into unequal parts: the larger one is an eastern foredeep and, the smaller one, a western foredeep. In its eastern part, foredeep substrata are cut by erosion and they age-wise differentiated West-European platform formations: Precambrian – Palaeozoic (Miechów – Rzeszów zone) and Mesozoic (Miechów Syncline). In the western part, the substratum is made up of Mesozoic rock complexes and mainly Paleozoic (Carboniferous) of Górny Śląsk Syncline resting on Precambrian metamorphic rocks of the Górny Śląsk block (Harasimiuk et al., 2012; Peryt, 2012).

The occurrence of geothermal waters within Carpathian Foredeep relates to carbonate Devonian and Carboniferous formations in the western part of the foredeep, sandstone Middle Jurassic formations in the area extending to the south and north-east of Lubaczów, in carbonate Upper Jurassic formations (the area south of Brzesko–under Carpathian Overthrust), as well as Cenomanian sandstones in the area of Bochnia and Brzesko. It is just the Cenomanian reservoir where the highest potential well outflows, in excess of 200 m^3/h, are expected. It is totally unusual in this area, since almost on the whole foredeep area, in most of geothermal reservoirs outflows of several, rarely several dozen m^3/h are anticipated, however, they do not exceed 60 m^3/h, which is a big problem in the context of using geothermal resources for heating purposes (Sowiżdżał, 2015, Górecki, Sowiżdżał (eds.) et al., 2012).

It is just low water outflows of wells in almost all hydrogeothermal reservoirs that area basic issue in the area of Carpathian Foredeep. As mentioned before, the exception is the Cenomanian reservoir, where almost on the whole area of its occurrence one should expect high outflows. Zones with higher potential well outflows occur rarely in Middle and Upper Jurassic and Miocene reservoirs. These are thus reservoirs, which are the most prospective in terms of geothermal water use. Waters accumulated in clastic Carboniferous formations and in carbonate Carboniferous and Devonian formations locally may be characterised by favourable parameters. Hydrogeothermal parameters of Triassic and Cretaceous reservoirs (excluding Cenomanian) do not offer any possibilities of effective use of geothermal resources.

Changeability of geothermal water parameters with regard to particular intervals of Miocene reservoir is presented in Table 5.1.1.

Table 5.1.1. Geothermal water parameters in the Miocene reservoir (Górecki, Sowiżdżał (eds.) et al., 2012)

Depth interval	Temperature	Mineralisation	Flow rate
m b.s.l.	**°C**	**g/dm³**	**m³/h**
500–1000	30–40	50–>150	To ca.100
1000–1500	40–60	to 150	To ca. 30
1500–2000	50–60	to ca. 200	low, rarely 20–30
2000–2500	60–>70	to over 300	from several
2500–3500	80–100	high, locally over 300	up to ca. 20

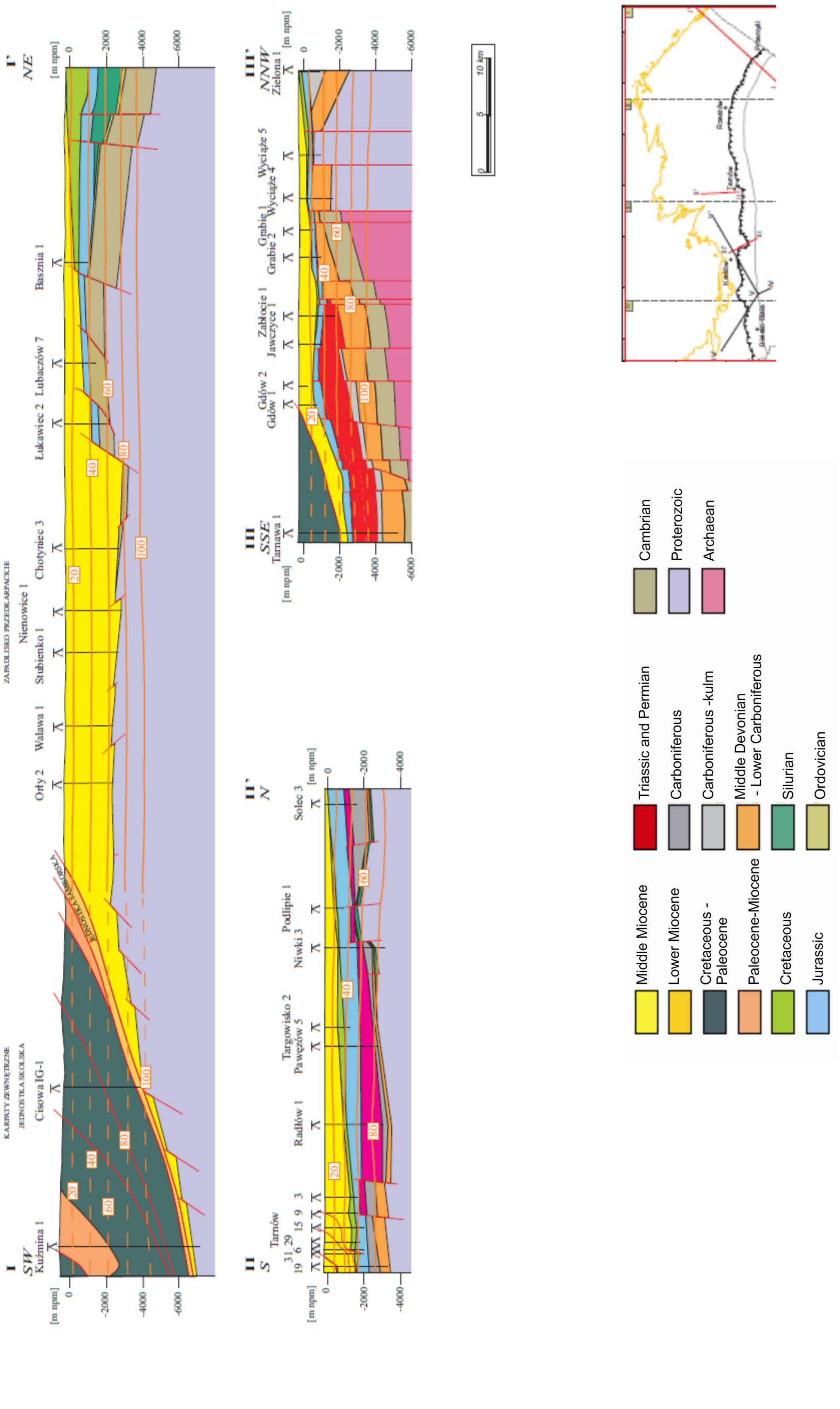


Fig. 5.1.7. Geological cross-sections through Carpathian Foredeep (Górecki, Sowiżdżał (eds.) et al., 2012)

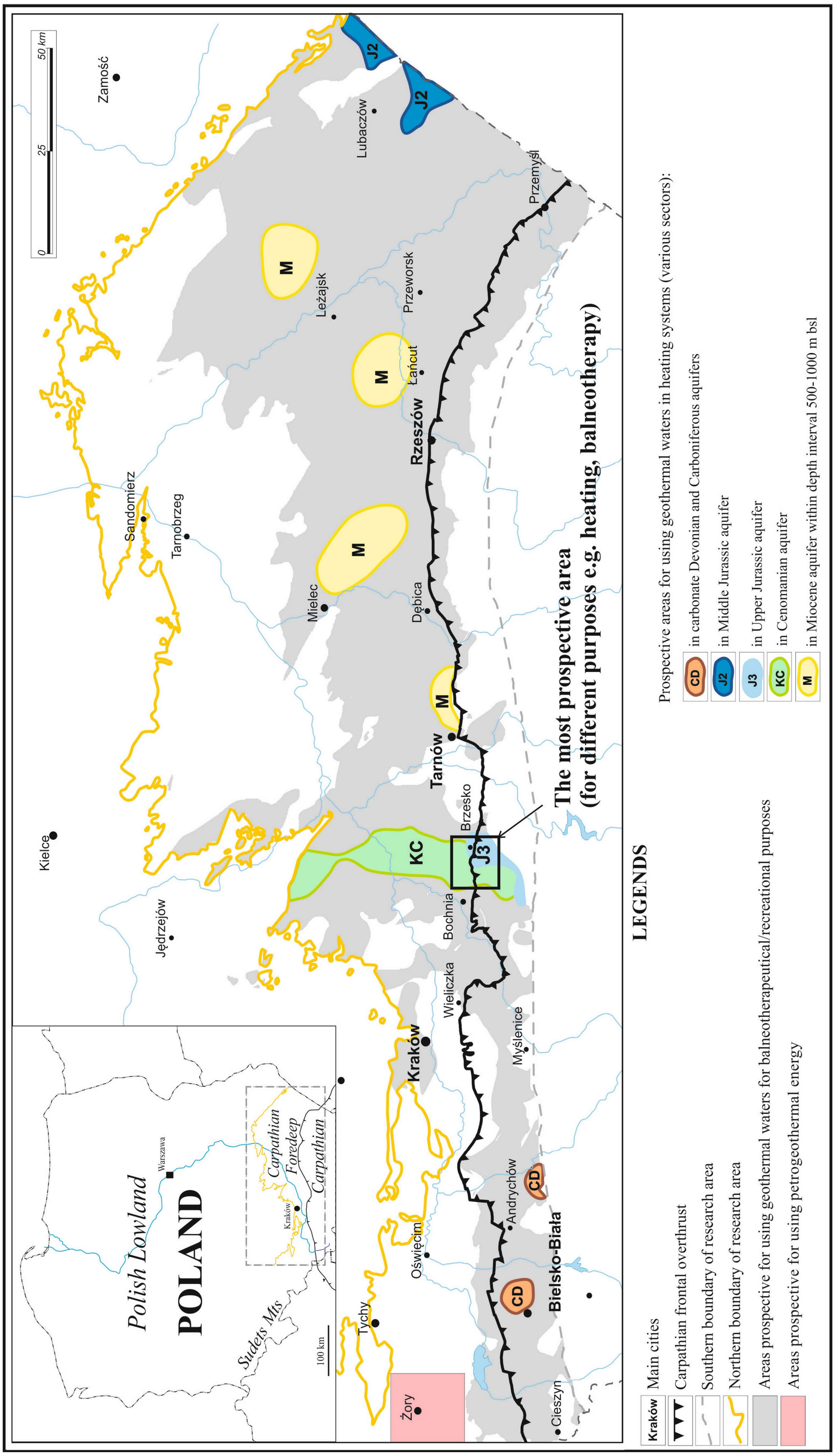


Fig. 5.1.8. Map of prospective areas for the use of geothermal water in Carpathian Foredeep (Górecki, Sowiżdżał (eds.) et al., 2012)

Prospective areas of geothermal water occurrence in Carpathian Foredeep relate mainly to the marginal zone of Carpathian Overthrust and they cover such cities as Bochnia, Brzesko and Tarnów. A basic problem in the area of Carpathian Foredeep is low outflows of waters from well both in Miocene reservoirs and in Mesozoic-Palaeozoic substratum. The exception is the Cenomanian reservoir, where one could expect high outflows almost on the whole area of its occurrence. The Cenomanian reservoir presents itself very favourably. It is characterised by considerable water outflows, low mineralisation, very favourable reservoir parameters on a regional scale, the existing artesian conditions and surface size of the reservoir enabling energy use on a large area. An unfavourable feature of the Cenomanian reservoir waters are low temperatures relating to a small depositing depth, which, at the same time, lowers the costs of opening the reservoir. Zones with higher potential well outflows occur very rarely in Middle and Upper Jurassic and Miocene reservoirs.

On the area of Carpathian Foredeep (taking into account the overthrust zone),the best parameters for using water for heating purposes have waters accumulated in carbonate Devonian and Carboniferous formations in the area of Bielsko – Biała and Sucha Beskidzka, in Middle Jurassic sandstones in the area extending south and north-east from Lubaczów, in carbonate Upper Jurassic formations (the area south of Brzesko–under Carpathian Overthrust), as well as in Cenomanian sandstones in the area of Bochnia and Brzesko. In the Miocene reservoir, the highest geothermal potential was identified in the depth interval from 500 to 1000 m below sea level. From the area of Tarnów to Przeworsk – Lubaczów line in the east, several areas could be pointed out where potential geothermal water outflows may range from 30–60 m^3/h (up to 100–130 m^3/h locally between Biłgoraj and Leżajsk), with similar temperatures from 30–40ºC and water mineralization ranging from 25–50 g/dm^3. They include an area east of Tarnów, an area between Biłgoraj and Leżajsk, an area east of Mielec and north of Ropczyce, as well as an area north of Łańcut.

Table 5.1.2. Hydrogeothermal parameters of geothermal waters in the Carpathian Foredeep (based on (Górecki, Sowiżdżał (eds.) et al., 2012)

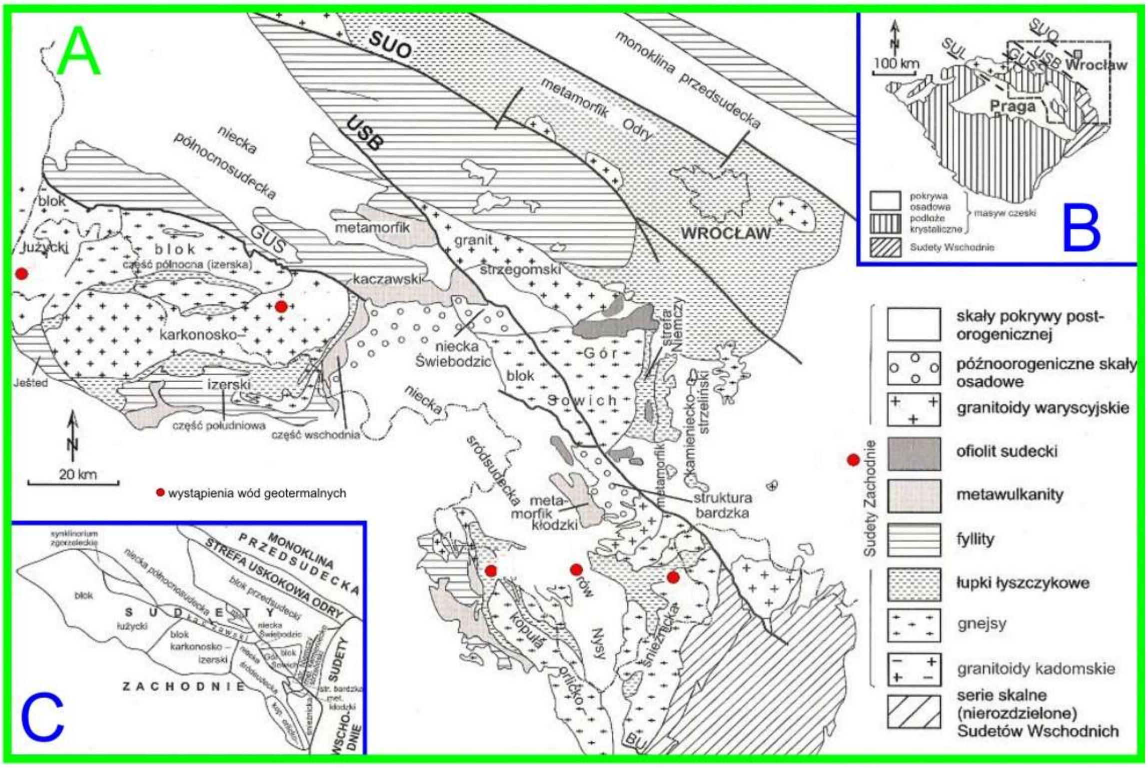
Geothermal reservoir	Depth of reservoir deposition* top/bottom	Temperature**	Mineralisation**	Discharge of wells
m below sea level	**m b.s.l.**	**°C**	**g/dm^3**	**m^3/h**
Miocene	500–1000	30–40	50–>150	do ok.100
Miocene	1000–1500	40–60	up to 150	do ok. 30
Miocene	1500–2000	50–60	to ca. 200	low, rarely 20-30
Miocene	2000–2500	60–>70	to over 300	about several
Miocene	2500–3500	80–100	high, locally in excess of 300	to ca. 20
Cenomanian	0–4000	30–100	several dozen g/dm^3, locally to over 150 g/dm^3	locally over 250 m^3/h
Upper Jurassic	250–4500	to 60, locally over 100	from several up to several dozen g/dm^3	locally over 30 m^3/h
Middle Jurassic	250–4750	to over 120	from ca. 20 to one hundred and several dozen g/dm^3	rarely over 100 m^3/h
Carboniferous - clastic	250–6750	to over 100	from several up to over 250 g/dm^3	rarely exceeding 10 m^3/h
Devonian and Carboniferous - carbonate	100–5000	to 200	from 0.5 g/dm^3 to over 300 g/dm^3	to max. 60 m^3/h

**in case of Miocene reservoir, the depth interval being analysed*
***the value given in the middle of the depth interval, in case of other reservoirs, the value given in the roof (min-max)*

5.1.3. Sudetes

The Sudetes, located in south-western Poland, are built by crystalline rocks, which lower down in steps towards north-east, creating characteristic steps (Fig.5.1.9). The highest is the uplifted Sudetes massif, in some places covered with sedimentary rock swith the thickness up to several hundred metres. Along the so-called marginal Sudetic fault lower than the Sudetes is a lower step of the crystalline, the so-called Fore-Sudetic block. It stretches NW-SE in the form of a belt to the so-called Odra faults zone, where the substratum creates another, third, step, inclined towards north-east, covered with a thick cover of the so-called Fore-Sudetic Monocline sediments. The Fore-Sudetic block, in a larger part is also covered with younger sedimentary rocks with thickness up to several hundred metres. On the other hand, Fore-Sudetic Monocline constitutes a series of Permian and Triassic strata subsiding at a small angle to NE.

The Sudetes and most of the Fore-Sudetic block constitute a north-eastern part of the Czech massif (Fig.5.1.9 B), being the largest crystalline massif in Central Europe. Precambrian rocks occurring there were rebuilt mainly during Baikal (Assyntian) orogeny, and next Caledonian orogeny (Oberc, 1972). Intense and multi-phase Variscan movements ended with granite intrusions played a major role in creating of the present tectonics. Variscan tectonics caused a number of dislocations, along which created blocks were moved vertically. On the area of the massif there are pieces of a Young Palaeozoic-Mesozoic cover filling the Czech, Intra-Sudetic and North-Sudetic Basin. Tectonic movements of the Alpine orogeny caused rejuvenation of old lines and creation of new lines as well as uplifting of blocks along them, which created mountainous areas on the massif margin, uplifted hundreds of metres high (Mísařet al., 1983; Oberc, 1972; Przewodnik…, 1995; Żelaźniewicz, 2005).



GUS – main Sudetic Fault, SUL – Łaba fault zone, SUO – Odra fault zone, USB – Sudetic marginal fault

Fig.5.1.9. Geological open sketch of Lower Silesia – A (acc. to Żelaźniewicz, 2005)
B – location of Lower Silesia within the Czech massif
C – diagram of a split into stratigraphic-tectonic units

The geological structure of the Sudetes region– crystalline massive substratumun covered on the surface or covered with not very thick sedimentary rocks stratum – causes that geothermal waters occurring there relate to zones of cracks in crystalline rocks. Precambrian and Lower Palaeozoic gneisses and metamorphic shales, frequently containing marble interlayers were formed by Upper Carboniferous granites, which make up, inter alia, the core of the Karkonosze-Izery massif. In synclines, crystalline rocks are covered with Phanerozoic sediments (age: Silurian-Quaternary) (Dowgiałło, 2000).Geothermal waters occur in this area only in crystalline formations. Most of hydrogeothermal studies performed so far have shown that geothermal waters in the Polish part of the Sudetes are fit only to be used for treatment purposes (Dowgiałło, 2002). However, as proven by the so-far studies, the whole Sudetic region is characterised by favourable geothermal conditions. For example, in the area of Cieplice, the occurrence of deep waters with the temperature of 86.7ºCwas reported(at the depth of 2002.5 m) (Fig. 5.1.10). In Cieplice, there are Poland's hottest natural springs and poorly mineralised water drilled at the shallowest level with the temperature in excess of 80ºC (C-1 well).

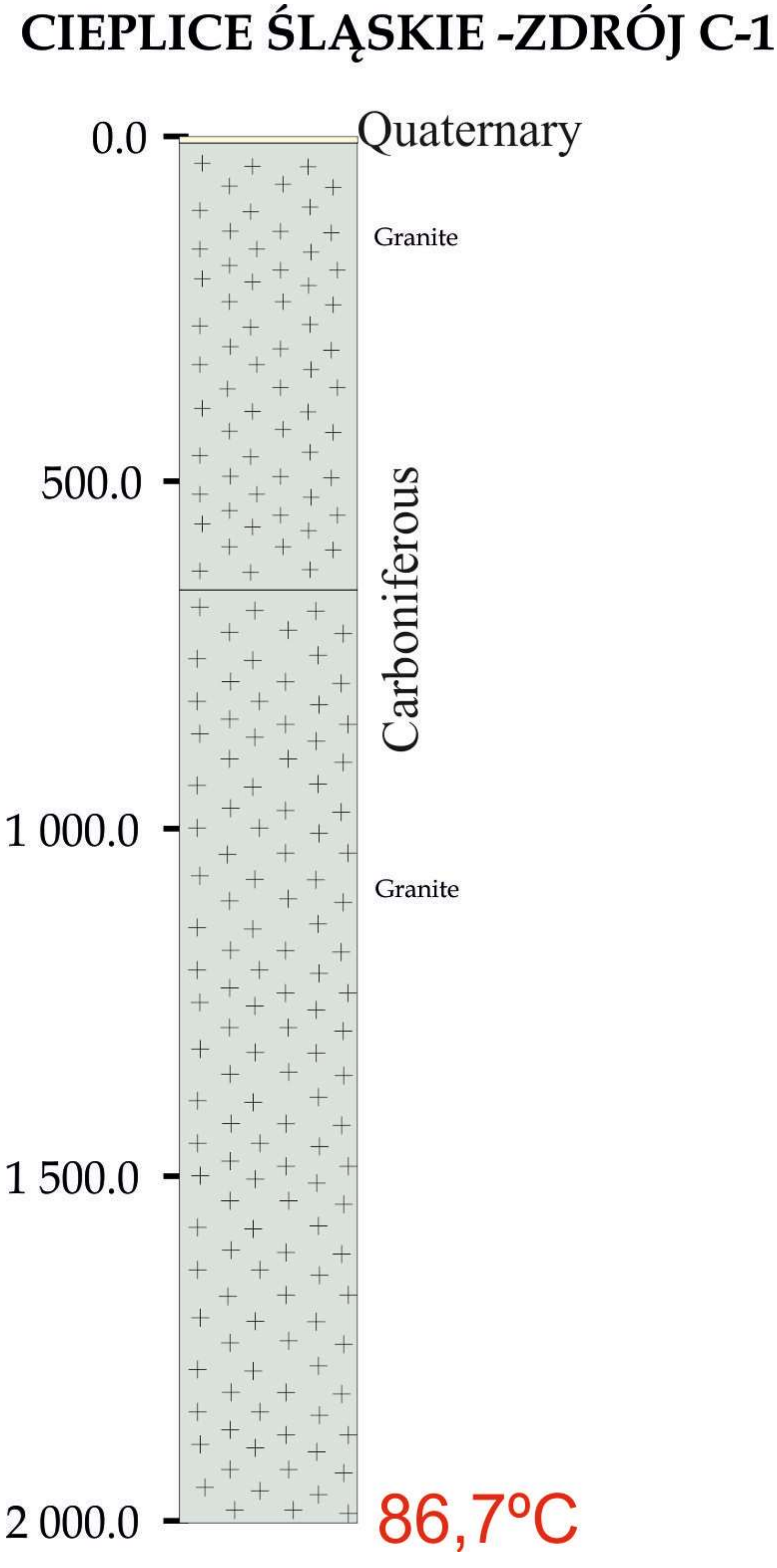


Fig. 5.1.10. Lithostratigraphic profile of Cieplice Śląskie – Zdrój C-1 well

Therefore, the area of Cieplice is considered the most prospective for the location of HDR systems (Wójcicki, Sowiżdżał, Bujakowski (eds.) et al., 2013), as well as for the location of projects using geothermal heat for electricity production in binary systems in Poland (Bujakowski, Tomaszewska (eds.) et al., 2014).

The oldest information about geothermal waters in the Sudetes region regard waters in Cieplice Śląskie-Zdrój and Lądek-Zdrój. The first studies of Cieplice waters come from 1572 (Ciężkowski, 1994; 1998). At the end of 1960's, larger-scale works started to be carried out. After completion of extensive prospecting works, on the basis of their results, waters with higher temperatures were abstracted in Lądek-Zdrój (1973, L-2 well, water temperature: 45°C) and in Cieplice (in years 1972–73, C-1 and C-2 wells, water temperatures: 41.5°C and 63.3°C). At the beginning of 1980's, accidentally geothermal water outflows were discovered in a drainage galleries of Turów lignite mine (1981, 26°C) and in Grabin on the Fore-Sudeticm block (1983, Odra-5/I well, 31.4°C).

The above suggestions, confirmed with drilling results in Cieplice Śląskie-Zdrój (1997, C-1 well deepening, 86.7°C), and also in Duszniki-Zdrój (2002, GT-1 well, 35°C) caused a clear growth of interest in obtaining new water resources with high temperatures in different areas of the Sudetes region. In the last decade, a number of deep drilling projects were performed in Cieplice Śląskie-Zdrój (C-3), Wojcieszyce (WT-1), Karpniki (KT-1) and Podgórzyn (Podgórzyn GT-1) in Jelenia Góra Valley, and also in Polanica-Zdrój (GT-1 i GT-2), Bolesławów (BT-1) and on Puchaczówka Pass (CG-1) in Kłodzko Land and in Lipowa on the Fore-Sudetic block (Ciężkowski, 2011).

Geothermal waters occur in Sudetes only in crystalline rocks, and their presence is reported either indirect outflows on the surface or they are abstracted at higher depths, sometimes under the sedimentary rocks cover. The elevated areas and lines of deep discontinuances in crystalline substratum are crucial for the creation of mineral and geothermal waters. Elevated areas constitute zones of precipitation and surface water infiltration, whereas fault lines are paths of underground, frequently deep, flow. Owing to this, waters obtain higher temperature, become enriched in different ingredients and sometimes they are saturated with juvenile carbon dioxide. As a result of very deep flow infiltrating waters in Sudetes appear also within the Fore-Sudetic block (Ciężkowski, 2011).

In Sudetes, geothermal waters have been reported in several places, presented and described on the map (Fig.5.1.11).

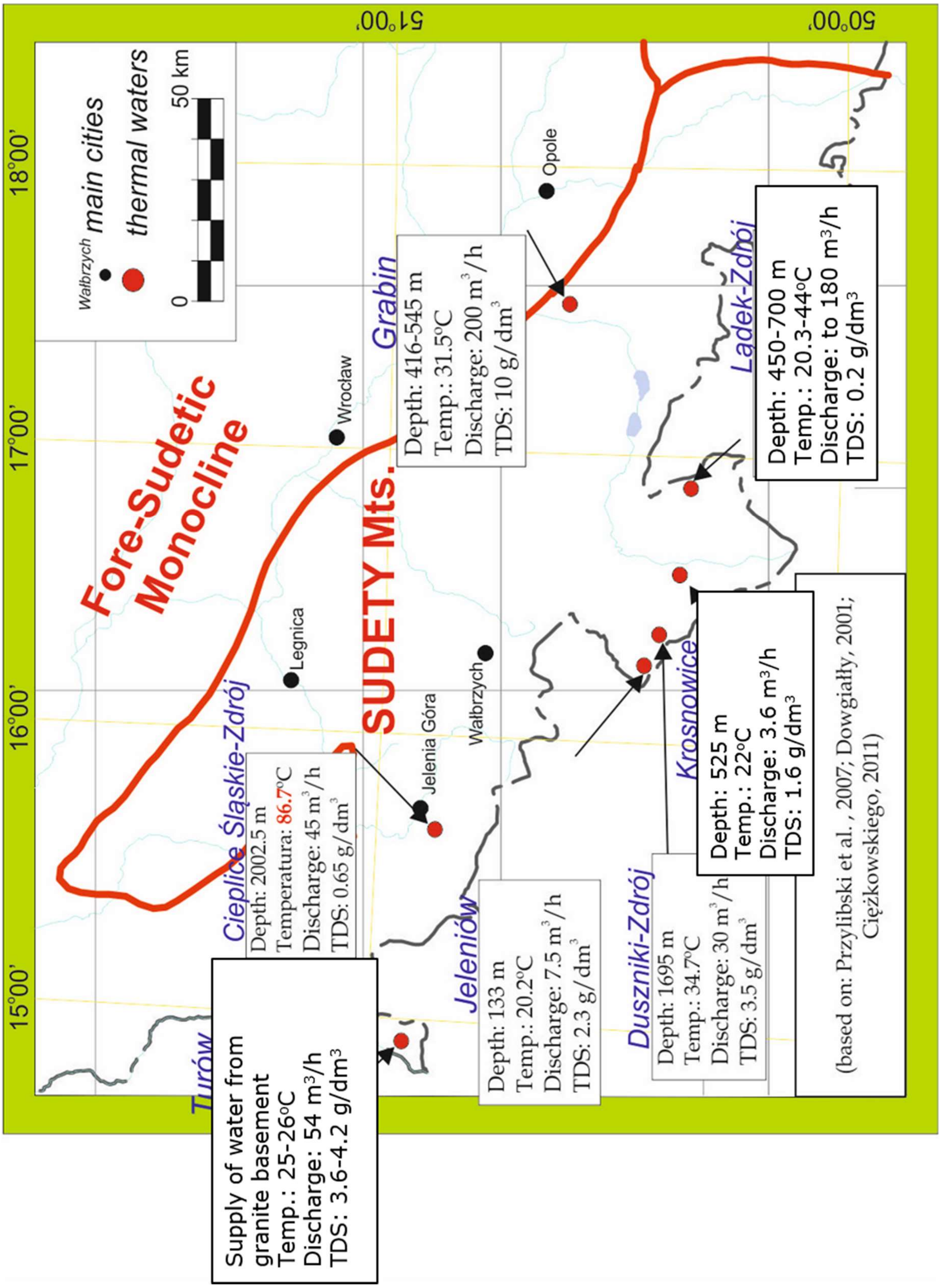


Fig. 5.1.11. Map of geothermal waters in the Sudetes

5.1.4. Summary

The occurrence of geothermal resources strictly depends on geological conditions of a given region. In Poland, we can distinguish four regions characterised with different hydrogeothermal conditions (tab.5.1.3). The highest geothermal potential relates to the area of the Polish Lowland and Podhale, being a part of the Carpathians. Much lower perspectives relate to the area of the Carpathian Foredeep (due to low well outflows) and the remaining part of the Carpathians. In the Sudetes, geothermal waters occur in spots, and geothermal reservoirs, unlike in other regions, are built of crystalline rocks.

Table 5.1.3. Hydrogeothermal parameters of geothermal waters in different Polish regions

	Polish Lowlands	**Carpathian Foredeep**	**Carpathians**	**Sudetes**
Geothermal reservoir	sedimentary	sedimentary	sedimentary	crystalline
Temperature [°C]	30–130	20–120	20–120	max. 86.7
Discharge of wells [m³/h]	high, locally even above 300	usually less than 20, the exception is the Cenomanian aquifer-max. ca. 250	from low (Outer Carpathians) to up to 550 (Inner Carpathians - Podhale)	from several to even 200
Mineralization [g/dm³]	Varied, locally high, sometimes exceeding 300	Varied, , locally high, sometimes exceeding 300	from several to 120	To ca.10
Prospective areas	Mid-Polish Trough	Central part	Podhale	point – Cieplice Śląskie-Zdrój and other

References:

Bujakowski W, Tomaszewska B, (red.) i in., 2014: Atlas wykorzystania wód termalnych do skojarzonej produkcji energii elektrycznej i cieplnej w układach binarnych w Polsce [Atlas of the possible use of geothermal waters for combined production of electricity and heat using binary system in Poland], MEERI PAS, Kraków, 305 s.

Chowaniec J., 2009: Studium hydrogeologii zachodniej części Karpat polskich; Biuletyn Państwowego Instytutu Geologicznego z. VIII Nr 434.

Chowaniec J., Poprawa D., Witek K., 2001: Występowanie wód geotermalnych w polskiej części Karpat. Przegląd Geologiczny: 49, 8, s. 734–742.

Ciężkowski W., 1994: Cieplickie wody termalne. Karkonosz, 1994, nr 3-4 (10-11)/93, s. 20-29.

Ciężkowski W., 1998: Lądek Zdrój. Dolnośląskie Wydawnictwo Edukacyjne, 1998, Wrocław, 235 s.

Ciężkowski W., 2011: Kierunki rozwoju i możliwości wykorzystania geotermii głębokiej na Dolnym Śląsku Instytut Górnictwa, Politechnika Wrocławska, Wrocław, 2011.

Dowgiałło J. 1980: Poligenetyczny model karpackich wód chlorkowych i niektóre jego konsekwencje. Współczesne problemy hydrogeologii regionalnej, Jachranka k. Tom konferencyjny. Warszawy: 275–290.

Dowgiałło J., 2002: The Sudetic geothermal region of Poland. Geothermics, 2002, Vol. 31 (3), s. 343–359.

Dowgiałło, J., 2000: The Sudetic geothermal region of Poland – new findings and further prospects; Proceedings World Geothermal Congress 2000, Kyushu-Tohoku, Japan, May 28 – June 10.

Górecki W, Sowiżdżał A, Hajto M, Wachowicz-Pyzik A., 2015: Atlases of geothermal waters and energy resources in Poland. Environmental Earth Sciences, 74 (12), 7487–7495.

Górecki W., Hajto M. (red.) i in., 2006a: Atlas zasobów geotermalnych na Niżu Polskim – formacje mezozoiczne. Kraków.

Górecki W., Hajto M. (red.) i in., 2006b: Atlas zasobów geotermalnych na Niżu Polskim – formacje paleozoiku. Kraków.

Górecki W., Hajto M. (red.) i in., 2011: Atlas zasobów wód i energii geotermalnej Karpat Zachodnich. Kraków.

Górecki W., Hajto M. (red.) i in., 2013: Atlas geotermalny Karpat Wschodnich. Kraków.

Górecki W., Hajto M., Strzetelski W., Szczepański A., 2010: Dolnokredowy oraz dolnojurajski zbiornik wód geotermalnych na Niżu Polskim. Przegląd Geologiczny, vol. 58, nr 7, pp. 589–593.

Górecki W., Kozdra T., Hajto M. i in., 2003: Analiza geologiczna i ocena zasobów wód i energii geotermalnej w wytypowanych zbiornikach geotermalnych dewonu, karbonu i permu Na Niżu Polskim. Projekt badawczy KBN nr 9 T12B 005 19. ZSE AGH Kraków.

Górecki W., Sowiżdżał A. (red.) i in., 2012: Atlas geotermalny zapadliska przedkarpackiego. Kraków.

Hajto M., 2011: Potencjał geotermalny w rejonie zewnętrznych Karpat Zachodnich — Geothermal potential of the Outer Western Carpathians. Technika Poszukiwań Geologicznych. Geotermia, Zrównoważony Rozwój. 2011 R. 50 z. 1–2, s. 37–49.

Hajto M., 2012: Zasoby oraz możliwości zagospodarowania wód geotermalnych w Karpatach Zachodnich – od Cieszyna po Gorlice — Geothermal resources and possibilities of use of geothermal waters in the Western Carpathians – from Cieszyn to Gorlice] [W:] SOLINA 2012: IV konferencja: architektura – budownictwo – inżynieria – technika : nowoczesne technologie energooszczędne – wykorzystanie odnawialnych źródeł energii: Rzeszów–Polańczyk, 30 maja – 02 czerwca 2012 roku : streszczenia referatów konferencyjnych / Politechnika Rzeszowska. Wydział Budownictwa i Inżynierii Środowiska. Zakład Budownictwa Ogólnego.

Hajto M., 2013: Zasoby oraz możliwości wykorzystania energii geotermalnej w Polsce [Geothermal resources and possibilities of its utilization in Poland]. [W:] Złoża kopalin - aktualne problemy prac poszukiwawczych, badawczych i dokumentacyjnych: IV ogólnopolska konferencja naukowa. Warszawa 15-17.04.2015. abstrakty / pod red. Magdaleny Pańczyk. Warszawa: Państwowy Instytut Geologiczny - Państwowy Instytut Badawczy, 2015. S. 29–30.

Hajto, M., 2014: Zasoby i możliwości zagospodarowania wód termalnych w rejonie Pogórza Środkowobeskidzkiego, Beskidu Środkowego oraz Beskidu Lesistego — Geothermal resources and possibilities of use of geothermal waters in the area of

Środkowobeskidzkie Foothills, Middle Beskidy and Beskid Lesisty. Czasopismo Inżynierii Lądowej, Środowiska i Architektury = Journal of Civil Engineering, Environment and Architecture; ISSN 2300-5130. — Tytuł poprz.: Zeszyty Naukowe Politechniki Rzeszowskiej. Seria: Budownictwo i Inżynieria Środowiska. 2014 t. 31 z. 61 nr 3, s. 209–226.

Harasimiuk M., Sowiżdżał A., Zubrzycki A., 2012: Ogólna charakterystyka rejonu zapadliska przedkarpackiego. [W:] Atlas geotermalny zapadliska przedkarpackiego (Górecki (red.), 2012). KSE AGH Kraków.

Jasnos J., 2012: Charakterystyka występowania wód mineralnych, swoistych, leczniczych oraz solanek [W:] Atlas geotermalny zapadliska przedkarpackiego (Górecki (red.), 2012). KSE AGH Kraków.

Karnkowski P., Jastrząb M., 1994: Wody geotermalne depresji strzyżowskiej Karpat. Przegląd Geologiczny, 42, 2, s. 121–123.

Kępińska B., 2016: Przegląd stanu wykorzystania energii geotermalnej na świecie i w Europie w latach 2013–2015, Technika Poszukiwań Geologicznych Geotermia, Zrównoważony Rozwój nr 1/2016.

Kępińska B., Wieczorek J., 2011: Charakterystyka geologiczno-złożowa podhalańskiego systemu geotermalnego [W:] Górecki W., Hajto M., W. (red.), 2011: Atlas zasobów wód i energii geotermalnej Karpat zachodnich. KSE AGH Kraków.

Książkiewicz M., 1972: Budowa geologiczna Polski. IV – Tektonika, 3–Karpaty. Wyd. Geol. Warszawa.

Misar Z. i in., 1983: Geologie ČSSR I, Český Masiv. SPN, Praha, 1983.

Oberc J., 1972: Budowa geologiczna Polski. T. IV, Tektonika, cz. 2: Sudety i obszary przyległe. Wydawnictwa Geologiczne, Warszawa, 1972.

Oszczypko N., 2006: Late Jurassic-Miocene geodynamic evolution of the Outer Carpathian fold and thrust belt and its Foredeep Biostratigraphic Standarts. Biul. Pol. Acad. Sc., Earth Sc., 40: 83–96.

Oszczypko N., 2011: Przekrój geologiczny przez Karpaty Zachodnie W: Górecki W., Hajto M. (red.) i in., 2011: Atlas zasobów wód i energii geotermalnej Karpat Zachodnich. Kraków.

Oszczypko N., Krzywiec P., Popadyuk I., Peryt T., 2006: Carpathian Foredeep Basin (Poland and Ukraine) – its sedimentary, structural and geodynamic evolution. [W:] J. Golonka and F. J. Picha (eds.), The Carpathians and their foreland: Geology and hydrocarbon resources. Mem. AAPG, 84: 293–350.

Oszczypko N., Tomaś A., 1978: Charakterystyka własności zbiornikowych osadów jurajskich na przedgórzu Karpat środkowych. Kwart. Geol.; 22, 3: 585–600.

Oszczypko N., Zając R., Garlicka I., Mencik E., Dvorak J., Matejovska, 1989: Geological map of the substratum of the Tertiary of the Western Outer Carpathians and their foreland, [In:] D. Poprawa, and J. Nemcok, cords., Geological Atlas of the Western Outer Carpathians and their foreland. PIG.

Peryt T., 2012: Zarys budowy geologicznej zapadliska przedkarpackiego. [W:] Atlas geotermalny zapadliska przedkarpackiego (Górecki (red.), 2012). KSE AGH Kraków.

Rajchel L., 2011a: Balneoterapia i rekreacja z zastosowaniem wód geotermalnych. [W:] Górecki W. (red.) i in. – Atlas zasobów wód i energii geotermalnej Karpat Zachodnich. s. 142–145.

Rajchel L., 2011b: Wykorzystanie wód geotermalnych w uzdrowisku Rabka Zdrój. [W:] Górecki W. (red.) i in.- Atlas zasobów wód i energii geotermalnej Karpat zachodnich. Wyd. AGH KSE, Kraków.

Sokołowski J., 1992: Dokumentacja geosynoptyczna otworu geotermalnego Bańska IG-1. Geosynoptyka i Geotermia, t. 1, PAN CPPGSMiE, Kraków.

Sowiżdżał A, Kaczmarczyk M. 2016: Analysis of thermal parameters of Triassic, Permian and Carboniferous sedimentary rocks in central Poland. Geological Journal, 51(1), 65–76.

Sowiżdżał A, Papiernik B, Machowski G, Hajto M. 2013: Characterization of petrophysical parameters of the Lower Triassic deposits in prospective location for Enhanced Geothermal System (central Poland). Geological Quarterly, 57, 4, 729–744.

Sowiżdżał A. 2015: Characterization of geothermal reservoirs parameters in Polish part of Carpathian Foredeep, Carpathian Journal of Earth and Environmental Sciences, May 2015, Vol. 10, No. 2, p. 237–246.

Sowiżdżał, Górecki, 2013: Możliwości wykorzystania energii geotermalnej w rejonie zapadliska przedkarpackiego; Possibilities of geothermal energy utilization in the Carpathian Foredeep, Technika Poszukiwań Geologicznych. Geotermia, Zrównoważony Rozwój. 2013 R. 52 z. 2, s. 59–73.

Stupnicka E., 1997: Geologia regionalna Polski. Wyd. Uniw. Warsz. Warszawa.

Wójcicki A, Sowiżdżał A, Bujakowski W, (red.) i in., 2013: Ocena potencjału, bilansu cieplnego i perspektywicznych struktur geologicznych dla potrzeb zamkniętych systemów geotermicznych (Hot Dry Rocks) w Polsce [Evaluation of potential, thermal balance and prospective geological structures for needs of closed geothermal systems (Hot Dry Rocks) in Poland]. Warszawa/Kraków 246.

Żelaźniewicz A. i in., 2011: Regionalizacja tektoniczna Polski, Komitet Nauk Geologicznych PAN, Wrocław 2011, ISBN 978-83-63377-01-4, s. 20–24.

Żelaźniewicz A., 2005: Przeszłość geologiczna. W: Fabiszewski J. (red.) – Przyroda Dolnego Śląska. Polska Akademia Nauk, Oddział we Wrocławiu, 2005, s. 61–134.

5.2. Current state of geothermal uses and development prospects in Poland

5.2.1. Introduction

The prospects for wider geothermal district heating systems development in Poland are predominantly connected with the territory of Polish Lowlands and the Podhale Region (Inner Carpathians). In the case of the former region, especially promising is the vast area located within the contour showing the underground temperatures above 60°C, mostly in the Lower Cretaceous and Lower Jurassic formations. Besides, numerous district heating systems are operating on that area and geothermal energy can be introduced at least to some of them (Fig. 5.2.1). The main parameters that characterize the Polish Lowlands are the following:

- Reservoir temperatures >60ºC,
- Depths of aquifers up to 3–4 km.

It shall also be pointed out that the geothermal space heating systems will be feasible mainly in localities witch possess operational district heating grids, preferably with wells located close to such grids and customers. Such conditions, whatever available, present particular opportunities for an increase of the number of geoDHs in Poland in the near future.

To supplement this information and illustrate the theoretical potential, let us mention that there are ca. 5,000 district heating systems in Europe, with ca. 500 of them or 10%, located in Poland (Fig. 5.2.2). Particular chance for geoDH both introduction in both Europe and Poland are offered to suitable locations.

Taking into account the current number of geoDH systems in Europe, i.e. ca. 270 of them operating in 2014, with many other project in progress, and only 6 geoDH in Poland, the figures are much below the resource potentials and needs.

The above statements conclude the findings and outcomes of the EU project called “Promote geothermal district heating in Europe” (Report on Geothermal DH Potential in 14 EU-countries, 2014; www.geodh.eu). Poddębice is one of the places located on the prospective area.

The facts quoted above require undertaking proper activities to speed up geothermal heating development in Poland. Very strong arguments for that were emphasised by heavy atmospheric pollution (smog) suffered in winter heating season 2016/2017, caused by coal burning in many localities, while clean and ecologically friendly geothermal potential remained unused.

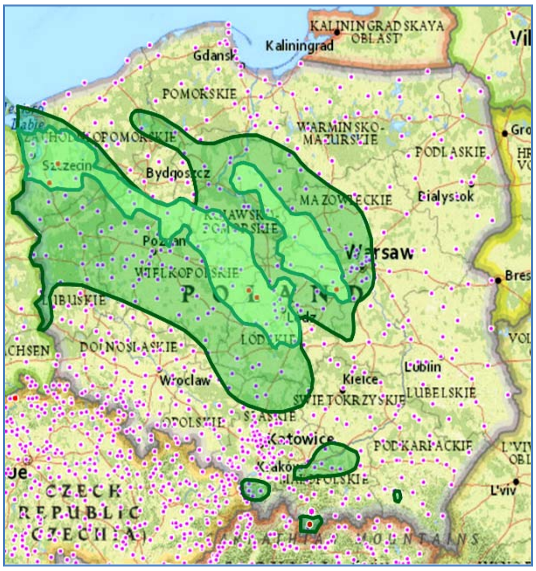


Fig.5.2.1.Poland: the most prospective areas for geothermal district heating systems
[in:] Report on Geothermal DH Potential in 14 EU-countries, 2014 (www.geodh.eu)

Dark green line – isotherm 60°C underground. Marked by green – areas with underground temperatures above 60°C, depths to 3-4 km b.g.l. (mostly in the Lower Jurassic and Lower Cretaceous formations). Red dots – operating district heating systems

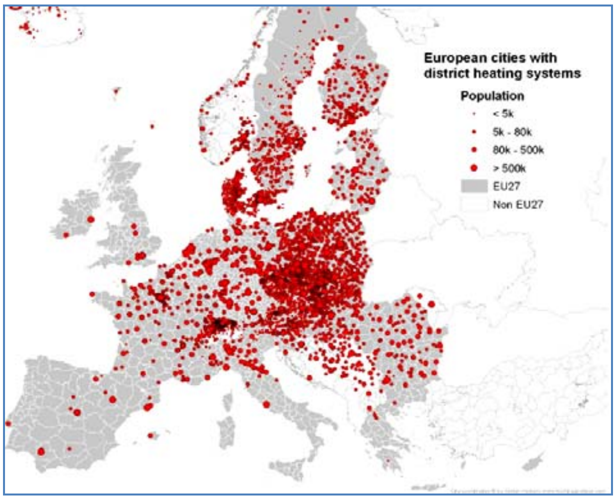


Fig. 5.2.2. District heating systems in Europe (red dots) according to HUDC database (June 2012) [in:] Report on Geothermal DH Potential in 14 EU-countries, 2014 (www.geodh.eu)
Source of map: Persson et al. (2012) – HUDC Database 2012 (The Halmstad University District Heating and Cooling Database).
Note very high density of district heating systems in Poland

5.2.2. Current geothermal energy uses

Even though Poland has a substantial geothermal potential of geothermal energy, so far it has been poorly utilised. Current geothermal direct uses, based on the-so-called deep geothermal sources (i.e. those using 1– 4 km deep wells) are designed for the following: space heating, balneotherapy and recreation, fish farming, some other minor uses.
Figure 5.2.3 shows the location of geothermal energy use in Poland. The overview presented below is based on Kępińska (2016) and updated in some cases.

In case of district heating – first plant was opened in last decade of 20th century in the Podhale region (S–Poland) and it has been under constant development till now. At the end of 2016 six geothermal district heating plants were operating (opened between 1993–2015): in Podhale and in towns in the Polish Lowlands: Mszczonów, Poddębice, Pyrzyce, Stargard, Uniejów.

Ten health resorts are using geothermal water for treatment. Some have old historical roots dating back to 13th century while the youngest one was established in 2012 (Uniejów). In recent decade (2006–2016) fourteen new recreation centres were constructed. Some of them apply geothermal water both for the pools and other facilities and for heating their objects and warm water preparation (sometimes with ca. 1 MW_{th} compressor heat pumps' usage).

In 2017 several next investments oriented for recreation were at various stages of realization or under projects' elaboration.

In 2015a a large-scale modern atlantic salmon's farm using geothermal water (Janowo at the Baltic coast) was opened. Water comes from the well drilled in 2012 and is applied both for culturing and for heating the farm's facility. At initial stage of farm's operation, the average water flow rate was ca. 20 L/s. Target fish production will reach 1000 T/y (Kępińska, 2016).
Other direct geothermal uses comprise semi-technical wood drying (MEERI PAS installation in the Podhale Region; earlier in integration with other R+D scale applications like fish farming, greenhousing, foil tunnels), and heating up of a football playground (Uniejów).

In recent years, a constant progress of shallow geothermal sources, or the ground sourced heat pumps' sector (GSHP) was practiced (part of the progress in the area of heat pump sector), in contrast to earlier types of operations. In 2015, heat pump sales increased by 14% on average, as compared to 2014 (the most spectacular 70% market growth was recorded in case of air heat pumps in 2015). As to the GSHP's the average market growth was noted at ca. 5% (data based on *www.portpc.pl*). At the end of 2015, the number of GSHP's was estimated at ca. 45,000 units (at least 500 MW_{th} and heat production at least 695 GWh / 2500 TJ; Kępińska, 2016). The largest single units reach 1 MW_{th}, and some of them work in the geothermal district theating plant at Mszczonów, while others in recreation centres).

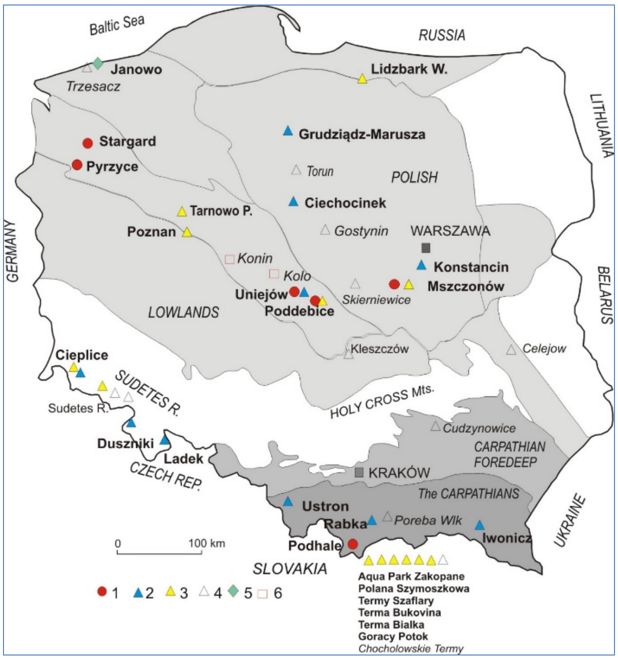


Fig. 5.2.3. Poland – geothermal direct uses, 2017 (based on Kępińska, 2016, updated):
1. district heating plants in operation, 2. health resorts, 3. recreation centers in operation, 4. some recreation centers under construction, 5. fish farming, 6. co–generation plants at early stages of investment projects
In several past years by (2012) a semi-technical fish farming (a part of R+D cascaded system) was operating by MEERI PAS in the Podhale Region – that facility initiated geothermal aquaculture in Poland

5.2.3. Geothermal heating – an overview of operating plants

As mentioned above, at the end of 2016 six geothermal district heating plants were operating in Poland. In 2015 their total installed geothermal capacity amounted to 76.2 MW_{th} (Kępińska, 2016) while in 2016 geothermal heat sales ca. 702 TJ. In specific localities, geothermal water parameters, as well as installed capacities and heat production, vary considerably, e.g. the highest geothermal water temperatures discharged by the production wells were 82-86°C and 85°C (in the Podhale region and the town Stargard, respectively), while the lowest temperature was 42°C (at Mszczonów). The Podhale geoDH is probably the largest geothermal heating system in Europe (except for Iceland), owing to its thermal capacity and annual heat sales. Significant capacity and geothermal heat sales are also in case of Stargard. The main data on geoDH operating in Poland are given in Table 5.2.1.

All plants represent good examples of clean geothermal energy applications, resulting in a significant reduction of GHG emissions generated before by burning fossil fuels (coal) for heating purposes.

Table 5.2.1. Poland: geothermal district heating plants, 2015–2016 (based on Kępińska, 2016; updated heat sales in 2016)

Locality	Opening year	Outflow water temperature [°C]	Maximum water flow rate [m^3/h]	TDS [g/dm^3]	Geoth. capacity installed 2015 [MW_{th}]	Total capacity installed 2015 [MW_{th}]	Geoth. heat sales 2016 [TJ]	Geoth. share in total sales (%)
Podhale R.	1993	82-86	960	22.5	40.7	82.6	384.3	91.2
Mszczonów	2000	42	60	00.5	3.7	8.3	14.3	38.2
Poddębice	2013	68	252	00.4	10	10	56.5	100
Uniejów	2006	68	120	66-8	3.2	7.4	9.0	29
Pyrzyce	1994	61	360	1120	6	22	50.3	57
Stargard	2012	83	180	1150	12.6	12.6	187	100
Total					76.2	142.9	702	

The Podhale region – the plant has been operating by PEC Geotermia Podhalańska SA since 1994 (on a larger scale since 2001) as the biggest geoDH in the country and one of the biggest in Europe. It was preceded by comprehensive geological, drilling, and geothermal exploration and by Experimental Geothermal Plant Bańska – Biały Dunajec (designed and operated by MEERI PAS). The geothermal aquifer is hosted by Middle Triassic limestone and dolomites and Middle Eocene limestones (top aquifer's part), situated between depths 2–3.7 km b.g.l. The total maximum flow rate (artesian!) produced by 3 wells is 960 m^3/h of 82–86°C water. Water mineralization (TDS) is ca. 2.5 g/dm^3. These are very good reservoir and exploitation parameters.
In 2016 the installed geothermal capacity was ca. 41 MW_{th} (total ca. 83 MW_{th} including gas and fuel peaking boilers). Geothermal heat sales amounted to 384 TJ. Ca. 1470 receivers were hooked to geoDH (mostly in Zakopane – the main city of that region and main heat market; geoDH meets ca. 405% of its heat demand). Part of spent geothermal water is injected back while part supplies 2 recreation centres. The Podhale geoDH system has resulted in significant reduction of CO_2 emissions generated early by coal burning. The system is planned to be extended (to Nowy Targ, Szaflary, Kościelisko) what will be possible thanks to more efficient energy management and new production well planned to be drilled.

Other five geothermal district heating plants (geoDH) are situated within the Polish Lowlands and all are based on sandstones, as reservoir rocks: in Mszczonów, Poddębice (town included into reported Project), Pyrzyce, Stargard, Uniejów. They operate on a basis of geothermal waters discharged by Lower Cretaceous or Lower Jurassic sandstones. Their brief characteristics is given below. They serve as examples and sources of experiences for next planned district heating systems within the Polish Lowlands , including Konstantynów Łódzki and Sochaczew – towns addressed by reported the EEA Project.

Mszczonów – the geoDH has been operating since 2000. Maximum flow rate is ca. 60 m3/h of 42.5°C water, while TSD are 0.5 g/dm^3. Geothermal aquifer is hosted by Lower Cretaceous sandstones at the depth 1.6–1.7 km b.g.l.

Water is discharged by a single well and it is not injected back. This is a former oil&gas exploration well from the 1970s, reconstructed and adopted for geothermal water production (project by MEERI PAS and Geotermia Mazowiecka SA).
In 2016 the total installed capacity was 8.3 MW_{th} (4.6 MW_{th} from low-temperature gas boilers, 2.7 MW_{th} absorption heat pump and high-temperature gas boilers and 1 MW_{th} from compressor heat pump). Geothermal heat sales was ca. 14.9 TJ (38.2% of total sales). The plant extracts heat from geothermal water in a very efficient way, from 42 to ca. 10°C for three important economic and social purposes: district heating, drinking (water cooled down by compressor heat pump is sent to local water works),for the pools in local recreation centre. Technological sketch of the described heating system is shown on Figure 5.2.4. R+D and other next projects of further innovative applications (e.g. mineral water production; construction of large recreation water center) are in progress.

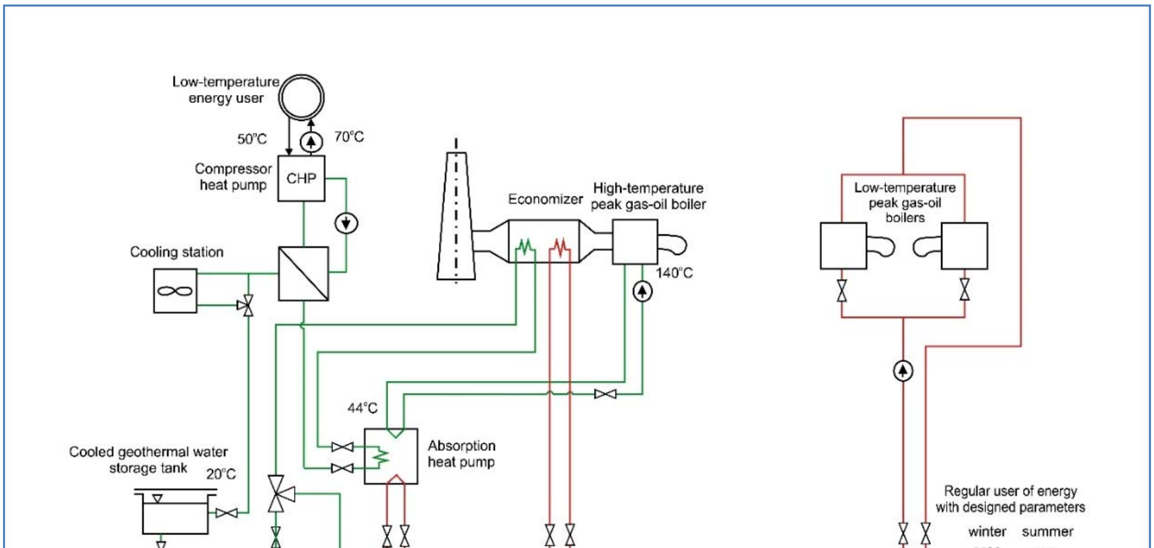


Fig. 5.2.4. Mszczonów – technological sketch of the geothermal district heating system (source: Geotermia Mazowiecka SA)

Poddębice. In that town the construction of geothermal district heating plant was commissioned in 2012. Geothermal aquifer is hosted by Lower Cretaceous sandstones at the depth 1.95–2.06 km b.g.l.

The geoDH of 10 MW_{th} geothermal capacity is based on 68°C water (maximum ca. 250 m3/h, mineralization 0.4 g/dm^3). Since 2014 the plant supplies some public buildings, school, hospital (and its rehabilitation part), several multi-family houses. Some part of water stream is sent to swimming pool. In 2016 geothermal heat sales amounted to 56.6 TJ. Poddębice have very prospective geothermal conditions therefore the extension of geoDH as well as other further investments are being considered. Thanks to low mineralisation and high quality water is also used for drinking (so far on a limited scale).

Poddębice represent a good study case and argument for wider geothermal energy development for space heating and introduction low-emission heating systems into the buildings. Those aspects were in focus of the project called "Geothermal Energy Utilization Potential in Poland – Town Poddębice" under the Fund for bilateral relations, Operational Programme PL04 „Energy savings and promoting RES", EEA Financial Mechanism2009-2014. Some topics touched in that Project were deepened, extended and proposals of further energetic-economic optimization of geothermal water and energy uses in this town were elaborated in the framework of next EEA Project – subject of this report.

Pyrzyce. The geoDH plant has been operating since 1996. The geothermal aquifer is hosted by Lower Jurassic sandstones at the depth 1.4–1.6 km b.g.l. The maximum flow rate from two production wells is ca. 100 dm^3/s of 61°C water (spent water is injected back by two wells). After recent optimisation works, the plant's maximum installed capacity is 22 MW_{th} including 16 MW_{th} comes from absorption heat pump.

The plant supplies heat and domestic warm water to over 90% users of the town's population (13,000) meeting ca. 60% of total heat demand. In 2016 geothermal heat sales was ca. 50.3 TJ (57% of total heat sales). In 2017 next geothermal exploitation well was drilled.

Uniejów. The geoDH has been operating since 2001. The geothermal aquifer is hosted by Lower Cretaceous sandstones at the depth 1.9–2.1 km b.g.l.

The maximum discharge from one production well is 33.4 L/s of 68°C water while TDS are ca. 6–8 g/dm^3. The exploitation system includes also two injection wells. By 2015 total installed capacity of the plant is 7.4 MW_{th} including 3.2 MW_{th} from geothermal, 1.8 MW_{th} from biomass boiler and reserve 2.4 MW_{th} fuel oil peak boilers (Kępińska, 2016). In 2016 heat was generated in new high-efficient co-generation system (based on gas). From that source ca. 22 TJ of heat was sold to the consumers while ca. 9 TJ of geothermal heat. Ca. 80% of all buildings in that town are connected to district heating grid.

Since 2008, a part of geothermal water has been used in geothermal spa and recreation centre "Termy Uniejów" for pools and curative treatments (ca. 8.4 L/s of 42°C water; ca. 1 MW_{th}, 7.7 TJ). The centre is also heated by geothermal energy. Some amount of spent water (ca. 5.6 L/s, 28°C) is later used to heat up the pit of the local football playground (ca. 1 MW_{th}, 8.7 TJ) and walking paths. In 2012, Uniejów received a formal status of health resort, owing to uses of curative geothermal water. Some new types of geothermal uses are at various stages of project preparation and planning.

Stargard. The plant was re-open after refurbishment in 2012 (closure in 2008–2012). It is based on a doublet of production and injection wells. The geothermal aquifer is hosted by Lower Jurassic sandstones (total well depths 2.6 – 2.9 km b.g.l.

The maximum production is ca. 50 L/s of 87°C water. In 2016 the installed geothermal capacity was 12.6 MW_{th} and geothermal heat sales was 187 TJ, entirely sold to the municipal district heating plant for heating and domestic warm water preparation (Kępińska, 2016). This plant is coal-fired (total capacity 116 MW_{th} serving about 75% of local population (75,000). Geothermal meets ca. 30% of total heat demand of that municipality.In 2017 the drilling of new wells started what will result in significant increase of capacity and clean heat generation for that town.

Summary of the basic data of six geoDH systems in Poland: In 2015,total installed geothermal capacity was ca. 76 MW_{th} while geothermal heat sales amounted to ca. 702 TJ in 2016. In particular cases, geothermal energy share in total heat production was from 29 to 100%.The biggest installed total and geothermal capacity had the geoDH in the Podhale region. It produced and sold the largest quantity of geothermal heat in Poland. It is one of the biggest geoDH systems in continental Europe. One shall also note remarkable geothermal capacity and heat sales by heating plant I Stargard.

However, Poland is only at the 12th place among 30 European countries covered by the statistics presented at European Geothermal Congress 2016 (Fig. 5.2.5). the place is far beyond geothermal potential, real needs, as well as ecological and social interest.

It is hoped that this situation will change thanks to more dynamic development of next geothermal heating plants. This is expected in the coming years due to supporting system for drilling exploration wells. Such a system was introduced thanks to governmental initiative in 2016 and realized by NFEP&WM. Thank to it by October 2017 five applications for drillings received financial support. Among them are projects in Lądek-Zdrój and Sochaczew – two from among four towns taking part in reported the EEA Project.

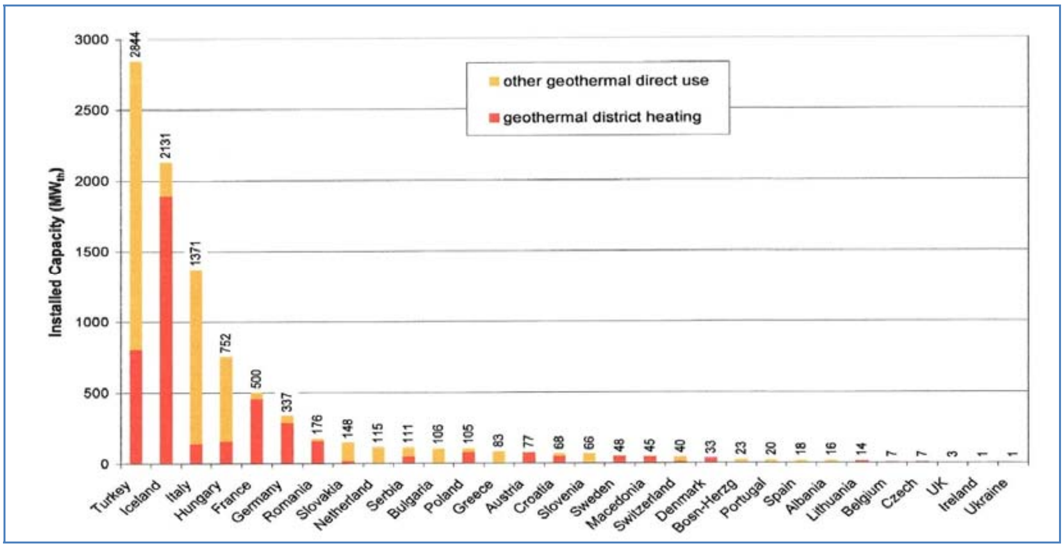


Fig. 5.2.5. Installed capacity in geothermal direct uses in Europe 2015 showing the share of district heating and position of Poland (Antics et al., 2016)

5.2.4. Geothermal projects, 2017

Among investment activities in 2017 one may list here:

- Several investments oriented for recreation and balneotherapy,
- Initial stages of a few projects aimed at CHP plants (based on ca. 90–110 °C water),
- Modernization and optimization of several operating geoDH plants (surface infrastructure, downhole equipment),
- Works on extension of existing geoDH systems. Some operators considered or prepared themselves for drilling new wells (depending on the availability of financial support),
- Several pre-investment works and feasibility studies for various sites in the Poland (mostly recreation facilities, sometimes space heating, also in the hybrid systems with other RES and fossil fuels),
- Design of several new deep drilling projects: based on the government's support program introduced in 2016, more projects are expected to appear in the coming years: by end 2016, over a dozen projects applications for supporting the new well drillings (exploration and exploitation) were submitted to the National Fund for Environment Protection and Water Management and were in review process during preparation of this Report (spring 2017).

5.2.5. Comparison of geothermal heat prices with prices of heat from fossil fuels

Right at the beginning one shall point out that the prices of heat supplied by geothermal district heating plants are competitive with the costs of heat generated by incineration of fossil fuels – natural gas, fuel oil and even coal This fact creates a very important argument for wider geothermal heating sector development in Poland (especially in the towns where district heating systems are already exist).

Fig. 5.2.6. shows the heat prices (approved on the bases of tariffs) for the final user. The final price includes the cost of energy production and distribution. The presented data suggest that the price of geothermal energy is located within the interval, being typical for conventional energy carriers. In case of good reservoir conditions (temperature higher than 80°C and high flow geothermal water flow, e.g. Stargard and Podhale) the heat prices are comparable to those offered by coal-based heating plants. In other cases, the prices are close to the heat prices originated from natural gas or fuel oil burring.

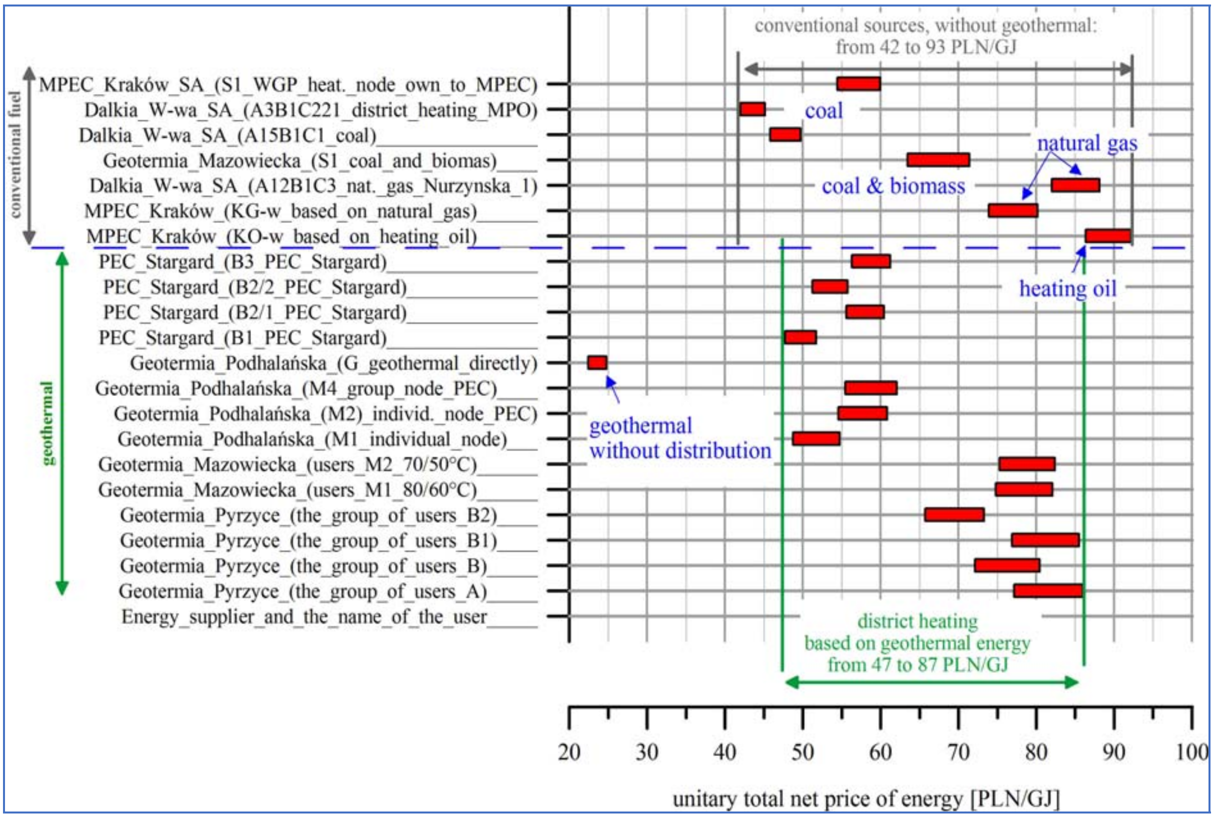


Fig. 5.2.6. Total final net thermal energy prices (including energy production and distribution): geothermal district heating plants vs. selected district heating plants based on fossil fuels, June 2016 (Pająk, Bujakowski, 2016)

All geothermal heating plants operating in Poland are working as the part of a hybrid energy sources. Also heating plants in Stargard and Poddębice (which do not have other sources themselves i.e. as parts of geothermal heating stations) are working in combination with conventional heating stations (boilers). Geothermal sections serve as basic energy sources, while the conventional ones as peak-demand sources. The main problem in the wider use of geothermal energy, in co-operation with district heating networks in Poland, consist in the lack of coherence between the available parameters of the geothermal source (mainly in terms of temperature) and the design parameters of the existing heating systems. In large cities, the most common heating systems are designed for the parameters of 130/70°C or even higher. Smaller heating plants usually are designed for the parameters of 90/70°C or 95/70°C. As Table 1.1 shows, the highest temperatures of geothermal waters are a bit over 80°C, but the use of heat exchangers limits the real temperature up to approx. 80°C. The geothermal plants working within hybrid systems are usually a necessity, regardless of the choice. Unfortunately, the companies maintaining heating networks do not wish to co-operate for the sake of the reduction of required temperature parameters. A common approach is rather to adjust the source to the requirements of the recipient.

5.2.6. Program of financial support for geothermal development introduced in 2016

In 2016, the program of public support for geothermal (energy generation uses) was launched by the Ministry of Environment to enhance wider development of this sector. It uses, inter alia, 200 mio PLN (ca. 45 mio Euro) allocated for drilling the first exploration well and 500 mio PLN (ca. 113 mio Euro) for drilling subsequent well and erecting heating infrastructure (www.nfosigw.gov.pl). The beneficiaries will be local authorities, investors, and operators. Types of support include grants (up to 100% for local self-governments), loans, or capital expenditures. The program has already resulted in fact that over 30 projects applications for drillings and other works were prepared and submitted to program operator by the end of 2016 and beginning of 2017. Some of them will be assigned for funding in course of 2017.

Other funding opportunities for geothermal sector can be found in frames of national, EU, NFM and EEA programs by 2020 and beyond (those related to various thematic areas/objectives, etc. where one may find the space for geothermal).

5.2.7. Some bottlenecks for geothermal energy uses development in Poland

A measure that is still missing, but indispensable to assure proper long-term operation and maintenance of geothermal plants, is a risk guarantee fund (already operating in several countries), as well as common technical and consultation assistance for all plants, etc.

We should also indicate an insufficient level of knowledge and awareness of geothermal resources, developmental opportunities, and various benefits among some circles of the decision makers, local administration people, and other potential stakeholders. Therefore, further dissemination and training activities tailored to the particular groups of receivers are needed.

In this respect, one of the best opportunities is related to the possibility to make use and transfer the examples of good practice, proven technologies, and professional expertise from Iceland, within the frame of bilateral Polish-Icelandic co-operation under the EEA grants.

We should also mention that the energy sector in Poland: power generation, co-generation, and heat production, has been based on coal (hard and brown coal) and natural gas. Therefore, it is a challenging task for other energy sources, including geothermal energy, to enter the market, the more so as the market conditions remain unequal for all the players. On the other hand, competitive heat prices, specific benefits, the ecological role, other factors and, last but not least, the current political situation will increase the geothermal energy share on local and regional heat markets in Poland.

5.2.8. The prospects of the development of geothermal energy use in Poland

The current applications of geothermal energy in Poland, even on a limited scale, have brought positive economic, environmental, social and other effects. Although the Polish energy generation sector is based on fossil fuels (especially coal), there is space and potential for a wide development of geothermal heating systems, especially in district heating.

Geothermal energy should be managed on a wider scale than it is the case now, in the existing central heating networks, as well as agricultures, aquacultures, ecological food production, spa clinics, recreational facilities etc. Cogeneration of heat and electricity is possible on a local scale (in binary systems applying 80-100°C thermal water, with the anticipated electrical power from several hundred kWe to 1-2 MWe). Interesting methods of using geothermal waters can be associated with the production of mineral water, potable water, and other mineral articles.

Such wider applications will bring a number of important effects, e.g. low-emission heating (with the reduction of CO_2), improvement of the standard of life, increased use of local energy sources, and sustainable development and innovative local and regional development. Geothermal energy can be used either as a stand-alone system or within a hybrid power generation system, integrated with other conventional or renewable energy sources, heat pumps etc.

Besides, to increase an relatively low level of savings and efficient use of energy in Poland, it is recommended to apply a more comprehensive and holistic approach to the issue of energy as the foundation of economic development and improving the standard of live, based on the Icelandic and Norwegian models, adopted from the EOG Donor countries.

References

Aktualizacja projektu założeń do planu zaopatrzenia w ciepło, energię elektryczną i paliwa gazowe dla miasta Katowice. Energoprojekt Katowice company, 2016(*Updating the draft guidelines to plan for supply of heat, electricity and fuel gas for the city of Katowice*). In Polish (http://www.katowice.energiaisrodowisko.pl/energia-w-twoim-miescie/13-dynamika-wzrostu-cen).

Antics M., Bertani R., Sanner B., 2016: Summary of EGC 2016 Country Update Reports on Geothermal Energy in Europe. Proceedings European Geothermal Congress 2016. Strasbourg, France, 2016 (electronic version).

Berent-Kowalska G., Kacprowska J., Moskal I., Jurgaś A. et al., 2015: Energy from renewable sources in 2014. Central Statistical Office, Warszawa (in Polish).

Bujakowski W., Tomaszewska B. [eds] et al., 2014: Atlas of the possible use of geothermal waters for combined production of electricity and heat using binary systems in Poland. Pbs House MEERI PAS, Kraków.

Bujakowski W., Pająk L., 2016: The changes of cost of thermal energy derived from geothermal in reference to other heat carriers in district heating systems in 2007-2016. Exploration Geology. Geothermics. Sustainable Development. No. 1/2016 (in Polish, English abstract).

Górecki [ed.] and Hajto et al., 2006a: Atlas of geothermal resources of Mesozoic formations in the Polish Lowlands. Ministry of Environment. Ed. ZSE AGH, Kraków.

Górecki, W., [ed.], Hajto, M., et al., 2006b: Atlas of geothermal resources of Paleozoic formations in the Polish Lowlands. Ministry of environment. Ed. ZSE AGH. Kraków.

Kępińska B., 2016: Geothermal energy use – country update report for Poland, 2013-2016. Proceedings of the European Geothermal Congress 2016.Strasbourg.

Pająk L., Bujakowski W., 2016: Analiza zmian cen energii cieplnej pochodzącej z instalacji geotermalnych i wybranych źródeł konwencjonalnych na podstawie taryf rozliczeniowych w latach 2007-2016 (*Analysis of changes in the prices of thermal energy derived from geothermal installations vs prices of selected conventional energy sources according to tariffs settlement from 2007–2016*). Geological Exploration Technology. Geothermics, Sustainable Development (Technika Poszukiwań Geologicznych. Geotermia, Zrównoważony Rozwój). No 1/2016(in Polish, English abstract).

Persson et al., 2012: HUDC Database 2012 (The Halmstad University District Heating and Cooling Database).

Potencjał dla wykorzystania energii geotermalnej w Polsce – Miasto Poddębice. Raport z wizyt studyjnych. Projekt EOG. Program Operacyjny PL04 „Oszczędzanie energii i promowanie odnawialnych źródeł energii". Umowa 115/2016/Wn05/OA-XN-04/D, EOG 2009-2014 (*Geothermal energy utilization potential in Poland – Town Poddębice. Study Visit Report. The EEA Project. Operational Programme PL04 "Energy saving and renewable energy sources" Contract 115/2016/Wn05/OAXN-04/D, EEA 2009-2014*) (www.eeagrants.agh.edu.pl).

Report on Geothermal DH Potential in 14 EU-countries, 2014 (www.geodh.eu)

http://www.katowice.energiaisrodowisko.pl/energia-w-twoim-miescie/13-dynamika-wzrostu-cen

www.eeagrants.agh.edu.pl

www.geodh.eu

www.nfosigw.gov.pl

www.portpc.org

5.3. Analysis of geological and hydrogeothermal parameters and evaluation of geothermal resources of Lower Cretaceous and Lower Jurassic reservoir of the Mogilno – Łódź basin aimed to location of new heating installations

The area of Mogilno-Łódź basin (named also as aTrough) located in the central part of the Polish Lowland, is one of the most attractive areas in Poland in terms of geothermal resources. The so-far research works confirm the existing geothermal potential and possibilities of further effective management of geothermal waters in this region (Górecki, Kuźniak et al., 1996).

Regional analysis of geothermal conditions within Mogilno–Łódź Trough was the subject of a number of research works conducted during the last decade. One should note Atlases of geothermal resources on the Polish Lowland, which were published in 2006 (Górecki, Hajto (eds) et al., 2006a,b).

The results of the studies carried out on the area of Mogilno–Łódź Trough indicate that this area is characterised by the most favourable hydrogeological conditions on the Polish Lowland, and geothermal energy should be first harnessed in the Lower Jurassic and Lower Cretaceous reservoirs. Geothermal waters in the above-mentioned reservoirs, within the area of the central part of the Polish Lowland, are characterised by temperatures ranging from ca. 40 to 90°C, which confirms excellent suitability of those waters for heating purposes on an extensive area of central Poland.

The only unfavourable elements, which might affect exploitation of geothermal waters with relatively high temperatures in this region is high mineralisation, which regards particularly geothermal waters in the Lower Jurassic reservoir, which may be produced from the depth of over 2000 m under ground level. In some deepest areas of the Trough, mineralisation of those waters may even exceed 80-100 g/dm^3.

In recent years, on the basis of regional exploration of hydrogeothermal properties in the area of Mogilno–Łódź Trough, several new places were located, which are characterised by favourable reservoir parameters for geothermal waters. All of them confirm excellent geothermal parameters of both Lower Cretaceous and Lower Jurassic intakes. In some cases, intake outputs may be even as high as 300 m^3/h, which is confirmed by hydrogeological studies of the Lower Cretaceous reservoir performed in 2015 in Poddębice.

5.3.1. Geographic location of the study area

In accordance with the physico-geographic division adopted by Kondracki (2009), Mogilno–Łódź Trough is located in the area of the Central European Plain Province, the south-eastern part of which located in Poland is called Polish Lowland.

Mogilno–Łódź Trough occupies the surface of ca. 17 940 km^2 and it covers five main physico-geographic units (macro-regions) with latitudinal range. They are as follows: Toruń–Eberswald ice-marginale valley (a part), Greater Poland Lakeland, South–Wielkopolska Plain, Central–Mazovian Plain, South–Mazovian and South–Mazovian Elevation. Within the Trough, one can distinguish a number of mezoregions, characterised by different geographic features and differentiated natural environment, and the like.

The division into physico-geographic units within Mogilno–Łódź Trough, based on Kondracki (2009) is presented in Fig. 5.3.1.

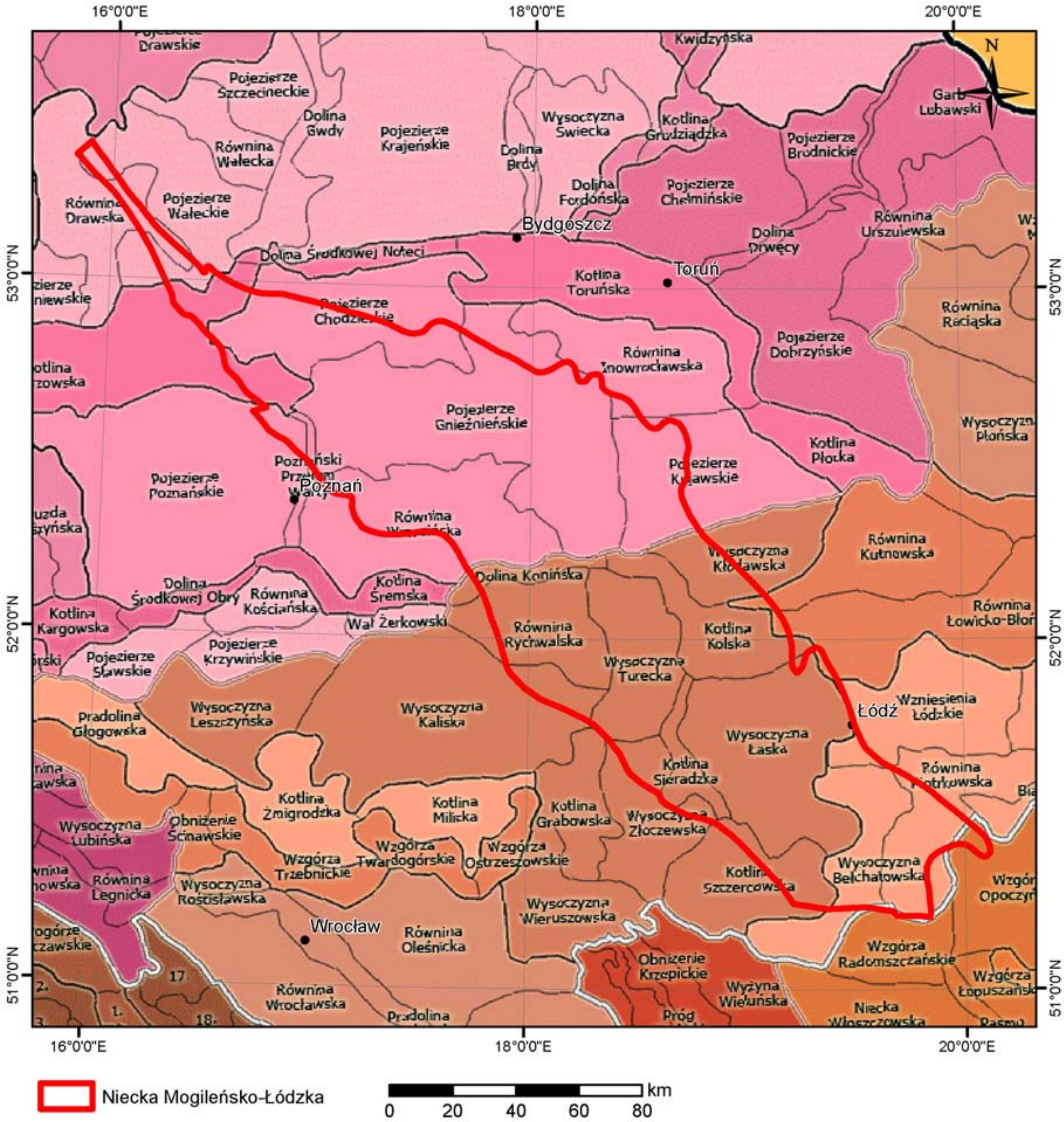


Fig. 5.3.1. Location of Mogilno–Łódź Trough against main physico-geographic units in Poland (based on Kondracki, 2009)

5.3.2. Geostructural position of the study area

Mogilno–Łódź Trough is a lower order structure being a part of a larger structure: Szczecin–Miechów Synclinorium, constituting a south-eastern part of Polish–Danish furrow. In Szczecin–Miechów Synclinorium, adjacent to Central Poland anticlinorium from the south-western side, one can distinguish the following segments: Szczecin–Gorzów and Mogilno–Łódź and Miechów. The border between Szczecin–Gorzów and Mogilno–Łódź segments should be the structure, which we propose to distinguish as Drawno–Poznań fold-fault range. It is a series of anticlines with Jurassic nuclei, cut by faults and creating semi-horsts or horsts. Further, to the south of Poznań, they connect several times with reactivated fault zone, the clearest element of which is a 1-3 km wide graben, ending in SSE with Permian Laskowice Oławskie graben. The whole structure is called Poznań–Gostyń–Uczeszowski–Oleśnicki graben by Sokołowski (1972). Taking into account the Mesozoic rejuvenation of faults limiting that graben, we propose to call that whole structure briefly the Luboń–Brzeg fault zone.

On the other hand, Mogilno–Łódź and Miechów segments are divided by the structure called in the past: "Kodrąbie Rock Mass", "Przedborze Bridge" and Radom elevation (Pożaryski, 1974). Since this structure is made up of numerous anticlines and Troughs, we suggest calling them Radom Folds, which shows the essence of its tectonic nature probably in the best way. In the Tertiary period, Radom folds were cut from the north by Miocene Wieluń-Kraśnik fault zone, which Kleszczów graben relates to. On the south-west, Mogilno–Łódź Trough borders with Fore–Sudetic Monocline.

Mogilno–Łódź Trough is an asymmetric structure, founded on an epivariscan graben in the NW-SE direction. A characteristic geo-structural element is the occurrence in a deep synclinal dip, of anticlinal upheavals, relating to underlying Zechstein salt structures. The final image of the tectonic structure was created during Alpine orogeny movements, which led to faulting of the Trough area and to the creation of a number of grabens and horsts (Dadlez et al., 2000; Dadlez, 2001).

The tectonic border of wide-radius Central Poland anticlinorium Szczecin–Miechów Synclinorium has not been delineated so far. Traditionally, it is understood as an arbitrary border and it was apparently constituted by an intersection line of the Upper Cretaceous bottom outcrop on the sub-Cenozoic surface (Pożaryski, 1974). The map showing the study area against the map of tectonic units of Poland under the Cenozoic cover has been presented in Fig. 5.1.3 (sub-chapter 5.1 of this Report).

5.3.3. Outline of geological structure

The area of Mogilno–Łódź Trough, in its geological evolution, initially constituted a part of Mid–Polish (Polish–Danish) Trough. As a result of Laramian movements, the trough was transformed into the Central Poland (Pomerania–Kujawy) anticlinorium. Lower Cretaceous sediments with the biggest thickness have been preserved along the anticlinorium edge, including also the area of Mogilno–Łódź synclinorium. This synclinorium is a paleo-depression, where the top of Lower Cretaceous formations is retained at the depth from 0 (outcrop area – a SW part) to over 2800 m under ground level (the area of Trzemżal and Wilczyn).

Thickness differentiation of particular stratigraphic groups in the area of the Trough (including Lower Cretaceous and Lower Jurassic formations) relates to disjunctive tectonics and Zechstein salt movements in the substrate. One of fundamental dislocation zones is Mogilno–Ponętów–Pabianice zone (Wiktorowicz, 2014). West of it, within Gniezno–Łask Block, reduction of the number of stratigraphic links and sediment thickness can be observed, expressed by the lack of older Neocomian links, i.e. Berriasian and Lower and Middle Valanginian, with the total Lower Cretaceous sediments thickness not exceeding 150 m.

Mogilno–Łódź Trough is filled with Upper Cretaceous sediments resting on older rocks emerging on the sub-Cenozoic surface in south-western wing of the Middle-Poland Ridge and on Fore–Sudetic Monocline and on elevations (Stupnicka, 1997; Mizerski, 2011).

The Permo-Mesozoic cover made up by the sediments filling Mogilno–Łódź Trough lies on older sediments: Rotliegend, Upper Carboniferous, Lower Carboniferous, Devonian, Silurian, Ordovician and Cambrian deposited on crystalline and volcanic rocks of Pre-Cambrian substrate (Fig. 5.3.2). Variscan orogeny units (Varistcan externides) are poorly recognised on this area, due to a very large thickness of the Permo–Mesozoic cover (P. Karnkowski, 1980; Narkiewicz, Dadlez, 2008; Mizerski, 2011).

The main factor leading to the current shape of the Permo–Mesozoic complex structure was vertical movements of the pre-Zechstein substrate blocks, topped with deformations caused by the movement of Zechstein salt masses. Thick Zechstein salt layers in the lower part of the complex gradually acquired plastic properties, together with development of younger sediment series. Thus, they could move influencing, in that way, further sedimentation (changes in thickness and facies, occurrence of erosive surfaces and sedimentary gaps) and they caused mechanical overburden deformations (Dadlez, Marek, 1974; Marek, Raczyńska, 1974).

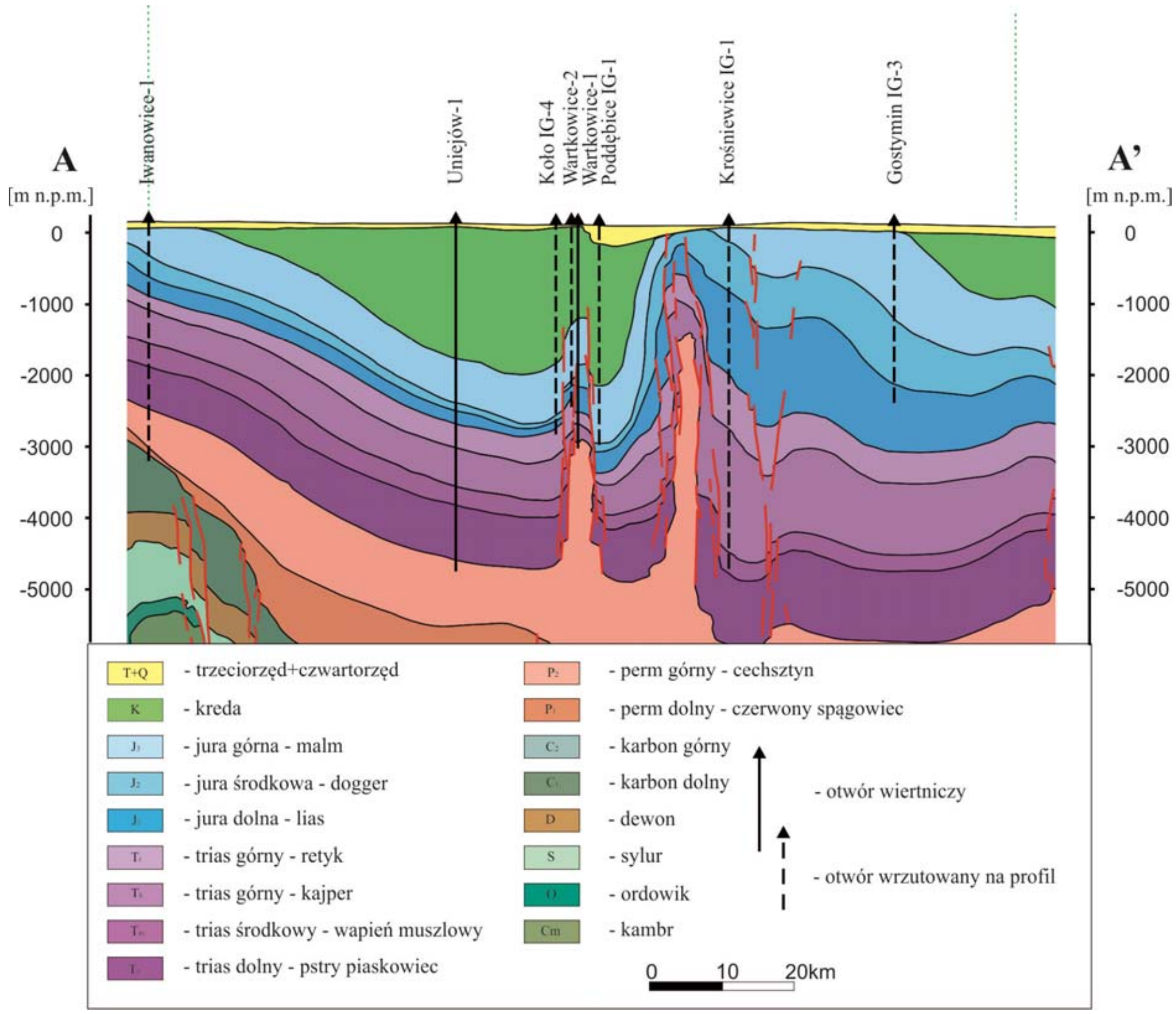


Fig. 5.3.2. Geological cross-section through Mogilno–Łódź Trough (acc. to P. Karnkowski,1977) – simplified, cross-section line visible in Fig. 5.3.4

5.3.4. Geological explorations of the area of Mogilno–Łódź Trough

5.3.4.1. Drilling explorations

The area under analyses is recognised with exploratory and reservoir drilling profiles, oriented mainly towards oil potential explorations in the Polish Lowland. Based on data collected in CBDG (Central Geological Database), 20 648 wells have been located in the area of Mogilno–Łódź Trough, including exploratory, cartographic, geological-engineering as well as reservoir and hydrogeological wells.

The usefulness of information included in well-related documentation, including data collected in CBDG, to evaluate geothermal potential depends on a number of factors. One of them, obviously regardless of the quality of the included information, is the wells depth. In accordance with the geothermal conditions in Poland, geothermal waters usually occur at depths higher than 1500-2000 m under ground level, and therefore, information from those wells seems to be a key for considerations regarding the evaluation of the potential and possibilities of using geothermal waters.

The final depth of most of the wells located on the study area (ca. 87%) does not exceed 100 m (Fig. 5.3.3). Those wells do not present significant information for geothermal purposes.

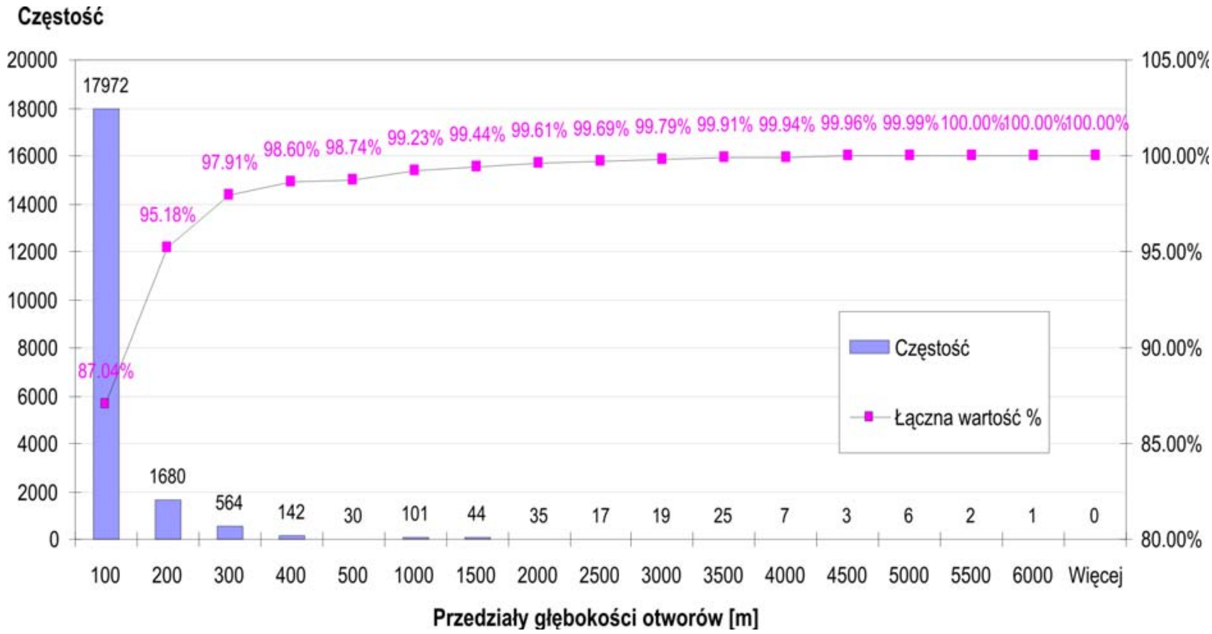


Fig. 5.3.3. Histogram of well number distribution in depth ranges in the area of Mogilno–Łódź Trough on the basis of CBDG information

From the point of view of evaluating geothermal water potential and management, data coming from deep drilling wells are particularly valuable. The analysis of collected archival data shows that 115 wells with the depth exceeding 1500 m were located in the area of the Trough, which constitutes only ca. 0.6% of all wells in the area of the Trough. Only 7 wells have the final depth over 3000 m under ground level. The location of drilling wells in the area of Mogilno–Łódź Trough against the geological map, without Cenozoic formations has been presented in Fig. 5.3.5.

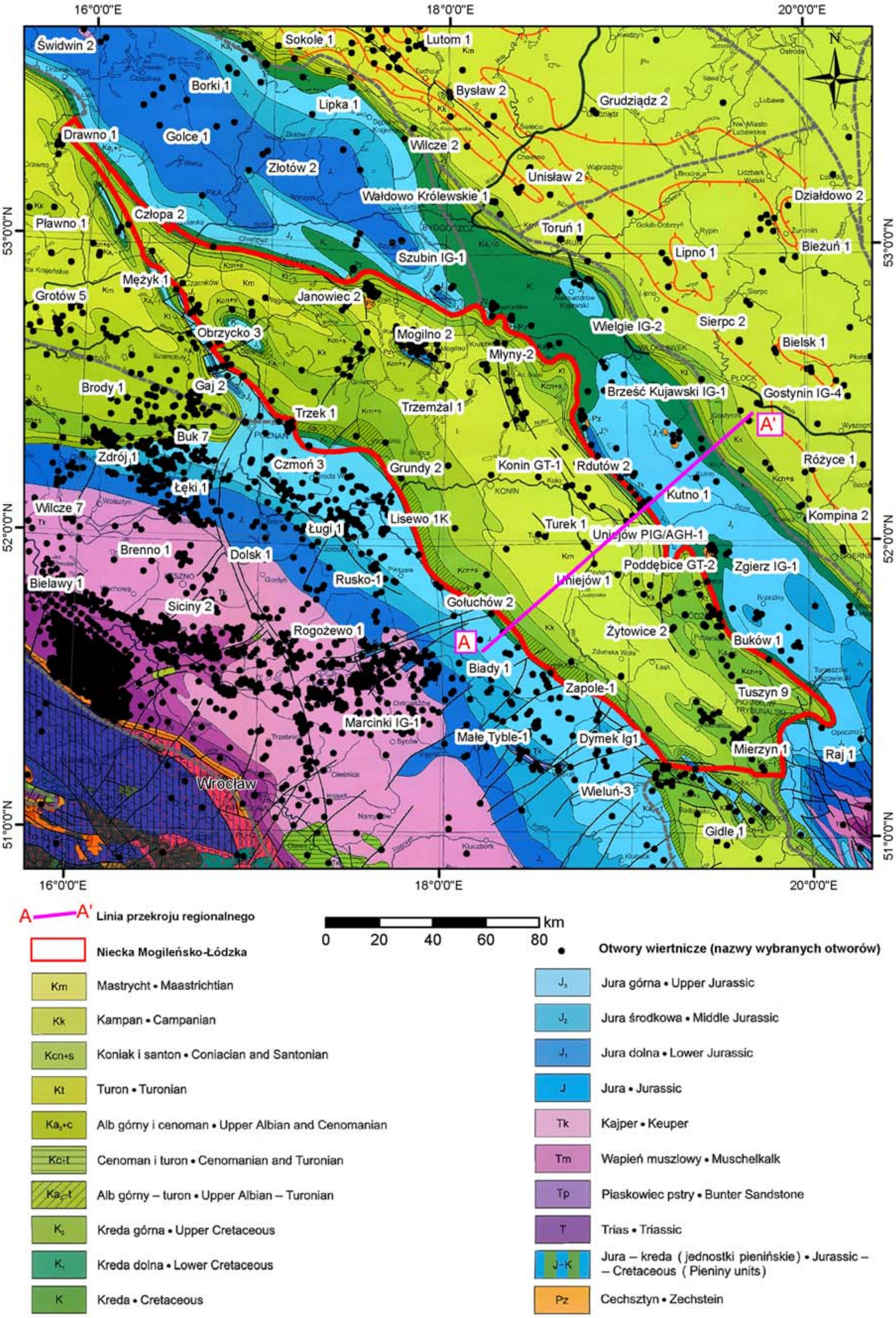


Fig. 5.3.4. Location of wells drilled in the area of Mogilno–Łódź Trough against the geological map without Cenozoic formations (on the basis of Dadlez et al, 2000)

5.3.4.2. Geophysical exploration

In the study area, several hundred 2D seismic lines have been found (Fig. 5.3.5), performed over the last 50 years, when prospecting hydrocarbons reservoirs and exploration of Poland's geological structure.

The analysis of CBDG data indicates that the oldest seismic works, covering the area of Mogilno-Łódź Trough date back to 1970's. The first seismic works, including reflection seismology, were performed in 1972 and covered the following areas/topics: Kalisz–Iwanowice (1-9-72K, 3-9-72K), Zduńska Wola–Szczerców–Mierzyn (5-2-72K, 7-2-72K, 8-2-72K, 17-2-72K, 13-2-72K, 14-2-72K, 6-2-72K), and in 1973: Szczerców–Sulejów (9-12-73K). In 1973, within the frameworks of the Deep Seismic Soundings Programme run by PAN (Polish Academy of Sciences), including the area of the Teisseyre–Tornquist zone, a refraction profile was made (VII). The most recent seismic studies in the area of the Trough were performed in 2007 and they regard exploration of deep geological structure, by means of reflection profiling, topics: Lubinia–Grundy–Pławce and Obrzycko–Szamotuły in the area of Tomice.

This material constitutes an important source of information about deep geological structure, thus supplementing well-related data available in this region and constituting valuable input material for the construction of a 3D geological model of Mogilno–Łódź Trough. The location of 2D seismic profiles in the area of Mogilno–Łódź Trough, against the geological map, in the area of Mogilno–Łódź Trough has been presented in Fig. 5.3.5.

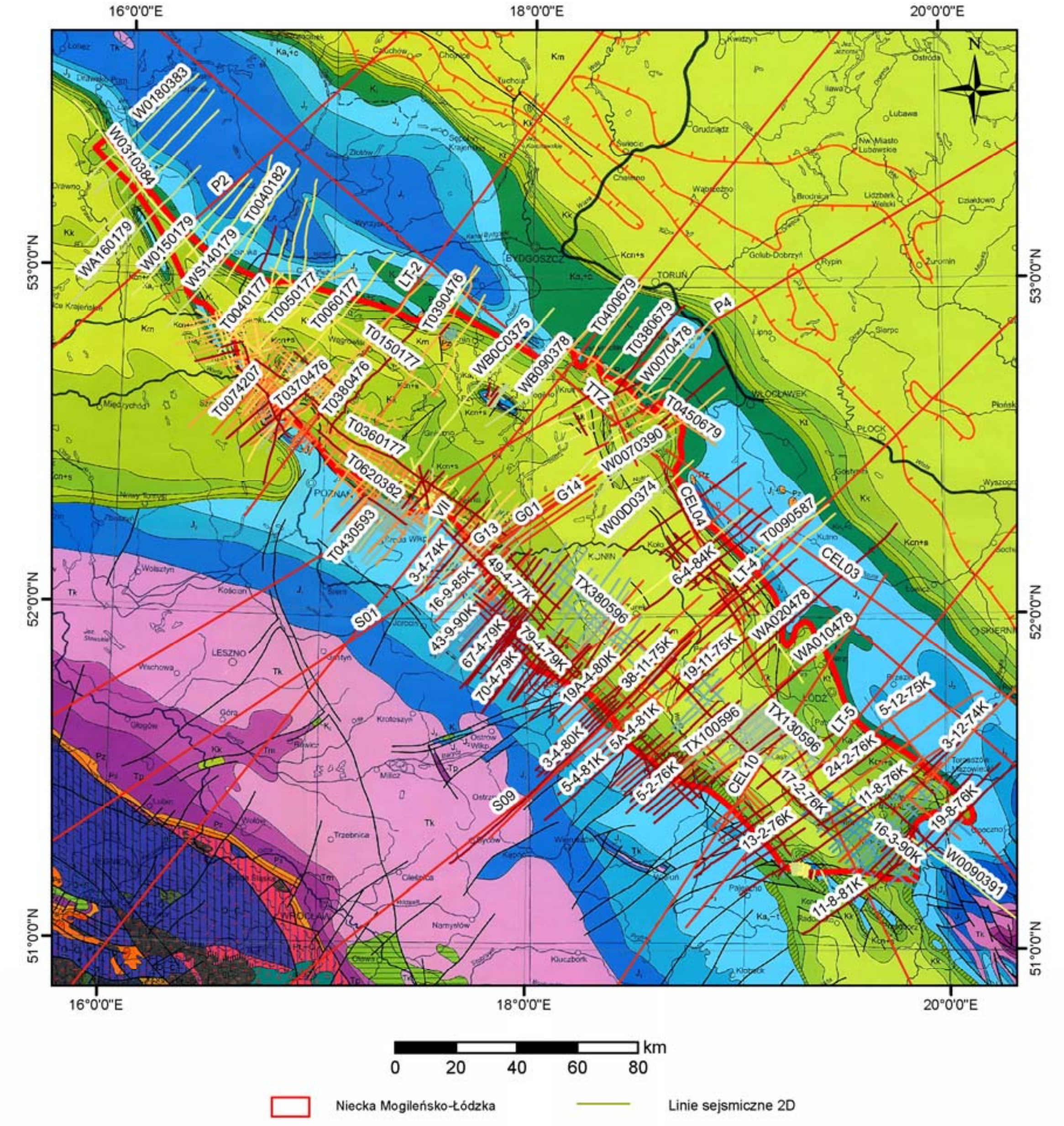


Fig. 5.3.5. Location of 2D seismic profiles in the area of Mogilno–Łódź Trough against the geological map without Cenozoic formations (based on Dadlez et al, 2000)

5.3.5. Hydrogeological explorations of the area of Mogilno–Łódź Trough

According to hydrogeological regionalisation of fresh groundwaters, Mogilno–Łódź Trough is located within two macro-regions: north-western, including Wielkopolska Region (VI) and central macro-region, including Łódź Region (VII) (Paczyński ed., 2005).

In accordance with a simplified regional fresh groundwater division (Paczyński, Sadurski (eds.) et al., 2007), the study area is located within Mogilno–Łódź–Nida region (X), where two subregions were separated, namely X_1 subregion – lakeland (Mogilno basin) and X_2 – Łódź subregion. Furthermore, on the southern edge, X_{2A} Bełchatów area (block) was separated, which due to a considerable share of Cenozoic levels was included in Łódź Trough.

The border of Mogilno–Łódź–Nida Region is delineated by the range of the Cretaceous aquifer, which makes up main or significant usable aquifer. The main part of Łódź section, characterised by predominance of the Cretaceous aquifer with clear division into the Upper Cretaceous level – in cracked marls and limestones, occurring up to the depth of 200-250 m and Lower Cretaceous – in pores and cracks in sands and sandstones, preserving usability nature up to the depth of 1000-1200 m. Łódź Trough belongs to the most depressive freshwater zones in Poland.

In central and northern part of Łódź Trough Quaternary aquifers occur equivalently, being locally supplemented with a Paleogene-Neogene level, characterised with poorer hydrogeological parameters. Within Łódź subregion (X_2), a significant part of the area of Lower Cretaceous level occurrence belongs to MUWR no. 401.

The northern section of X region is closed by Mogilno Trough (X_1 lakeland subregion) contoured on the west and south-east with the Cretaceous aquifer outreach, and on the north and north-east, conventionally, with Warta-Noteć proglacial valley and Wisła valley (Paczyński, Sadurski (eds.) et al, 2007). In earlier divisions, the share of Cretaceous aquifer was evaluated less favourably, that's why, Mogilno Trough was included in Greater Poland Region.

Within the study area, several areas of MUWR occurrence were located (Kleczkowski (ed.), 1990), delineating the ranges of reservoirs requiring special protection. These are reservoirs numbered: 127, 138, 139, 143, 144, 151, 312 and 401. MUWR location on the map of Mogilno–Łódź Trough range has been presented in Fig. 5.3.6.

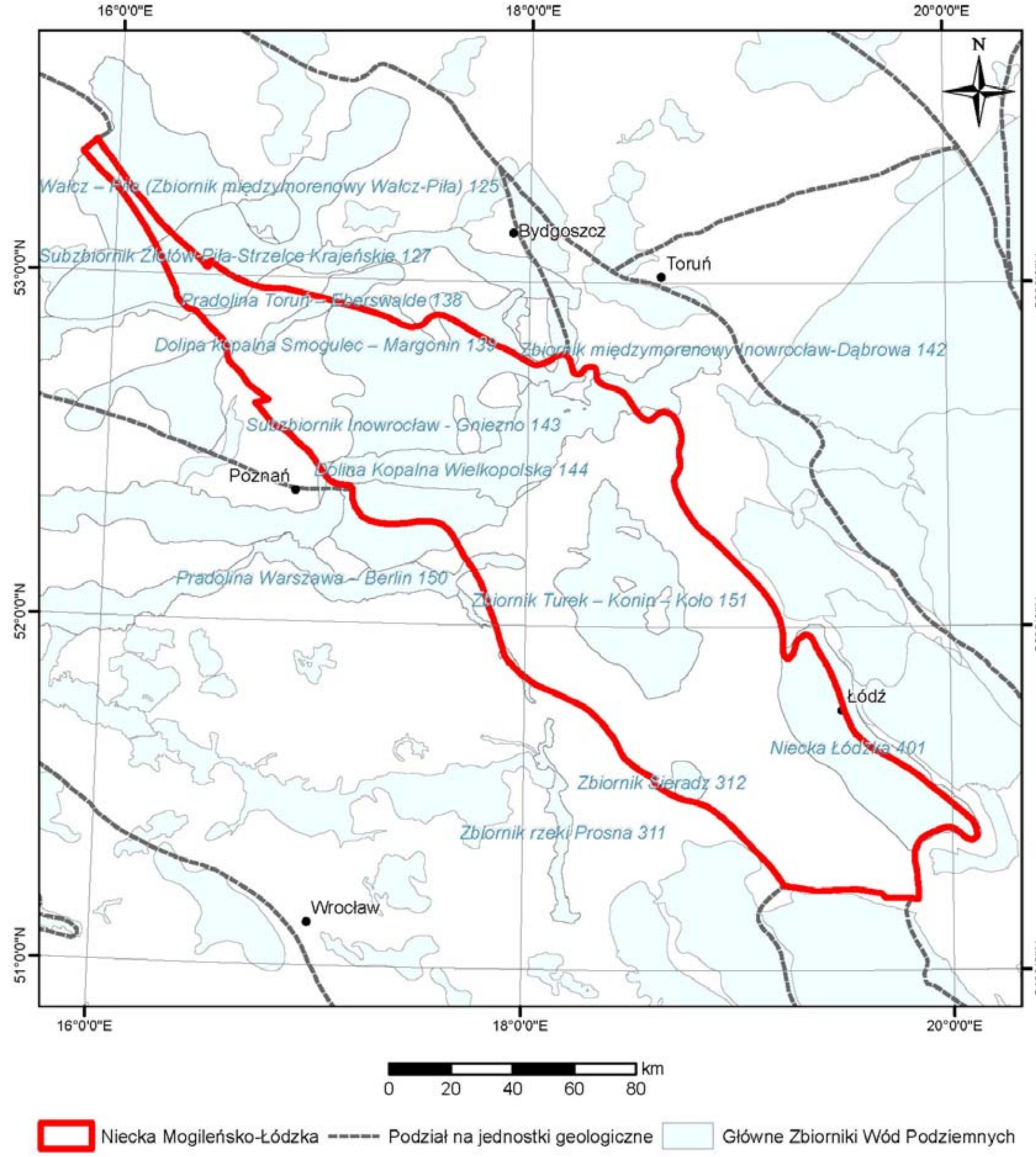


Fig. 5.3.6. Map of main groundwater reservoirs in the area of Mogilno–Łódź Trough (based on Kleczkowski (ed.), 1990)

Mogilno-Łódź Trough characterised by a very large thickness of freshwater layer, which occur in the axial zone to the depth of 1000–1600 m, including the whole Cretaceous and partially Jurassic complex (Płochniewski, 1975).

Mineral waters (>1 g/dm^3) were confirmed with numerous wells and in a deep geological profile, including Lower Cretaceous, Jurassic and Triassic formations. In Uniejów IGH1 well, Cl-Na, F, B artesian outflow was acquired from Lower Cretaceous sandstones, with temperature reaching 60°C and output of 55 m^3/h, with the maximum depression of 26 m. In years 1990–1991, another two wells were drilled: PIG/AGH 1 and PIG/AGH 2, acquiring artesian outflows of Cl-Na type and mineralisation of about 7 g/dm^3.

The fact of fresh water occurrence in a deep geological profile is confirmed by the results of drilling Poddębice GT-2 well (2010), where from Lower Cretaceous formations, at the depth of 1957–2059 m under ground level, artesian outflow of 116.5 m^3/h of HCO_3-Na-Ca geothermal water was acquired, with very low mineralisation: 0.432 g/dm^3.

5.3.6. Geothermal waters occurrence in Mogilno–Łódź Trough

As mentioned above, the area of Mogilno–Łódź Trough is one of the most prospective areas for managing geothermal waters for various purposes in Poland. The most prospective hydrogeothermal reservoirs in the area of Mogilno–Łódź Trough is the Lower Jurassic reservoir and the Lower Cretaceous reservoir. It is confirmed by the so-far exploratory works (Górecki, Hajto (eds.) et al., 2006, Górecki et al., 2015), and also the parameters of geothermal heating plants operating there (Tab. 5.3.1).

The Lower Cretaceous aquifer was recognised well in the area of Uniejów, where in 1970's groundwaters with the temperature of 68°C were drilled, thus confirming the occurrence of geothermal waters within Lower Cretaceous formations. Other wells were drilled in 1990's documented waters characterised with the output of around 90 m³/h and the temperature of ca. 70°C. Reservoir rocks build Lower Cretaceous sandstones located at the depth of ca, 1.9–2.0 km. In 2005, abstraction of geothermal waters was approved by means of a submersible pump with a volume flow at the level of 120 m³/h (Sapińska-Śliwa, 2011, Kępińska, 2016).

In 2010, Poddębice GT-2 well was made in the area of Mogilno–Łódź Trough well. Geothermal water of the Lower Cretaceous level occurs here in artesian conditions, which enables abstraction of 116 m³/h without using a pump. Water temperature at the output was 71°C (for temporary water flow at ca. 300 m³/h), and water was characterised with low mineralisation, namely 0.4 g/dm³ (water of bicarbonate–sodium–silicon–calcium type). The approved operational resources are 252 m³/h (Kępińska et al, 2017), with a depression of 85.3 m. Aquifer series in Lower Cretaceous formations of Poddębice area are built from porous fine-grained, and in places, medium-grained, sandstones. Presently (2017), geothermal water is used for heating purposes; balneotherapy; recreation and, on a limited scale, also for consumption. The parameters of both aforementioned geothermal heating plants have been presented in Tab. 5.3.1.

In September 2014, geothermal drilling began in Pociejewo Island in Konin. At the depth of 1620 meters, water with temperature of 62°C and mineralisation of 40 g/dm³ was obtained. Temperature in the reservoir (Lower Jurassic reservoir) at hte final depth of 2660 meters was 97.5°C, with mineralisation of 150 g/dm³ and high flow rate of ca. 150 m³/h (www.geotermiakonin.pl).

Table 5.3.1. Parameters of operating geothermal heating plants on the area of Mogilno–Łódź Trough (based on Kępińska, 2016, Kępińska et al., 2017)

Location	Year of commencement	Water temperature [°C]	Water capacity [m³/h]	Water mineral isation ([g/dm³]	Power from geothermal resources [MW_{Th}]	Total installed power [MW_{th}]	Heat sales t from geothermal resources in 2015 [TJ]	Share of geothermal resources in total heat sales (%)
Poddębice	2013	71	252	0,4	10	10	46	100
Uniejów	2006	68	120	6, 6	3,2	7,4	19,2	80

5.3.7. Physico-chemical parameters of waters in Mogilno–Łódź Trough

On the area of Mogilno–Łódź Trough, there is one of the largest ordinary water basins. It covers the southern and central part of Łódź Trough, as well as a part bordering with Fore–Sudetic Monocline. Cretaceous waters with low mineralisation are abstracted through deep wells, particularly in the area of Łódź. Due to low mineralisation, they are fit for consumption. Intense production of ordinary waters in this area has led to distortion in the hydrodynamic regime (Bojarski, 1996). On the area of Mogilno–Łódź Trough, the depth of freshwater (ordinary water) occurrence is even as high as ca. 1700 m. On the other hand, at relatively small distances from fresh waters there are brines with high mineralisations reaching up several dozen g/dm³. It is related to an operational decline of original reservoir pressures. It may cause ascension of brines from deeper parts of the reservoir or from aquifer horizons located below, e.g. Jurassic reservoir (Górecki (ed.) & Hajto et al., 2006).

In total, ca. 150 wells were analysed, which contained in their profile Lower Cretaceous and Lower Jurassic formations. Only those wells were selected, where water was found and analysed at least in the area of mineralisation and main ions.

5.3.7.1. Water chemistry – Lower Cretaceous

Waters with low mineralisations under 2 g/dm³ occur on a very large area of the Trough, especially in its southern and western area. In the north-central and north-western part of the Trough, mineralisation increases up to the level of ca. 10-20 g/dm³. The highest mineralisations are observed in north-eastern, the edge part of the Trough, reaching even up to 100 g/dm³. In this part of the Trough, also high depths of Lower Cretaceous formations retention are observed.

Table 5.3.2. Type and mineralisation of water from Lower Cretaceous formations on the area of Mogilno–Łódź Trough with regard to the depth of sampled intervals. Results were sorted with regard to growing top depth of the sampled interval

Top of sampled interval [m under ground level]	Chemical type of water	Water mineralisation [g/dm^3]
208	Na-Cl-HCO3	2.2
278	Na-Ca-Cl	1.9
295	Na-Cl	1.1
407	Na-Cl	3.4
518	Na-Cl	1.8
538	Na-Ca-HCO3	0.5
582	Na-Ca-HCO3-SO4	0.3
635	Na-Cl	35.0
714	Na-Cl	37.8
717	Na-Cl	11.8
760	Ca-Na-HCO3	0.2
825	Na-Cl	5.3
910	Na-Cl	41.0
1037	Na-Cl	26.1
1120	Na-Cl	34.4
1150	Na-Cl	29.4
1215	Na-Cl	3.0
1235	Na-Cl	35.4
1295	Na-Cl	37.1
1324	Na-Cl	32.0
1356	Na-Cl	11.0
1478	Ca-Na-HCO3	0.4
1607	Na-Ca-HCO3	0.4
1719	no data	21.0
1728	Na-Cl-HCO3	2.2
1751	Na-Cl	9.1
1773	Na-Cl	7.6
1865	Na-Cl	2.1
1898	Na-Cl	6.8
1918	Na-Cl	7.4
1927	Na-Cl	9.2
1962	Na-Ca-HCO3	0.4
1996	Na-Cl	90.0
2060	Na-Cl	100.8
2110	Na-Cl	74.2
2150	Na-Cl	25.1
2182	Na-Cl	57.8
2386	Na-Cl	93.5
2438	Na-Cl	94.7
2448	Na-Cl	93.0

Table 5.3.2 presents dependency between occurrence of particular water types and mineralisations, on the one hand, and the depth of sampled interval retention. Waters from deeper parts of the reservoir are usually of Na-Cl type. Waters of Na-Cl type occur in the central and northern part of the Trough. In waters coming from smaller depths, and particularly, from the southern part of the Trough we can distinguish waters of Na-(Ca)-HCO_3 type (multi-ion waters). Mineralisation of those waters does not exceed 0.5 g/dm^3. Sometimes, Na-(Ca)-Cl-(HCO3) type waters occur with mineralisation of ca. 2 g/dm^3.

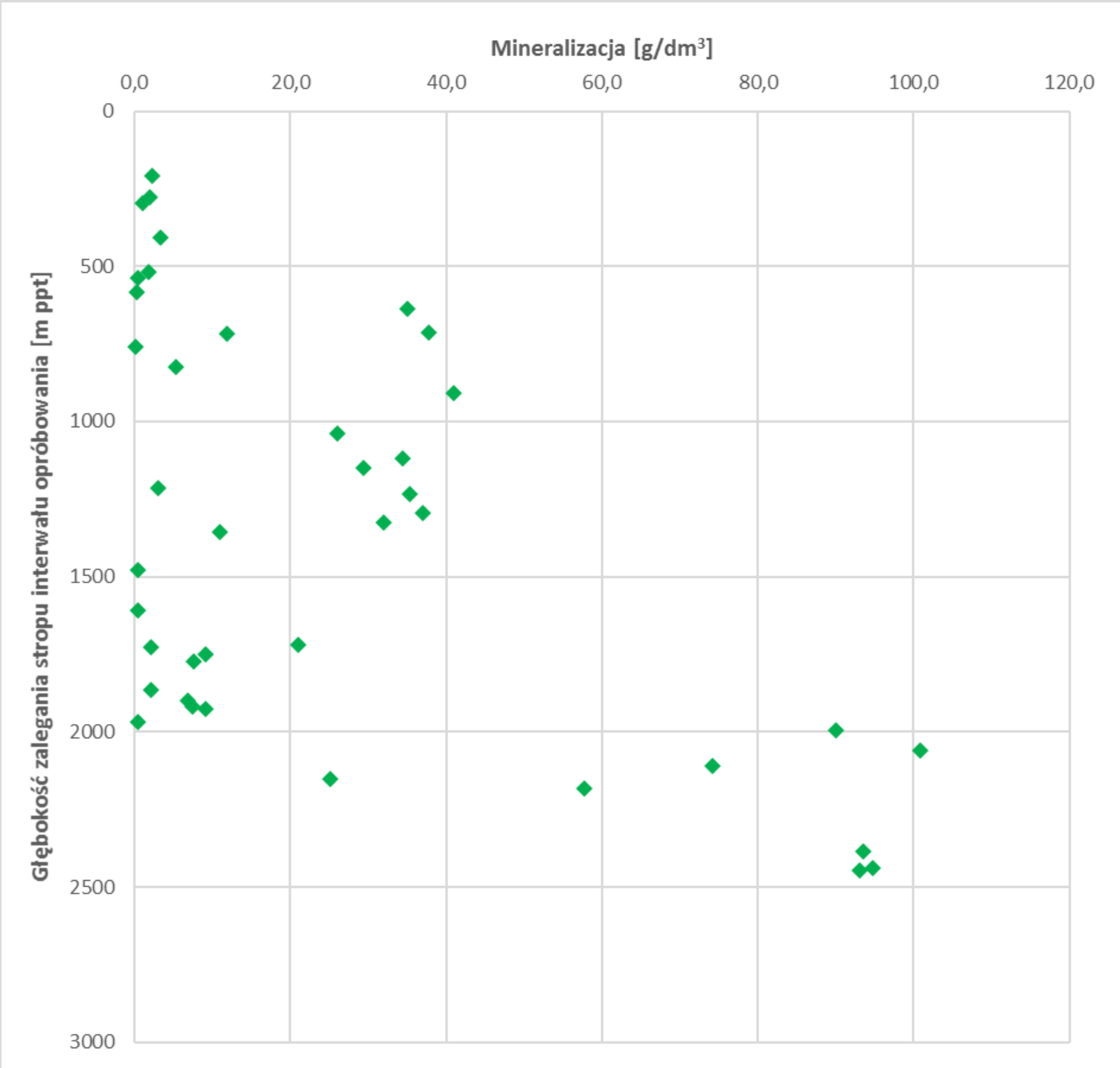


Fig. 5.3.7. Diagram of dependence between mineralisation in [g/dm^3] of water samples from Lower Cretaceous formations and depth of the sampled interval [m under ground level]

Waters from Lower Cretaceous formations, similarly to samples from Lower Jurassic formations, demonstrate the presence of components important from the point of view of balneotherapeutic application. Such components include Fe, I and Br. However, it should be pointed out that not all water samples were analysed in terms of iodine, bromine or iron contents.

Iron occurs in numerous samples, yet, in most cases, its contents do not exceed the minimum level of 10 mg/dm^3 enabling to call such water medicinal (acc. to the Regulation…, Dz.U. 2006.80.565, as later amended), so it will be of no significant balneotherapeutic importance. Only in the central part, considerable iron quantities were reported in waters, which exceed that limit (ca. 16-26 mg/dm^3).

High bromine concentration is observed both in the northern and central part of the Trough. In most cases, bromine content exceeds the limit set in the previous legislation, enabling referring to those waters bromide and medicinal waters – 5 mg/dm^3. This limit is given only approximately. In the northern part, bromine occurs in waters at different depths, usually ca. 800–1300 m. In the central part of the Trough, it occurs much more deeply, within the range of ca. 1700-2100 m. In some waters, bromine content is even as high as several dozen mg/dm^3.

Water samples under analysis also show iodine presence. Particularly, samples from the northern and central part are characterised by higher content, very often in quantity exceeding the limit of 1 mg/dm^3, stipulated for iodide waters in Regulation…. (Dz. U. 2006.80.565, as later amended). Those waters are medicinal and, depending on other parameters, they can be used for balneotherapeutic purposes. Iodine content is usually several mg/dm^3. Waters from the southern area of the Trough have low iodine and bromine contents. Iodine content in the northern part increases together with depth. Contents significant from the balneotherapeutic point of view occur in this area in waters at depths from ca. 1000 m. In the central part, the highest iodine values occur in quantity over 1 mg/dm^3 at depth within the range ca. 2000-2500 m.

An interesting case, from the chemical point of view, are waters from Lower Cretaceous formations made available through Poddębice GT-2 well. A sampled interval is located at the depth of 1962-2063 m. Waters made available through this well have the temperature of ca. 71°C at the outflow and very low mineralisation, at the level of 0.432 g/dm^3. The diagram below (Fig. 5.3.8) shows main water ion contents.

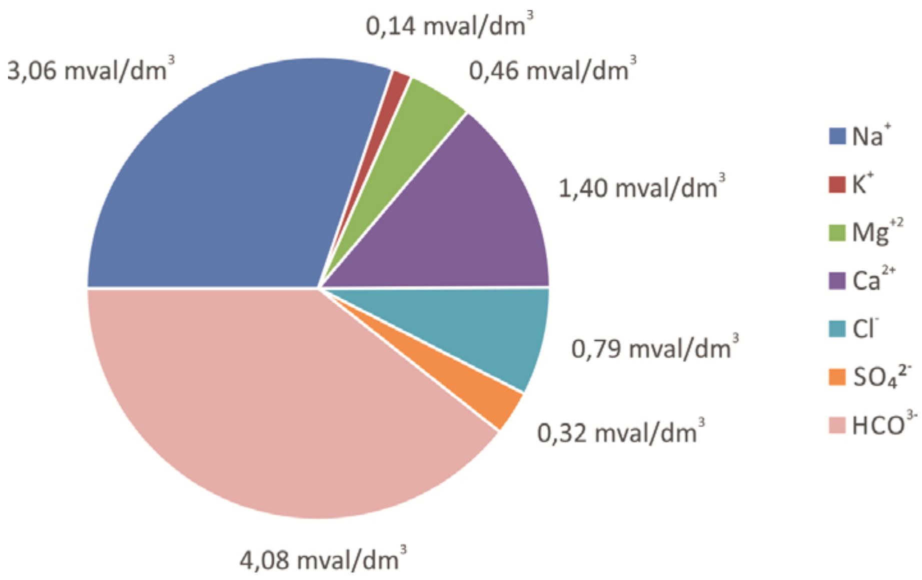


Fig. 5.3.8. Udluft pie chart regarding water from Poddębice GT-2 well, presenting main ion contents (on the basis of water analysis for sample taken 1 February 2017)

These are waters of the HCO_3-Na-Ca type, which distinguishes them from among waters from the area of the central part of the Trough, where waters of the Na-Cl type prevail. Diagram (Fig. 5.3.9) compares water types from wells located in the vicinity of Poddębice GT-2 well and those occurring at similar depths. A diagram for water from Poddębice GT-2 well was marked with red. All other waters in the diagram are of the Na-Cl type (except for one case) and they show similar peaks of main ion contents. Their mineralisations range from ca. 2-9 g/dm^3 and 21-74 g/dm^3, which increases considerably water mineralisation from Poddębice GT-2 well, which is freshwater. Water form Poddębice GT-2 well shows also a slight content of iron, iodine and bromine ions.

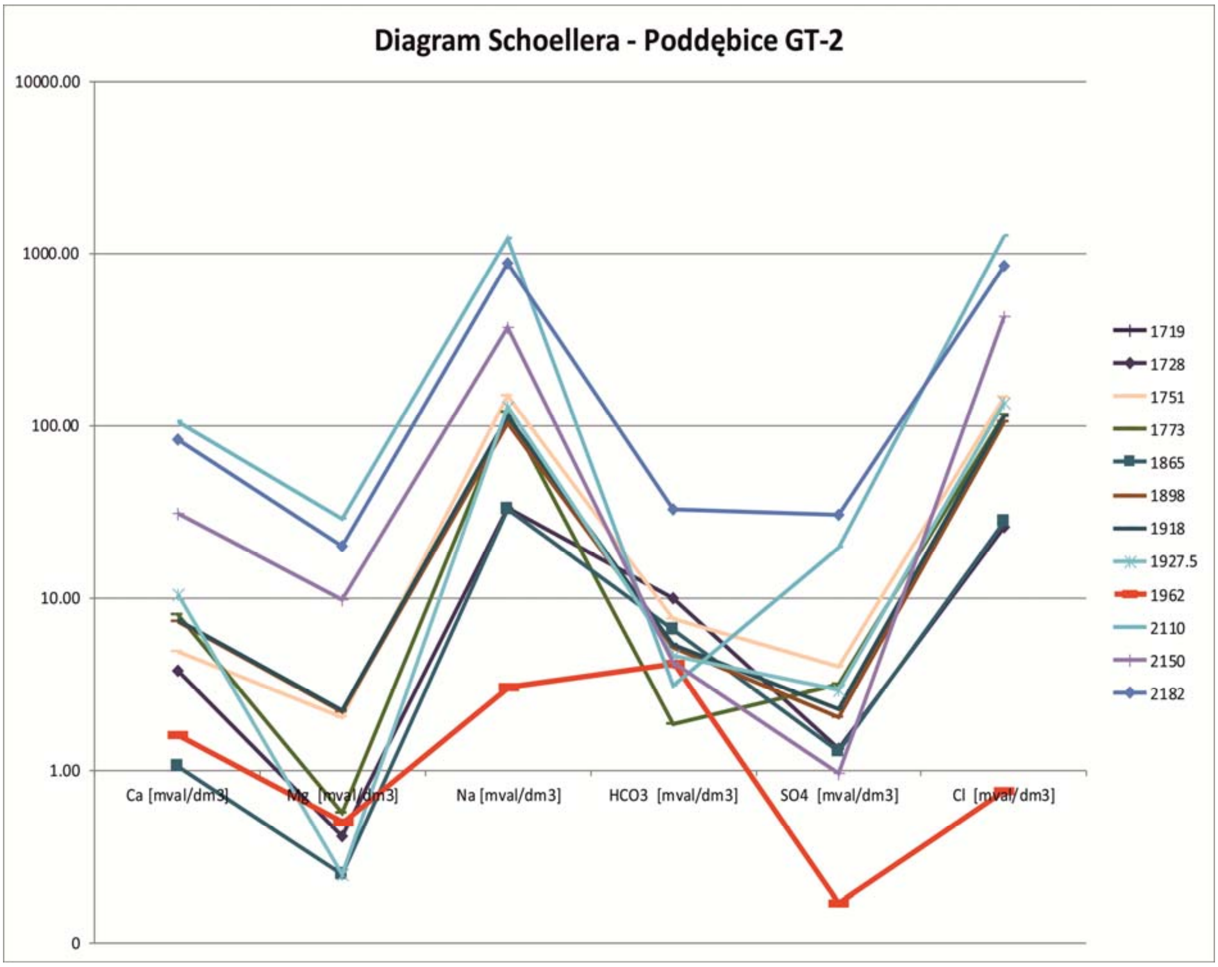


Fig. 5.3.9. Schoeller's diagram showing main ion contents in waters from Poddębice GT-2 well and neighbouring wells. The legend shows depths of top occurrence in sampled intervals in meters under ground level

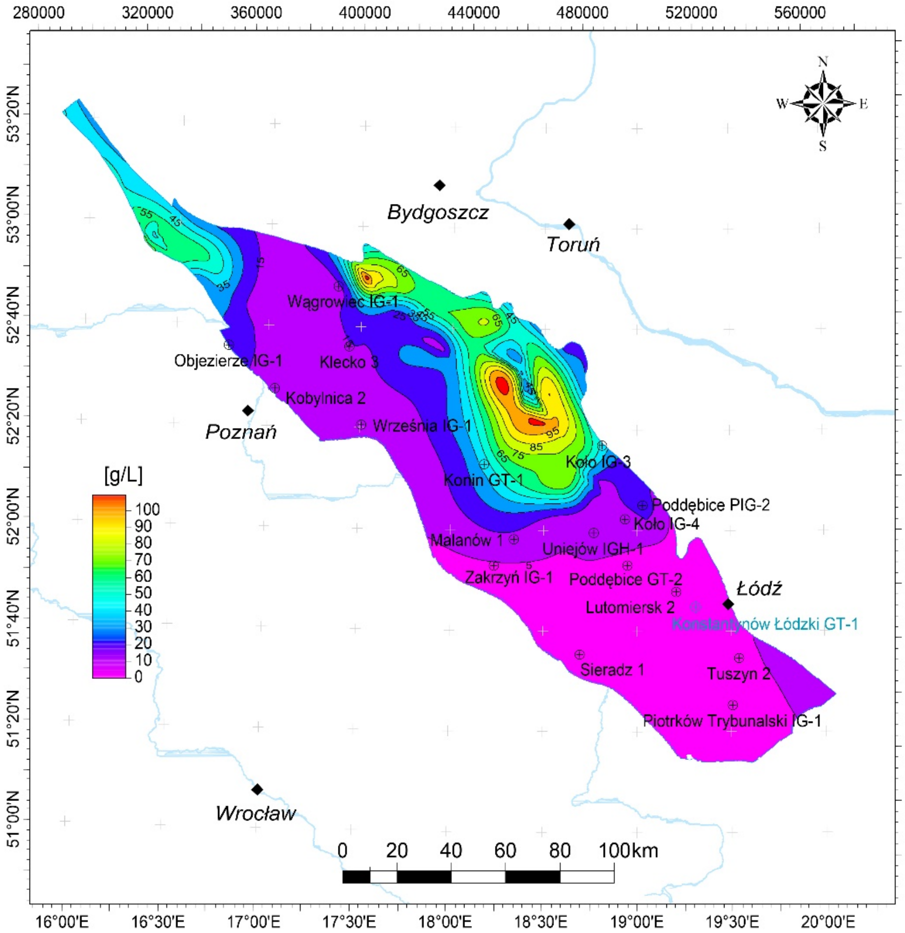


Fig. 5.3.10. Map of the TDS at the top surface of Lower Cretaceous formation

5.3.7.2. Water chemistry – Lower Jurassic

When analysing values for Mogilno–Łódź Trough, one can observe that for the Lower Jurassic level mineralisation values are much higher than for the Lower Cretaceous level. Maximum mineralisation values occur in the north-eastern and eastern part of the Trough, where they are as high as over 150 g/dm^3. The more to the south-west and to the south, the more mineralisation values decrease, reaching a dozen g/dm^3. In the southern edge part, the mineralisation value is the lowest and it does not exceed several g/dm^3.

Table 5.3.3. Type and mineralisation of water collected from Lower Jurassic formations on the area of Mogilno–ódź Trough with regard to the depth of sampled interval retention. Results were sorted with regard to growing top depth of the sampled interval

Top of sampled interval [m under ground level]	Chemical type of water	Water mineralisation [g/dm^3]
815	Na-Ca-SO4	1.2
960	Na-Cl-SO4	3.5
1046	Na-Cl	26.8
1126	Na-HCO3	0.4
1275	Na-Cl	0.46
1332	Ca-Na-Mg-Cl	63.2
1355	Na-Cl	86.96
1446	Na-Cl	31.2
1489	Na-Cl	4.6
1583	Na-Cl	7.6
1593	Na-Cl	8.5
1606	Na-Cl	1.53
1607	Na-Cl	3.1
1620	Na-Cl	52.7
1670	Na-Cl	9.3
1678	Na-Cl	13.6
1714	Na-Cl	15.2
1716	Na-Cl	16.7
1777	Na-HCO3-SO4-Cl	1.8
1821	Na-Cl	107.0
1850	Na-Cl	30.9
2180	Na-Cl	100.5
2197	Na-Cl	124.7
2333	Na-Cl	114.7
2485	Na-Cl	36.0
2580	Na-Cl	83.4
2741	Na-Cl	99.8
2901	Na-Mg-Cl	92.0
3364	Na-Cl	172.0

Waters under analysis come from the depth of ca. 800-3400 m. Table 5.3.3 shows types of water coming from Lower Jurassic and its mineralisation, depending on the top depth of the sampled interval. The majority of them are Na-Cl waters. In few cases, especially in shallower Lower Jurassic formations, in the southern part of the Trough, these are multi-ion waters with low mineralisation, with SO_4 or HCO_3 ions. In several wells, waters contain higher quantities of magnesium or calcium. General water mineralisation ranges from 0.4-172 g/dm^3, whereas the lowest values (usually several and sometimes a dozen g/dm^3) can be observed in the southern area of the Trough (supply zones).

Figure 5.3.11 presents distribution of water mineralisations from Lower Jurassic formations, depending on the depth. In general, mineralisation increases proportionately with the depth growth and vertical water zonation is preserved. On the other hand, waters coming from the central and northern part of the Trough have much higher mineralisation values than waters from similar depths, but coming from the southern part of the Trough. Water mineralisation in the southern part of the Trough rarely exceeds 20 g/dm^3, whereas waters with mineralisation not exceeding 5 g/dm^3 occur to the depth of ca. 1800 m. On the other hand, most of analysed waters from the northern and central part of the Trough show mineralisation higher than 25 g/dm^3 and they come from depths higher than 1300 m.

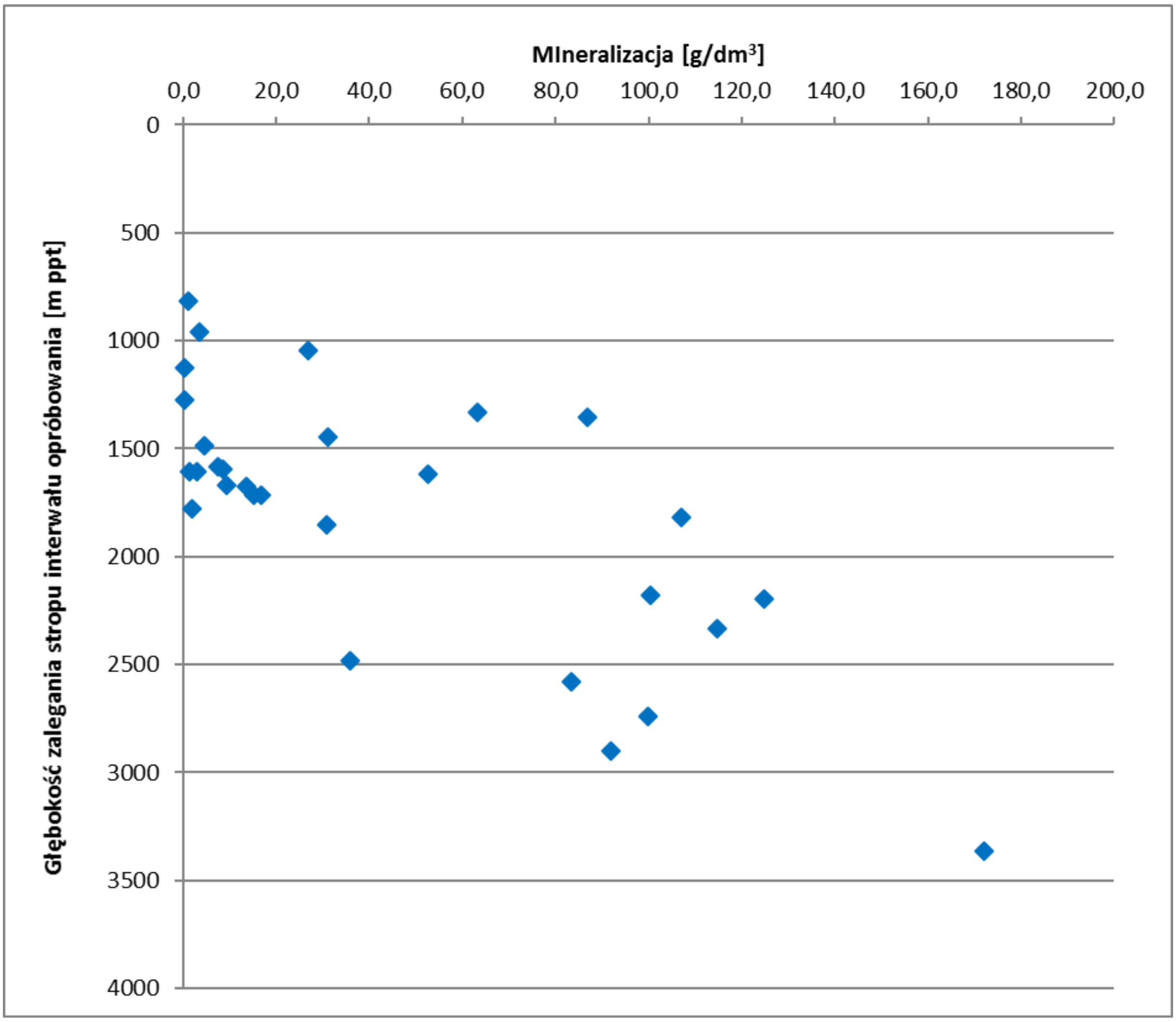


Fig. 5.3.11. Diagram of dependencies between mineralisations of water samples from Lower Cretaceous formations and the depth of the sampled interval

In waters from Lower Jurassic formations, iron occurs in quantities exceeding 10 mg/dm^3 (a dozen mg/dm^3), in several samples coming from the southern part of the Trough. Iodine and bromine occur in quantities much exceeding the earlier indicated limits. Their contents are ca. 3-4 g/dm^3 for iodine and over ca. 50 to over 120 g/dm^3 for bromine. Both iodine and bromine occur at similar depths, ca. 1300-2300 m, usually in the northern area of the Trough.

Some of waters, especially those coming from Lower Jurassic formations, have parameters enabling recovery of certain macro-components (e.g. potassium, magnesium). Due to the lack of detailed chemical analyses, one cannot state whether waters contain micro-components or other rare elements in quantities, e.g. enabling their recovery.

In summary, one can say that waters from Lower Cretaceous formations have, on average, lower mineralisations than waters from Lower Jurassic formations, 26.2 and 45.2 g/dm^3, respectively. On the other hand, waters from Lower Jurassic formations are more predictable in chemical terms, their mineralisation increases, in principle, proportionately to depth and they are characterised, in principle, by a uniform chemical type of water. It should be expected that Lower Jurassic strata, as strata retained below, will be characterised with waters of higher mineralisation, contrary to the Cretaceous formations, where water mineralisation variability is much higher.

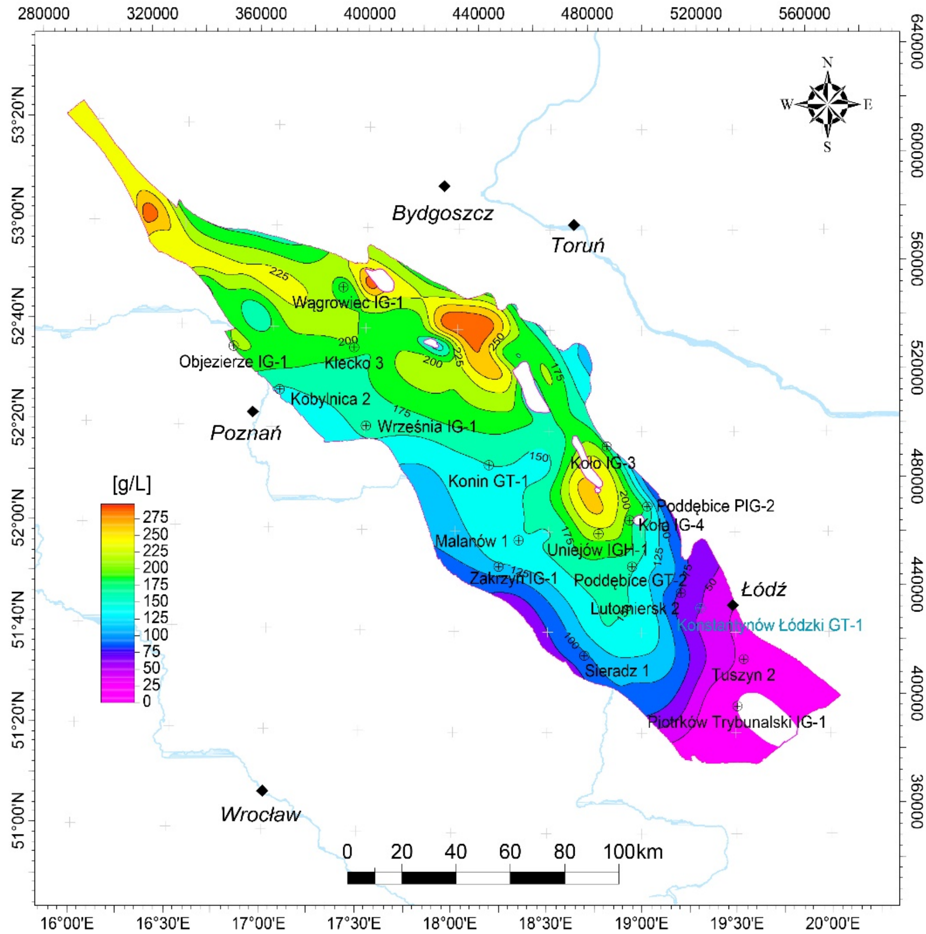


Fig. 5.3.12. Map of the TDS at the top surface of Lower Jurassic formation

5.3.8. Three-dimensional geological model of Mogilno– Łódź Trough

Within the frameworks of the project, 3D computer structural-parametric models were made, which represent the structural arrangement and variability of reservoir parameters on the area of Mogilno–Łódź Trough.
Modelling was performed in Petrel program owned by WGGiOŚ AGH, owing to an agreement on supporting scientific, research and educational works, concluded between GGiOŚ Department and Schlumberger Information Solutions.

5.3.8.1. Input data for modelling

- Digital structural maps

The most important source of data necessary to develop digital structural maps were partial numerical models (2D grids) developed on the basis of archival maps, seismics and borehole data by KSE AGH team in years 1990-2013, when dealing with a dozen scientific and research topics (Wójcicki, Sowiżdżał & Bujakowski (eds) et al., 2013; Górecki (ed.) et al., 1995; Górecki et al., 1996; Górecki et al., 1999; Górecki et al., 2000; Górecki et al., 2003; Górecki, Hajto (eds) et al., 2006 a, b; Papiernik [in] Wójcicki et al., 2010).

- Tectonics

The course of faults was determined on the basis of above-described analogue and digital input data. In order to achieve satisfactory quality of numerical models used for developing geometric structure of the model, those elements had to be edited in order to remove any interpretation discrepancies of sources used. Recreation of the course of dislocation network required combining numerous partial sources. Depending on the age of mapped complexes, different sets of input data were used.
The course of dislocations on Mesozoic cover maps was based on maps from Geothermal Atlases (Górecki, Hajto (eds.) et al., 2006a) and Atlas of the Lower Permian Basin (Peryt et al., 2008; Doornenball et al., 2010), partially supplementing it with the course of dislocations from the Geological Map Without Quaternary Formations (Dadlez et al., 2000), and also from many archival maps (e.g. Czulińska et al., 1988a, b; Woźniak et al., 1987; Wróbel 1984; Wróbel et al., 1988a, b; 1990).

- Borehole data used to develop stratigraphic structure

Developed maps, and later, structural 3D models were bound to the results of structural interpretation and boreholes located on the study area. Working surfaces used in structural modelling went beyond the agreed boundaries of Mogilno–Łódź Trough. In order to avoid boundary errors, they were bound to the interpretations and wells located there (Fig. 5.3.13). Eventually, however, a 3D model was bound only to wells and seismic interpretations, located only on the study area. The number of wells used for attachment depends on slumping of a structural boundary. The applied procedure of binding borehole data ensured high compliance between a 3D model and borehole information. It was of key importance for the precision of parametric modelling.

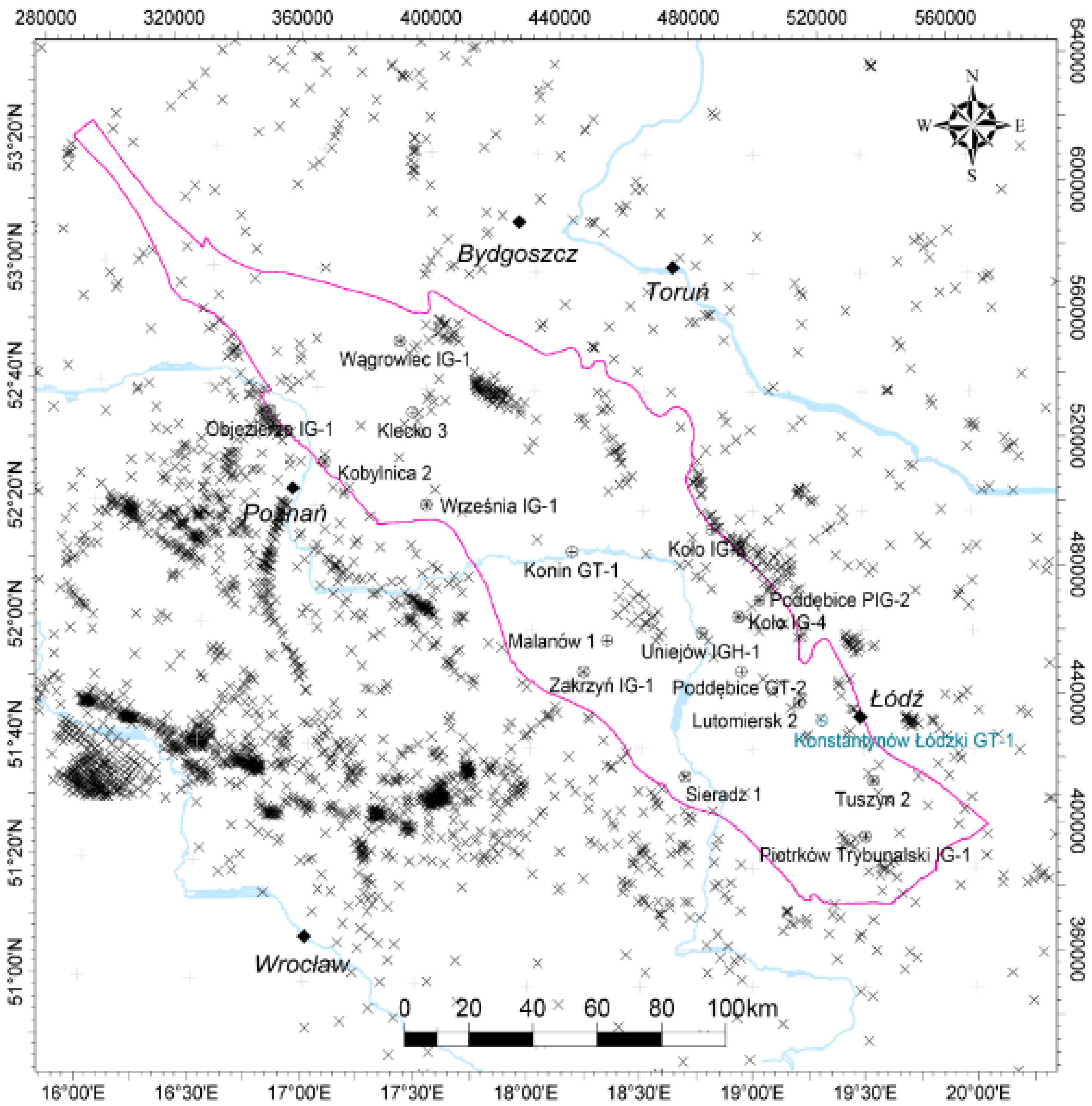


Fig. 5.3.13. Location of borehole data used for bouding maps and structural models

5.3.8.2. Outline of methodology

Static 3D parametric modelling is a part of the spatial modelling procedure and simulation of reservoir processes. This methodology was developed, first of all, for the needs of reservoir engineering in oil prospecting. Currently, it is also used for the purposes of carbon sequestration.

Computer software used nowadays presents a diversified way of "constructing" 3D models. Apart from software based on the idea of 3D grids, built on the basis of regular interpolation or 2D grids (Tipper, 1992; Cosetino 2001, Dubrule 1998, 2003), There are programs belonging to the CAD family, e.g. GoCad program, where stratigraphic structure is built based on parametric surfaces, which might show more than one Z value for one X,Y location, whereas the structure of a 3D model uses the Discrete Smooth Interpolation algorithm (Mallet 2002, Mallet 2008). The above-presented model has been developed by means of Petrel program. Without going into details of the initial stages, covering database presentation and structural –geological interpretation, the static model in the form of a 3D grid covers in the simplest form the following:

- Development of structural maps in the format of regular interpolation grids [RSI] (2D grids) on the basis of the following data:
  - ➢ seismic and borehole data;
  - ➢ digital archival maps and borehole data;
  - ➢ borehole data (usually only maps of average or interval speeds, if necessary to make time depth conversion;
- Creation of a 3D structural model, using RSI and interpretation of disjunctive tectonics;
- Development of a Fault Model;
- Development of a grid skeleton as a result of employing the pillar gridding procedure;

- Creation of stratigraphic zones as a result of introducing stratigraphic surfaces to the model (surface= grid 2D) and transformation into the form of irregular 3D Horizon grids, where the mesh shape depends on the results of the pillar gridding procedure;
- Introduction of layers inside stratigraphic zones;
- Creatin of facies or lithological modeling on the basis of borehole data;
- Averaging lithological data in formations profiles (wells upscaling, well model);
- 3D modellingn of facie variability in separate zones and layers, with the application of determinist or stochastic algorithms;
- Modelling of changeability of petrophysical parameters (porosity, claying of permeability) using results of structural and lithological-facial modelling (*Petrophysical Modeling*);
  - Creation of basic models such as porosity and claying models for particular zones and lithology;
  - Creation of derivative models, such as quality of sealing and quality of reservoir rocks in stratigraphic zones.

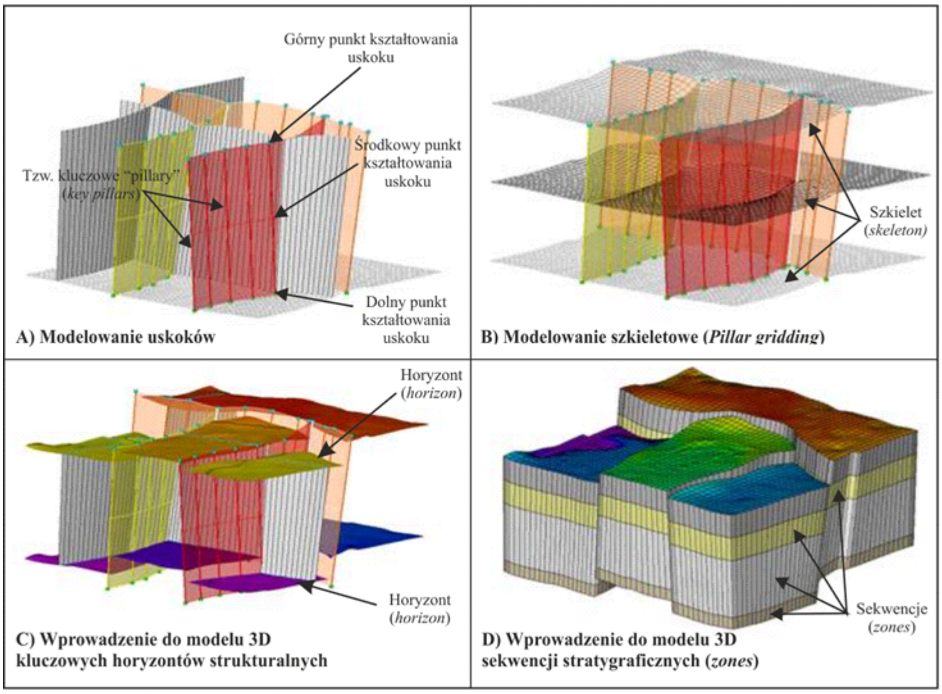


Fig. 5.3.14. Diagram of structural modelling by means of Petrel program

Results of 3D modelling can be presented in the form of pseudo-3D figures: maps and fence diagrams, or in the form of 2D maps presenting average values of the selected parameters and zonesi/layers/facies.

5.3.8.3. Structural model

The structure of a 3D model has been built on the basis of regional structural and thickness maps developed in the form of regular interpolation grids with 250m x 250m spacing (*grid 2D*). Results of structural modelling have been presented in Fig. 5.3.15– 5.3.18.

The structural model includes 5 stratigraphic horizons (Upper Triassic, Lower Jurassic, Middle Jurassic, Upper Jurassic, Lower Cretaceous). The surface of the area covered by modelling is 54 868 km^2, the surface of the model for Mogilno–Łódź Trough is 18 157 km^2.

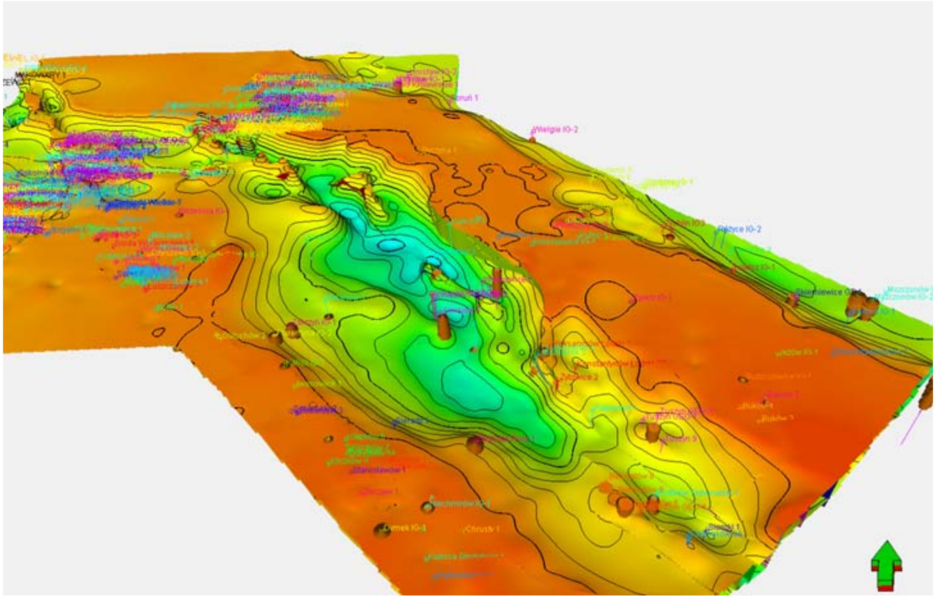


Fig. 5.3.15. Results of structural modelling – extended area – visible Lower Cretaceous structural surface

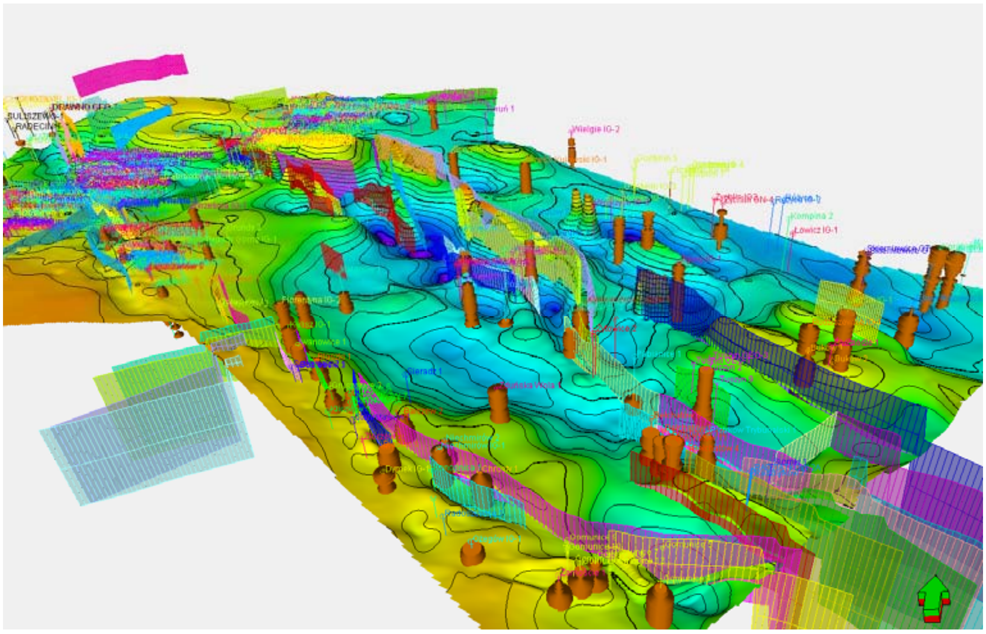


Fig. 5.3.16. Results of structural modelling – extended area – visible Lower Jurassic structural surface

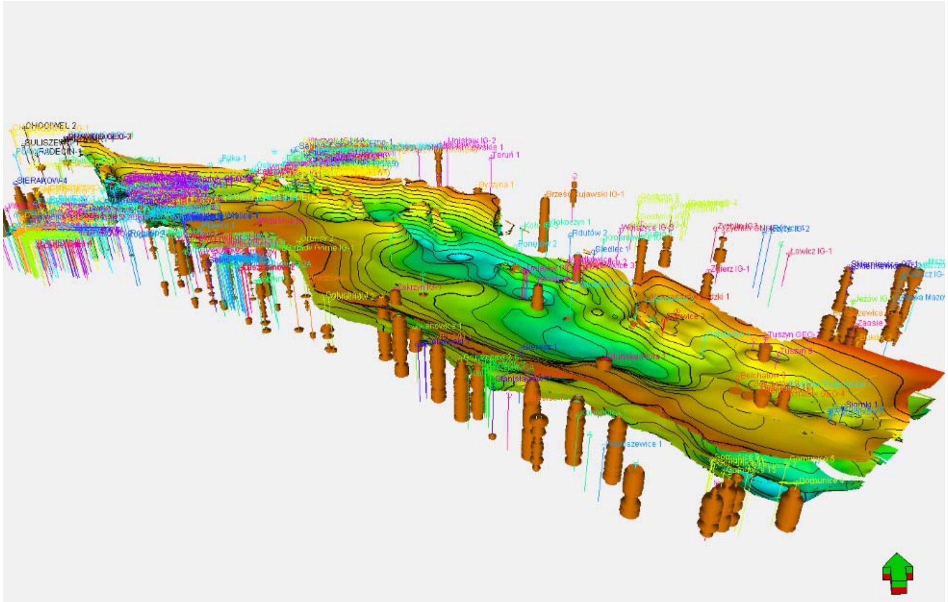


Fig. 5.3.17. Structural model of Mogilno–Łódź Trough

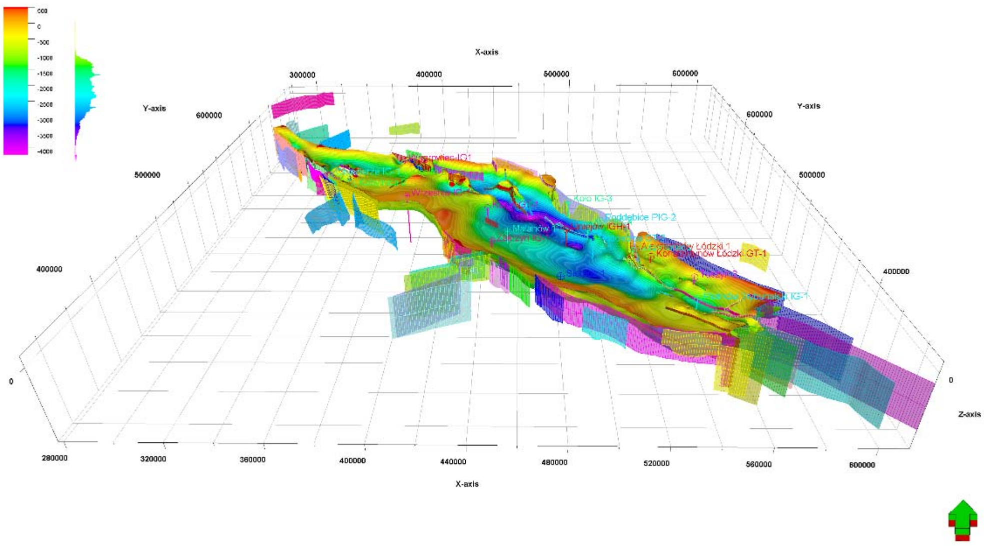


Fig. 5.3.18. Fault model of Mogilno–Łódź Trough

5.3.8.4. Parametric models

Models of petrophysical parameters for the area under analysis have been developed on the basis of drilling geophysical curves and laboratory data. Input data covered the following set: porosity curves (PHI), claying (Vsh), bulk density (RHOB) and permeability curves, together with laboratory markings (PERM).
It enabled calculation of the porosity, permeability, permeability and bulk density models. Results of modelling have been presented below.

- Porosity

The porosity model was calculated on the basis of porosity curves (PHI) coming from 82 drilling wells, by means of Kriging Interpolation algorithm, separately for particular complexes (zones). The modelling procedure was preceded by data analysis and variograms construction, used during modelling.
3D distributions of porosity modelling results (PHI) have been presented in Fig. 5.3.19–5.3.20.

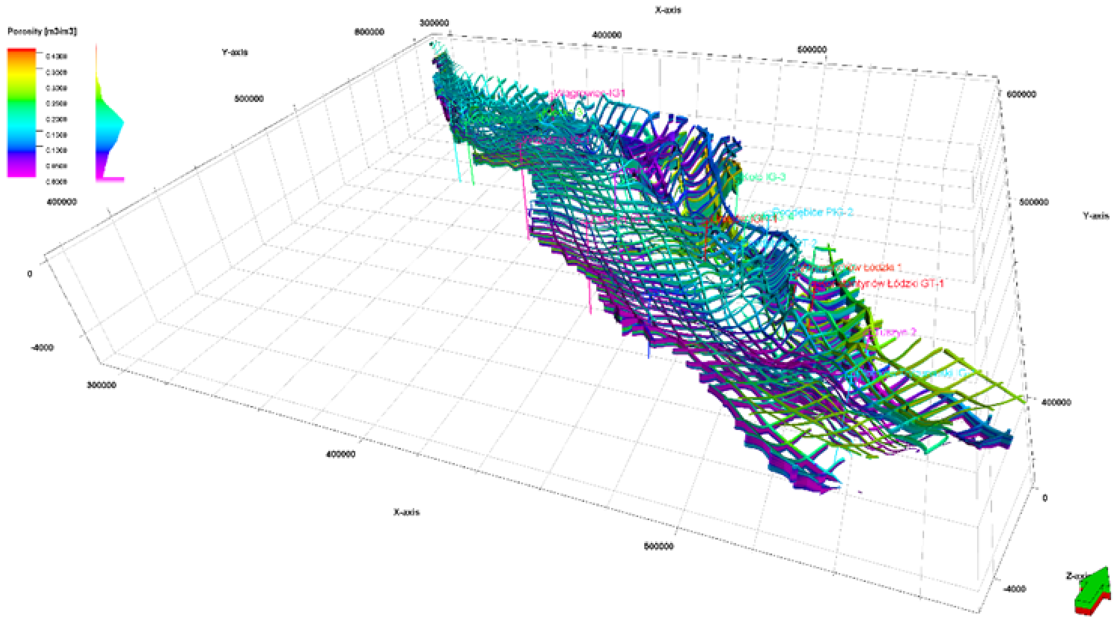


Fig. 5.3.19. Porosity model of Mogilno–Łódź Trough

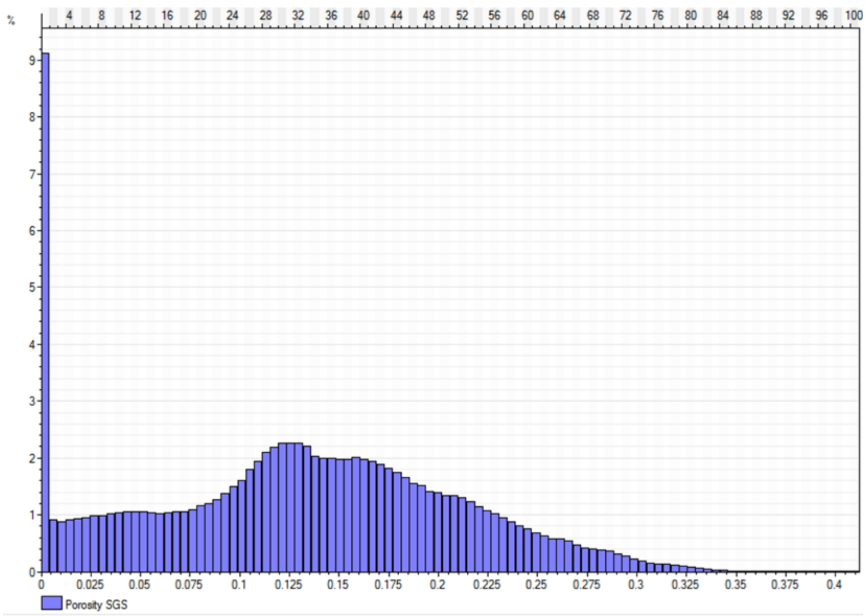


Fig. 5.3.20. Histogram of the porosity model of Mogilno–Łódź Trough

- Permeability

Input data for the permeability model were permeability curves and laboratory permeability markings coming, in total, from 104 boreholes from the study area.
The borehole permeability model (PERM) was calculated using geometric averaging – suitable for data with very high logarithmic variability (Ahmed 2001). Modelling was done with the application of Kriging algorithm, using the same modelling parameters as in case of porosity model (PHI). Simulations in this model were made separately for particular zones, by controlling the result porosity model (PHI). The modelling procedure was preceded with data analysis and variogram construction, used during modelling. Synthetic results of permeability modelling in a 3D model were presented in Fig. 5.3.21–5.3.22.

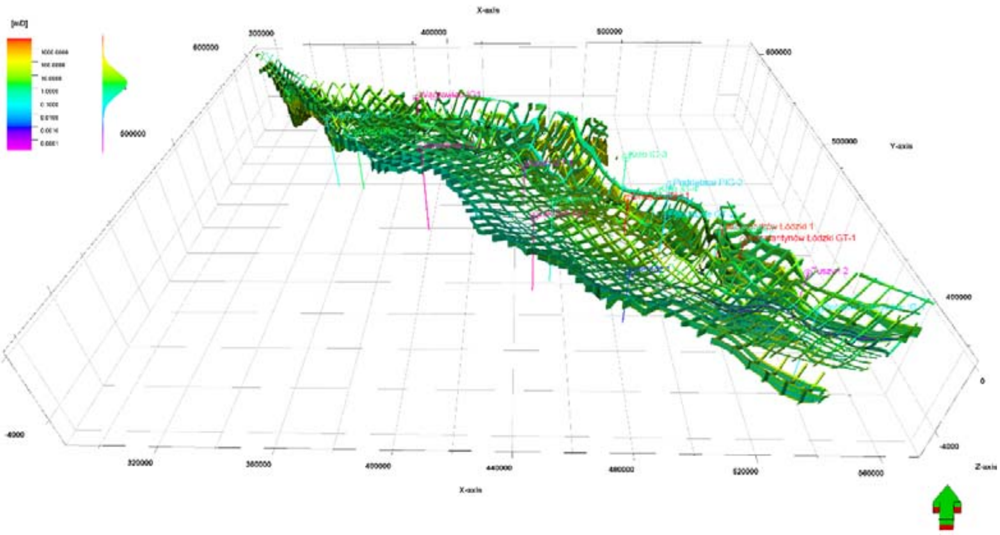


Fig. 5.3.21. Permeability model Mogilno–Łódź Trough

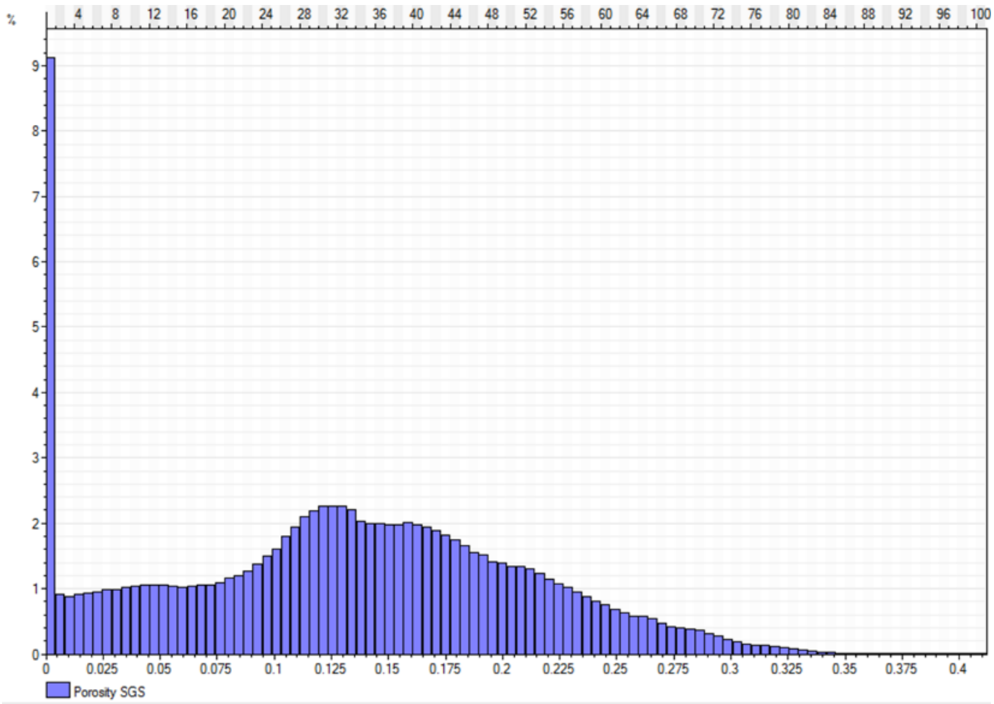


Fig. 5.3.22. Histogram of the permeability model of Mogilno–Łódź Trough

- Bulk density

Bulk density model was calculated on the basis of geophysical curves (RHOB) coming from 40 boreholes, using *Kriging Interpolation* algorithm, separately for particular zones. The modelling procedure was preceded by data analysis and variogram construction, used during modelling.
3D distribution of results of bulk density modelling (RHOB) has been presented in Fig. 5.3.23–24.

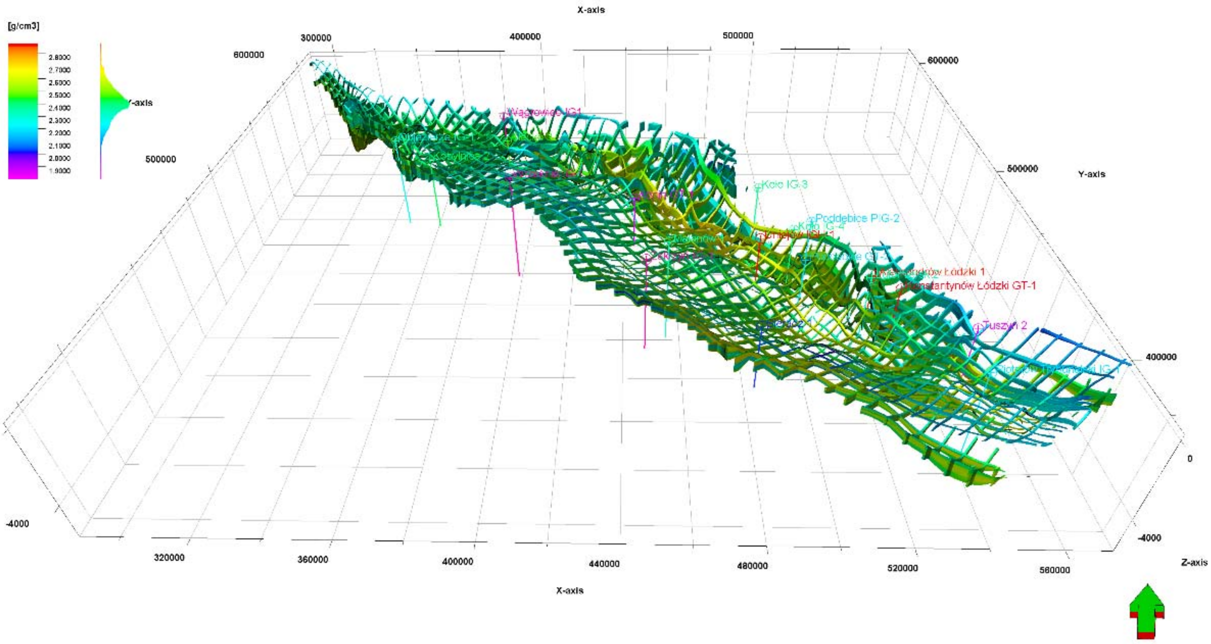


Fig. 5.3.23. Bulk density model of Mogilno–Łódź Trough

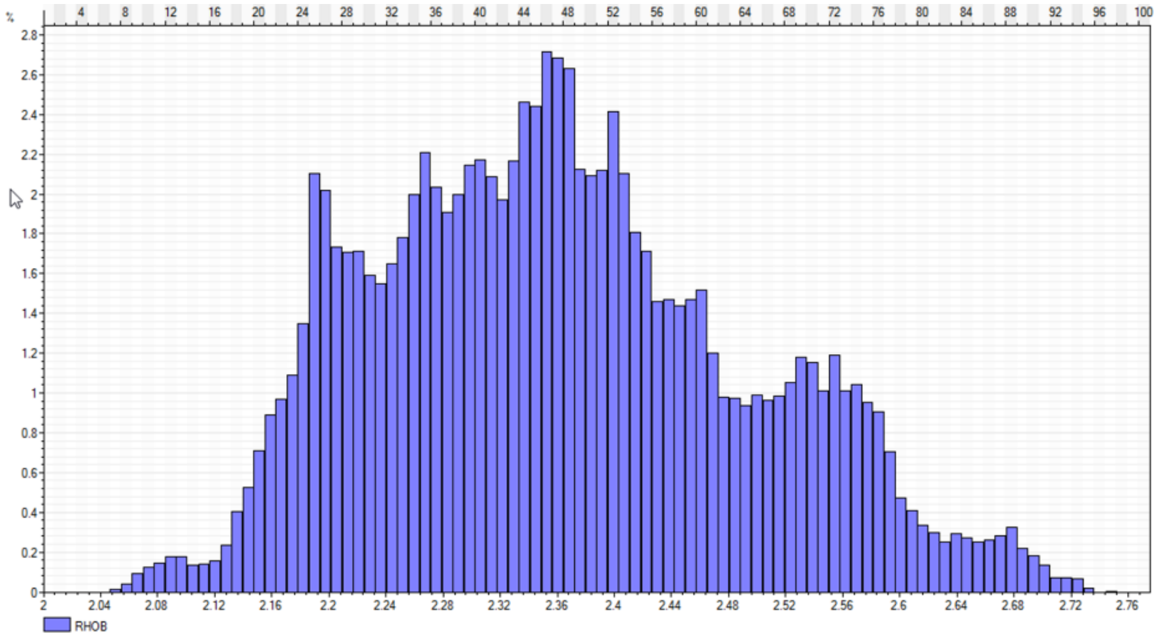


Fig. 5.3.24. Histogram of bulk density model of Mogilno–Łódź Trough

5.3.8.5. Structural and thickness maps

On the basis of 3D modelling results, structural maps of the top and maps of Lower Cretaceous and Lower Jurassic formation thicknesses were created (Fig. 5.3.25–5.3.28). Results of parametric modelling enabled making effective thickness maps for particular reservoirs (Fig. 5.3.29–5.3.30) – formations with porosity exceeding 5% were accounted for in calculations.

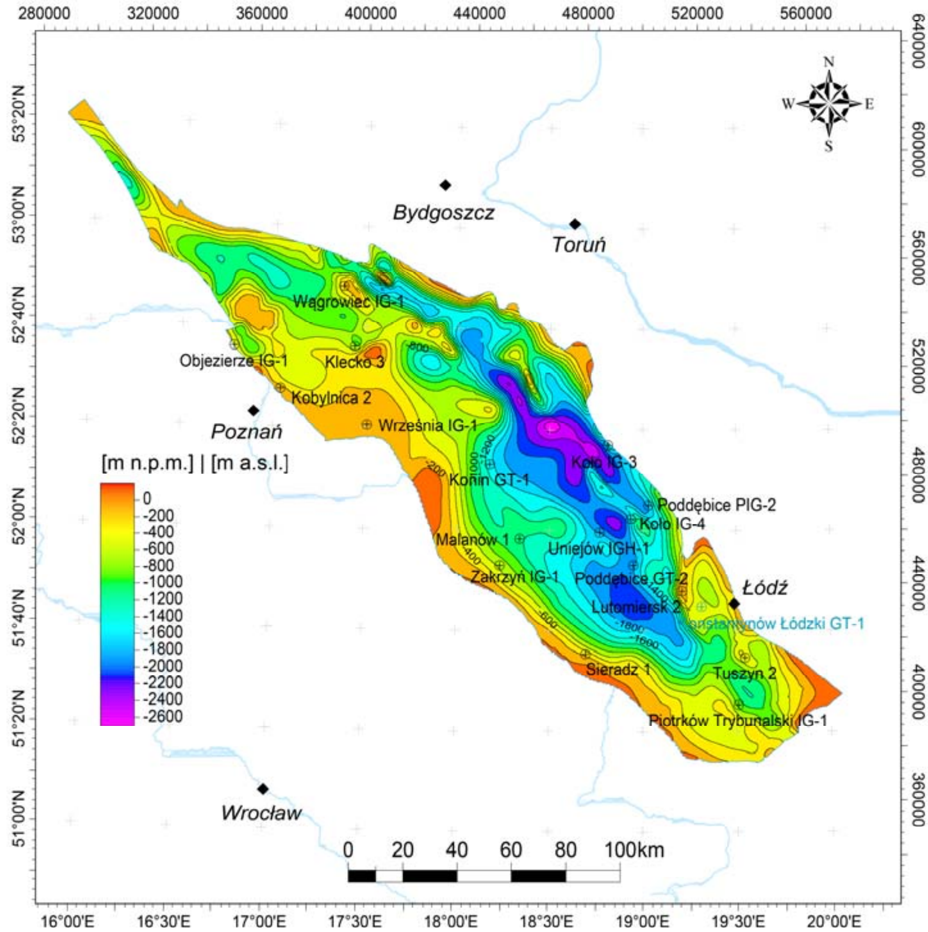


Fig. 5.3.25. Structural map of the top of Lower Cretaceous formations

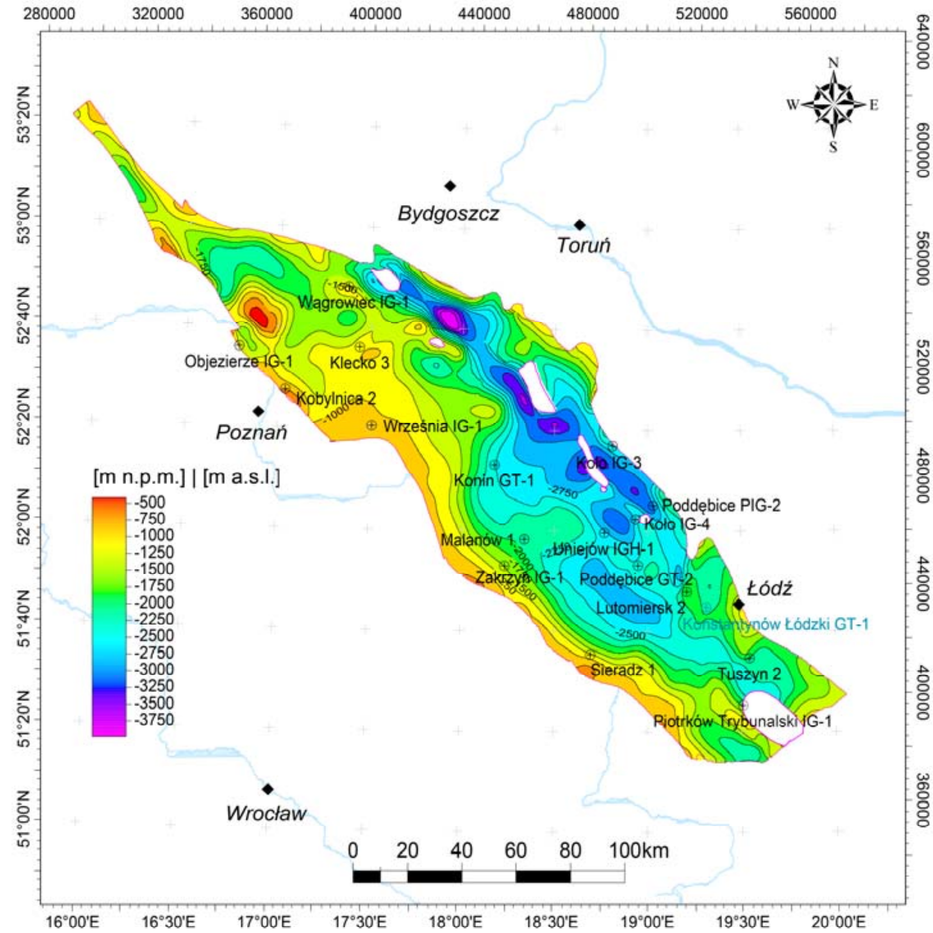


Fig. 5.3.26. Structural map of the top of Lower Jurassic formations

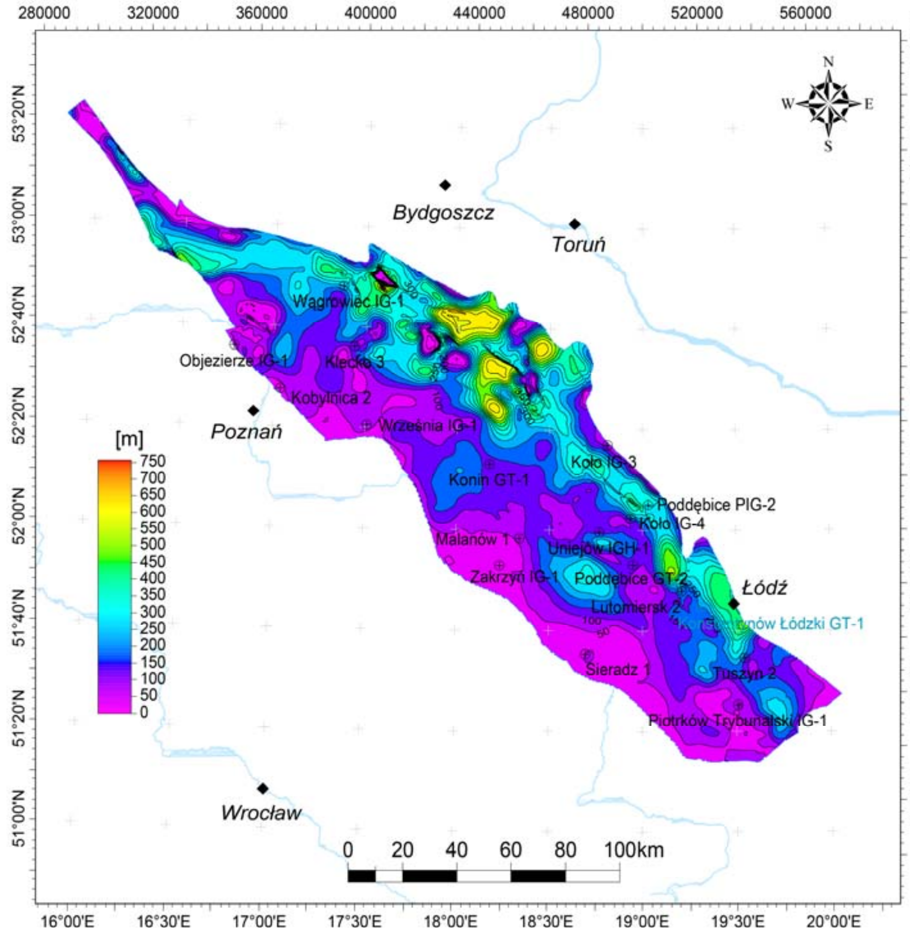


Fig. 5.3.27. Map of total thickness of Lower Cretaceous formations

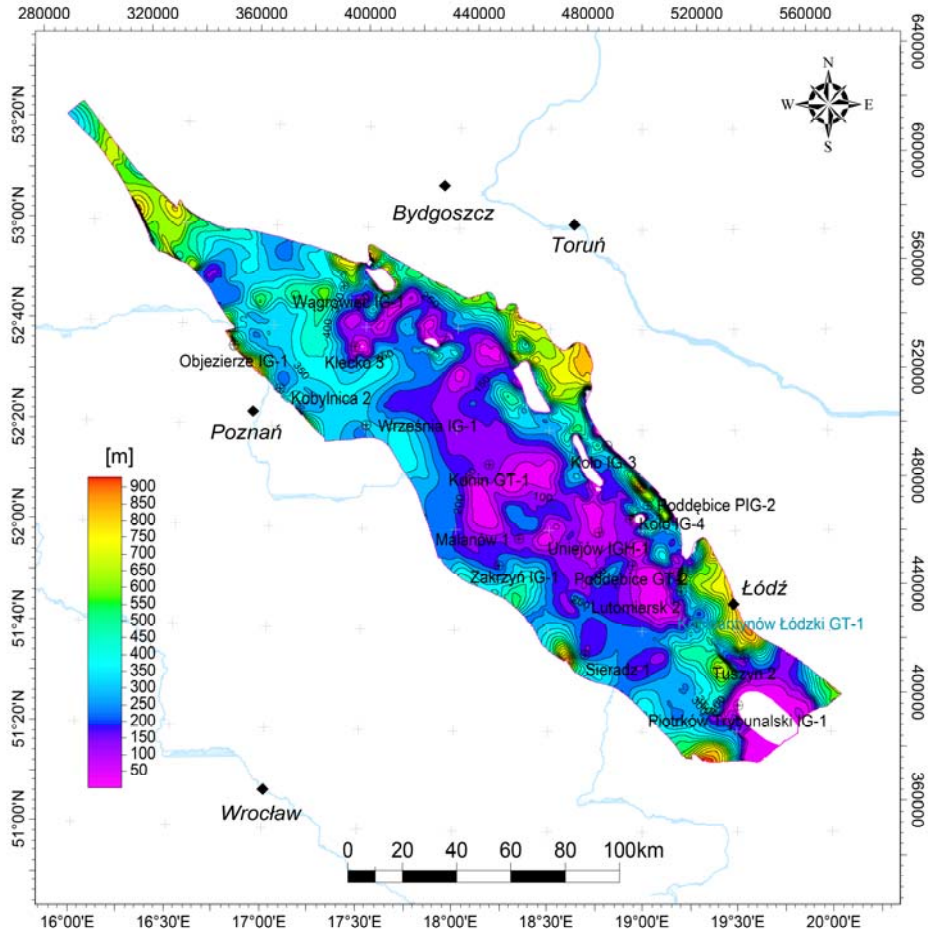


Fig. 5.3.28. Map of total thickness of Lower Jurassic formations

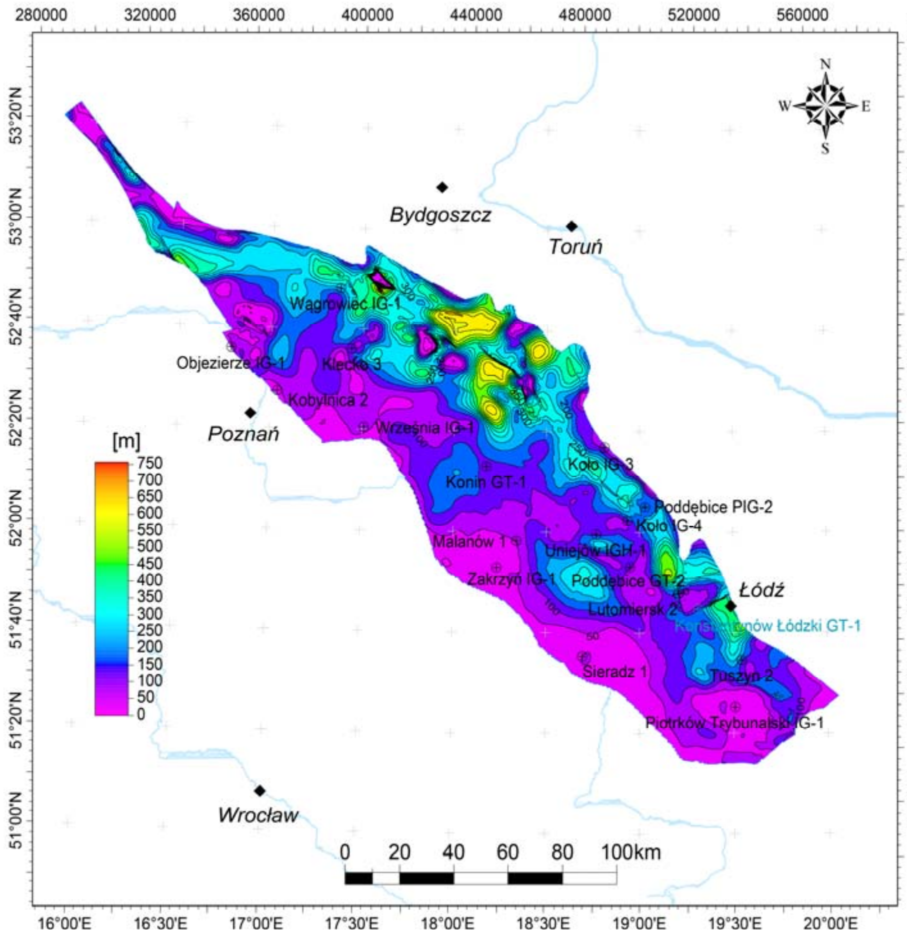


Fig. 5.3.29. Map of effective thickness of Lower Cretaceous formations

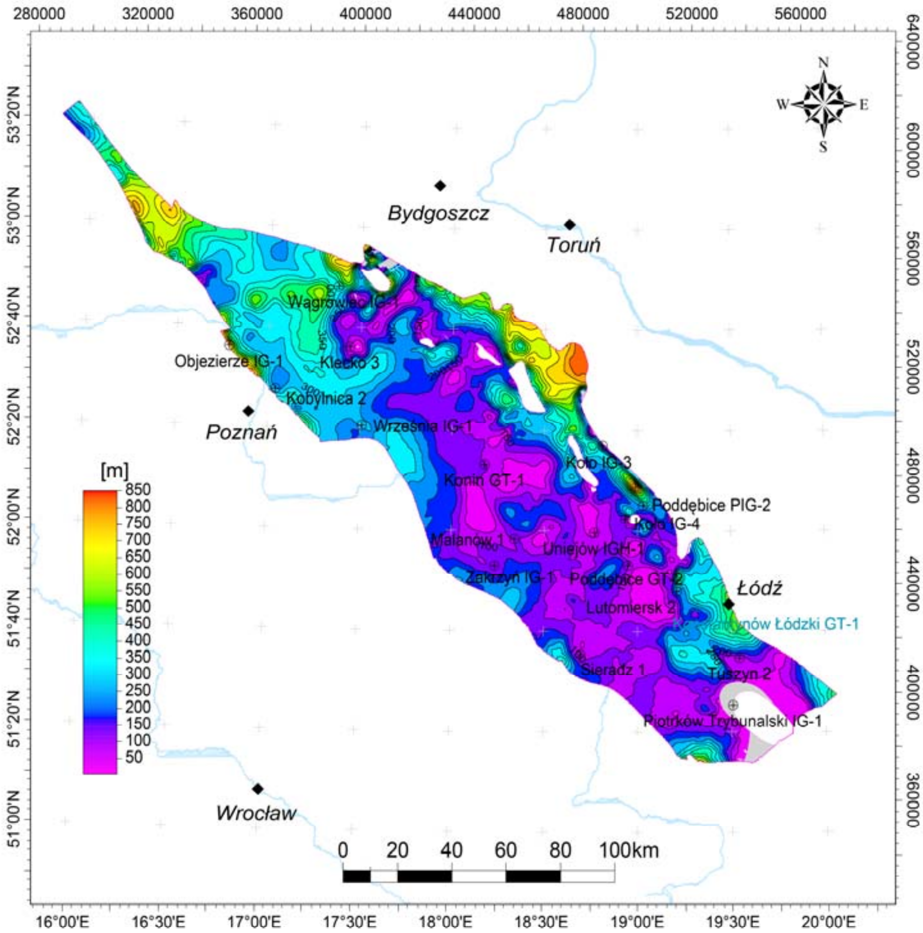


Fig. 5.3.30. Map of effective thickness of Lower Jurassic formations

5.3.9. Evaluation of basic hydrogeological and geothermal parameters within Lower Cretaceous and Lower Jurassic reservoirs in Mogilno–Łódź Trough

5.3.9.1. Thermal model

To construct a thermal model, data from 25 wells, located on the study area, were used. The results have been presented below (Fig. 5.3.31–5.3.34).

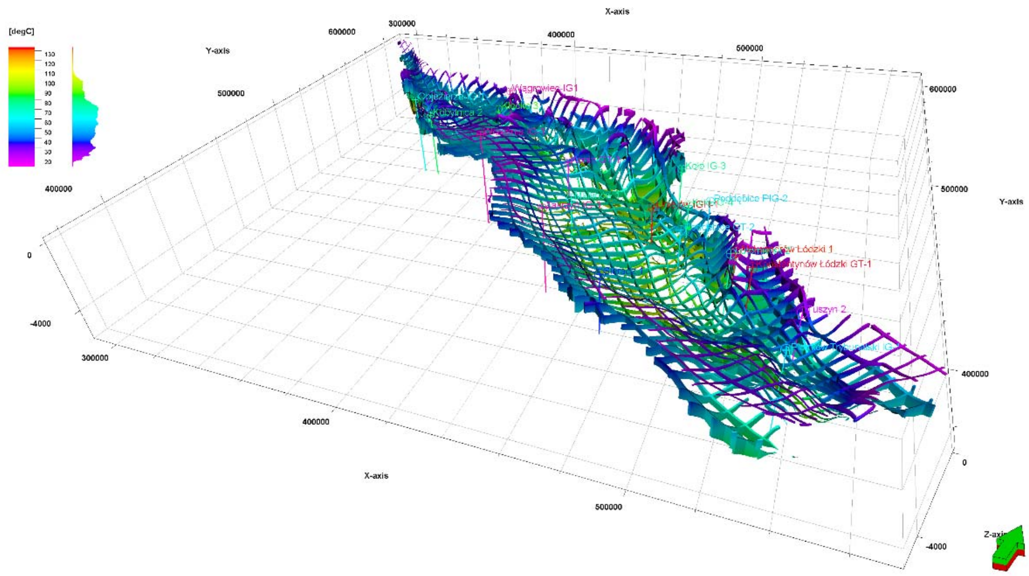


Fig. 5.3.31. Thermal model of Mogilno-Łódź Trough

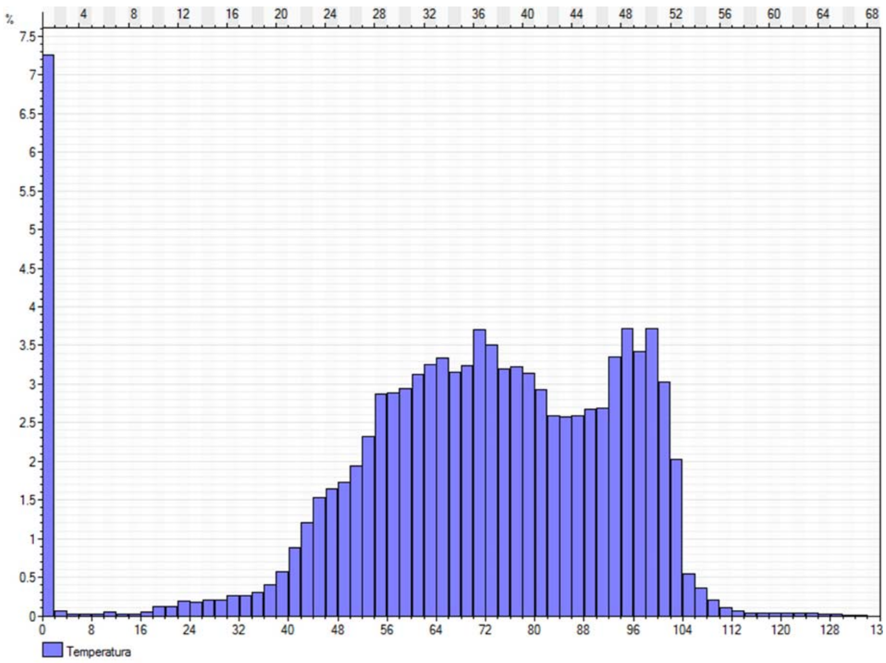


Fig. 5.3.32. Histogram of the thermal model of Mogilno–Łódź Trough

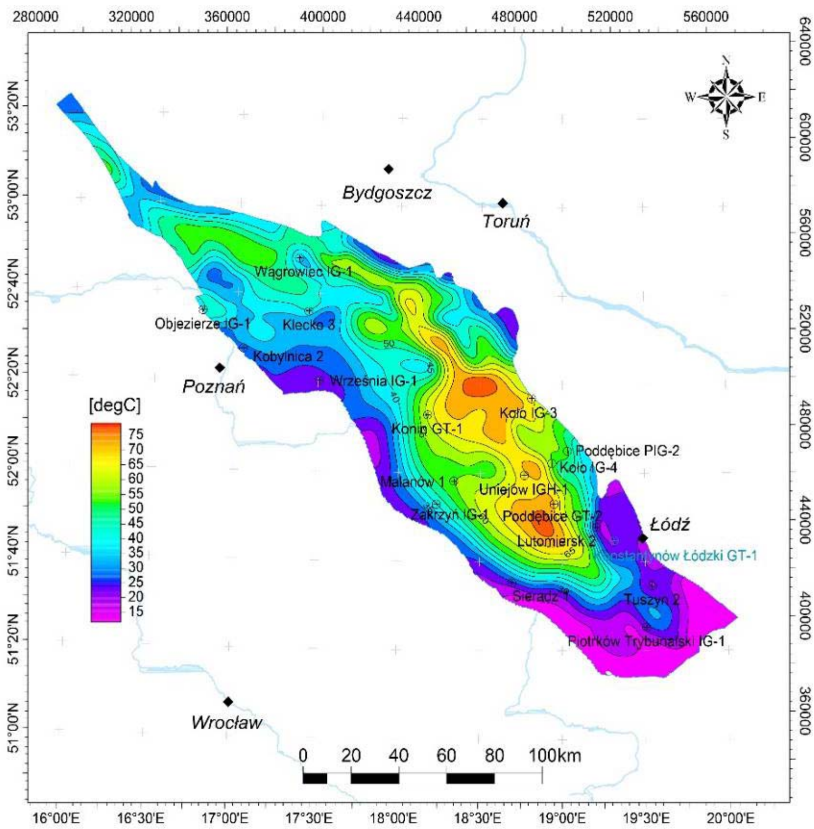


Fig. 5.3.33. Map of temperature distribution in the top of Lower Cretaceous formations

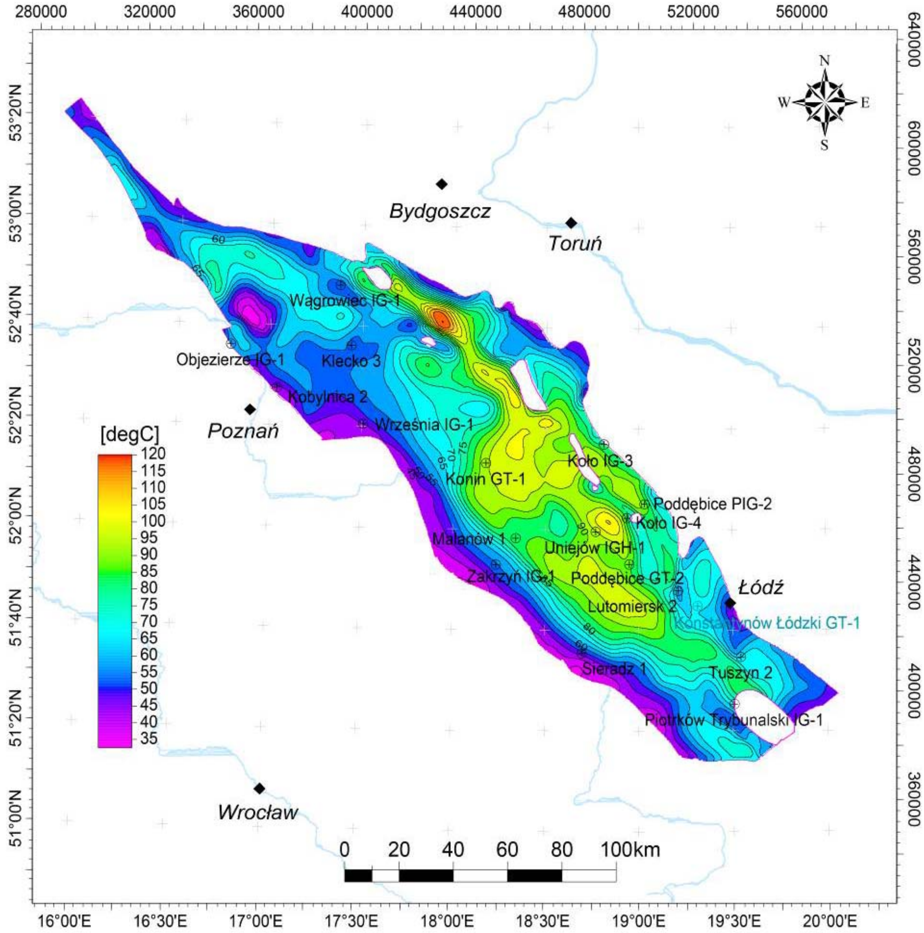


Fig. 5.3.34. Map of temperature distribution in the top of Lower Jurassic formations

5.3.9.2. Assessment of potential discharges of wells in the Mogilno–Łódź Trough

Discharges were calculated with the Darcy-Dupuit formula, applied for unlimited groundwater horizon exploited understationary conditions. (Paczyński et al., 1996; Pazdro, 1990).

Calculations of potential discharges of hydrogeological wells assumed the optimum development modes of groundwater horizons. Therefore, calculated parameters were diversified within analyzed aquifers under the following theoretical assumptions:

– diameter of working part of screen in production well, R = 15” (0,381 m),
– drawdown during production will not exceed 100 m
– thickness of exploited groundwater horizon M=100 m or thickness of groundwater horizons in the reservoir, is equal to the working part of a screen.

$$Q = 2\pi * k * m * \frac{S}{\ln \frac{R}{r}}$$

where:

• Q - discharge of production well [m3/s];
• k - hydraulic conductivity coefficient [m/s];
• m - thickness of groundwater horizon (limited by working length of screen) [m];
• S - permissible drawdown [m];
• r - radius of production filter [m];
• R - radius of depression cone [m].

Radius of depression cone was calculated with the Sichardt's formula:

$$R = 3000 * S * \sqrt{k}; [m]$$

where:
• S - drawdown [m];
• k - hydraulic conductivity coefficient [m/s].

The results of calculation are shown in the following maps (Fig.5.3.35-36).

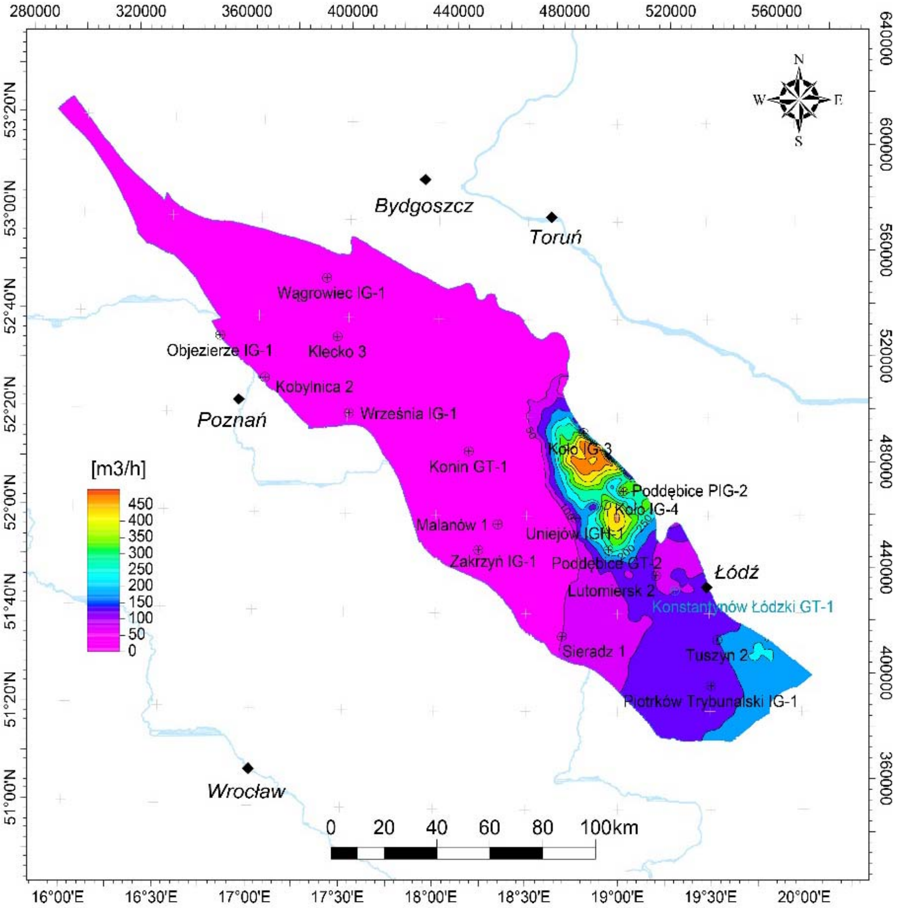


Fig. 5.3.35. Map of potential discharge of wells in the Lower Cretaceous reservoir

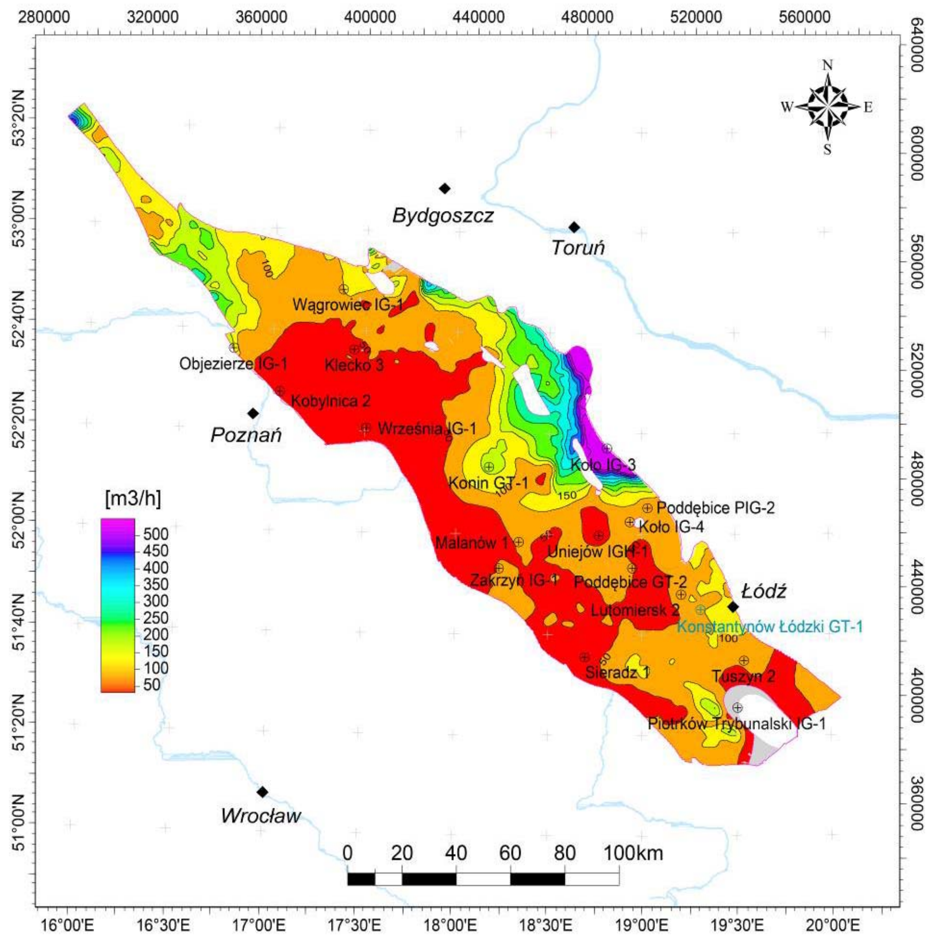


Fig. 5.3.36. Map of potential discharge of wells in Lower Jurassic reservoir

5.3.10. Assesment of geothermal resources of Lower Cretaceous and Lower Jurassic aquifers

The static geothermal resources

The static resources of geothermal waters and energy are the amounts of heat accumulated in the volume of free water hosted within the pore or fracture spaces and within the rock framework of given groundwater reservoir or horizon. The static resources EZS are calculated according to the following formula (Górecki, Hajto (eds) et al., 2006):

$$Ezs = A * m * \left[(1 - p_e) * \rho_s * c_s + p_e * \rho_w * c_w\right] * (T_s - T_o)$$

where:

Ezs - static resources of geothermal energy, [J];
A - area of calculation block, [m^2];
m - cumulative thickness of groundwater horizons in the reservoir, [m];
pe - effective porosity, [-];
Ts - temperature at the top surface of groundwater reservoir, [^{o}C];
To - mean annual temperature at the Earth's surface, [^{o}C];
ρs - mean specific heat of rock framework, 2200 [kg/m^3];
ρw- mean specific heat of water , [kg/m^3];
cs - mean specific heat of rock framework, 840 [J/ kg°C];
cw - mean specific heat of water,4180 [J/kg°C];

The results of calculation are shown in the following maps (Fig. 5.3.37– 5.3.38).

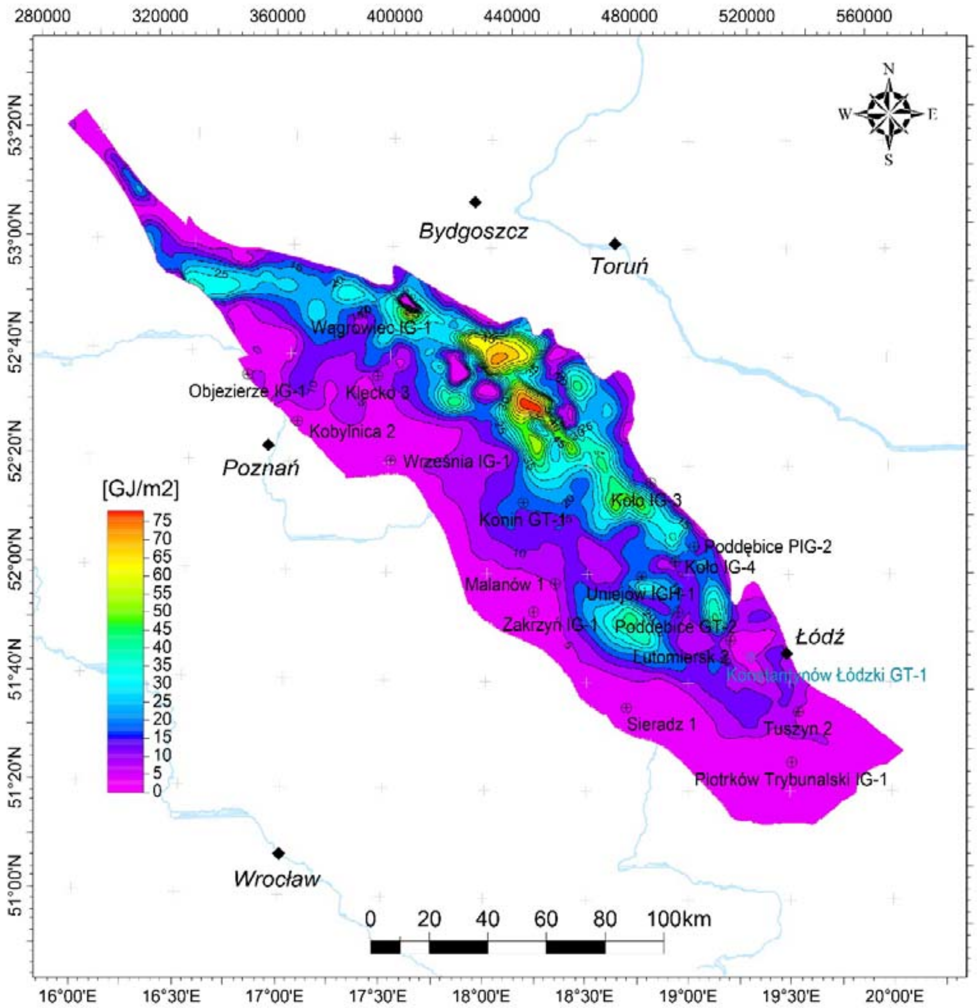


Fig. 5.3.37. Map of unit static resources of Lower Cretaceous aquifer in the Mogilno–Łódź Trough

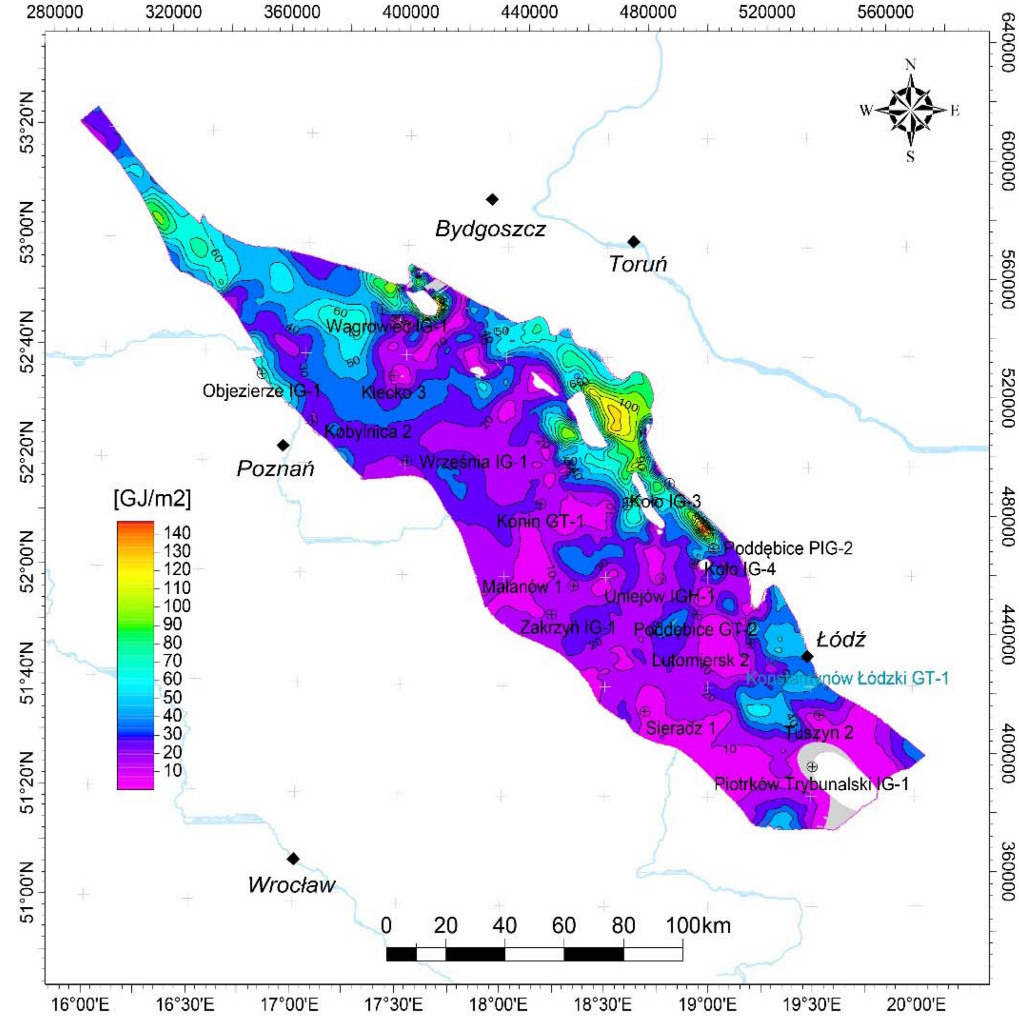


Fig. 5.3.38. Map of unit static resources of Lower Jurassic aquifer in the Mogilno–Łódź Trough

5.3.11 Calculation of the thermal power of geothermal installations

Thermal power of geothermal installations is defined as follows (Górecki, Hajto (eds) et al., 2006):

$$P = Q * \rho w * cw * (T - Tz) \text{ [W]}$$

where:

- Q - rated discharge of geothermal water [m^3/s];
- ρw - density of geothermal water [kg/m^3];
- cw - specific heat of geothermal water [J/kg°C];
- T - temperature of produced geothermal water [°C];
- Tz - temperature of waste water (i.e. geothermal water after heat recovery) [°C] (assumed Tz = 25°C).

The results of calculation are shown in the following maps (Fig. 5.3.39–5.3.40).

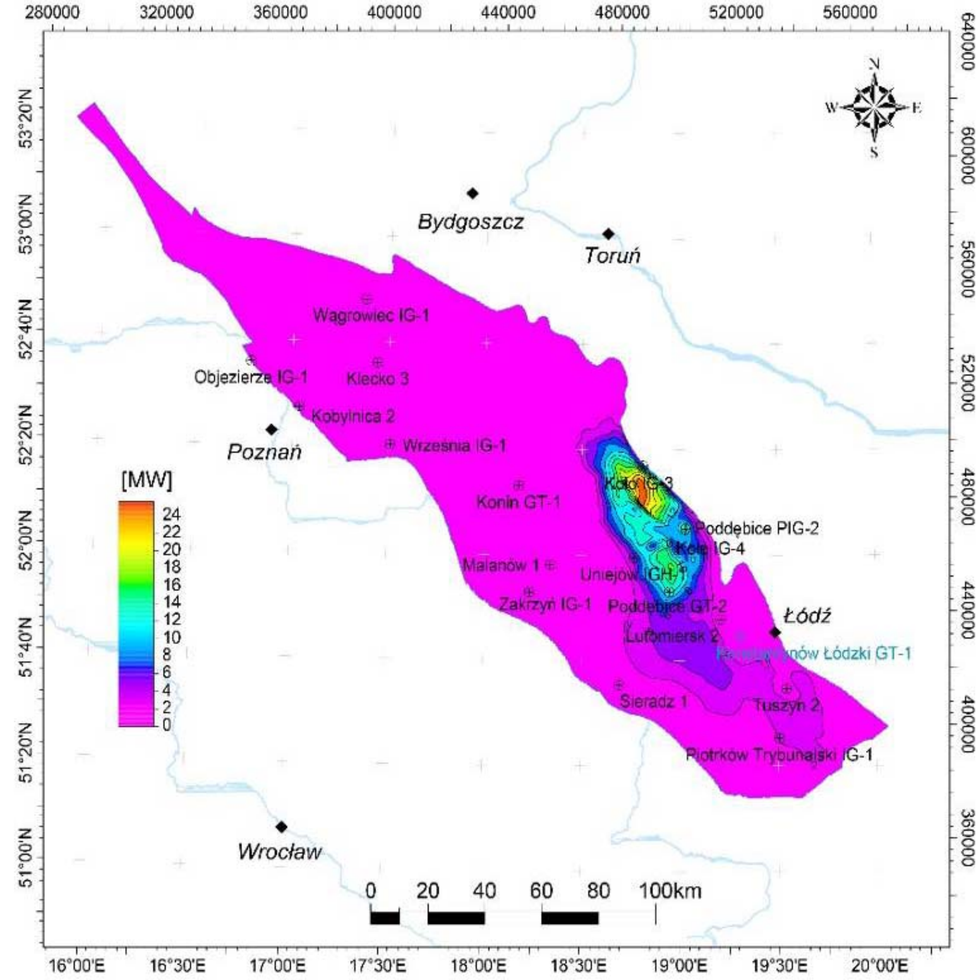


Fig. 5.3.39. Map of thermal power of a geothermal installation developed in Lower Cretaceous aquifer in the Mogilno–Łódź Trough

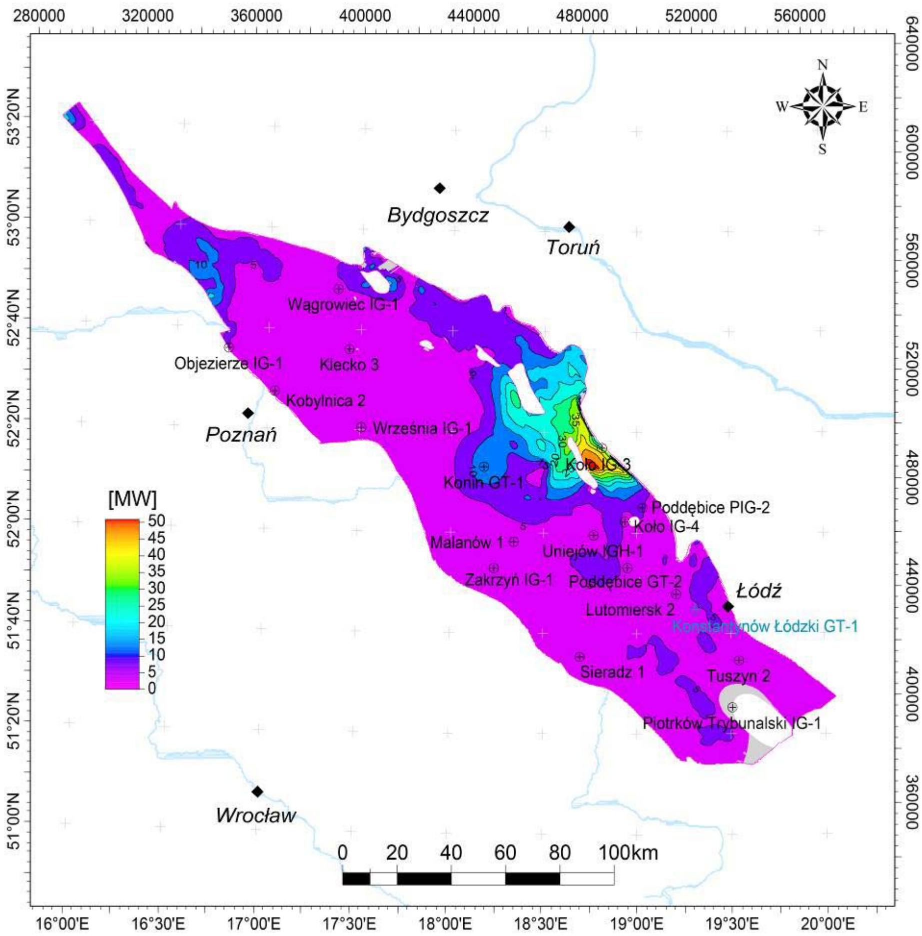


Fig. 5.3.40. Map of thermal power of a geothermal installation developed in Lower Jurassic aquifer in the Mogilno–Łódź Trough

References:

Bojarski L. 1996: Atlas hydrochemiczny i hydrodynamiczny paleozoiku i mezozoiku oraz ascenzyjnego zasolenia wód podziemnych na Niżu Polskim 1:1 000 000, PIG, Warszawa.

Ciesliński S., Jaskowiak M., 1973: Kreda górna. Niecka mogileńsko–łódzka [in:] Sokołowski S. (ed.) – Budowa geologiczna Polski. T. 1. Stratygrafia. Cz. 2. Mezozoik. Wyd. Geol. Warszawa.

Cosentino L., 2001: Integrated Reservoir Studies. Enfield Distribution.

Dadlez R, Iwanow A. Papiernik. B., 2000: Mapa strukturalna stropu wapienia muszlowego [in:] Wagner et al. 2000, Blok I.: Pozycja poziomu dolomitu głównego w układzie strukturalnym kompleksu permsko–mezozoicznego Kotarba M. (ed.) – Potencjał i bilans generowania utworów dolomitu głównego basenu permskiego Polski. CAG Warszawa.

Dadlez R. 2001: Mid-Polish Trough — geological cross-sections. Państwowy Instytut Geologiczny.

Dadlez R., Franczyk M.,1977: Retyk i lias [in:] Marek S. (ed.): Budowa geologiczna wschodniej części niecki mogileńsko-łódzkiej (strefa Gopło – Ponętów – Pabianice). Prace Inst. Geol., t. 80. Wyd. Geol. Warszawa.

Dadlez R., Kowalczewski Z., Znosko J. 1994: Some key problems of the pre-Permian tectonics of Poland. Geol. Quart., 38: 169–189.

Dadlez R., Marek S., 1969: Styl strukturalny kompleksu cechsztyńsko-mezozoicznego na niektórych obszarach Niżu Polskiego. Kwart. Geol., t. 13, nr 3.

Dadlez R., Marek S., 1974: Struktury epoki tektonicznej alpejskiej. Polska północno-zachodnia i środkowa. Uwagi ogólne. Budowa geologiczna Polski. Tektonika. Cz.1 Niż Polski. Wyd. Geol. Warszawa.

Dadlez R., Marek S., Pokorski J., 2000: Mapa geologiczna Polski bez utworów kenozoiku w skali 1:1 000 000. Państwowy Instytut Geologiczny. Warszawa.

Dayczak-Calikowska K., 1977: Jura środkowa [in:] Marek S. (ed.) - Budowa geologiczna wschodniej części niecki mogileńsko-łódzkiej (strefa Gopło – Ponętów – Pabianice). Prace Inst. Geol., t. 80. Wyd. Geol. Warszawa.

Dayczak-Calikowska K., Kopik J., 1973: Jura środkowa [in:] Sokołowski S. (ed.) - Budowa geologiczna Polski. T. 1. Stratygrafia. Cz. 2. Mezozoik. Wyd. Geol. Warszawa.

Dubrule O., 1998: Geostatistics in Petroleum Geology. AAPG Continuing Education Course Note Series #38. AAPG. Tulsa, Oklahoma, USA 1998.

Dubrule O., 2003: Geostatistics for Seismic Data Integration in Earth Models. 2003 Distinguished Instructor Short Course. Distinguished Instructor Series. No. SEG/EAGE. Tulsa, Oklahoma, USA. 279 p.

Gajewska I., 1977: Wapień muszlowy i kajper [in:] Marek S. (ed.): Budowa geologiczna wschodniej części niecki mogileńsko-łódzkiej (strefa Gopło – Ponętów – Pabianice). Prace Inst. Geol., t. 80. Wyd. Geol. Warszawa.

Gajewska I., 1997: [in:] S. Marek, M. Pajchlowa (ed.) Epikontynentalny perm i mezozoik w Polsce. Prace PIG, t. 153. Wyd. Geol. Warszawa.

Górecki (ed.) et al., 1995: Atlas zasobów energii geotermalnej na Niżu Polskim.

Górecki et al., 1996: Studium możliwości inwestycyjnych nad wykorzystaniem energii geotermalnej w zbiornikach dolnojurajskim i dolnokredowym w synklinorium mogileńsko-łódzkim na Niżu Polskim.

Górecki et al., 1999: Modele geotermalne formacji mezozoicznej na obszarze niecki warszawskiej konstruowane z wykorzystaniem systemu Landmark i studium techniczno-ekonomiczne.

Górecki et al., 2000: Analiza geologiczna i ocena zasobów wód i energii geotermalnej w formacjach jury środkowej i górnej oraz triasu na Niżu Polskim.

Górecki et al., 2003: Analiza geologiczna i ocena zasobów wód i energii geotermalnej w wytypowanych zbiornikach geotermalnych dewonu, karbonu i permu na Niżu Polskim.

Górecki W, Sowiżdżał A, Hajto M, Wachowicz-Pyzik A., 2015: Atlases of geothermal waters and energy resources in Poland. Environmental Earth Sciences, 74 (12), 7487–7495.

Górecki W., Hajto M. (ed.) et al., 2006a: Atlas zasobów geotermalnych na Niżu Polskim – formacje mezozoiku. Kraków.

Górecki W., Hajto M. (ed.) et al., 2006b: Atlas zasobów geotermalnych na Niżu Polskim – formacje paleozoiku. Kraków.

Górecki W., Kuźniak T. et al., 1996: Studium możliwości inwestycyjnych nad wykorzystaniem energii geotermalnej w zbiornikach dolnojurajskim i dolnokredowym w synklinorium mogileńsko-łódzkim na Niżu Polskim. Arch. ZSE AGH, Kraków.

Karnkowski P. H., 1977: Facies of the Rotliegendes in the northern part of the Fore–Sudetic Monocline (in Polish with English summary). Acta Geol. Pol., 27, p. 481–495, no. 4.

Karnkowski P., 1980: Wgłębne przekroje geologiczne przez Niż Polski. Wyd. Geol. Warszawa.

Karnkowski P.H. 1999: Origin and evolution of the Polish Rotliegend Basin. Pol. Geol. Inst. Sp. Pap., 3: 1–93.

Kasiński J. R., 2004: Paleogen i neogen w zapadliskach i rowach tektonicznych. [in:] Peryt T.M., Piwocki M. (eds) - Budowa geologiczna Polski. T. 1. Stratygrafia. Cz. 3a. Kenozoik, paleogen, neogen. Wyd. Geol. Warszawa.

Kępińska B., 2016: Przegląd stanu wykorzystania energii geotermalnej na świecie i w Europie w latach 2013–2015, Technika Poszukiwań Geologicznych. Geotermia, Zrównoważony Rozwój, nr 1/2016.

Kępińska B., Pająk L., Bujakowski W., Kasztelewicz A., Hajto M., Sowiżdżał A., Pétursson B., Tulinius H., Thorgilsson G., Einarsson Ó. P, Karska A., Peraj A., 2017: Geothermal utilization potential in Poland – the town of Poddębice. Technika Poszukiwań Geologicznych Geotermia, Zrównoważony Rozwój nr 1/2017.

Kleczkowski A.S. (ed.), 1990: Mapa obszarów Głównych Zbiorników Wód Podziemnych (GZWP) wymagających szczególnej ochrony, 1500 000. AGH. Kraków.

Kondracki J., 2009: Geografia regionalna Polski. Wyd. Nauk. PWN, Warszawa.

Kulikowski A., 1977: Pstry piaskowiec górny [in:] Marek S. (ed.): Budowa geologiczna wschodniej części niecki mogileńsko-łódzkiej (strefa Gopło–Ponętów–Pabianice). Prace Inst. Geol., t. 80. Wyd. Geol. Warszawa.

Marek S., Raczyńska A., 1973: Kreda dolna. [in:] Sokołowski S. (ed.): Budowa geologiczna Polski. T. 1. Stratygrafia. Cz. 2. Mezozoik. Wyd. Geol. Warszawa.

Marek S., Raczyńska A., 1974: Struktury epoki tektonicznej alpejskiej. Polska północno-zachodnia i środkowa. Lokalne formy strukturalne Polski środkowej. Budowa geologiczna Polski. Tektonika. Cz.1 Niż Polski. Wyd. Geol. Warszawa.

Marks L., Ber A., Gogołek W., Piotrowska K. (ed.) et al., 2006: Mapa geologiczna Polski. Państw. Inst. Geol., Przeds. Geol. w Warszawie POLGEOL SA, Przeds. Geol. we Wrocławiu PROXIMA SA. Warszawa.

Mizerski W., 2011: Geologia Polski. Wyd. Nauk. PWN. Warszawa.

Narkiewicz M., Dadlez R., 2008: Geologiczna regionalizacja Polski – zasady ogólne i schemat podziału w planie podkenozoicznym i podpermskim. Przegl. Geol., vol. 56, nr 5.

Paczyński B. (ed.), 1995: Atlas hydrogeologiczny Polski 1:500000. Warszawa: Neokart.

Paczyński B., Sadurski A. (ed.), 2007: Hydrogeologia regionalna Polski. T I: Wody słodkie. Warszawa: Państwowy Instytut Geologiczny.

Papiernik B., 201 W: Wójcicki et al., 2010: Regionalne mapy strukturalne pokrywy mezozoicznej w rejonie Bełchatowa, wykorzystywane do opracowania regionalnego modelu statycznego dla celów wstępnej oceny możliwości wgłębnego składowania CO_2 w utworach wodonośnych.

Peryt T., Guterch, Górecki W. et al., 2008: Atlas polskiej części południowego basenu permskiego. Kierownik Peryt T. Realizacja 2005 – 2008, Umowa nr 870/2005/Wn-07/Fg-bp-tx/D Finansowanie: Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej.

Pożarski W. (ed.), 1974: Budowa geologiczna Polski, T. IV, Tektonika, cz. 1, Niż Polski. Wydawnictwa Geologiczne, Warszawa: 2–34.

Pożaryski W., Karnkowski P., 1992: Tectonic map of Poland during the Variscan time. Wyd. Geol. Warszawa.

Rozporządzenie Ministra Zdrowia z dnia 13 kwietnia 2006 r. w sprawie zakresu badań niezbędnych do ustalenia właściwości leczniczych naturalnych surowców leczniczych i właściwości leczniczych klimatu, kryteriów ich oceny oraz wzoru świadectwa potwierdzającego te właściwości (DZ. U. 2006.80.565 z późn. zm.).

Sapińska-Śliwa A., 2011: Wody termalne Uniejowa w świetle interpretacji wskaźników hydrochemicznych, Wiertnictwo, Nafta Gaz, vol. 28, No 1–2, p. 359–369.

Sokołowski, J. 1972: Rola tektoniki salinarnej cechsztynu w modelowaniu pokrywy mezo–kenozoicznej. Biuletyn Instytutu Geologicznego, 252: 99–118.

Stupnicka E., 1997: Geologia regionalna Polski. Wyd. Uniw. Warsz. Warszawa.

Szyperko-Śliwczyńska A., 1977: Piaskowiec pstry dolny i środkowy [in:] Marek S. (ed.) - Budowa geologiczna wschodniej części niecki mogileńsko-łódzkiej (strefa Gopło–Ponętów–Pabianice). Prace Inst. Geol., t. 80. Wyd. Geol. Warszawa.

Szyperko-Śliwczyńska A., 1979: Trias dolny w północno-wschodniej Polsce. Prace Inst. Geol. T.91. Wyd. Geol. Warszawa.

Trzepierczyński J., 2004: Karbon i perm platformy paleozoicznej na tle struktury głębokiego podłoża w regionie łódzkim. Przegl. Geol., vol. 52, nr 10.

Wiktorowicz B., 2014: Wody termalne niecki łódzkiej – zielona energia z wnętrza Ziemi. Wydawnictwo: PIG-PIB, Warszawa.

Woźniak B., Gabryszewska G., Nowicki M., 1987: Mapa miąższości triasu górnego i środkowego /wraz z retem/ mapa w skali 1:500 000. BG Geonafta Oddział Warszawa 1984.

Wójcicki A., Sowiżdżał A., Bujakowski W. (eds) et al., 2013: Ocena potencjału, bilansu cieplnego i perspektywicznych struktur geologicznych dla potrzeb zamkniętych systemów geotermicznych (Hot Dry Rocks) w Polsce Ministerstwo Środowiska, Warszawa, 246.

Wróbel J., 1984: Mapa strukturalna stropu doggeru w Polsce skala 1: 500 000. Materiały archiwalne PGNIG i PIG. Dział Geologii Polski Centralnej. Warszawa. Archiwum PGNIG.

Wróbel J., 1988: Mapa strukturalna spągu kredy górnej dla subbasenu grudziądzko – warszawskiego. Część wschodnia. Archiwum BG Geonafta-Warszawa, Warszawa.

Wróbel J., Nowicki M., Gabryszewska G., 1990: Mapa strukturalna stropu jury dolnej w skali 1:500 000. Archiwum Katedry Surowców Energetycznych AGH.

Wróbel J., Siwek T., 1988: Mapa strukturalna stropu jury górnej – mapa wykonana w skali 1:200 000. Część wschodnia. Archiwum BG Geonafta-Warszawa (PGNIG). Warszawa 1988 r.

www.geotermiakonin.pl

5.4 – 5.7 Preliminary pre-feasibility studies of geothermal energy uses for heating on a basis of selected towns

5.4. Poddębice study case

5.4.1. An update of geological and geothermal reservoir conditions and exploitation parameters of Poddębice area

Poddębice Town and Municipality are located in the central part of the Permian-Mesozoic geological structure called Mogilno-Łódź Syncline. It is a part of a larger structure called Szczecin-Łódź-Miechów Synclinorium – stretching from the Fore-Sudetic Monocline (to the SW), to Middle-Poland Ridge (on the NE). From NE, the Łódź Basin borders with Kujawy Ridge (with strongly advanced salt tectonics), and from north-west with Mogilno Syncline.

The geological structure of Łódź Basin is complex, which is the effect of the advanced salt tectonics. It causes local discontinuities in geological profiles, sudden changes in sediment thickness, especially in the area of anticlinal structures, which were formed during the Upper Triassic and Upper Cretaceous periods, as well as at the turning of Cretaceous and Paleogene – during the Laramidian inversion (Dadlez, 1968). Creation of anticlinal structures in the area of Poddębice was caused by a tectonic movement of salt sediments, which were active during depositing of Mesozoic formations. A simplified 3D geological model of the Łódź Basin, with special emphasis on tectonic elements, seen in the area of Lower Cretaceous and the Lower Jurassic formations have been presented in Fig. 5.4.1.1.

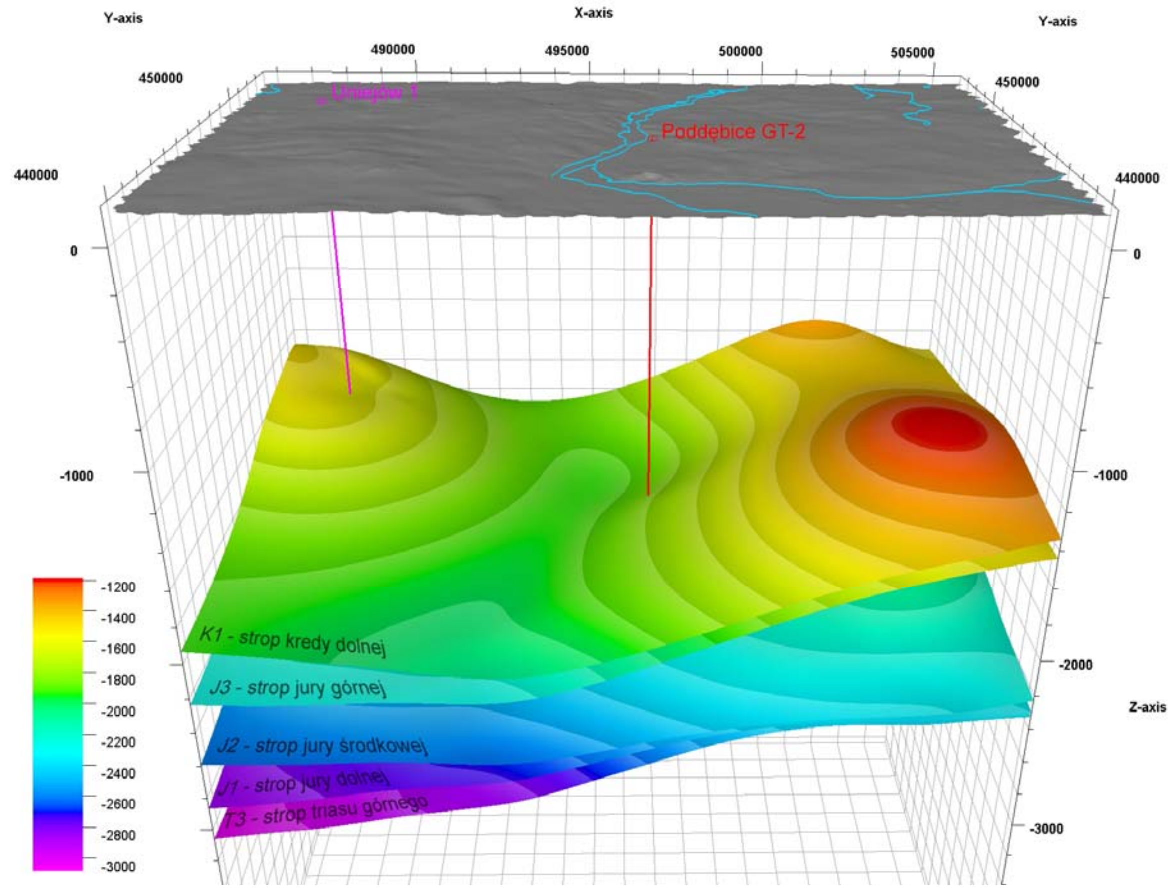


Fig. 5.4.1.1. 3D geological model of Łódź basin in the area of Poddębice

The profile of the Lower Cretaceous formations roof is the result of local salt tectonics, when plastic salt strata, while moving upwards, created the forms of Koło and Poddębice anticline, revealed in the Lower Cretaceous formations roof. The town's location, on the structural map of the Lower Cretaceous formations roof, together with the location of GT-2 Poddębice well, has been presented in Fig. 5.4.1.2.

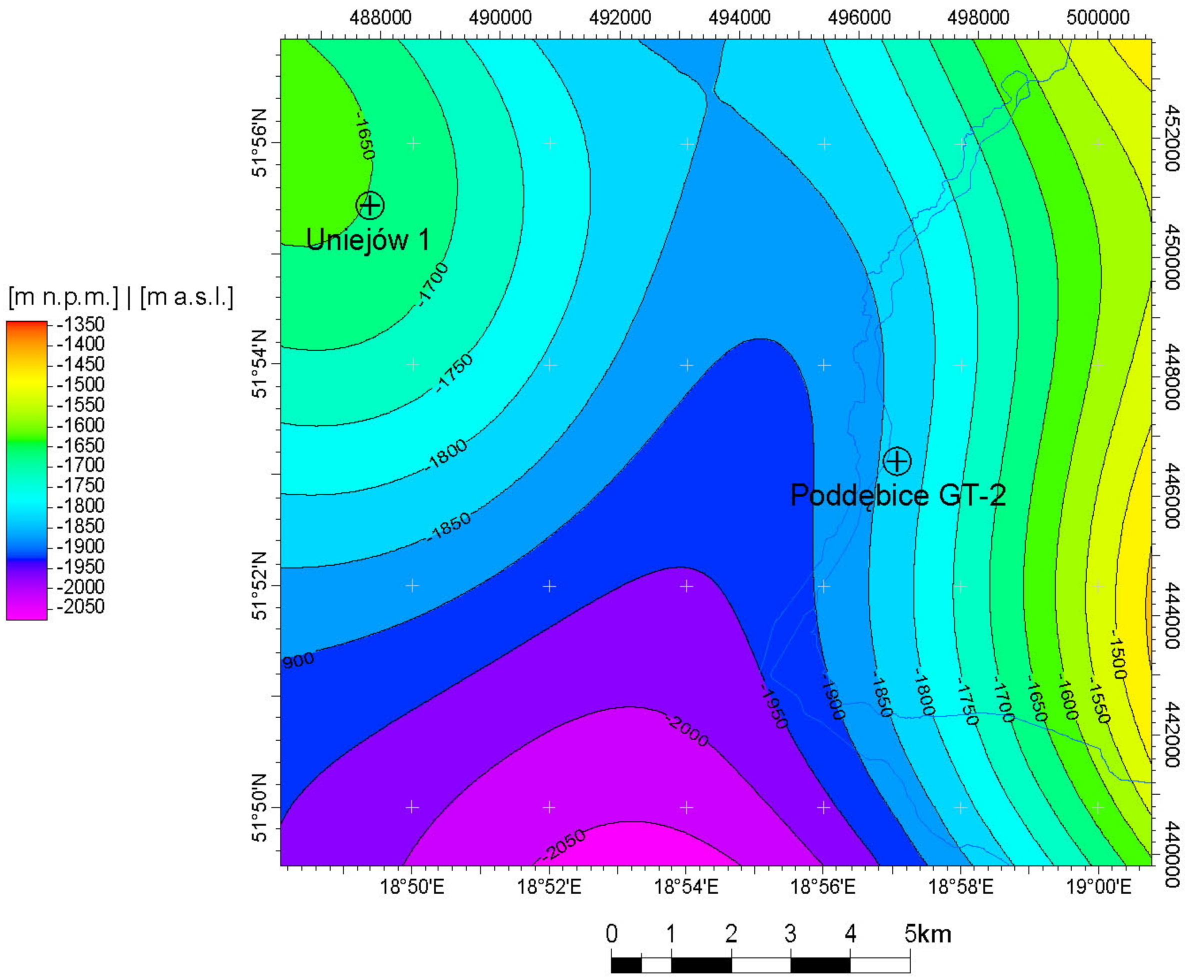


Fig. 5.4.1.2. Structural map of the Lower Cretaceous formations roof in the area of Poddębice

The occurrence of anticlinal structures in the area of Poddębice was frequently caused by sub-salinary dislocations, active in the period of Mesozoic formations sedimentations. Sometimes, incomplete formation and low sediment thickness, e.g. Lower Cretaceous, within the scope of salt pillows was caused by regional changes.

Along the Łódź Syncline there is an axis of maximum Upper Cretaceous basin burial, thus, the Upper Cretaceous sediments have the maximum thickness in the area of Poddębice, up to 2600-3000 m (in the area of Koło and Turek, respectively), and in the area of Poddębice the thickness is about 1952 m.

The oldest formations recognised with drilling are fine-grain Lower Triassic sandstones and mudstones interbedded with limestones. Those formations occur over Zechstein series. Overburden is made up of a series of evaporitic and clastic Röt formations, developed as anhydrides, dolomites and mudstones. Muschelkalk developed in pelitic limestone and marl facies. Upper Triassic is made up of fine-grain sandstones and claystone interlayers, transformed into claystones. A series of pellite sandstones with rare mudstone interlayers is characteristic for Triassic formations in this area. Maximum Triassic formations thickness is around 2000 m.

Above Triassic, there are strongly reduced, in terms of thickness, Lower Jurassic formations, the thickness of which is about 37 m. These are mainly sandstones with claystone interbeddings. Dogger (Middle Jurassic) formations are represented mainly by dolomites and mudstones with thin sandstone glauconite interlayers. Upper Jurassic (Malmian) formations are characterised by significant thicknesses, even up to ca. 600 m. They are formed mainly in the carbonate facie as limestones, marls, dolomites and mudstones. There are subordinate sandstones. Poddębice GT-2 well was drilled through the roof Upper Jurassic formations developed in the carbonate facie. These are mainly light-grey marls and marl limestones, locally sandstones. The Upper Jurassic roof was drilled in the area of Poddębice at the depth of 2072 m below ground level.

There are no older stratigraphic levels in the geological profile of Lower Cretaceous in Poddębice. The Lower Cretaceous profile starts with clay–mudstone Hauterivian formations. They are dark brown mudstones interbedded with claystones, which are proper sediments for formations of the sedimentary basin shelf zone. The thickness of Hauterivian formations is

small: only 7 m. Hauterivian sediments, together with Upper Jurassic marls, constitute natural sealing between the Lower Cretaceous geothermal reservoir and the Jurassic aquifer located underneath.
Over Hauterivian formations there are grey, fine- and medium-grain sandstones of land origin, which build the geothermal aquifer complex, made up of Albian, Aptianian and Barremianian levels. They were reported in Poddębice GT-2 well in the depth interval: 1962–2063 m below ground level. In the Lower Cretaceous aquifer profile, there is a claystone interlayer (at the depth of 2001–2004 m). The upper part of sandstone (above the clay stratum) contains a very pure rock skeleton, with a characteristic, local occurrence of glauconite. The upper part of the aquifer is characterised with better reservoir parameters (effective porosity is about 17%). In the lower part of the profile, below 2027 m below ground level, in the Lower Cretaceous formations profile, mudstone interlayers are present, quartz grains are smaller, and porosity is at the level of 14% (Posyniak, 2015). The thickness of the sandstone aquifer is 98 m (taking into account the above-mentioned 3 m thick layer of clay rocks).
Upper Cretaceous sediments – mainly marls, creamy–grey limestones and argillaceous limestone with dark claystone interlayers occurring in the profile of GT-2 Poddębice well at the depth of 10–1962 m below ground level. Cenomanian is developed in the form of characteristic limestones and cream marl limestones, similarly to Upper Albian formations. Turonianian formations are dichotomous: the middle part is marl-claystone, whereas the upper one is argillaceous limestone. Upper Turonianian formations are characterised by the occurrence of rocks with higher silica contents, including flints as interlayers within marl limestone and marls. Coniacian, Santonian and Campanian formations are represented by marl limestones and marls with a characteristic grey colour. Maastrichtian formations (the youngest Upper Cretaceous sediments) are represented only by the oldest Maastrichtian sediments, whereas younger ones eroded. These are mainly marl limestones and marl mudstones in the overburden. At the depth of do 10 m below ground level the Cretaceous profile builds yellow medium-grain sand (Posyniak, 2015).
In the area of Poddębice GT-2 well, there are no Paleogene and Neogene formations. They eroded as a result of glacial processes, the intensity of which was magnified by epeirogenic movements.

Lithostratigraphic characteristics of the Lower Cretaceous geothermal reservoir

In the area of Poddębice, the main geothermal water reservoir relates to fine-grain and, in places, medium-grain Lower Cretaceous sandstones, which are characterised by relatively high porosity. Lower Cretaceous formations were drilled at the depth of 1962 m below ground level, and the bottom at the depth of 1070 m below ground level. The total thickness of Lower Cretaceous formations is 108 m here (Fig. 5.4.1.3). Lower Cretaceous reservoir formations were drilled by Poddębice GT-2 well at the depth of 1962 m below ground level (roof) - 2063 m below ground level (bottom). The upper part of the aquifer complex is represented by grey, fine-grain sandstones, dating back to Lower Albian. In the depth range from 2001–2004 m (3 m) there is an interlayer of dark claystone and mudstone. Below the depth of 2027 m below ground level there are grey fine-grain sandstones with numerous mudstone interlayers. The total thickness of Lower Cretaceous reservoir formations in the area of Poddębice has been presented in Fig. 5.4.1.4.
Quartz prevails in the mineralogical composition of sandstones and it constitutes 95% of their volume. Other grain components are additives of glauconite, feldspars and clay minerals. Binder is mainly silica, with a small additive of secondary carbonates and clay minerals. Quartz grains are round and well sorted, their sizes range from 0.2 to 1.3 mm. Together with the depth of sandstone deposition the number of claystone interbeddings increases, which, in the bottom part of the Barremianian sandstone aquifer complex, reaches 23% of the profile thickness (Posyniak, 2015).
From the depth of 2063 m below ground level impermeable Hauterivian formations (mudstones and claystones) were reported, which lie under Lower Cretaceous aquifers. At the depth below 2070 m below ground level, they are transformed into carbonate Upper Jurassic formations.

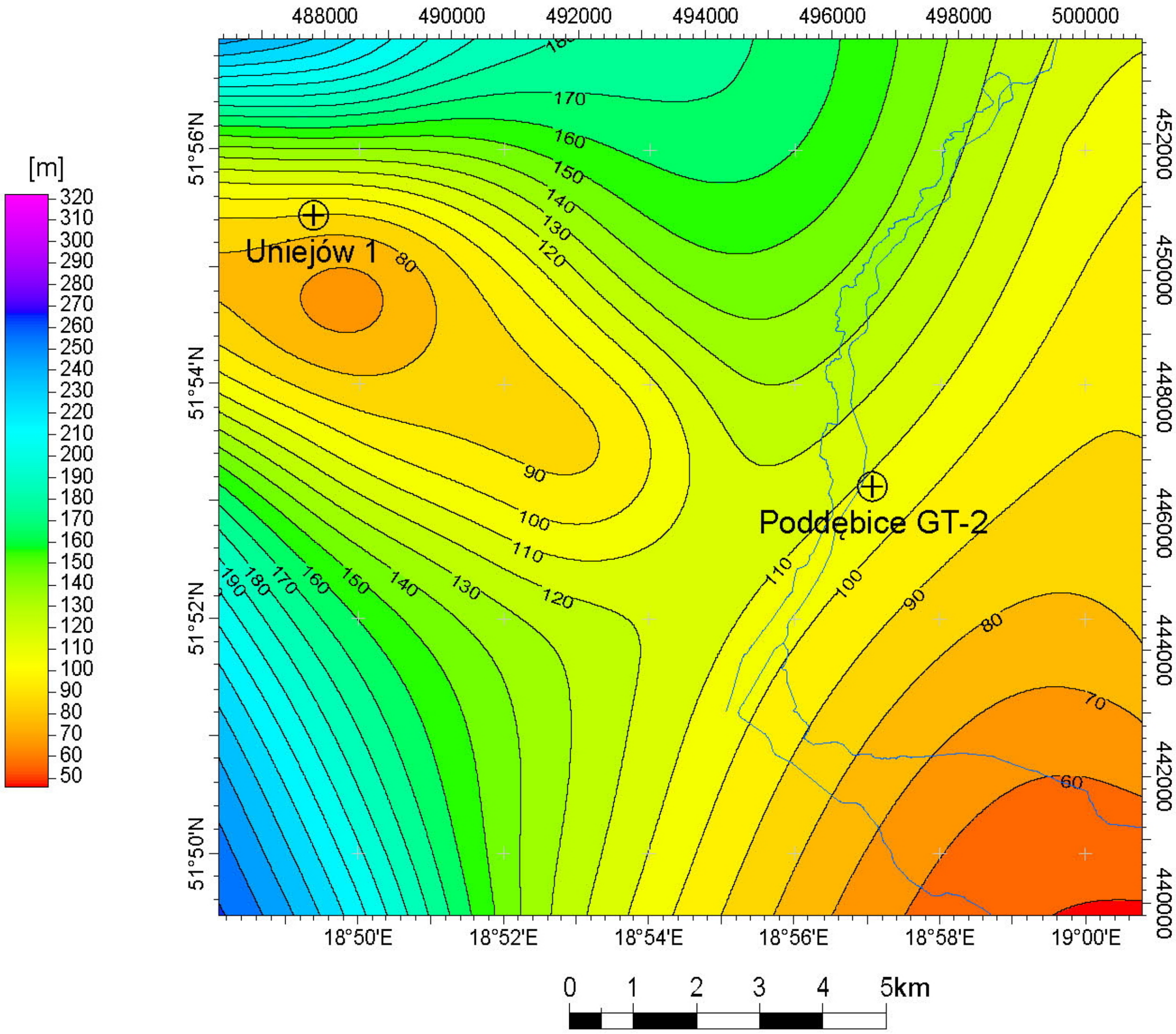


Fig. 5.4.1.3. Map of total thickness of Lower Cretaceous formations in the area of Poddębice

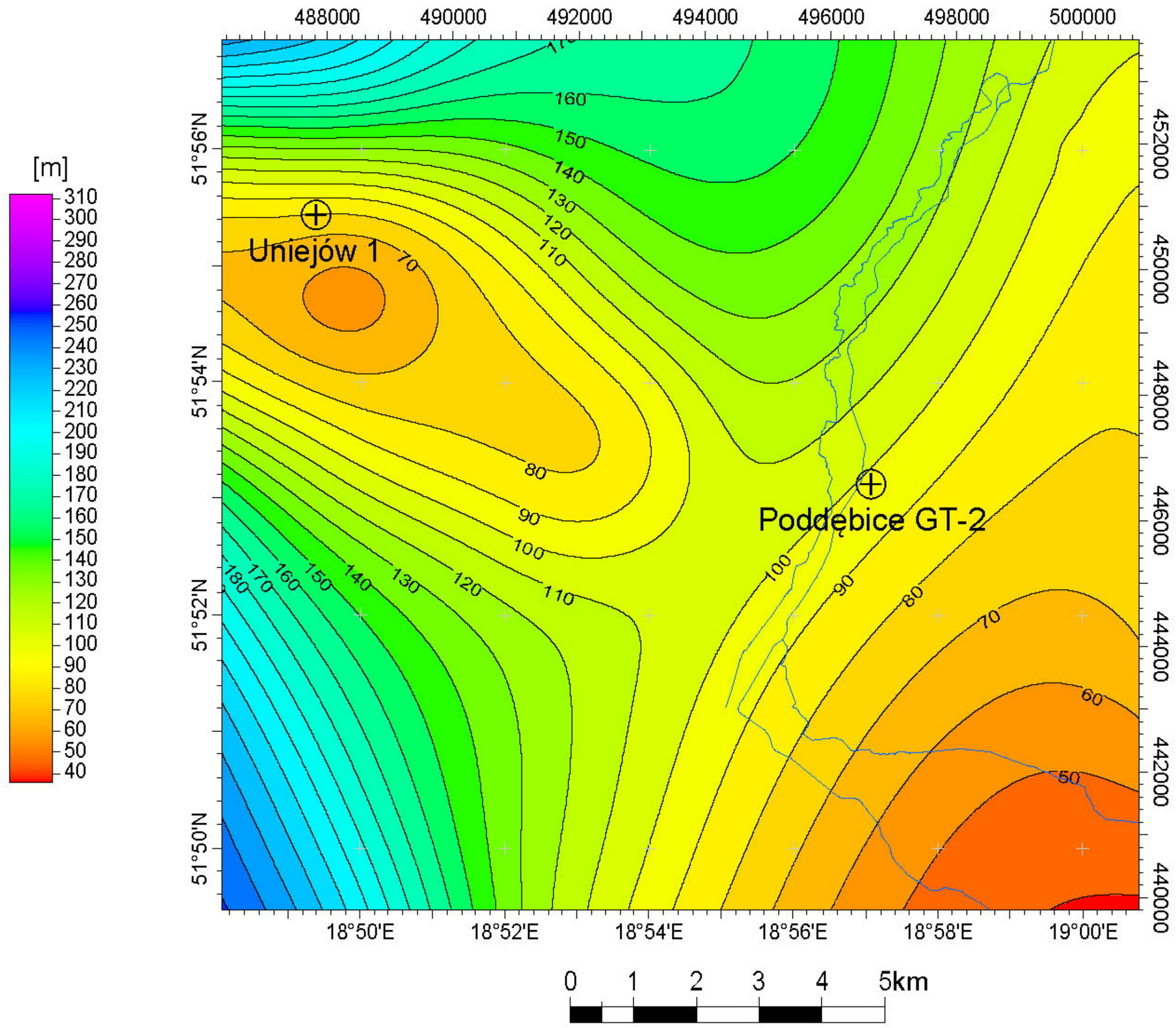


Fig. 5.4.1.4. Map of total thickness of Lower Cretaceous aquifers in the area of Poddębice

Basic reservoir parameters of Lower Cretaceous formations

Lower Cretaceous (Lower Albian-Aptianian-Barremianian) reservoir sandstones found in the depth range between 1962–2063 m below ground level in Poddębice GT-2 well show relative lithological homogenicity. They are characterised by high porosity (13.7–17.0%) and permeability (87.98–1021.10 mD). Core sample analyses demonstrate slight content of carbonate minerals, usually less than 2% of calcite and 1% of dolomite. Thus, carbonate minerals in Lower Cretaceous sandstones constitute a subordinate mineral of the whole lithological profile of aquifers (Posyniak, 2015).

Sandstones have relatively good petrophysical properties. A table of basic petrophysical-reservoir parameters of Lower Cretaceous formations in Poddębice GT-2 well has been presented in Table 5.4.1.1.

Table 5.4.1.1 Table of petrophysical-reservoir parameters of Lower Cretaceous formations relatied to a geothermal water intake in Poddębice GT-2

Parameter	Value
Well depth	2101 m
Water type / mineralisation	HCO_3-Na-Ca / 432 mg/dm^3 (considerable SiO_2 content)
Water temperature at outflow	68.4^{o}C
Total thickness of Lower Cretaceous formations	108 m
Aquifer	1962–2063 m below ground level

Aquifer thickness	98 m
Intergranular porosity (total)	16–23% (no secondary porosity)
Effective porosity (uncovered)	13.7–17.0% (average: 16.2%)
Shaliness	VCL = 9.8%
Permeability	87.98–1021.10 mD (average: 620 mD)
Productivity index PHI*NET	17.76 nV/V
Water saturation	100%
Reservoir pressure	not measured for technical reasons (neither in 2010 nor in 2014)
Resistance of reservoir water	Rwa = 2,6 ohmm (*resulting from low mineralisation*)
Age of water	10–14 thous. years (glaciation); based on analysis (C14) - 27 thous. years

Technological and exploitation conditions of a geothermal water intake for the Lower Cretaceous reservoir

Poddębice GT-2 exploitation and research well was drilled in a period from 10 October 2009 until 28 January 2010 by means of a drilling rig type TD-160, using a rotation method with drilling fluid, up to the final depth of 2101 m. Drilling started with a drill bit with a diameter of 580 mm (0.0–84.0 m), next it was continued to the depth of 450 m with a drill bit with a diameter of 444,5 mm. In the interval down to 1974 m a drill bit with a diameter of 311 mm was used, with which a borehole was deepened down to the roof of Lower Cretaceous sandstones. Those sandstones were drilled using a drill bit with a diameter of 216 mm and a diamond tube core barrel with a diameter of 141 mm. Drilling was ended at the depth of 2101 m, after drilling of the Cretaceous formation bottom (at the depth of 2070 m) and roof parts of Jurassic formations, with a drill bit with a diameter of 216 mm (Tadych et al., 2010).

In the interval 2070–2101 m, in clay-carbonate Upper Jurassic formations, a clay sealing was made to prevent a potential hydraulic contact or water inflow from the lower reservoir. Next, the well was extended to a diameter of 381 mm (15”) within the range of 1970–2070 m depth in order to obtain a larger diameter for gravel backfilling and to improve filtration parameters of rocks in a three-well zone.

In the reservoir zone, at the depth of 1914.5–2065.0 m below ground level a Johnson filter was installed, whereas the space around the filter was filled with gravel backfilling with grains ranging 0.71–1.25 mm. Hydrogeological tests were conducted once drilling was completed and the filter installed.

The condition of well cementation was checked by means of acoustic geophysical profiling, type RBT. After drilling completion within a range of 1914.5–2065.0 m, a column of exploitation tubes was installed, with the tubes placed on 9 5/8” casing. The active part of the Johnson filter was placed within the depth range of 1957–2059 m below ground level. The upper part of the exploitation column (1957–1964,0 m) was put inside 9 5/8” casing.

When the column of exploitation tubes and the filter were installed and a whole set of studies and tests were performed, a head was installed on 13 3/8” tubes, at the well outlet (Tadych et al., 2010).

Resources of the geothermal reservoir produced from Poddębice GT-2 well

Exploitable water reserves of the Lower Cretaceous reservoir produced by means of Poddębice GT-2 well were determined twice. The first time in 2010, after well drilling and in 2015, when exploitable resources increased up to 252 m^3/h.

Exploitable water reserves of geothermal water produced by means of Poddębice GT-2 well are documented in “*Supplement no. 1 to the hydrogeological documentation for Poddębice GT-2 well*” (Posyniak, 2015). This document was approved by the Marshal of Łódź Province (decision of March 2015). The basis for specifying exploitation reserves was the results of hydrogeological tests conducted on 29–30 October 2014.

The approved exploitable water reserves in Poddębice GT-2 well were determined at Q = 252 m^3/h, with an exploitation depression at the level of 85.3 m below ground level. The temperature of geothermal water measured at the outflow is 68.4°C. The mining area is equal is the concession area and it is 7.18 km^2. At the initial stage, exploitation was conducted using artesian pressure, which, at the present well filtration allows producing of 116.5 m^3h water (which covers the customers’ demand for heat in the summer season).

Table 5.4.1.2 Table of basic exploitation parameters of Poddębice GT-2 geothermal water intake

Parameter	Unit	Value
Exploitable water reserves (Qe)	m^3/h	252.0
Unit discharge (q)	$m^3/h/1$ m of depression	2.96
Hydraulic conductivity	m^2/h	4.184
Exploitation depression (Se)	m	85.3
Radius of a depression cone (R)	m	857.0
Depth of static water table	m above ground level	26.0
Depth of dynamic water table	m below ground level	59.3
Ground ordinate	m n.p.m.	119.5
Mineralisation (TDS)	mg/dm^3	432.0
Temperature	^oC	68.4
Mining area	km^2	7.18

Geothermal water exploitation from the Lower Cretaceous reservoir by means of Poddębice GT-2

Geothermal water production by means of Poddębice GT-2 well began on 18 January 2010. The so-far exploitation of Poddębice GT-2 geothermal water intake, disregarding the drilling period, can be divided into 2 main stages, namely from drilling until 2015, from 2015 until now. It relates to the fact that the reservoir reserves were determined twice, i.e. in 2010, immediately after the completion of drilling, and in 2015, during the second system exploitation phase and they were related to the plans of Geotermia Poddębice Sp. z o.o. concerning the extension of the geothermal heating system in the town, which made it necessary to increase intake outflow (252 m^3/h).

At the first stage until 2013, a number of cleaning pumping procedures and reservoir tests were made in order to determine exploitable water reserves (conducted in years 2010 and 2014), whereas the main reservoir exploitation for district heating purposes began in 2013. At the first stage, only artesian outflow was used (outflow: 116.5 m^3/h), and later exploitation, up to the stream size of 190 m^3/h (stipulated in the first production concession obtained in 2010), was performed using a submersible pump located at the depth of 36 m below ground level.

The size of exploitation, and thus also the use of a submersible pump depends on the demand for geothermal energy or water on the part of future customers.

At the second stage, taking into account exploitation with the maximum outflow of 252 m^3/h, exploitation is conducted by means of a submersible pump located at the depth of 90 m below ground level, i.e. 30 m deeper than the depth of dynamic water table, reported during measurement-related pumping with the outflow of 252 m^3/h. During designed intake exploitation, this outflow will not be exceeded, since it constitutes, at the same time, the size of approved intake exploitable water reserves. During measurement-related pumping, dynamic water table was at the depth of 59.3 m below ground level (ordinate 60.2 m above ground level). Sinking of a submersible pump at the depth of 90 m gives 30 m of a safe distance from the water table, guaranteeing suitable pump utilisation, and hence, exploitation safety. A typical submersible pump will be sunk to the well, with a wave motor on the surface, due to high temperature of geothermal waters being exploited (temperature: 68.4°C).

Mining supervision over proper and safe geothermal water exploitation will be provided by the District Mining Agency in Kielce.

Discharge of used geothermal water

After use, abstracted geothermal water is partly discharged to nearby Ner River (transmission by a pipeline). A water law permit acquired by the entrepreneur stipulates the maximum amount of water possible to be discharged to the river, which is 160 m^3/h by 1 October 2016, with a review to 70 m^3/h after that period. The remaining part of geothermal water being exploited after giving away some heat in a heat exchanger station is sent to geothermal pools, to a hospital for rehabilitation purposes, entering, at the final stage, the sewage system as sewage. Water used in balneology and physical therapy gets also to the sewage network.

A part of cooled down geothermal water is transported to a geothermal water pump room and to the sewage system in order to possible bottle it or distribute as potable water.

As per the water law permit spent geothermal water, before being discharge to Ner River, should be cooled down to the maximum temperature of 35°C. To this end, water is sent to a ground reservoir built for this purpose (next to the central heating plant), where it is cooled down from the temperature of 50–55°C down to the required temperature of 35°C or lower.
The original technological reservoir with the outflow of 3378 m^3 (5852 m^3 to the top of the embankments) was extended in 2017 by ca. 1500 m^3. (Fig. 5.4.1.5). Outflow extension, together with building of a two-stage flow structure with the length of 9 m and the width of 50 m will allow cooling down of the additional amount of geothermal water after increasing maximum production from 190 m^3/h up to 252 m^3/h.

Fig. 5.4.1.5. Technological reservoir for cooling down of geothermal water with the capacity of ca. 1500 m^3, made in 2017 (photo made by Oskar P. Einarsson)

Monitoring of operating parameters of the intake

The amount of geothermal water intake and water distribution are measured by means of water meters installed on pipes supplying water from the well and on pipes discharging it to the reservoir to cool down water and at the exit from the reservoir to the river, as well as on all pipelines transporting geothermal water to customers.
The measurement of the amount of thermal energy taken from exchanger stations to customers is recorded by a heat meter made by Kamstrup with an ultrasound flow sensor.
Pressure at the intake head is also controlled with regard to the reported reservoir pressure. Measurement is done by means of a manometer, installed on the head. The water table level in the well and geothermal water temperature are measured as well. Temperature measurement is done directly at the water outflow from the well, in a heat exchanger station and before discharging spent geothermal water to Ner River. Before discharging spent geothermal water, temperature is measured again by means of an external temperature transmitter with a sensor installed close to the bottom of the ground reservoir, before a lock. The diagram presenting the amount of production from Poddębice GT-2 well in a time interval from 4 July 2012 to 26 September 2016, taking into account an average daily flow (m^3/h), has been presented in Fig. 5.4.1.6.

In addition, the production capacity possible to acquire by means of artesian outflow (116.5 m³/h) and the amount of abnormal geothermal water intake, taking place in October 2014, relating to the performance of measurement-related pumping, have been taken into consideration in order to determine exploitable water reserves at the level of 252 m³/h.

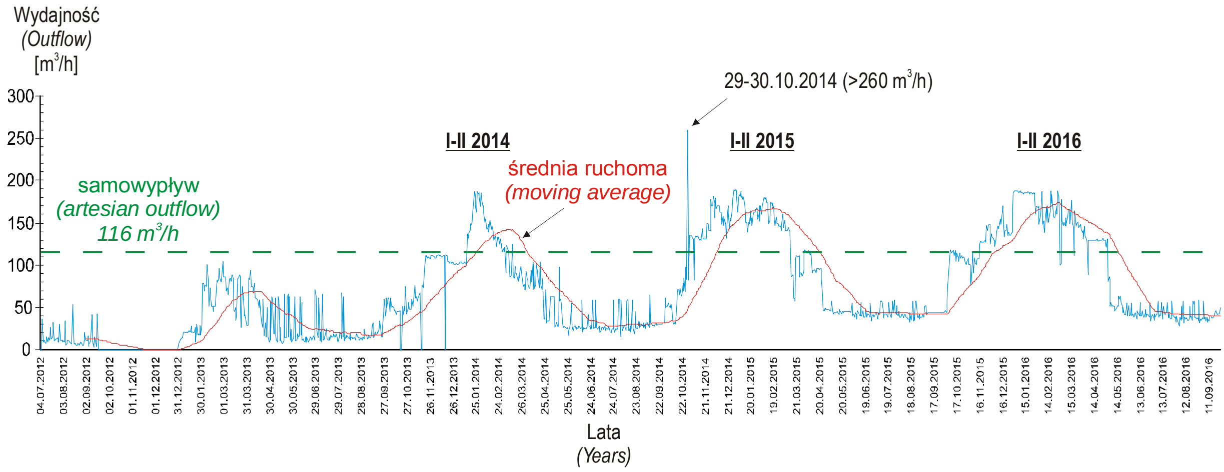


Fig. 5.4.1.6. Size of geothermal water production from Poddębice GT-2 well in a time interval from 4 July 2012 to 26 September 2016 – average daily flow

Elements of rational exploitation of Poddębice GT-2 intake

The Lower Cretaceous aquifer being exploited, due to the depth of occurrence and artesian pressures reported there, is not at any risk of contaminations occurring on the area surface. It regards also contaminations which might migrate through the well casing zone, since casing columns are cemented to the top. Due to the nature of area management and urbanisation as well as resistance of the geothermal water reservoir to contaminations from the area surface, investment opportunities are not limited in this area. However, mainly due to the quantitative protection of water on the mining area, prohibition of locating other groundwater intakes from Lower Cretaceous formations should be introduced.

The geothermal water level being exploited is characterised by good insulation against the impact of external factors, which is confirmed by the updated chemical composition (no anthropogenic contaminations or toxic compounds) and the bacteriological condition of water.

The initial results of the analyses consisting in the simulation of geothermal water production through Poddębice GT-2 well by means of "Simple Lumped Parameter Modelling", conducted under the project titled: "Potential of geothermal energy use in Poland, Poddębice Town" - Report from study visits (Kępińska et al. 2017), point out stable geothermal water exploitation conditions. Yet, due to unexpectedly low general water mineralisation and a possibility of infiltration, particularly at an increased intake stream (252 m³/h) over a longer period of exploitation, of heavier geothermal waters from deeper reservoir zones, located in the area of Uniejów, the issue of the necessity of regular and more frequent monitoring of general mineralisation and physicochemical composition of water being exploited is raised. In the future, it is to enable seizing the moment when physicochemical composition of water loses its stability, which might indicate triggering of new directions of deep-seated water migration, including perhaps more mineralised waters from the west and north-west.

Taking into account the fact that Poddębice GT-2 geothermal water intake is in the second phase of exploitation (beginning for heating purposes in 2013), it is suggested to maintain monitoring in the area proposed in "Hydrogeological documentation establishing exploitable resources of Poddębice GT-2 geothermal water intake" (Tadych et al., 2010), applicable for the first 3 years of exploitation, namely:

- once a quarter – water tests within the scope of small basic analysis,
- once a year – tests within the scope of complete analysis.

In order to check the so-far analyses of hydrochemical parameters of Lower Cretaceous reservoir waters, stemming from the recommendation of the previous project carried out with the use of EEA funds, titled: "Potential for the geothermal energy use in Poland – Poddębice Town" - Report from study visits (Kępińska et al., 2017), it was recommended to conduct a detailed physicochemical analysis of geothermal water. The analysis was conducted on 2 February 2017. Report from studies no. SPRI20/2017 does not specify intake conditions during water sample collection, i.e. flow size and water temperature at the outflow. It can be implied that during water sample collection (winter) intensive exploitation was run with discharge at the level of ca. 200 m^3/h, at temperature of 68-71°C. On the basis of the analysis, ion balance was done, covering major ion contents in geothermal water, and the results have been presented at the Udluft diagram (Fig. 5.4.1.7).

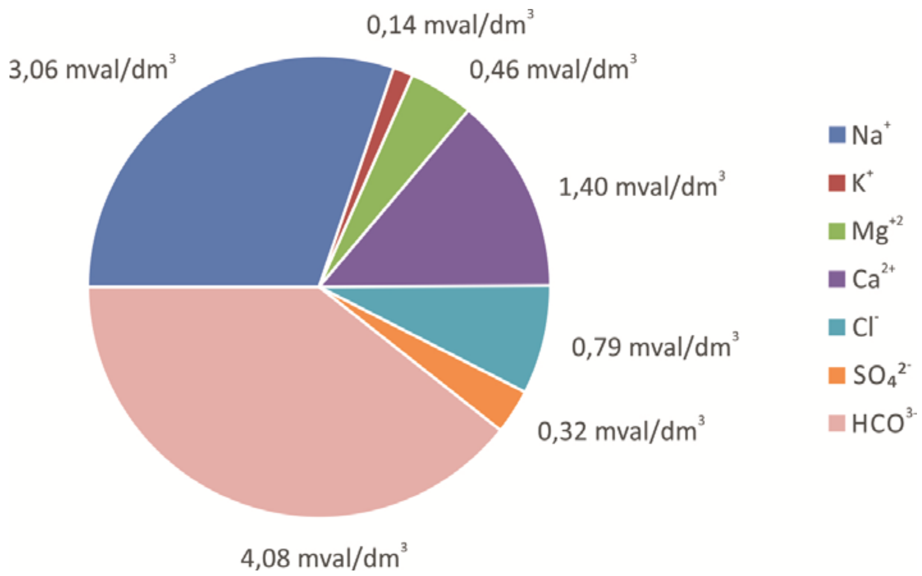


Fig. 5.4.1.7. Udluft pie chart of geothermal water from Poddębice GT-2 well, showing major ion contents (on the basis of the analysis of 1 February 2017)

The analysis confirms that these are HCO_3-Na-Ca type waters, with significant SiO_2 contents. Water from Poddębice GT-2 well shows also negligible iron, iodine and bromine ion content. A special value of water from Poddębice GT-2 well is high temperature of 68.4°C at the outflow and the original purity. Among anions, bicarbonates prevail (249.6 mg/dm^3 – calculated from CO_2), whereas among cations: sodium (70.3 mg/dm^3) and calcium (28.0 mg/dm^3), and metasilicic acid content is (38.1 mg/dm^3). From the beginning of physicochemical composition monitoring of water from Poddębice GT-2 well, no significant changes have occurred. In the light of percentage evaluation, changeability of particular components does not exceed 10%. The obtained results confirm stability of physicochemical composition of produced geothermal water.

A revised map of water mineralisation distribution regarding the Lower Cretaceous reservoir in the area of Poddębice, taking into consideration the results of hydrochemical analyses of water produced through Poddębice GT-2 well, has been presented in Fig. 5.4.1.8.

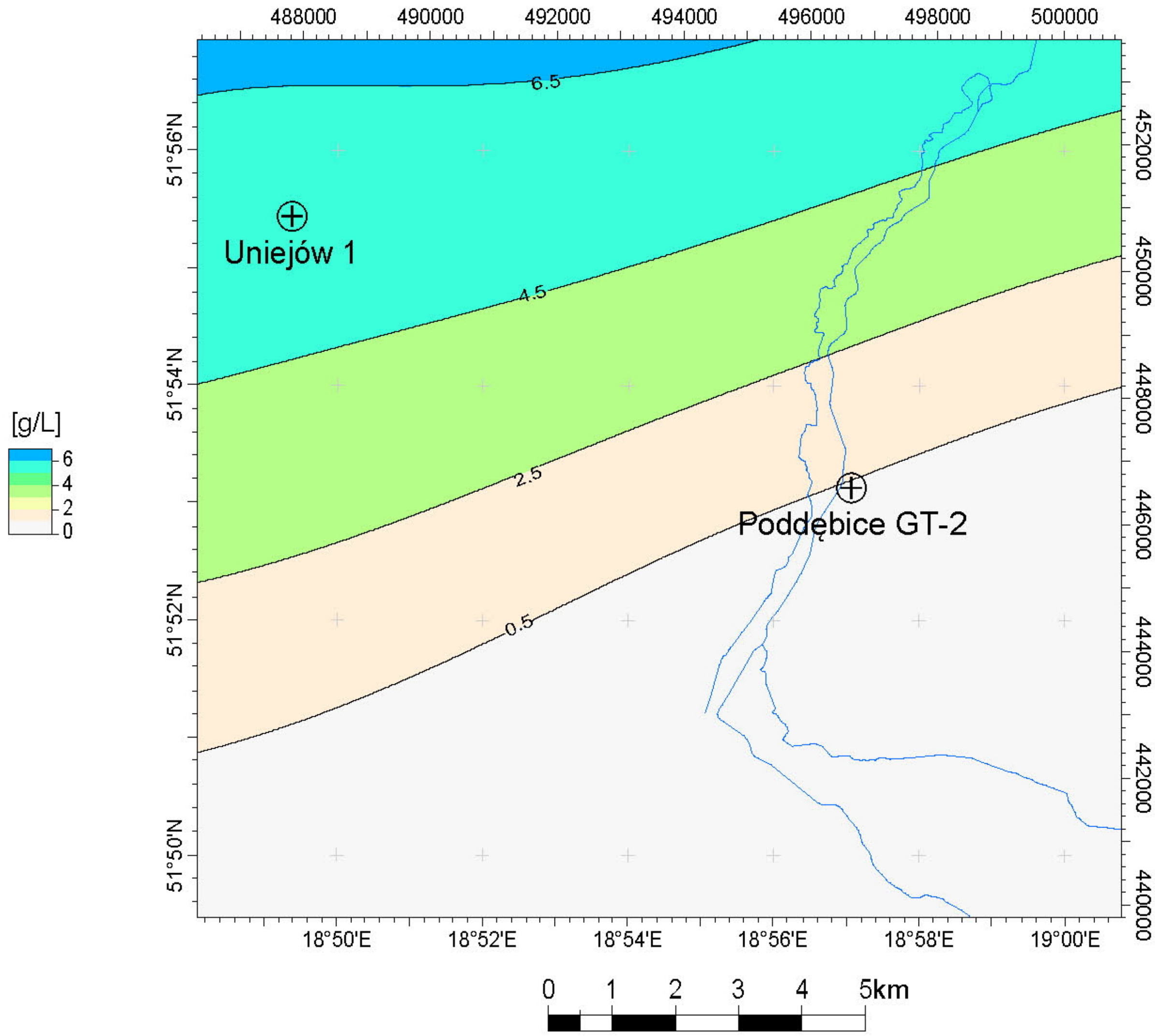


Fig. 5.4.1.8 Map of water mineralisation of the Lower Cretaceous reservoir in the area of Poddębice

Hydrochemical isses of the Poddebice GT-2 well fluid

The results of the chemical analysis of the sample 1047 collected from geothermal well GT-2 in Poddebice on February 2nd, 2017 (Table 5.4.1.3) was used to calculate the *in situ* composition at deep aquifer temperature, and the saturation state of the fluid with respect to some secondary minerals. The calculations were performed using 1) the WATCH geochemical speciation code (Arnórsson et al., 1982; Bjarnason, 2010); 2) PHREEQC Version 3 geochemical computer code (Parkhurst and Appelo, 1999) and the standard phreeqc.dat database.

The WATCH computer code is often used for simulations of high temperature geothermal waters (up to about 350°C), however it can also be applied for waters at much lower temperatures. The PHREEQC and its phreeqc.dat database is suitable for low salinity and moderate temperatures waters such as water from the GT-2. The PHREEQC computer code contains thermodynamic data for chemical species which are not included in WATCH database. It also predicts the saturation state of the fluid with respect to several other mineral phases not included in the WATCH. Both WATCH and PHREEQC code can simulate conductive cooling for investigating the dependence of the saturation state of fluid with respect to mineral phases on the temperature.

The results of speciation calculations indicate that the water is supersaturated with respect to calcite at temperature of about 70°C but this saturation decreases with decreasing temperature (Fig. 5.4.1.10). Drop of temperature below about 35°C will result in undersaturation of the fluid with respect to calcite. Note the close correspondence between WATCH and PHREEQC models which supports the outcome of simulation.

According to the results of the PHREEQC calculations the maximum amount of calcite possibly precipitated from the deep fluid at *in situ* temperature is 0.1766 mmoles per kilogram of water, corresponding to 18 milligrams of solid per each kilogram of water at 71°C. This amount decreases with decreasing temperature. This decrease is due to decreasing carbonate mineral saturation with decreasing temperature. Note that this simulation assumes that calcite will precipitate instantly when the water reaches saturation but kinetic rates of calcite precipitation are not taken into account. Therefore, the calculations may overestimate the amount of calcite precipitation.

The PHREEQC conductive cooling simulation reveals that at the deep fluid temperature of about 70°C the water is supersaturated with respect to other phases such as talc, goethite, aragonite and quartz (Fig. 5.4.1.10). As the temperature decreases (<55°C) water becomes supersaturated with respect to chalcedony which is the low temperature SiO_2 phase. In addition, the water becomes supersaturated with respect to clays (here exemplified by Ca-montmorillonite and kaolinite), and gibbsite at temperatures below 40-55°C. The water was undersaturated with respect to sulphides minerals based on H_2S concentration as indicated in Table 5.4.1.3.

Table 5.4.1.3. The chemical composition of fluid from well GT-2 in mg/dm^3

Location Site No.	**Poddebice GT-2 well**		
Date	**07.10.2013**		**02.02.2017**
Sample No.	HU-16/2015	5B/61819	1047
Temperature (°C)	67.7	60.1	71.0
Discharge (kg/s)	41.94	-	-
pH/(°C)	6.96/n.a.	7	7.6/20°C
CO_2	190.28*	248.85	180#
H_2S	<0.01		<0.050
SiO_2	19.18**		38.1#
Na	79.7	66.5	70.3
K	4.8	4.6	5.52
Mg	6.68	4.43	5.60
Ca	30.06	26.4	28.0
F	0.11	0.18	<0.20
Cl	27.65	23.3	28.0
Br	<0.05	<0.05	n.a.
SO_4	20.88	13.3	15.4
NO_3			<2.2
Dissolved O_2/(°C)			5.1/12°C
NH_3			0.020
Ag			<0.0010
Al	<0.01		<0.010
As	<0.01		<0.050
B			0.041
Cd	<0.003		<0.0004
Cr	<0.01		<0.0010
Cu	<0.01		<0.002
Fe	0.25	0.2	0.160
Hg			<0.000010
Mn		11.6	<0.05
Ni	<0.01		<0.0020
Pb	<0.01		<0.005
Zn	<0.01		0.0022
TDS	468.16	218.0	339.0
Conductivity (mS/cm)/(°C)	0.478	478/20	0.488/25

*measured as HCO_3, **measured as H_2SiO_3, #inserted as CO_2 and SiO_2 in WATCH and PHREEQC simulation

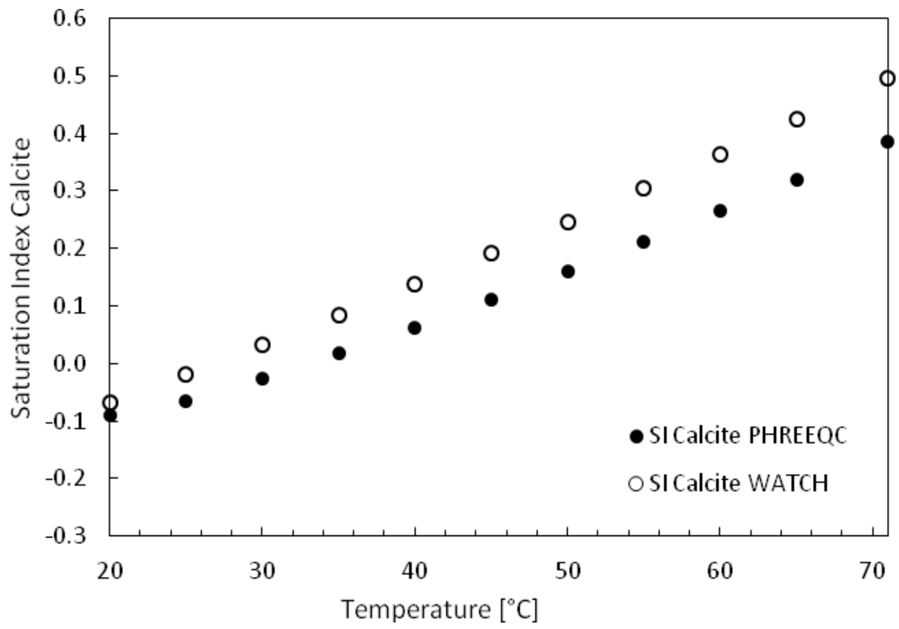


Fig. 5.4.1.9. The temperature dependence of the saturation state of the fluid with respect to calcite as calculated using WATCH and PHREEQC computer codes

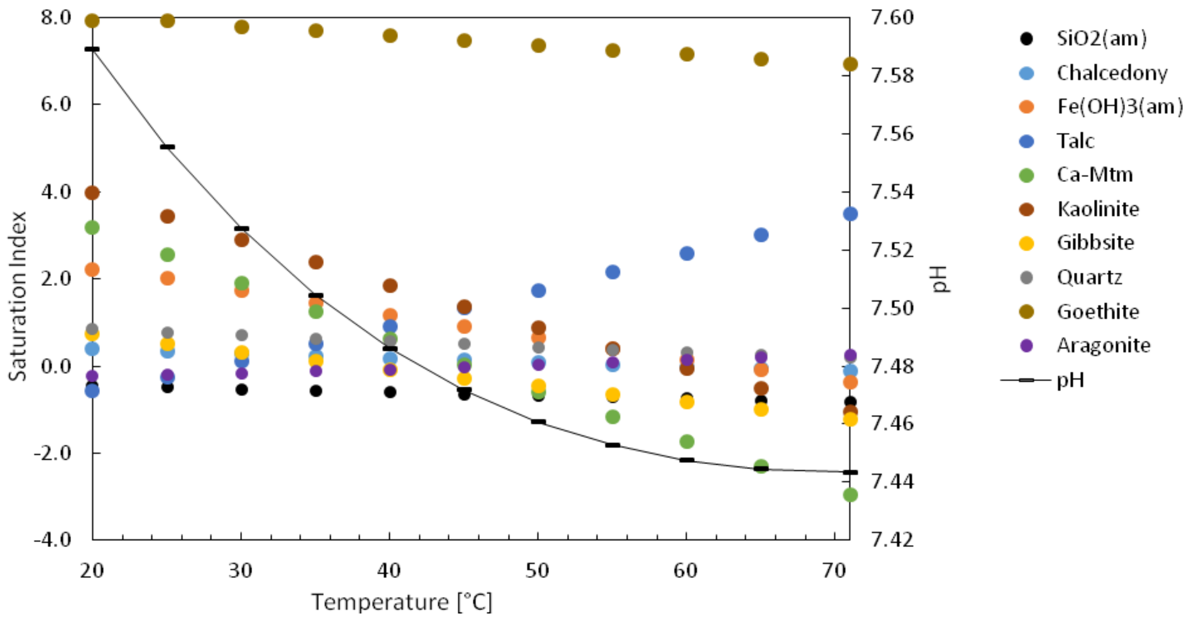


Fig. 5.4.1.10. The temperature dependence of the saturation state of the fluid with respect to calcite as calculated using PHREEQC computer code

The so called 'bubble point' calculations using WATCH reveals that degassing will proceed at pressures lower than 0.34 bars absolute. Because the partial pressure of CO_2 at all stages of cooling is higher than atmospheric it indicates that the dissolved CO_2 will diffuse from water at atmospheric conditions.

The concentration of toxic and heavy metals (As, Cd, Hg, Cr, Ni, Pb) are below quantification limits of the methods indicating negligible potential of harvesting the biological activity if this water would be discharged to the surface waters.

Chemical composition of 2017 sample is very similar to the composition of the sample collected in 2013 (Table 5.4.1.3). The difference between conductivity measured in both samples is 2%, wherease the differences between concentrations of Na, Ca, CO_2, Cl in both samples are 12%, 7%, 5%, and 1%, respecitvely. The concentrations of trace constiutents including heavy and toxic metals have not increased during this period. Both pH and SiO_2 concentration is higher in recent sample comparing to the previous one, however evaluation of the long term chemical composition trends is not possible at this stage. Note that only two complete chemical analysis are available.

Conclusions and recommendations

1. The results of 3D modelling of geological and petrophysical conditions throughout Mogilno-Łódź Syncline confirm also a complex geological structure in the area of Poddębice. Information coming from subsequent studies/drillings may constitute a significant contribution to the discussion on providing explanations of complex hydrogeological interdependencies, including those regarding water mineralisation and chemical composition distribution in the Lower Cretaceous reservoir in that area.
2. In the context of the plans to extend the system and increase production of about 45 GWh of heat per year, we maintain recommendations regarding the necessity to monitor hydrochemical composition of geothermal waters in the Lower Cretaceous reservoir through regular laboratory analyses.
3. It would be also advisable to consider development of a more advanced hydrogeological model of the Poddębice reservoir, using Visual Modflow or TOUGH software, and all available geological, hydrogeological information, as well as exploitation parameters and the like.
4. In case of heating system extension and an increase in the demand for geothermal water from the Lower Cretaceous reservoir, the necessity to drill the second production well and injection wells should be considered. It is important that, in the event of higher exploitation, the necessity to inject geothermal water to a geothermal reservoir should be considered, which would have an impact on exploitation parameters stability, including pressure and water level in the reservoir.
5. We maintain our recommendations regarding continuity of careful monitoring of exploitation parameters as well as periodic interpretation and simulations by means of Lumpfit program, especially in the event that the development of the geothermal network is planned, together with an increased demand for a stream of geothermal waters from the well up to ca. 250 m^3/h.
6. Although the geothermal water has very low concentrations of dissolved constituents comparing to other waters utilized for geothermal production it has the potential to produce some limited amount of calcite scaling at higher temperatures and some clays/oxyhydroxide/chalcedony precipitation at lower temperatures. Not that positive saturation index reveal only the theoretical potential for precipitation. Precipitation is often limited due to kinetic inhibition. The pH of the water sample is neutral/alkaline and therefore there is low risk of corrosion. At pressures higher than 0.34 bars there will be no degassing. Low toxic and heavy metal concentrations indicate limited effect on the biological activity if this water would be discharged to the surface waters. Comparing to other low temperature geothermal waters this fluid is good for utilization. The water chemical composition is similar to the composition of water collected in 2013 indicating no substantial changes of the aquifer fluid during recent years.

References:

Arnórsson, S., Sigurðsson, E. and Svavarsson, H. 1982: The chemistry of geothermal waters in Iceland. I. Calculation of aqueous speciation from 0°C to 350°C, Geochimica et Cosmochimica Acta, 46, 1513-1532.

Bjarnason, J.Ö., 2010: The speciation program WATCH, Version 2.4, user's guide. The Iceland Water Chemistry Group, Reykjavík, 9 pp., http://www.geothermal.is/software.

Dadlez R., Marek S., 1969: Styl strukturalny kompleksu cechsztyńsko-mezozoicznego na niektórych obszarach Niżu Polskiego. Kwart. Geol., T. 13, nr 3.

Kępińska B., Pająk L., Bujakowski W., Kasztelewicz A., Hajto M., Sowiżdżał A., Pétursson B., Tulinius H., Thorgilsson G., Einarsson Ó. P, Karska A., Peraj A., 2017: Geothermal utilization potential in Poland – the town of Poddębice. Technika Poszukiwań Geologicznych Geotermia, Zrównoważony Rozwój nr 1/2017.

Parkhurst, D.L., Appelo, C.A.J., 1999: User's guide to PHREEQC (Version 2) — a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. U.S. Geological Survey Water-Resources Investigations Report 99-4259, 312 pp.

Posyniak A., 2015: Dodatek nr 1 do „Dokumentacji hydrogeologicznej ustalającej zasoby eksploatacyjne ujęcia wód termalnych „Poddębice GT-2" z utworów kredy dolnej w miejscowości Poddębice". A. Posyniak. Warszawa. Luty 2015. Arch. Geotermia Poddębice Sp. z o.o. (Annex no. 1 to Hydrogeological documentation establishing exploitation reserves of thermal water intake "Poddębice GT-2" from Lower Cretaceous formation in Poddębice. A. Posyniak. Warszawa. February 2015. Archives Geothermal Poddębice Sp. z o.o.). In Polish.

Tadych J., Rasala M., Tadych A., 2010: Dokumentacja hydrogeologiczna ustalająca zasoby eksploatacyjne ujęcia wód termalnych „Poddębice GT-2" w miejscowości Poddębice. Thermhouse. Inowrocław. 2010. Arch. Geotermia Poddębice Sp. z o.o. (Hydrogeological documentation establishing exploitation reserves of thermal water intake "Poddębice GT-2" in Poddębice. Thermhouse. Inowrocław. 2010. Archives Geothermal Poddębice Sp. z o.o.). In Polish.

5.4.2. Current geothermal uses and development plans

5.4.2.1. Current state of geothermal energy use

In the vicinity of the town of Poddębice, the main geothermal reservoir consists of medium-grained Lower Cretaceous grey sandstones, which exhibit a relatively high porosity. The Lower Cretaceous reservoir was drilled through in late 2009/early 2010 with the Poddębice GT-2 well and is situated at depths ranging from 1,962 m b.g.l. (ceiling) to 2,063 m b.g.l. (floor). From a depth of 2,063 m b.g.l. down, impermeable Hauterivian formations were found which underlie Lower Cretaceous aquifers. The well ended at a depth of 2,101 m after drilling through the floor of Cretaceous formations (at a depth of 2,070 m) and the upper part of Jurassic formations.

After the drilling had been finished, tubing was installed in the 1,914.5–2,065.0 m interval, which was suspended on 9 5/8" casing pipes. The active portion of the Johnson screen was placed in the depth interval from 1,957 to 2,059 m b.g.l. The upper section of the tubing (1,957–1,964.0 m) was placed inside the 9 5/8" casing.

After the tubing and screen had been installed, the wellhead was installed on 13 3/8" pipes at the well opening (Fig. 5.4.2.1, Fig. 5.4.2.2). Geothermal water is under artesian pressure, with the static water table 26 m above the ground level. As concerns the mineralogical composition of sandstone, quartz dominates, accounting for 95% of total volume. Other ingredients that form grains include glauconite, feldspar and clayey minerals. The matrix is mostly silica.

Fig.5.4.2.1. Geothermal well heat „Poddebice GT-2"

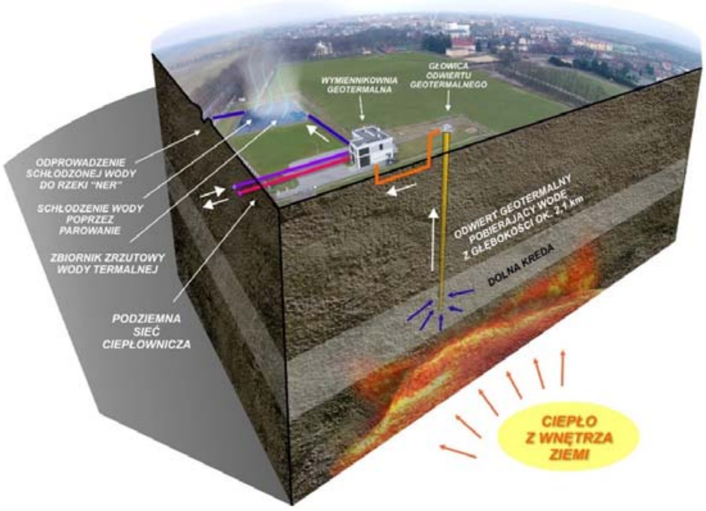


Fig.5.4.2.2. Scheme of abstraction geothermal energy and district heating network in Poddębice

The exploitable resources approved for the Poddębice GT-2 well have been determined at Q=252m^3/h, with an operating water level of 85.3 m b.g.l. The geothermal water temperature measured at the wellhead is 68.4°C. The mining terrain and mining area are identical and equal to the licensed area of 7.18 km^2. At the initial stage of geothermal water extraction, the well was operated at artesian pressure, which, given the present well screening, allows for an average output of 116.5 m^3/h of water (which covers the summer demand for heat from the customers connected to the geothermal district heating network). In the winter, the well is operated using a pump unit, which allows for an output of up to 252 m^3/h. The pump unit is situated at a depth of around 90 metres, using Eco Connect stainless steel pumping tubes.

The extraction of geothermal water using the pump enables the town to be heated using geothermal energy during the winter season. Geothermal heat sales are presented in the Table 5.4.2.1.

Table 5.4.2.1. Geothermal heat sales since February 2013 – June 2017

Year	Heat sales [GJ/y]
2013	15 002
2014	39 733
2015	47 277
1st half 2-17	56 470
	36 149

Calculations concerning the environmental effect obtained that were conducted after commissioning the geothermal heat exchange plant demonstrate that air pollutant emissions in Poddębice were reduced as follows:

– dust – by 6.3 tonnes/year;
– sulphur dioxide (SO_2) – by 6.2 tonnes/year;
– nitric oxides (NOx) – by 4.4 tonnes/year;
– carbon monoxide (CO) – by 54.7 tonnes/year;
– carbon dioxide (CO_2) – by 4,297.6 tonnes/year.

Within the framework of the “Geothermal Energy Use Potential in Poland – the Town of Poddębice” EEA project, on the basis of the 2016 geothermal heat sales of 56,470 GJ reported by Geotermia Poddębice Sp. z o.o. [limited liability company], the environmental effect was estimated (expressed as the aggregated values of pollution reduced/avoided as a result of the replacement of hard coal with geothermal heat). This effect was estimated as follows: CO_2: 5,500 tonnes; CO: 25.8 tonnes; SOx: 42.1 tonnes; TSP (total suspended particles): 25.8 tonnes; NOx: 8.3 tonnes.

The current geothermal capacity of Geotermia Poddębice does not exceed 5 MW (geothermal water – heat exchangers) (Fig. 5.4.2.3). The heat tariff for the commissioning period approved by the Mayor of Poddębice includes two tariff groups:

– tariff group A: capacity ordered = PLN 0.00/MW, heat = PLN 38.85/GJ net;
– tariff group B: capacity ordered = PLN 7,345.5/MW, heat = PLN 40.00/GJ net.

Fig. 5.4.2.3. Geothermal heating plant – two heat exchangers a power of 5 MW each

Przedsiębiorstwo Usług Komunalnych w Poddębicach Sp. z o.o. (PUK) [utility operator], a Group B entity to which Geotermia provides geothermal heat, develops its own heat tariffs. This utility operator distributes around 80% of the heat purchased from Geotermia Poddębice Sp. z o.o. In the current year, the Poddębice Municipality, which is the owner of the Company, will transfer three boiler rooms and district heating networks that have been managed by PUK to date for use in the Geotermia district heating system. This may result in a change in the thermal capacity of Geotermia.

In 2017, Geotermia Poddębice Sp. z o.o. will draw up an application to the Energy Regulatory Office concerning the issuance of a licence for the production and distribution of heat. The company is also developing input data for a new heat tariff (which tariff will be subject to approval by the Energy Regulatory Office).

In 2015, a functional programme entitled "Construction of the second geothermal water heat recovery stage combined with the construction of district heating networks with connections and heat distribution centres for the town of Poddębice" was developed. This involves the extension of the district heating network and the use of a heat recovery technology as well as a more rational use of geothermal energy. Under the programme, 1,050 buildings may be connected to the geothermal district heating network. More than 33 km of distribution networks and connections need to be built and a heat source with a capacity of 14 MWt is required.

The team that developed the programme has proposed an investment project for the next few years that would cover 52% of all residential areas within the town limits that can be connected to geothermal heating.

The second functional-utility programme is entitled "Land without Barriers – a hydrotherapy and recreation centre in Poddębice using thermal water. Adapting the infrastructure of the centre for sports, tourism and recreation". The programme includes the extension of the seasonal pool complex to enable its use in winter as well, using modern technologies for the supply and circulation of thermal water for recreational and rehabilitation purposes as well as the heating of swimming pools, technical and accompanying facilities (catering, accommodation). The purpose of the programme is to broaden access to geothermal recreation for people with disabilities. This would be the first facility of this kind in Poland. Efforts have been undertaken to raise funds for the implementation of this programme.

The exceptional quality of thermal water from the Poddębice GT-2 well should be stressed. This water is characterised by "primary purity" and low mineral content, which allows its direct use without any treatment for rehabilitation procedures. Patients in Poddębickie Centrum Zdrowia Sp. z o.o. [health centre] use these procedures; the health centre has specialist rehabilitation staff and excellent premises at the local hospital. The Social Security Institution also offers rehabilitation stays there. Patients benefit not only from rehabilitation procedures, but also from bathing in the pools. Thermal water from Poddębice is suitable for use in rehabilitation following traumatic and orthopedic injuries and also in the treatment of skin diseases, since it contains valuable silicon compounds.

5.4.2.2. Geotermia Poddębice development plan for the years 2017-2020

I. ENERGY

A. Heat sources

1. Construction of tank No. 2 for cooling geothermal water

Until cooled thermal water can be used for other purposes as indicated further in the plan, additional amounts of geothermal water will need to be cooled when the output increases from 190 m^3/h to 252 m^3/h. For this purpose, tank No. 2 must be built with a capacity of around 1,500 m^3 plus a two-stage overflow with a length of 9 m and a width of 50 m (Fig. 5.4.2.4). As at the date of report preparation, the facility is being readied for final acceptance. The use of the tank will require a use permit. In the near future, Geotermia Poddębice will apply to the District Mining Authority for the necessary permit.

Fig. 5.4.2.4. Tank No. 2 for cooling geothermal water

2. Adapting three peak load/reserve boiler rooms for efficient interoperation with the geothermal plant

In the event of prolonged periods with low ambient temperatures (below -10°C) in winter, a peak source must be used since the temperature of thermal water from the Poddębice GT-2 well is slightly too low. At present, the peak source consists of three local boiler rooms, which require upgrades. Upgrade work will include:

a) C-4 boiler room – the replacement of two briquette-fired boilers with a total capacity of 1 MW with a single oil-fired boiler with a capacity of 1 MW, including an upgrade of the internal installation. Implementation schedule: buffer tank replacement in 2017, the replacement of boilers and the upgrade of the technological installation including the extension of the heat exchanger in 2018.

b) Z-14 boiler room: the replacement of gas burners with oil burners in two gas boilers with a total capacity of 1 MW, including the oil installation. Implementation schedule: 2017. The removal of one briquette-fired boiler with a capacity of 1 MW and the construction of a heat distribution centre (a plate heat exchanger with a capacity of 3 MW) separating the transmission system from the distribution system together with the internal installation. Implementation schedule: 2018.

c) K-15 boiler room: the replacement of three burners (two gas burners and one gas/oil burner) with oil burners in gas-fired boilers with a total capacity of 3.36 MW. Implementation schedule: 2018.

- Node No. 1, Krasickiego 15 – the installation of a heat distribution centre (dual-function plate heat exchanger) – 2018;
- Node No. 2, Krasickiego 9 – the installation of a heat distribution centre (dual-function plate heat exchanger);
- Node No. 3, Krasickiego 1a – the installation of a heat distribution centre (dual-function plate heat exchanger);

Node upgrade schedule – 2018/2019.

3. Purchase and installation of a generator set with a capacity of ca. 200 kW

In order to maintain continuous heat production, a continuous electricity supply must be ensured. To this end, a generator set needs to be purchased as a reserve electricity source, although no power supply interruptions have been recorded in the past. However, with the aim of ensuring energy security and providing residents with “clean” geothermal heat, the investment expenditure related to the purchase of a generator set must be made. The planned implementation schedule is until the end of 2017.

4. Extension of the geothermal heat plant to include a second geothermal water heat recovery stage

Under this task, the geothermal heat plant is to be extended by a heat pump, which will enable the extraction of additional energy from geothermal water after the first heat recovery stage (plate heat exchangers), i.e. lowering its temperature from around 50°C to around 35°C; the task may also include the increase in feed water temperature using a gas/oil-fired boiler to heat the water supplied to the heat pump. In order to carry out the extension, a technical design will have to be developed covering the technology to be used and the extension of the heat exchanger building (Fig. 5.4.2.5). As concerns the adoption of an advantageous technological solution, Geotermia plans to rely on Icelandic and Norwegian standards. Implementation schedule: 2018/2019

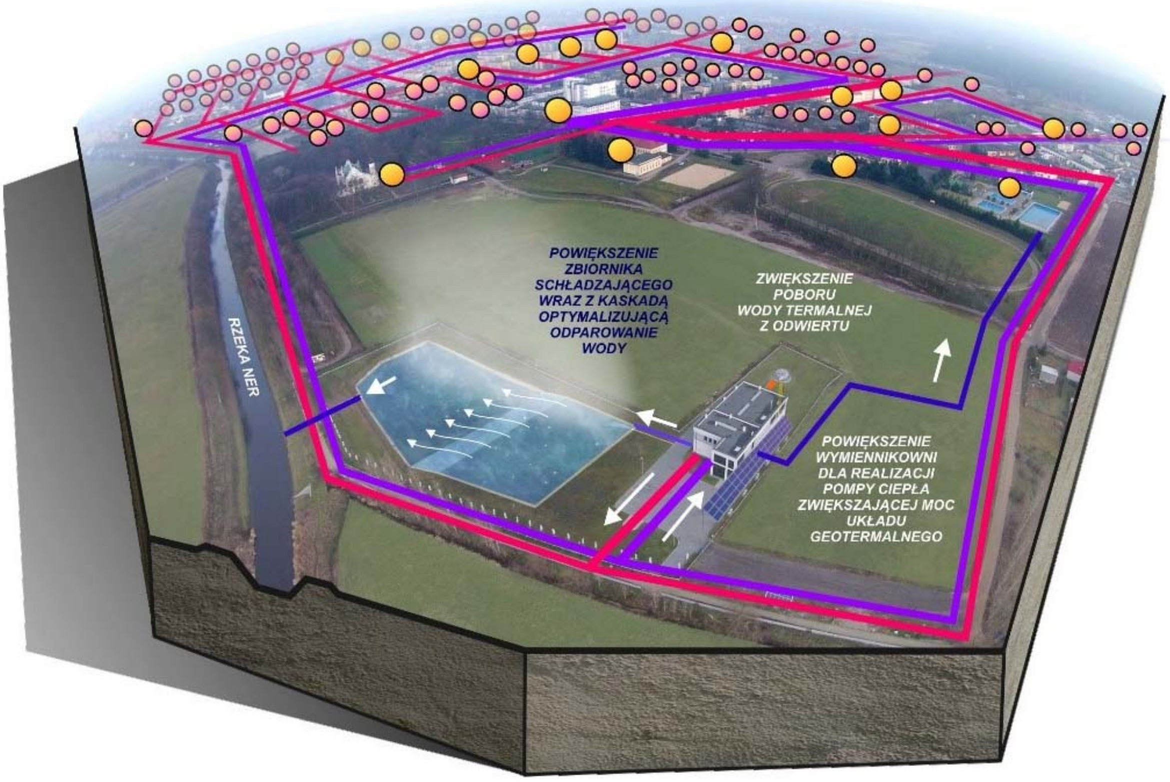


Fig. 5.4.2.5. Visualization geothermal heating network – stage II

B. District heating networks

Extension of the geothermal district heating network with customer connections and heat distribution centres.

Promoting the possibility of producing heat from geothermal energy and leveraging the residents’ interest in using “clean energy”, Geotermia Poddębice held meetings with residents of several housing estates and is looking for funding to finance pilot district heating network sections and connections (Fig. 5.4.2.6). In order to reduce low-stack emissions, expansion is planned in the following areas:

1. Dojazd housing estate in Poddębice – 24 flats in two one-story buildings with a total capacity of about 150 kW. Implementation schedule: 2018

2. Byczyna settlement – around 10 single-family houses with a total capacity of about 200 kW. Implementation schedule:

2018:

3. Reja housing estate in Poddębice – 63 residential buildings, planned capacity: 700 kW. Implementation schedule: 2019/2020

4. Spokojna, Radosna and Miła streets – around 10 single-family houses and the “MOŻ-MED” health centre with a total capacity of about 300 kW. Implementation schedule: 2018/2019

5. Connection for ZOO Safari in Borysew in order to provide heating to the planned “Biały Lew” hotel Implementation schedule: 2017/2018.

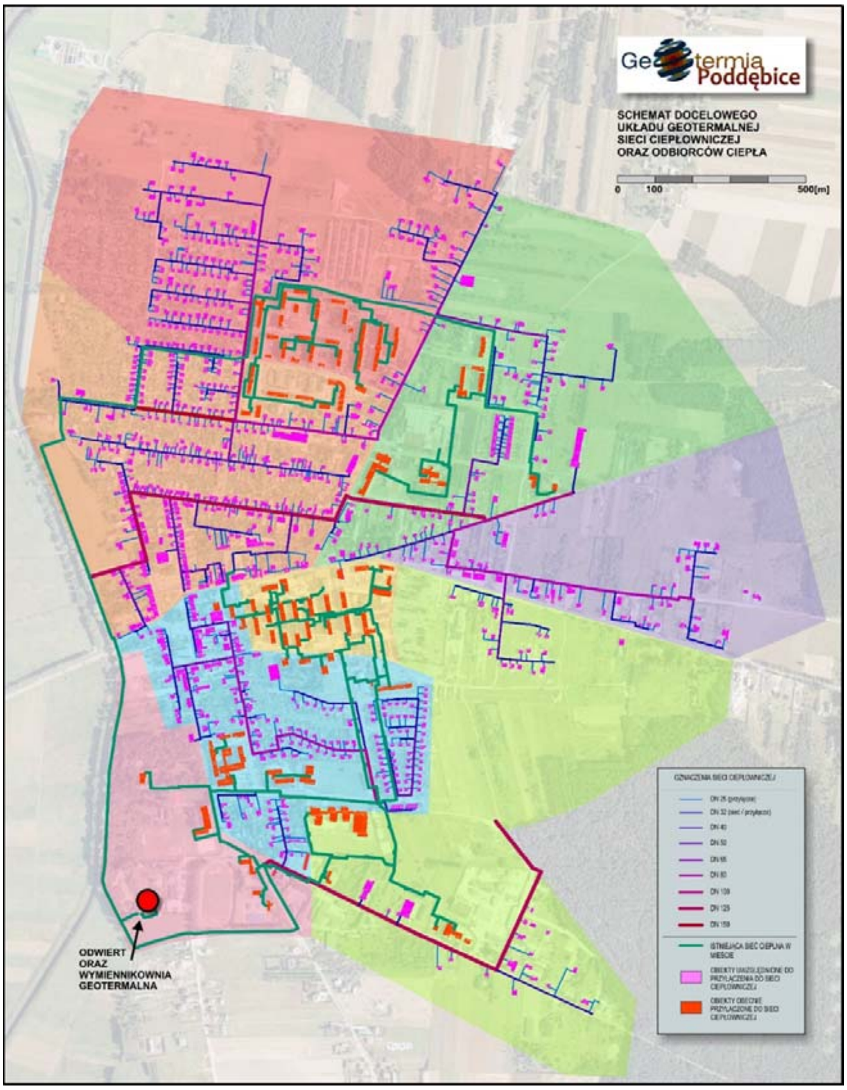


Fig. 5.4.2.6. Scheme of the target system geothermal heating network and heat recipients

II. FOR DRINKING CONSUMPTION PURPOSES

Along the geothermal heat pipeline used to provide heat to housing estates and public buildings in the town of Poddębice, a raw geothermal water pipeline was constructed that leads to the Municipal Water Supply and Sewerage Company in Poddębice. After it has been cooled down to below 20°C (e.g. using a graduation tower and a heat pump), the thermal water from Poddębice could potentially be treated and pumped into the municipal water network for human consumption. Tests and trials in this area are ongoing and conversations are being held with a partner in order to determine the prospective location of the graduation tower. Implementation schedule: 2018/2019.

III. FOR COSMETICS PURPOSES

The use of thermal water from the Poddębice GT-2 well for the production of cosmetics and dermocosmetics. Expanding cooperation with the BIOGENED company and Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (PAS MEERI) in order to conduct a broad spectrum of physical and chemical tests (Fig. 5.4.2.7). Implementation schedule: 2018/2019.

Fig. 5.4.2.7.Signing a cooperation agreement between Geotermia Poddebice Ltd. and Biogened inc. in the production of cosmetics based on geothermal water – December 2016

IV. FOR ANIMAL BREEDING PURPOSES

1. Animal breeding at ZOO Safari Borysew (crocodiles and other animals from the Mediterranean and African climate zones). Implementation schedule: 2018/2019 (Fig. 5.4.2.8).
2. Breeding fish or algae using experience from Iceland and Poland. Market research and preparing design assumptions. Implementation schedule: 2018/2019.

Fig. 5.4.2.8.ZOO Safari in Borysew close to Poddebice town

V. FOR PLANT GROWING PURPOSES

1. Preparing the installation and determining the location of a pilot greenhouse facility for the cultivation of thermophilic plants using cooled thermal water (Fig. 5.4.2.9). Implementation schedule: 2019
2. Greenhouse construction. Implementation schedule: 2020

Fig. 5.4.2.9. Example of algae cultivation

VI. FOR RECREATION AND TOURISM PURPOSES

Closer cooperation with the Poddębice Municipality in order to improve the technical and catering facilities and shared spaces of the thermal pool complex and to upgrade the existing pools.
Another option for using thermal water will be to use it within the thermal pool complex designed under the functional and utility programme (Fig. 5.4.2.10). This project was entitled: "Fighting Exclusion – Land without Barriers in Poddębice – the Revitalisation of the Geothermal Complex". The project envisages the construction of a geothermal pool complex open all year round, which will cater to users of all ages, including the disabled and elderly for whom special facilities have been designed. The project owner is the Poddębice Municipality.

Fig. 5.4.2.10. Geothermal swimmingpools in Poddebice

VII. WITH RESPECT TO THE GEOTERHMAL WELL

In cooperation with the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (PAS MEERI) and a partner from Iceland, the reservoir will be modelled using a simple lumped parameter model. In cooperation with the AGH University of Science and Technology, a model of the aquifer from which geothermal water is extracted using the Poddębice GT-2 well will be developed.

References:

Kępińska B., Hajto M., Petursson B., Einarsson Ó.P., Pająk L., Tulinius H., Þorgilsson G., Axelsson G., Gudmundsson J.R., Karska A., Peraj A., Sęczkowski P., Bujakowski W., Kasztelewicz A., Sowiżdżał A., Papiernik B., Miecznik M., Tomaszewska B., Bielec B., 2017: Potencjał dla wykorzystania energii geotermalnej w Polsce – miasto Poddębice. Raport z wizyt studyjnych [Potential for the use of geothermal energy in Poland – the town of Poddębice. Report from study visits]. Kraków-Reykjavik (www.eeagrants.agh.edu.pl).

Posyniak A., 2015: Dodatek nr 1 do „Dokumentacji hydrogeologicznej ustalającej zasoby eksploatacyjne ujęcia wód termalnych „Poddębice GT-2" z utworów kredy dolnej w miejscowości Poddębice" [Addendum No. 1 to the hydrogeological documentation determining exploitable resources of the Poddębice GT-2 well extracting thermal waters from Lower Cretaceous formations in the town of Poddębice]. Warszawa, Archives of Geotermia Poddębice Sp. z o.o.

Thermhouse, 2010: Dokumentacja hydrogeologiczna ustalająca zasoby eksploatacyjne ujęcia wód termalnych „Poddębice GT-2" w miejscowości Poddębice [Hydrogeological documentation determining exploitable resources of the Poddębice GT-2 well extracting thermal waters from Lower Cretaceous formations in the town of Poddębice]. Inowrocław, Archives of Geotermia Poddębice Sp. z o.o.

Low-carbon economy plan for the Poddębice Municipality. Resolution of the Town Council in Poddębice No. XXXI/204/16 of 28 October 2016.

www.eeagrants.agh.edu.pl

5.4.3. Analysis and proposal for heat pump in geoDH in Poddębice

Available resources

Assumptions concerning the geothermal parameters (Kępińska et al., 2017a):

- aquifer level: Lower Cretaceous
- borehole depth:2,101 m under the ground level
- assumed maximum water flow rate: 252 m^3/h
- assumed temperature of geothermal water in the deposit: 73°C
- water represents low mineralisation allowing for a single-well operation. Cooled water can be reused, e.g. as potable water (similarly to the system used in Mszczonów).

Existing infrastructure

The existing district heating network operates at full (quantitative and qualitative) control, providing the heating power delivered, design parameters for central heating (supply-return-external temperature-calculated external temperature:) 90/70/20/-20°C and for the hot utility water (in the summer) (supply-return:) 65/45°C.

Presently, the heating needs are satisfied by the existing geothermal installation and 3 boilers of which one is biomass-fired boiler and the other two use heating oil. The total thermal capacity installed is ca. 10 MW (7 MW from the geothermal system and ca. 3 MW from the peak heat demand boilers).The maximum capacity that is realistically used, estimated on the basis of measured data can stay at 5.5 MW: the operation monitoring data of 2015 and 2016 state that, at the external temperature of -10°C, the demand for capacity amounts to ca. 4 MW (Kępińska et al., 2017b).The total thermal energy generated by various energy source is estimated at ~50 - 55 TJ/y (Kępińska et al., 2017).Consequently, the maximum capacity used, estimated on the basis of the quantity of energy generated by a source, can be estimated at ca. 6.5 MW.

Method of use

With reference to the Operator's assumption (Geotermia Poddębice Sp. z o.o.) geothermal plant should be based on a geothermal well supported by heat pumps. The type of the heat pump has not been clearly determined yet. It could be a compression or absorption type. It is expected that the ordered capacity from the district heating system will be increased within several years, owing to the connection of additional customers, e.g. the following:

- municipal housing (council housing): connection of new customers will cause an increase of the maximum ordered capacity by ca. 12 MW,
- a swimming-pool complex, that is presently undergoing a modernisation and expansion project, will cause an increase of the maximum ordered capacity by ca. 1,100 kW in winter and 1,500 kW in summer,
- additional facilities in the Borysew ZOO, including new buildings (estimated at ca. 600 kW) and external pools for animals (ca. 6,000 $m^2$of water-mirror surface area).

Energy source model

The first step in the determination of the effects of using an energy source consists in the determination of the customer's profile. That profile will decide about the type of heating installation: its design parameters and local climatic conditions. The climatic conditions have been described on the basis of typical meteorological years, recommended by the Polish Ministry of Infrastructure and Building for making power calculations. The closest meteorological station is located in Łódź (coordinates: 51.7500000 N, 19.4666667 E).Fig. 5.4.3.1 presents the air temperature and wind speed distribution for that meteorological station. The parameter distribution showed on the graphs are shown in the increasing order after air temperature. The lowest temperature, oryginally recorded in the specific meteorological years was –12.5°C. The Polish Standard (PN-EN 12831) recommends the use of the external calculation temperature for the zone in which Poddębice is located: –20°C. Consequently, the original file of the "Typical meteorological years" the temperature of -12.5°C was replaced by that recommended by the Polish Standard. The graph accounts for that change.

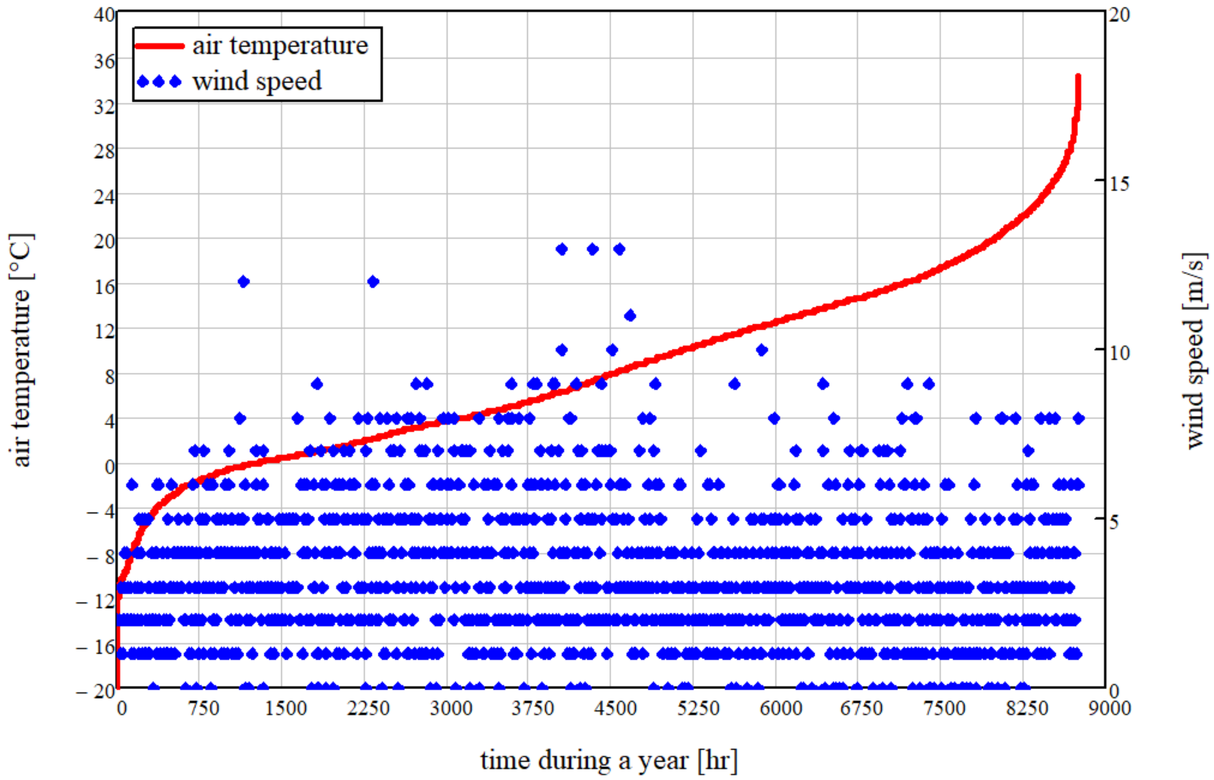


Fig. 5.4.3.1. Local weather conditions for the meteorological station in Łódź (MIiB 2017)

Figs. 5.4.3.2-5.4.3.5 present the thermal characteristics of a model customer presently supplied from the district heating network of Poddębice

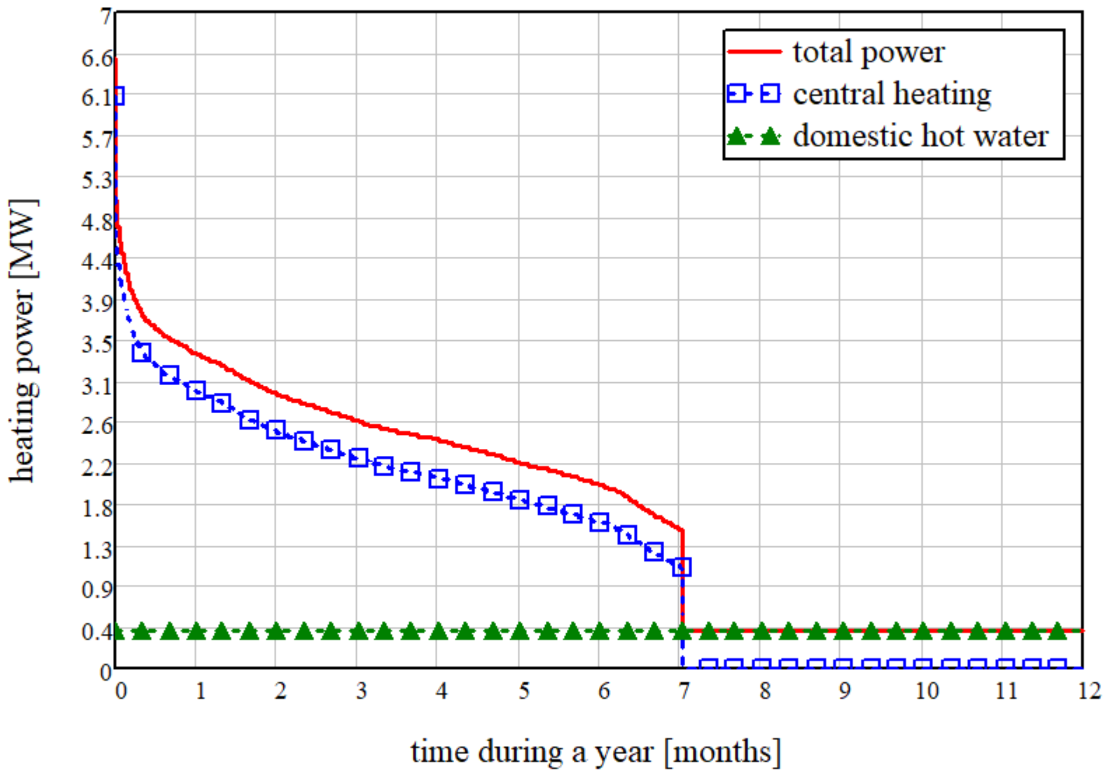


Fig. 5.4.3.2. Characteristics of the thermal power demand for the customer being currently served vs. time

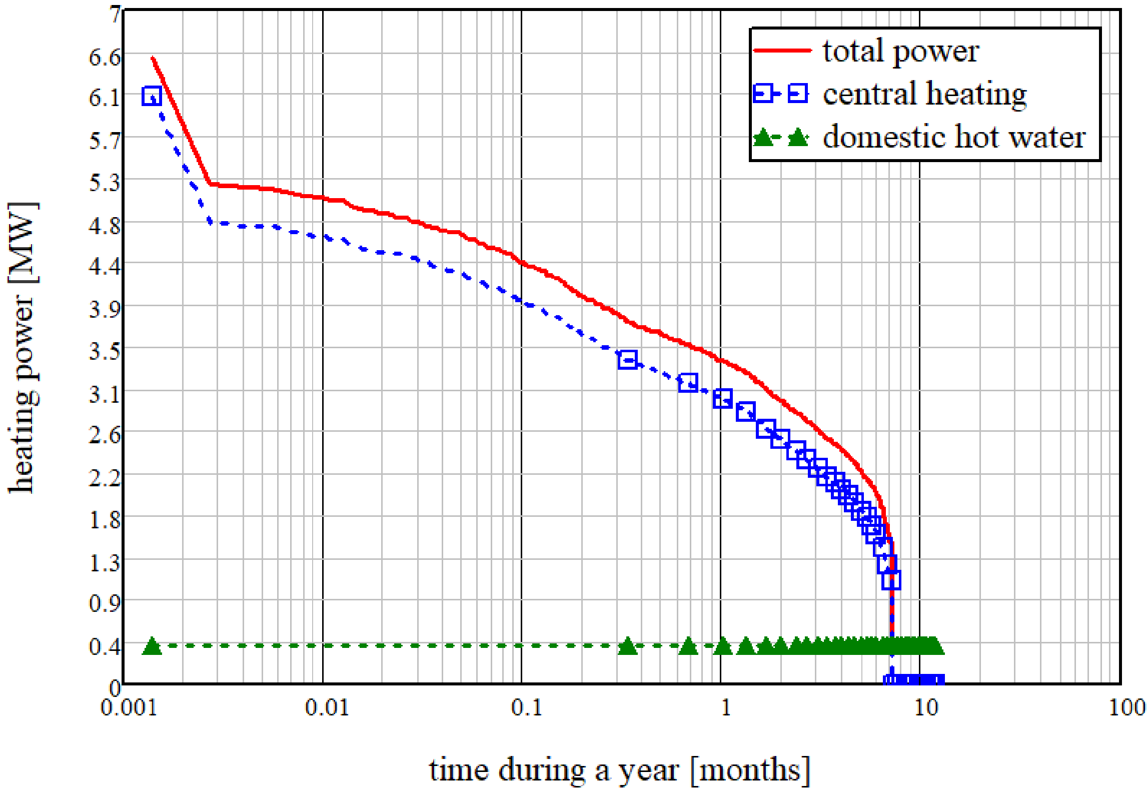


Fig. 5.4.3.3. Characteristics of the instantaneous power demand for the customer being currently served, as a function of time – logarithmic scale

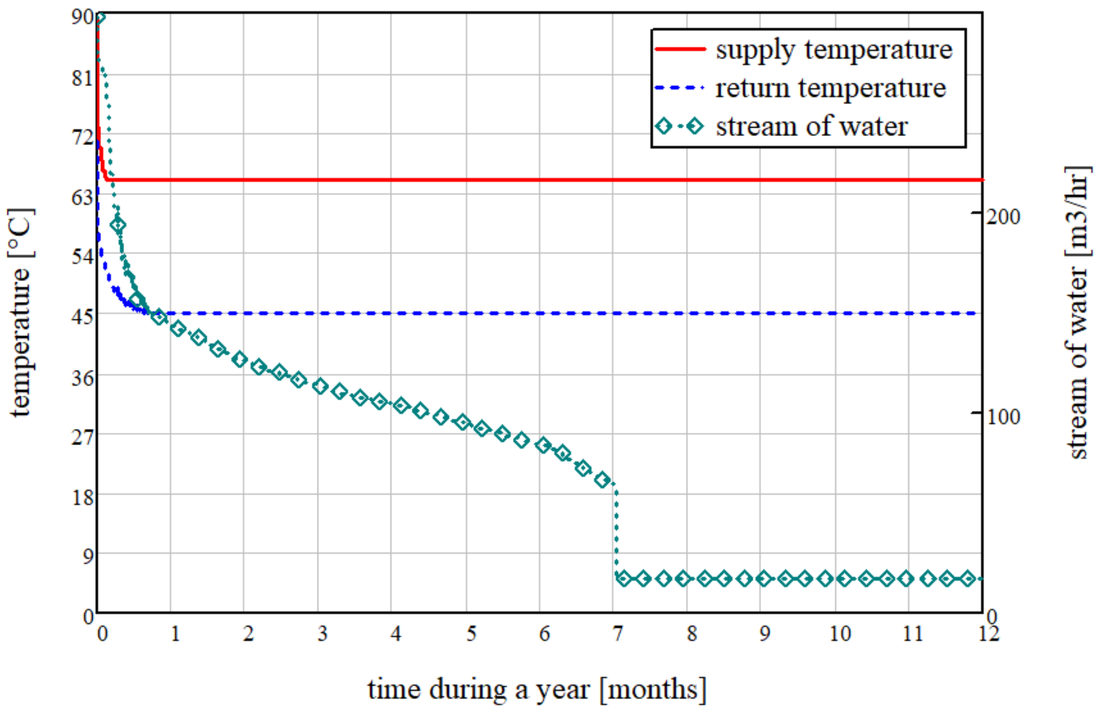


Fig. 5.4.3.4. Dynamic characteristics of the variation of the required flow temperature and the flow of the working fluid, as well as the return temperature obtained, for the customer being currently served by the system

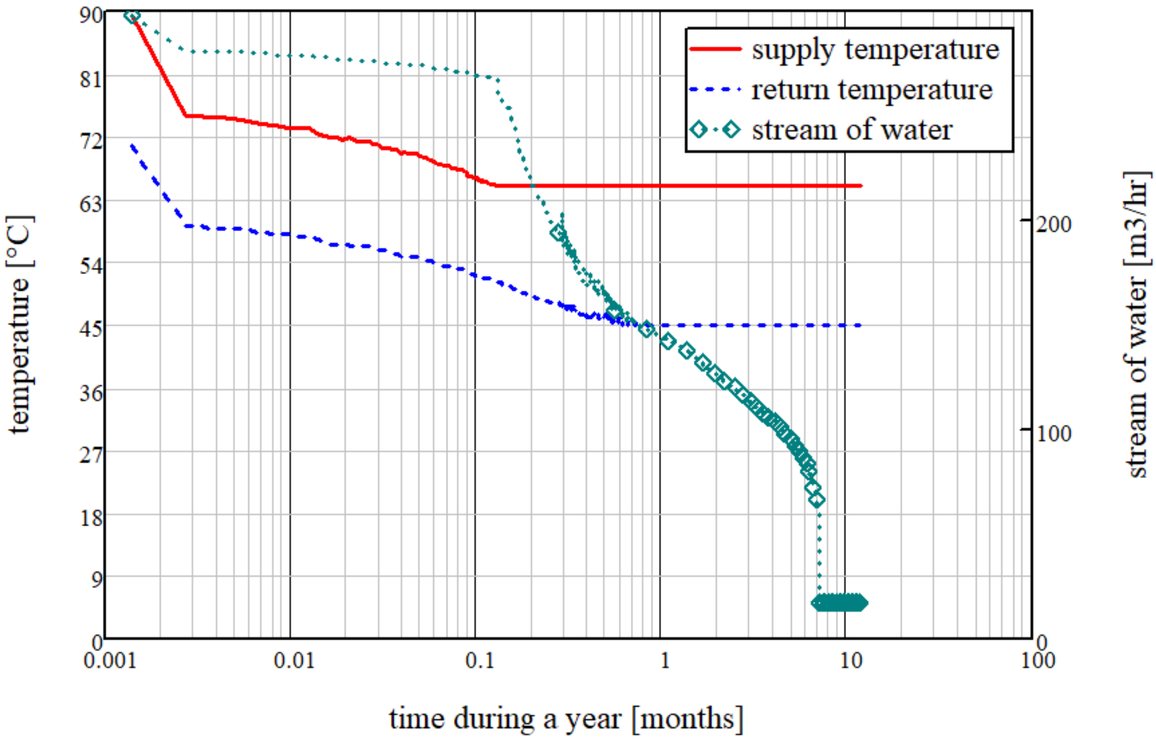


Fig. 5.4.3.5. Dynamic characteristics of the variation of the required flow temperature and the flow of the working fluid, as well as the return temperature obtained, for the customer being currently served by the system – logarithmic scale

Based on the above-described assumptions of the district heating system development, the target customer profile was drafted and presented on Figs. 5.4.3.6–5.4.3.9.It was assumed that the installation supply temperature control depended only on air temperature. The characteristics presented on the graphs are shown in a decreasing after total capacity demand. Owing to the fact that the total capacity demand by the outdoor swimming pools strongly depends on wind speed and air humidity, the temperature demand curves and the return temperature obtained curves (Figs. 5.4.3.8 and 5.4.3.9)display certain distortions. Those result from the fact that air temperature was relatively low in the specific periods, while the capacity demand was not significant because of high air humidity and low wind speed. That results in low demand for heating energy. Non-standard working temperature values concern outdoor swimming pools.

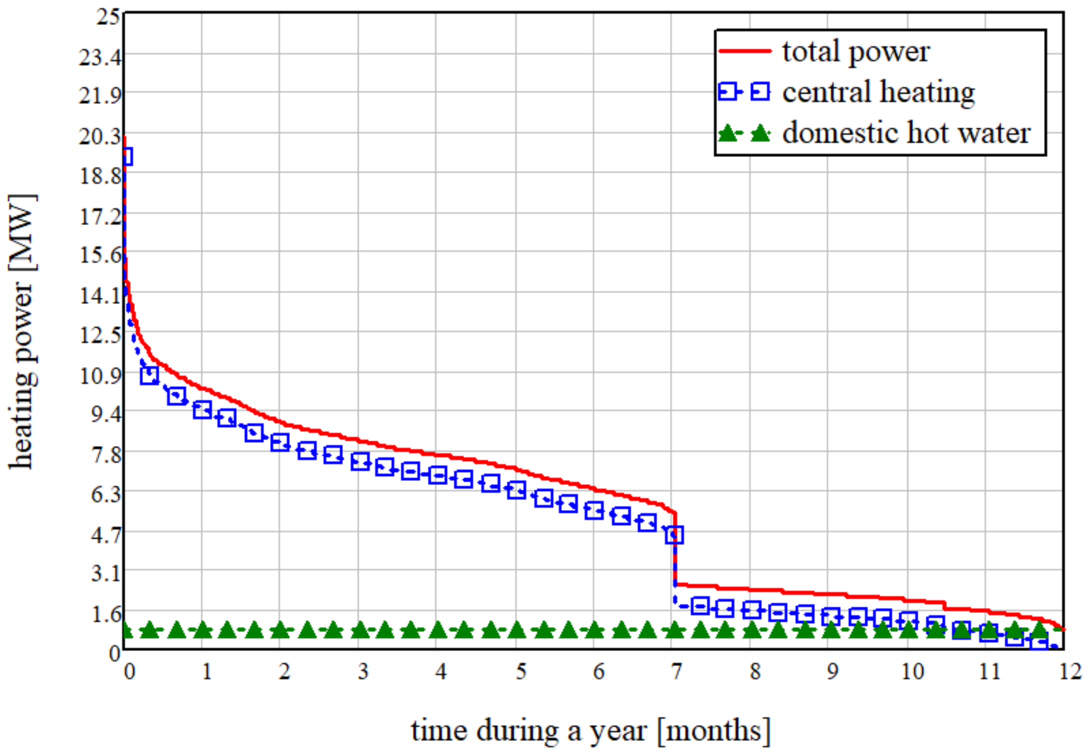


Fig. 5.4.3.6. Dynamic characteristics of the variation of the required flow temperature and the flow of the working fluid, as well as the return temperature obtained, for an "extended customer"

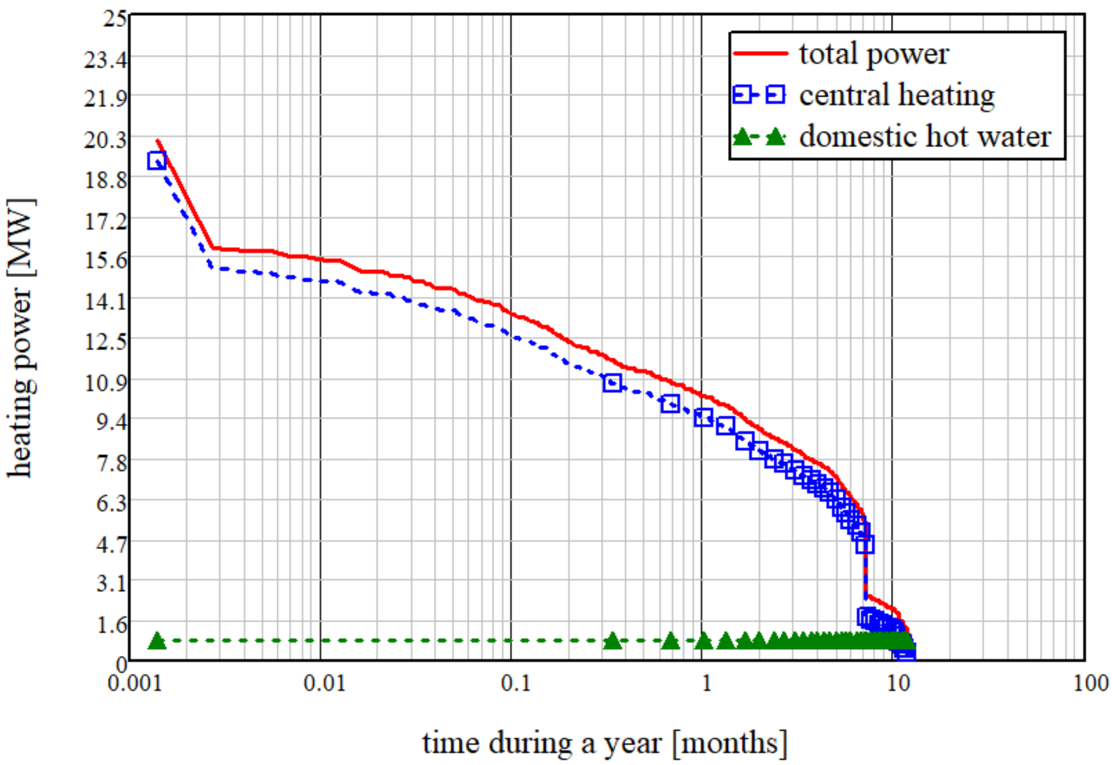


Fig. 5.4.3.7. Dynamic characteristics of the variation of the required flow temperature and the flow of the working fluid, as well as the return temperature obtained, for an "extended customer" – logarithmic scale

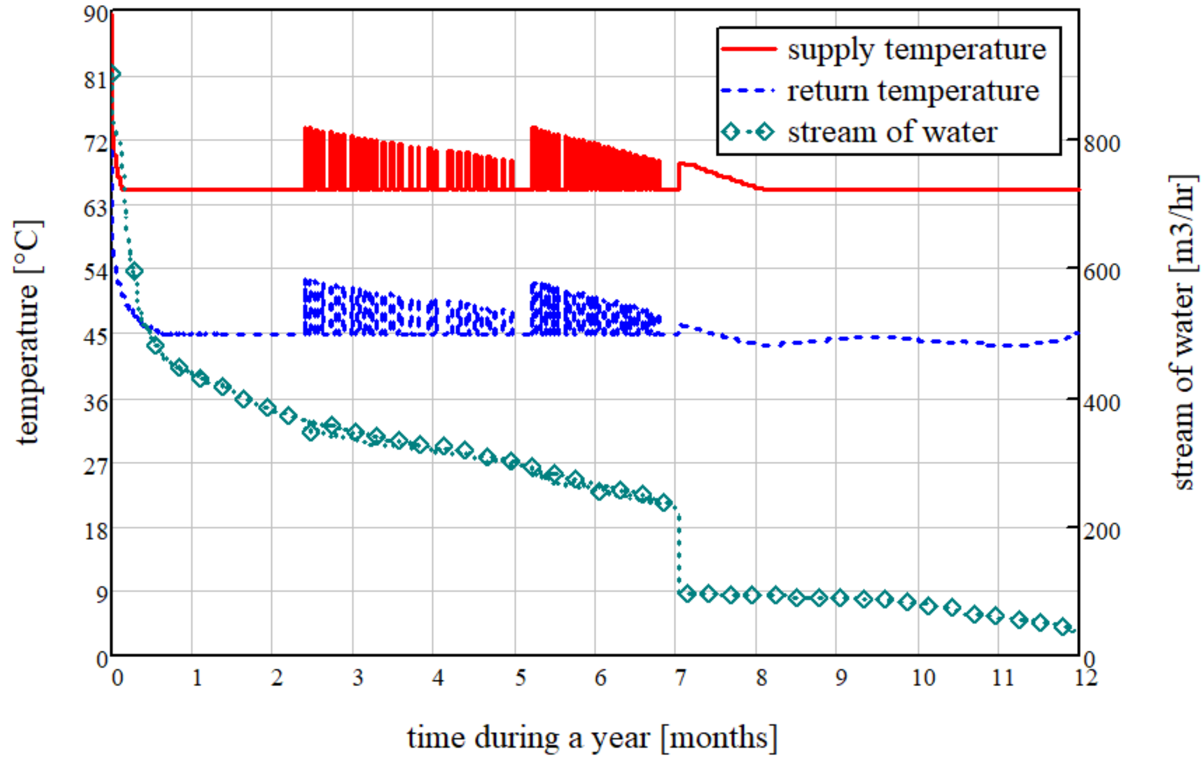


Fig. 5.4.3.8. Dynamic characteristics of the variation of the required flow temperature and the flow of the working fluid, as well as the return temperature obtained, for an "extended customer"

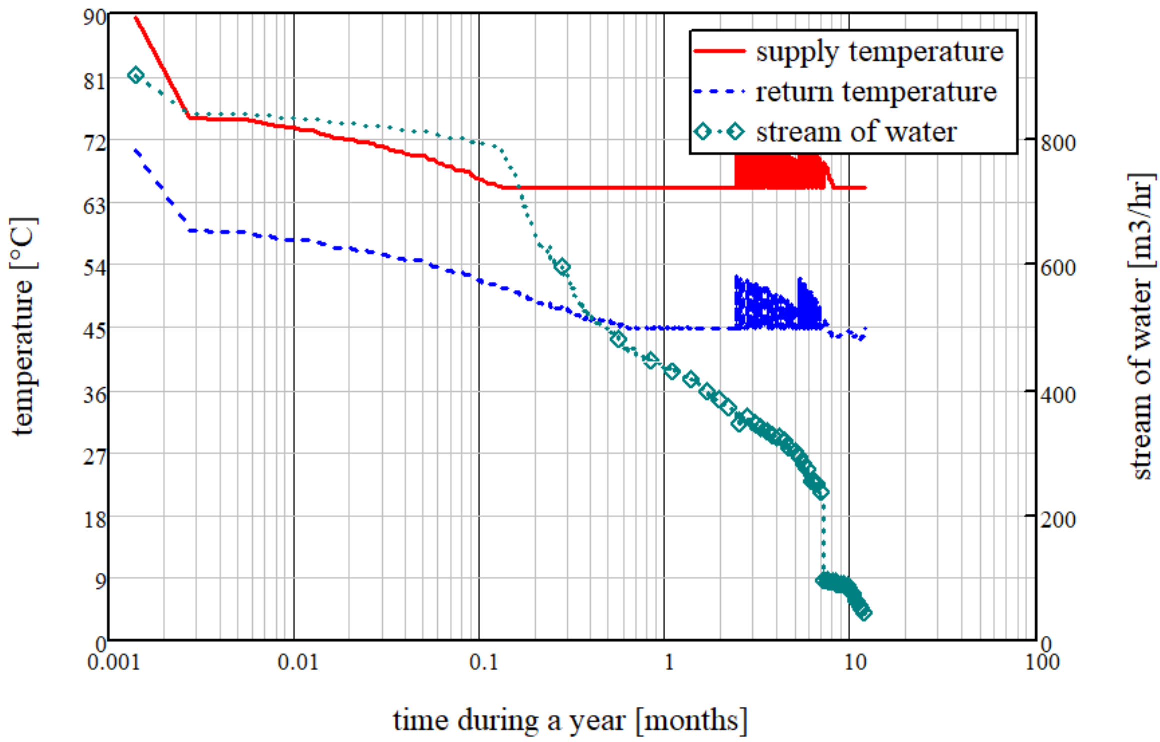


Fig. 5.4.3.9. Dynamic characteristics of the variation of the required flow temperature and the flow of the working fluid, as well as the return temperature obtained, for an "extended customer" – logarithmic scale

Power and economic calculations, as well as the estimations associated with the determination of the ecological effects, were carried out with the use of a mathematical model of the energy source, combined with the predefined customer. The energy source allowed for the possibility of analysing the effects of the operation of many integrated sources under a hybrid system. The general diagram of the source is presented in Fig. 5.4.3.10. The diagram was adjusted to the applicable requirements. The model contained the following elements: a direct geothermal heat exchanger, absorption or compression heat pumps (alternative solution, depending on the calculation option), and peak-demand boilers burning network high-methane natural gas. The following was excluded from analysis: solar collectors, heat-current modules, and alternative-fuel boilers. In the case of the compression heat pumps, our assumption concerned the use of the pumps allowing to obtain the condenser output temperature being higher than that of standard solutions (offering low capacity). That will require the application of high pressure for the condensation of the working medium and other special solutions available on the market.

The prices of the conventional energy media were assumed in accordance with the suggestions of the experts who handle similar heating installations (Geotermia Mazowiecka S.A.). The prices were taken from the market offerings and they are current as of the second half of 2017. The net network natural gas purchase price was assumed at 110 PLN/MWhr (considering the gas-burning heat at the local area at the level of 39 MJ/m^3, the purchase price per volume will amount to ca. 1,204 PLN/m^3). The net grid electricity purchase price was assumed at 300 PLN/MWhr. The above purchase prices of conventional drive energy media can be recognised as favourable. To compare, the average net prices of those media, determined on the basis of standard settlement tariffs can be estimated at ca. 1.6-1.8 PLN/m^{3}for natural gas (in respect of the gas volume, with the heat of combustion at the level of 39 MJ/m^3) and 400-480 PLN/MWhr for the grid electricity.

The level of capital investment expenditure needs to be discussed and clearly resolved. The proposed plant, mainly the heat pumps, are not in serial production or on sale. The purchase prices depend on the course of commercial negotiations. The proposed prices can be recognised as realistic, based on the experience of the authors of this study. As to the absorption heat pumps, the price will also comprise the expenditures spent on the purchase of high-temperature driving boiler and economiser.

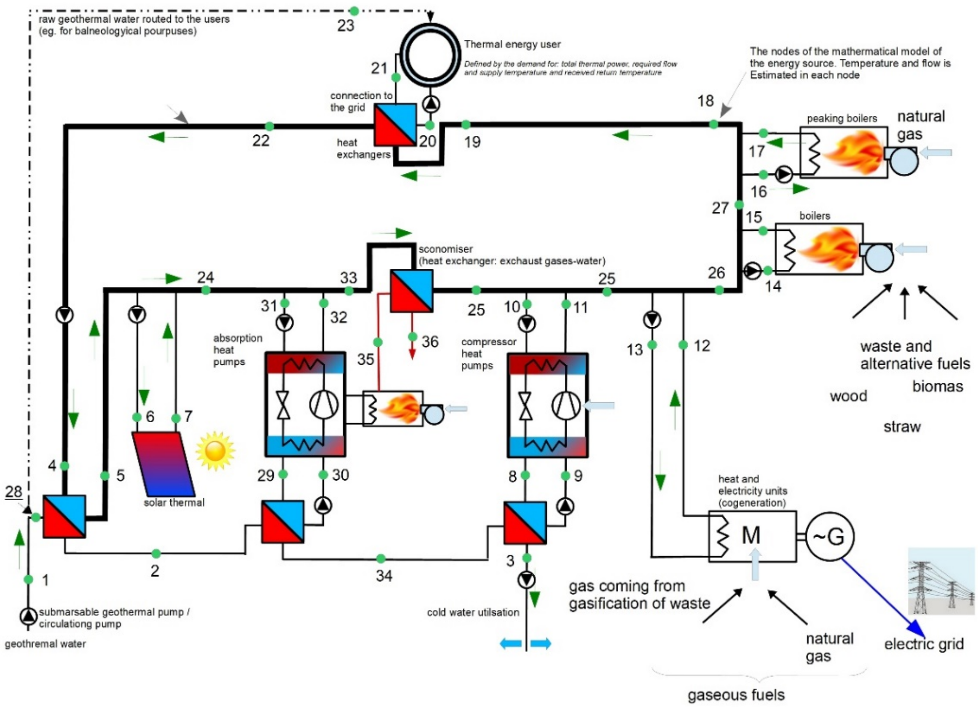


Fig. 5.4.3.10.A diagram of a hybrid energy source which was used for the estimation based on a mathematical model

The following options of using geothermal energy were analysed:

OptiongA (**g**-geothermal**A**-ctual (current) user) – comparative option – references. The option assumed the use of the currently operated system to satisfy the heating demand of a currently served customer (connected to the district heating network)whose profile is presented in Figs. 5.4.3.2, 5.4.3.3, 5.4.3.4, and 5.4.3.5.

OptiongE(**g**-eothermal**E**-xtended user) – comparative option, assuming that the system will satisfy the heating demand of the "extended customer" (upon connection of new facilities); the customer profile is presented in Figs. 5.4.3.6–5.4.3.9; the peak-demand source consists in natural-gas-burning boilers.

OptionahpA (**a**-bsorption **h**-eat **p**-ump **A**-ctual (current) user) – this option assumes that the energy source will serve the customers who are currently connected to the network (Figs. 5.4.3.2–5.4.3.5). The energy source uses geothermal resources with the application of absorption heat pumps.

OptionchpA (**c**-ompressor **h**-eat **p**-ump **A**-ctual (current) user) – this option assumes serving the customers who are currently connected to the network (Figs. 5.4.3.2–5.4.3.5), using geothermal resources with the application of compression heat pumps.

OptionahpE (**a**-bsorption **h**-eat **p**-ump **E**-xtended user) – this option assumes serving the "extended customer" (Figs. 5.4.3.6-5.4.3.9), using geothermal resources with the application of absorption heat pumps.

OptionchpE (**c**-ompressor **h**-eat **p**-ump **E**-xtended user) – this option assumes serving the "extended customer" (Figs. 5.4.3.6-5.4.3.9),using geothermal resources with the application of compression heat pumps.

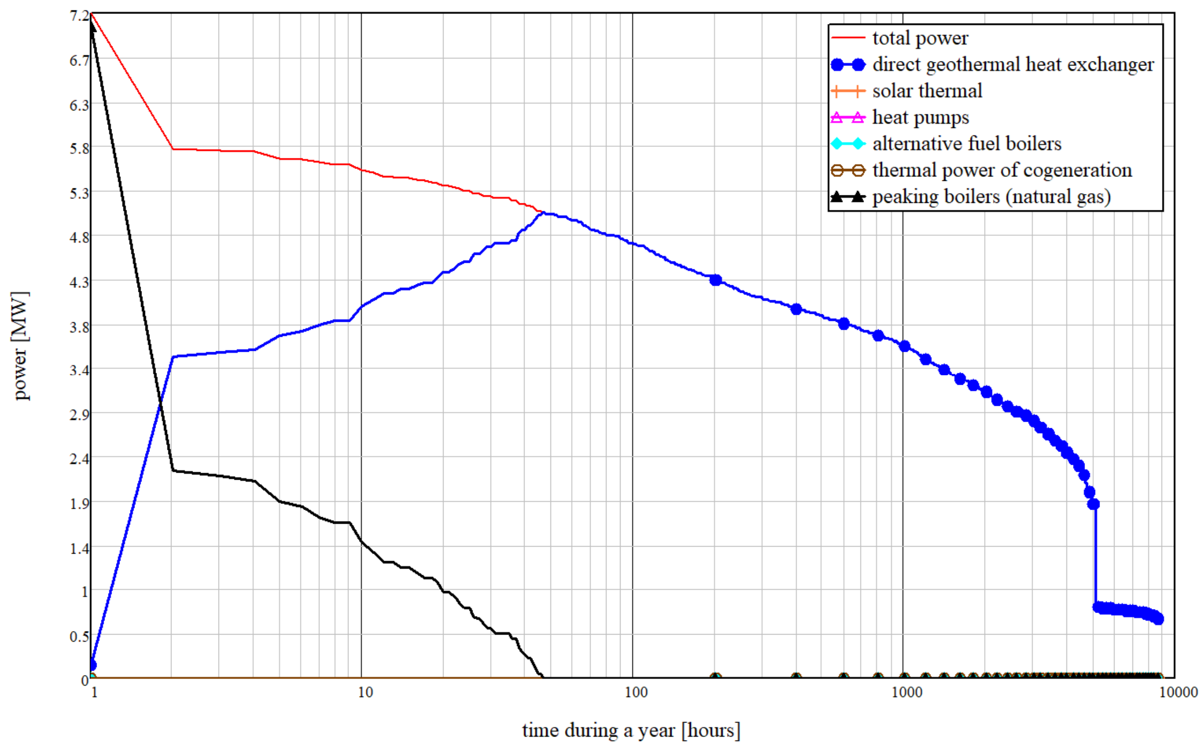


Fig. 5.4.3.11.A diagram of a source of energy operation in OptiongA (logarithmic time scale)

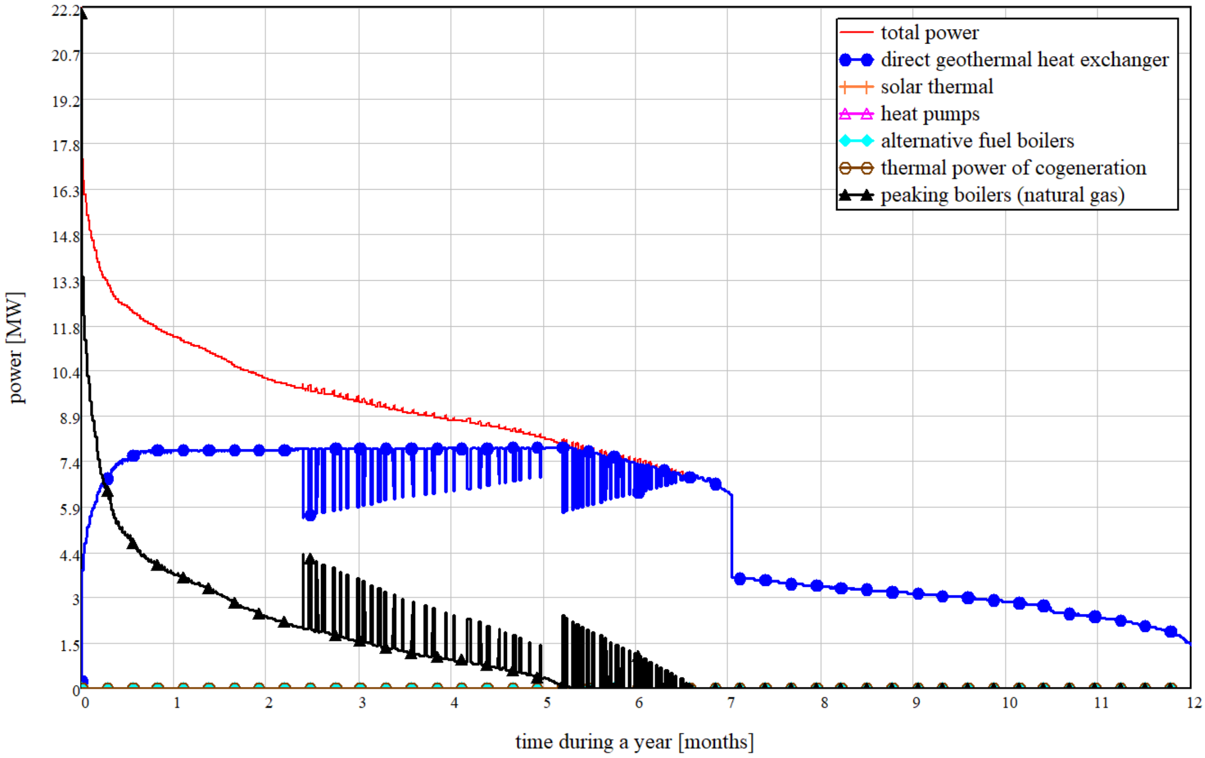


Fig. 5.4.3.12.A diagram of a source of energy operation in OptiongE

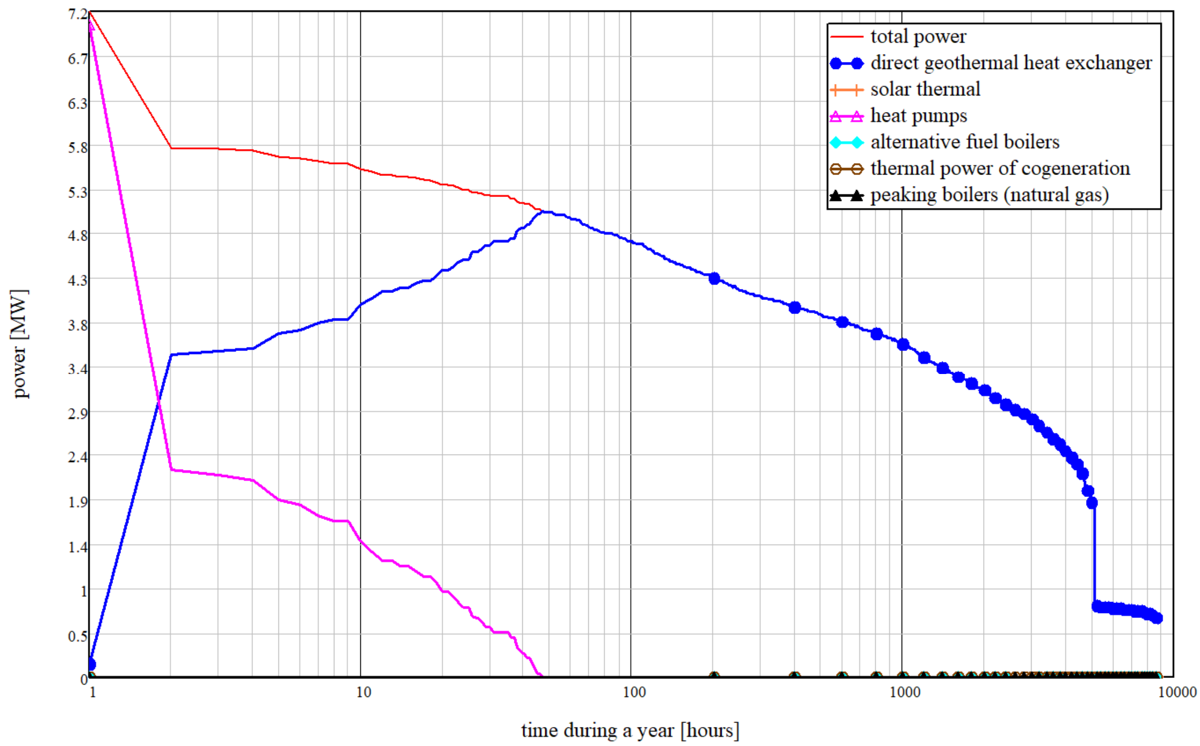


Fig. 5.4.3.13.A diagram of a source of energy operation in Option ahpA (logarithmic time scale)

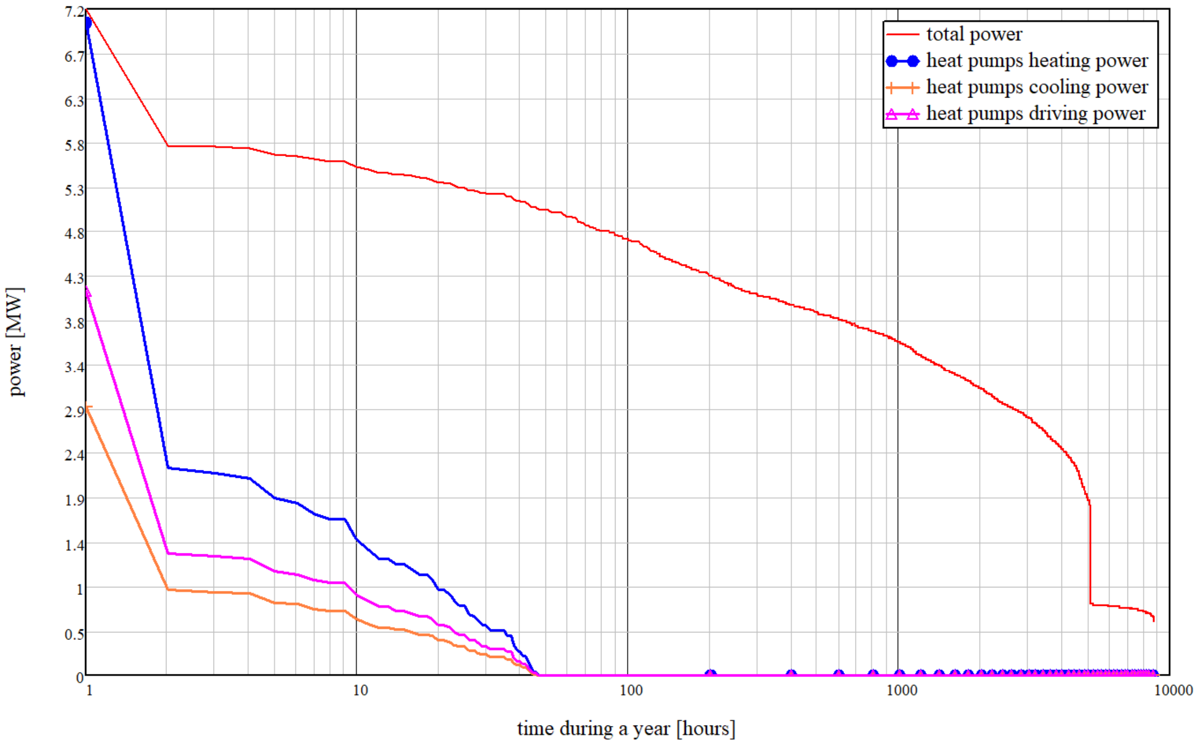


Fig. 5.4.3.14. Shares of cooling (geothermal) and drive power for the heat pumps in Option ahpA (logarithmic time scale)

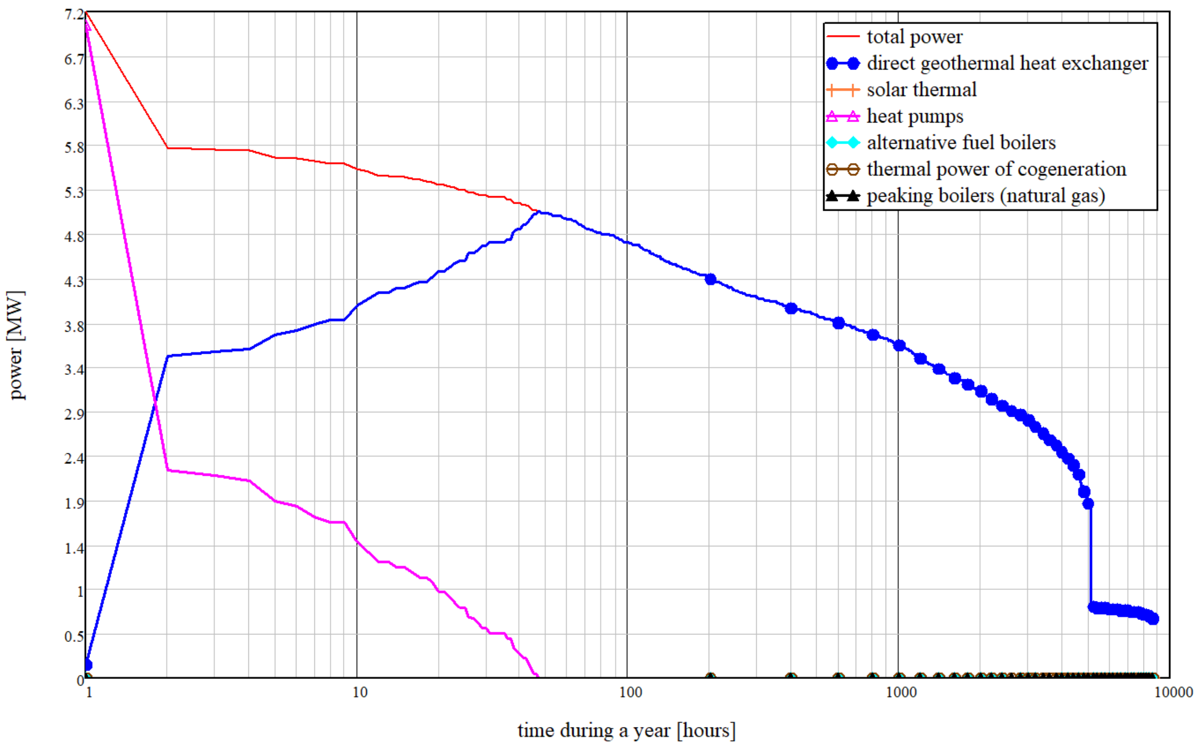


Fig. 5.4.3.15.A diagram of a source of energy operation in Option chpA (logarithmic time scale)

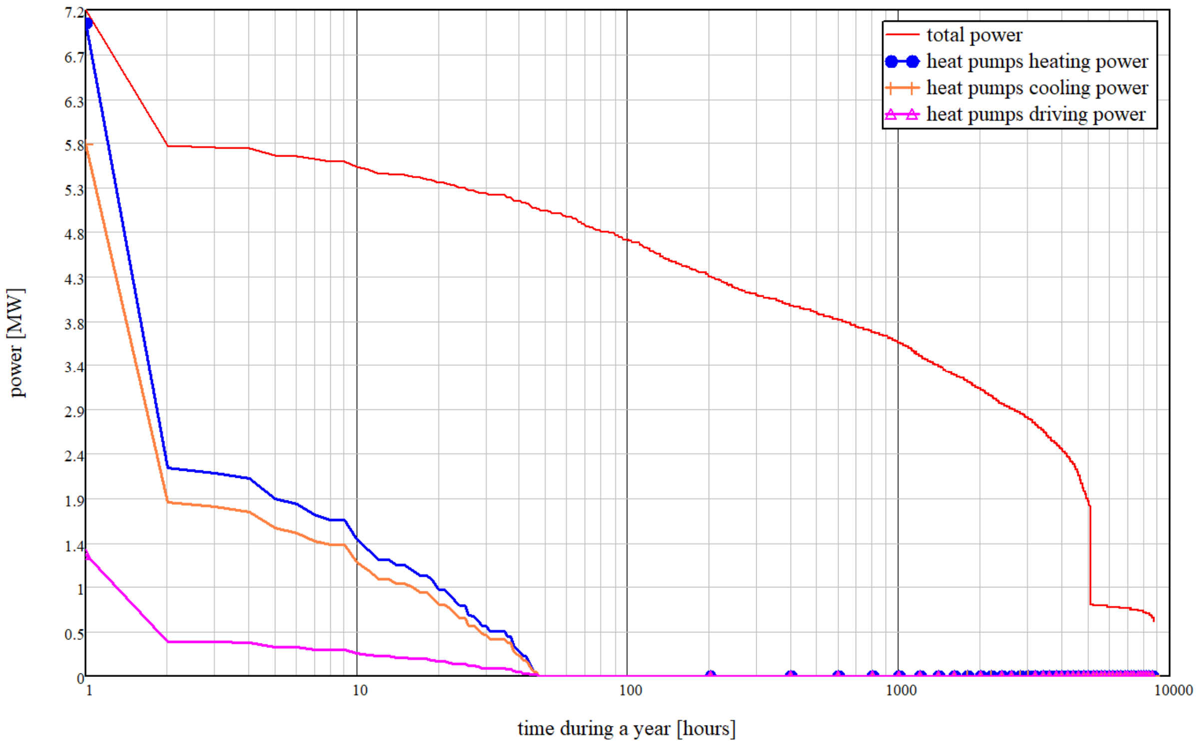


Fig. 5.4.3.16. Shares of cooling (geothermal) and drive power for heat pumps in Option chpA (logarithmic time scale)

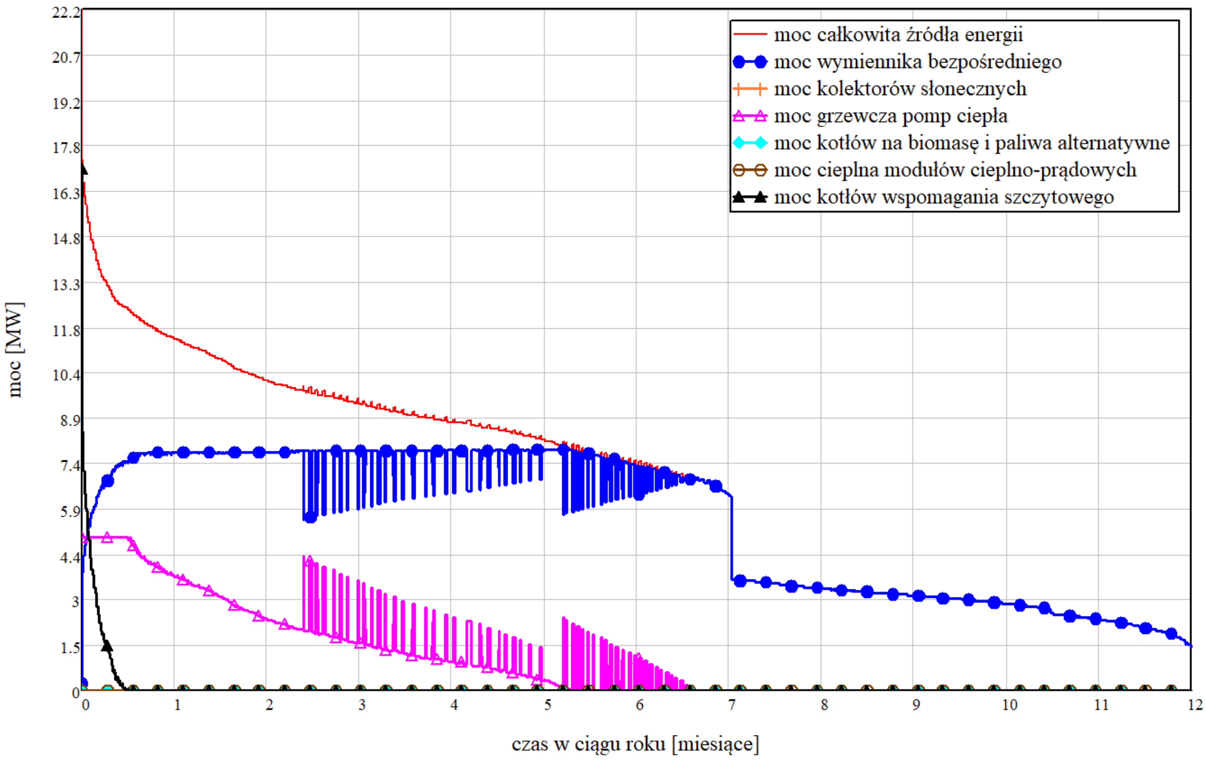


Fig. 5.4.3.17.A diagram of a source of energy operation in Option ahpE

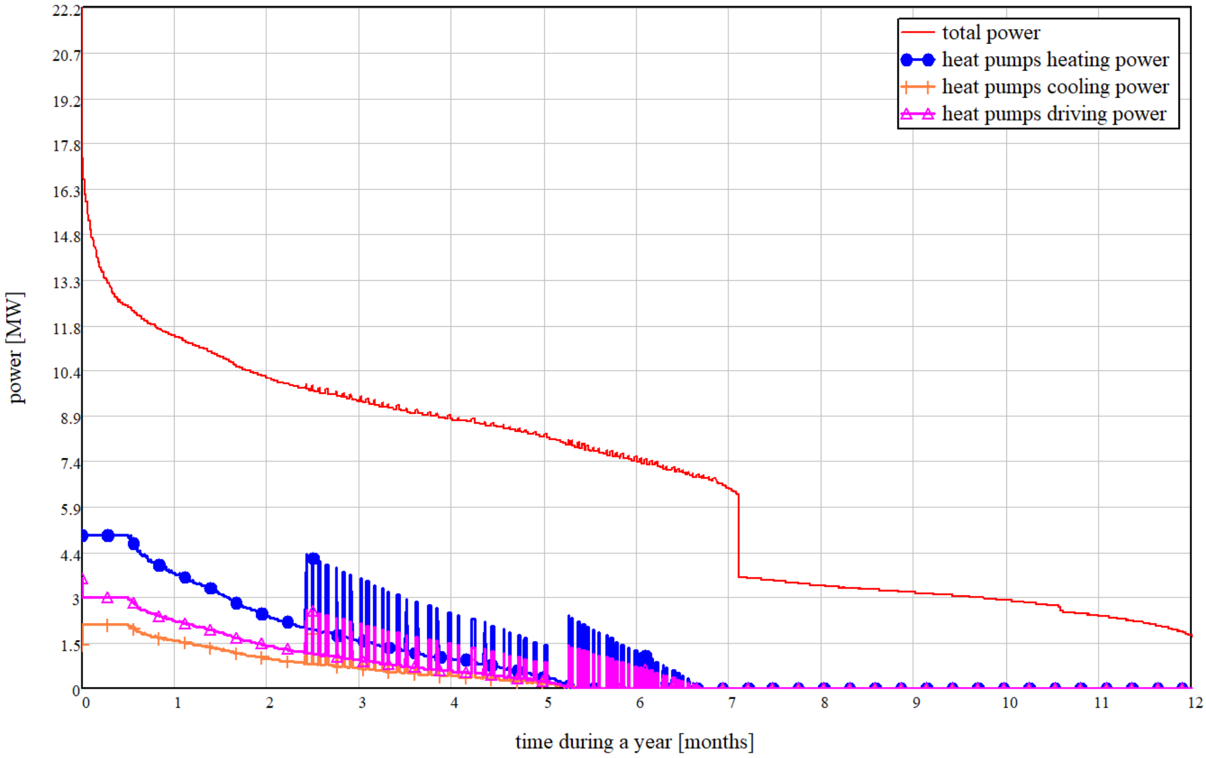


Fig. 5.4.3.18. Shares of cooling (geothermal) and drive power for heat pumps in Option ahpE

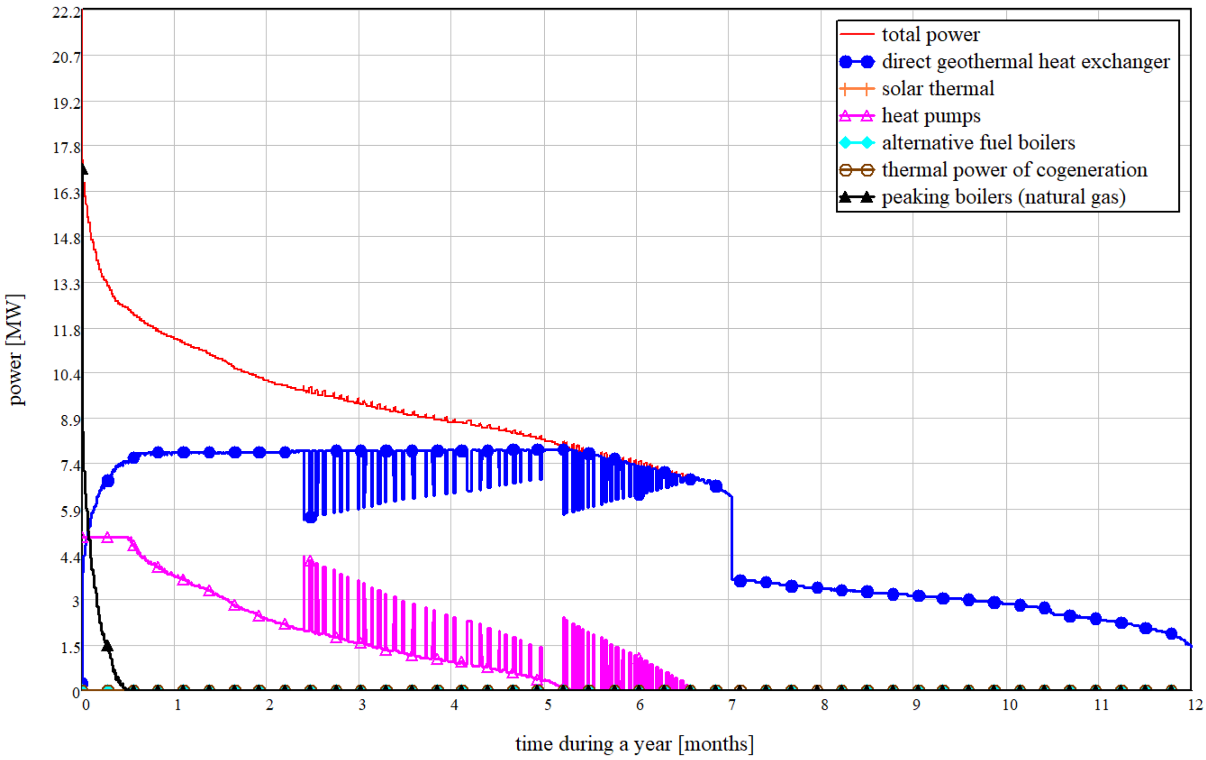


Fig. 5.4.3.19. A diagram of a source of energy operation in Option chpE

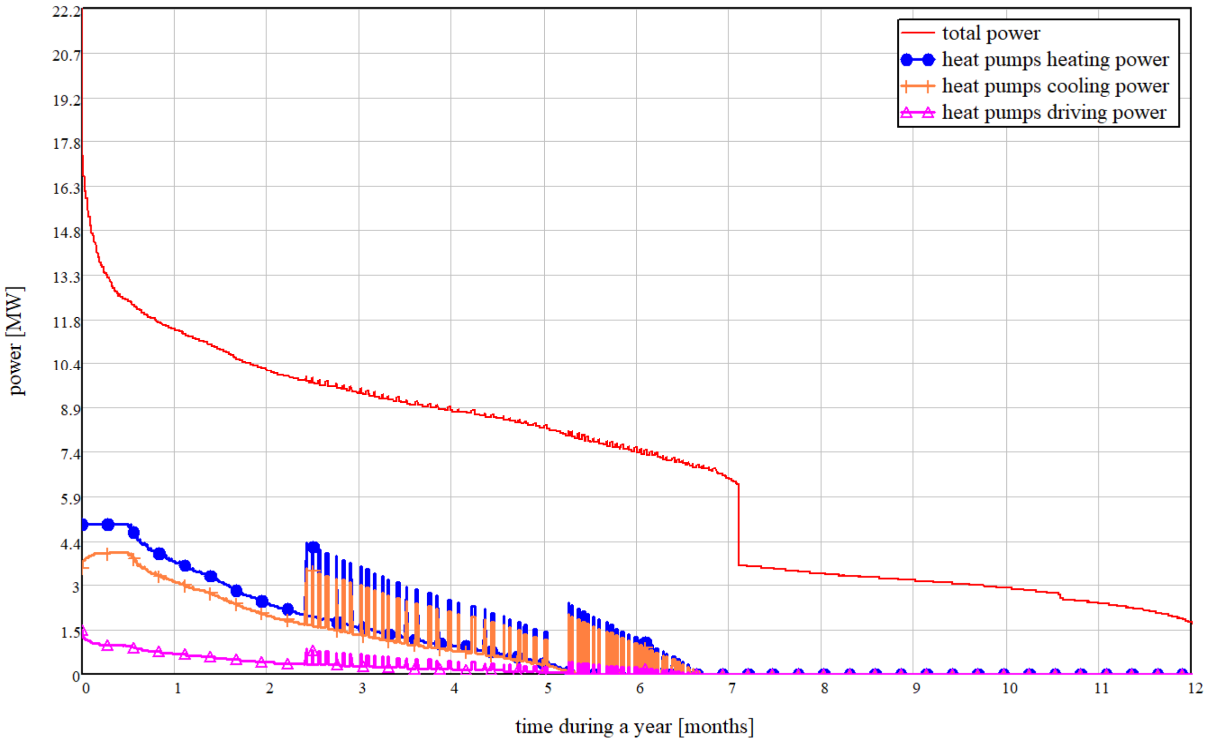


Fig. 5.4.3.20. Shares of cooling (geothermal) and drive power for heat pumps in Option chpE

Table5.4.3.1 contains the list of main technical, economic, and power parameters of the analysed Options. The estimated ecological effect was specified in two options:

- Local effect: referring to the forecast emissions of nine selected substances polluting the air.It does not take into account the emissions generated during the production of electricity used by the heat pump and circulation pump operation,
- Global effect (effect on a global scale): taking into account pollution emission generated by the power plant during the production of electricity used by the installation of the energy source analysed here.

In the Table presented below, the item associated with the costs borne for the drilling of a geothermal borehole, there are forecast capital investments costs. Although the level of the forecast capital investments expenditures does not refer to the existing borehole, the depreciation of the fixed assets generated by that borehole has been included in our calculations. All the tabularised price and cost values are net values.

Table 5.4.3.1. Summary of the main technical and economic parameters characterising the analyzed Options for the town of Sochaczew

Parameter	Wartość	Wartość	Wartość	Wartość	Wartość	Wartość
Description of the variant	gA	ahpA	chpA	gE	ahpE	chpE
Maximal thermal power consumption [kW]	6505	6505	6505	20117	20117	20117
Consumption of thermal energy consumed by the user [GJ/year]	53547	53547	53547	177042	177042	177042
Annual value of the load factor [-]	0,261	0,261	0,261	0,279	0,279	0,279
Supply temperature (maximum = nominal) [°C]	89,4	89,4	89,4	89,6	89,6	89,6
Return temperature (maximum = nominal) [°C]	70,6	70,6	70,6	70,3	70,3	70,3
Nominal flow of working medium [m3/hr]	297,8	297,8	297,8	899,5	899,5	899,5
Nominal geothermal water outflow [m3/hr]	0	0	0	0	0	0
Estimated length of main pipelines [m]	14000	14000	14000	40000	40000	40000
Calculated maximum power losses on transmission [kW]	714	714	714	2090	2090	2090
Calculated energy loss during distribution [GJ/year]	11278	11278	11278	32712	32712	32712
Net purchase price of natural gas [PLN/m3]	1,204	1,204	1,204	1,204	1,204	1,204
Net purchase price of electricity network [PLN/MWhr]	300	300	300	300	300	300
Selling price of electricity produced in thermal and current modules [PLN/MWhr]	250	250	250	250	250	250
----------- Description of energy sources ----------						
1. ----- Geothermal (direct use) -----						
1.1. Depth of geothermal horizon [m below ground level]	2063	2063	2063	2063	2063	2063
1.2. Water temperature driven to evaporator of heat pumps [°C]	73	73	73	73	73	73
1.3. Water stream [m3/hr]	252	252	252	252	252	252
1.4. Assumed static water level [m bgl]	-30	-30	-30	-30	-30	-30
1.5. Assumed unitary depression [m / m3/hr]	1	1	1	1	1	1
1.6. Production borehole status ('new', 'existing', 'reconstruction', 'no well')	existing	existing	existing	existing	existing	existing
1.7. Injection borehole status ('new', 'existing', 'reconstruction', 'no well')	no well	no well	no well	no well	no well	no well
1.8. Assembled borehole diameter [m]	0,244475	0,244475	0,244475	0,244475	0,244475	0,244475
1.9. Maximal temperature reached on the production wellhead [°C]	72,2	72,2	72,2	72,2	72,2	72,2
1.10. Maximal power achieved on direct heat exchanger (without heat pumps) [kW]	5058	5058	5058	7846	7846	7846
1.11. The amount of energy obtained from the direct heat exchanger [GJ/year]	64666	64666	64666	172824	172824	172824
1.12. Nominal driving power estimated for goethermal water pumps (exploitation and reinjection) [kW]	515	515	515	515	515	515
1.13. Electricity consumption by geothermal pumps [MWhr/year]	4510	4510	4510	4510	4510	4510
2 .----- Solar collectors -----						
2.1. Surface area of ??solar collectors [m2]	0	0	0	0	0	0
2.2. Thermal efficiency of collectors [-]	0,55	0,55	0,55	0,55	0,55	0,55
2.3. Solar radiation absorption coefficient [-]	0,9	0,9	0,9	0,9	0,9	0,9

2.4. Emission factor [-]	0,8	0,8	0,8	0,8	0,8	0,8
2.5. Maximum operating medium temperature [°C]	96,16	96,16	96,16	96,16	96,16	96,16
2.6. The amount of heat input to the customer's installation [GJ/year]	0	0	0	0	0	0
3. ----- Heat pumps (low energz source: geothermal) -----						
3.1. Heating capacity installed (maximal used) [kW]	0	7077	7077	0	5000	5000
3.2. Maximal working medium temperature at evaporator outlet [°C]	79,01	92,52	92,52	78,97	78,97	78,97
3.3. Maximal allowable water temperature at evaporator outlet [°C]	20	100	100	20	90	90
3.4. Minimum temperature of water at evaporator outlet [°C]	54,93	54,93	52,05	45,42	39,67	32,91
3.5. Maximum value of COP (on heating side) [-]	1,4	1,7	6	1,4	1,7	6
3.6. The amount of heat generated by heat pumps [GJ/year]	0	159	159	0	33883	33883
3.7. Amount of used drive energy consumed to drive the heat pump [MWhr/year]	0	26	7	0	5537	1684
3.8. Amount of used electric power used to drive geothermal pumps [MWhr/year]	4510	4510	4510	4510	4510	4510
4. ----- Thermoelectric units -----						
4.1. Thermal power of modules [kW]	0	0	0	0	0	0
4.2. Electrical power generated by modules [kW]	0	0	0	0	0	0
4.3. The amount of thermal energy generated by the thermoelectric modules [GJ/year]	0	0	0	0	0	0
4.4. The amount of electricity generated by the thermoelectric modules [MWhr/year]	0	0	0	0	0	0
4.5. Costs of obtaining biogas derived from gasification of waste [PLN/m3]	0,74	0,74	0,74	0,74	0,74	0,74
5. ----- Boilers for alternative fuels and biomass -----						
5.1. Maximum installed power (used) in alternative fuels and biomass boilers [kW]	0	0	0	0	0	0
5.2. The amount of heat generated in boilers for alternative fuels and biomass [GJ/year]	0	0	0	0	0	0
5.3. Cost of acquisition / purchase price of fuels and biomass (average) [PLN/Mg]	400	400	400	400	400	400
6. ----- Peak boilers for natural gas -----						
6.1. Maximum installed power (used) in gas boilers [kW]	7077	0	0	21994	16994	16994
6.2. The amount of thermal energy produced in gas boilers [GJ/year]	159	0	0	36931	3047	3047
Estimated investment outlays for heat source [thousands PLN]	21219	29499	29499	33476	39326	39326
- production well [thousands PLN]	13781	13781	13781	13781	13781	13781
- well for reinjection [thousands PLN]	0	0	0	0	0	0
- direct heat exchanger [thousands PLN]	253	253	253	392	392	392
- installation of solar collectors [thousands PLN]	0	0	0	0	0	0
- heat pumps [thousands PLN]	0	10615	10615	0	7500	7500
- installation of gasification of waste together with thermal and current modules [thousands PLN]	0	0	0	0	0	0
- alternative fuels and biomass [thousands PLN]	0	0	0	0	0	0
- peak boilers for natural gas [thousands PLN]	4246	0	0	13197	10197	10197
- connection pipelines and transmission lines [thousands PLN]	0	0	0	0	0	0
- energy source building [thousands PLN]	192	192	192	592	592	592

- cost of assembly, reserve for unexpected expenses [thousands PLN]	2747	4658	4658	5514	6864	6864
Total annual operating costs [thousands PLN/year]	2738	3274	3273	4940	4787	4531
- constant costs [thousands PLN/year]	1379	1917	1917	2176	2556	2556
- flexible costs [thousands PLN/year]	1359	1356	1355	2764	2231	1975
- depreciation of fixed assets [thousands PLN/year]	1061	1475	1475	1674	1966	1966
- costs of maintenance and repairs [thousands PLN/year]	318	442	442	502	590	590
- costs of buying conventional energy carriers [thousands PLN/year]	1359	1356	1355	2764	2231	1975
- incomes from the sale of electricity produced in combination by thermal current modules [thousands PLN/year]	0	0	0	0	0	0
Unitary costs of energy generation (excluding transmission losses) [PLN/GJ]	42	51	50	24	23	22
The price of energy for final customer (including transimission losses) [PLN/GJ]	51	61	61	28	27	26
Emission of pollutants emission related to the unit of generated heat [kg/GJ]						
- benzo (a) pyrene locally	0	0	0	0	0	0
- soot locally	0	0	0	0	0	0
- total dust locally	0	0	0	0	0	0
- CO2 locally	0,179	0,106	0	12,616	7,85	1,041
- CO locally	0	0	0	0,002	0,001	0
- NOx (recalculated to the NO2) locally	0	0	0	0,008	0,005	0,001
- SO2 locally	0	0	0	0	0	0
- aliphatic hydrocarbons locally	0	0	0	0,007	0,004	0,001
- aromatic hydrocarbons locally	0	0	0	0	0	0
- benzo (a) pyrene in global scale	0	0	0	0	0	0
- soot in global scale	0,002	0,002	0,002	0	0	0,001
- total dust in global scale	0,032	0,032	0,032	0,01	0,01	0,013
- CO2 in global scale	88,359	88,285	88,325	39,286	34,521	37,672
- CO in global scale	0,2	0,2	0,201	0,063	0,062	0,083
- NOx (recalculated to the NO2) in global scale	0,16	0,16	0,161	0,057	0,054	0,067
- SO2 in global scale	0,545	0,545	0,546	0,165	0,165	0,226
- aliphatic hydrocarbons in global scale	0	0	0	0,007	0,004	0,001
- aromatic hydrocarbons in global scale	0,01	0,01	0,01	0,003	0,003	0,004

Summary and conclusions

Our simulations of the district heating system operation in Poddębice indicated a considerable significance of the customer in relation to the economic, power, and ecological effects. In the case of Poddębice, the geothermal water temperature is high enough and the geothermal system operates with stable capacity during a large proportion of the heating season. Considering the customers being currently connected to the district heating system and based on weather date originating from typical meteorological years, the necessity of peak demand supply occurs during ca. 50 hrs/y (Fig. 5.4.3.11). Our calculations confirmed the previous conclusions (Kępińska et al., 2017b) stating that the use of the expensive energy source (heat pumps) is not rational in the present situation. The use of heat pumps in the present customer structure will cause the increase of the thermal energy sale price offered to the final customer. The pollution emission effects will be practically insignificant, even on the local scale.

However, the expansion of the customer base by inclusion of long-term planned facilities into the geothermal district heating network will change considerably the effects of the energy source operation. The geothermal source will operate during about six months with rated power (Fig. 5.4.3.12). The use of heat pumps in such conditions can be economically beneficial, although, as we can infer from our calculations (Figs. 5.4.3.17 and 5.4.3.19),the used of heat pumps' installed capacity will not be stable during the year. That fact will influence the economic effects of the power source operation, reflected in the purchase price to be paid by the final customer. In the event of using natural-gas-burning boilers, the net price will be ca. 28 PLN/GJ (Option gE, Table 5.4.3.1), or net 26-27 PLN/GJ in the Options assuming the use of heat pumps (Options ahpE and chp, Table 5.4.3.1). The estimated sale price offered to the final customer (including the costs of energy generation and distribution) is very low, and it can be successfully compared to the sale price of energy generated by coal-burning plants, although without the costs of distribution.

A considerable improvement of the geothermal system operation in Poddębice can be expected upon the implementation of the policy of reducing the required temperature of supply to the heating installation on the customer's side and reduction of return temperature (by using a cascade heat recipient and increase of radiator surface area). That is the direction for a further evolution of such a system. The heat pump installation does not guarantee obtaining beneficial effects, as indicated by our calculations.

References:

Kępińska B., Pająk L., Bujakowski W., Kasztelewicz A., Hajto M., Sowiżdżał A., Papiernik B., Pétursson B., Tulinius H., Thorgilsson G., Einarsson Ó. P., Karska A., Peraj A. 2017a: Geothermal utilization potential in Poland – the town of Poddębice. Part 1. Selected reservoir and exploitation aspects of current and further geothermal district heating and other uses' development in Poddębice. Technika Poszukiwań Geologicznych Geotermia, Zrównoważony Rozwój. No. 1/2017, pp. 3-21.

Kępińska B., Pająk L., Bujakowski W., Kasztelewicz A., Hajto M., Sowiżdżał A., Papiernik B., Pétursson B., Tulinius H., Thorgilsson G., Einarsson Ó. P., Karska A., Peraj A. 2017b: Geothermal utilization potential in Poland – the town of Poddębice. Part 2. Selected energetic aspects of current and future geothermal district heating in Poddębice. Technika Poszukiwań Geologicznych Geotermia, Zrównoważony Rozwój No. 1/2017, pp. 23-38.

5.4.4. Improved energetic and economic optimisation of geoDH system and increased efficiency by multipurposed geothermal water and energy use in Poddębice

The energy and economic optimisation of the district heating network (central heating and hot utility water preparation) in Poddębice should consist in the reduction of the required feed temperature and the return temperature. That goal can be attained by the following: increase of the surface areas of the radiator installations, increase of the coefficient of air heat recuperation by use of blow systems (enforced air movement andfans directed at heating elements).

In the calculations presented below refer to the municipal facilities (council housing and public utility buildings), planned to be connected to the network (maximum capacity: ca. 18 MW), excluding the Borysew Safari ZOO and the modernised swimming pools (described in Section 5.4.3).The swimming pools and the Safari ZOO are expected to be equipped with low-temperature heating systems or the systems that are implemented directly in the outdoor pools, using cooled geothermal water.

The municipal facilities that are currently equipped with central heating systems, designed for the following parameters: 90/70/20/-20°C, will be modernised and made suitable for the following parameters: 65/50/20/-20°C. The installations of hot utility water preparation will be modernised (presently: 65/45°C)and adjusted to: 65/25°C.The collective profile of the customer will be changed from that presented in Figs. 5.4.3.6, 5.4.3.7, 5.4.3.8, and 5.4.3.9 to that presented in Figs. 5.4.4.1, 5.4.4.2, 5.4.4.3.

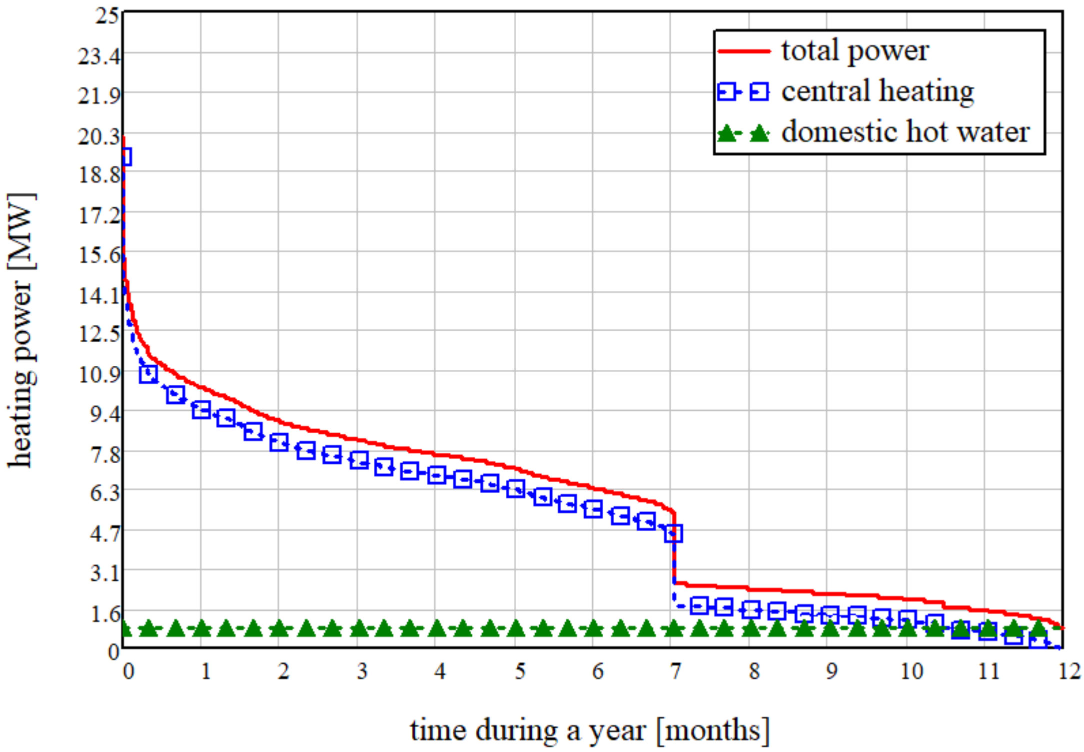


Fig. 5.4.4.1. Dynamic characteristics of the variation of the required flow temperature and the flow of working fluid, as well as the return temperature obtained, for the extended customer after retrofitting of central heating and hot water preparation installations

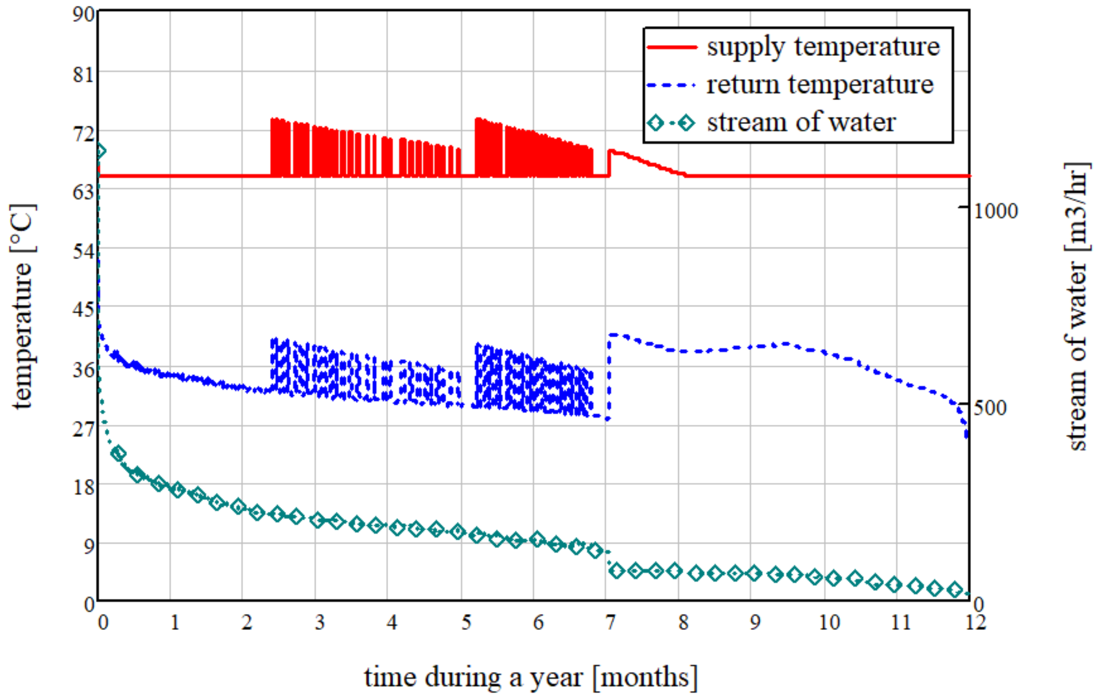


Fig. 5.4.4.2. Dynamic characteristics of the variation of the required flow temperature and the flow of working fluid, as well as the return temperature obtained, for the extended customer after retrofitting of central heating and hot water preparation installations

We can observe that the highest supply temperature of the heating installation after retrofitting will amount to 70°C, while the return water temperature will be lower than 45°C during most of the year. The method of supplied capacity control will change towards quantitative control, with changing return water temperature.

Fig. 5.4.4.3 presents the changing schedule of the source operation, co-operating with the newly defined customer profile.The technical, economic, and ecological parameters of the energy source with modernised energy recipients are presented in Table 5.4.4.1. The optimised option is marked gErf (**g**-eothermal **E**-xtended user **arf**-after retrofitting).

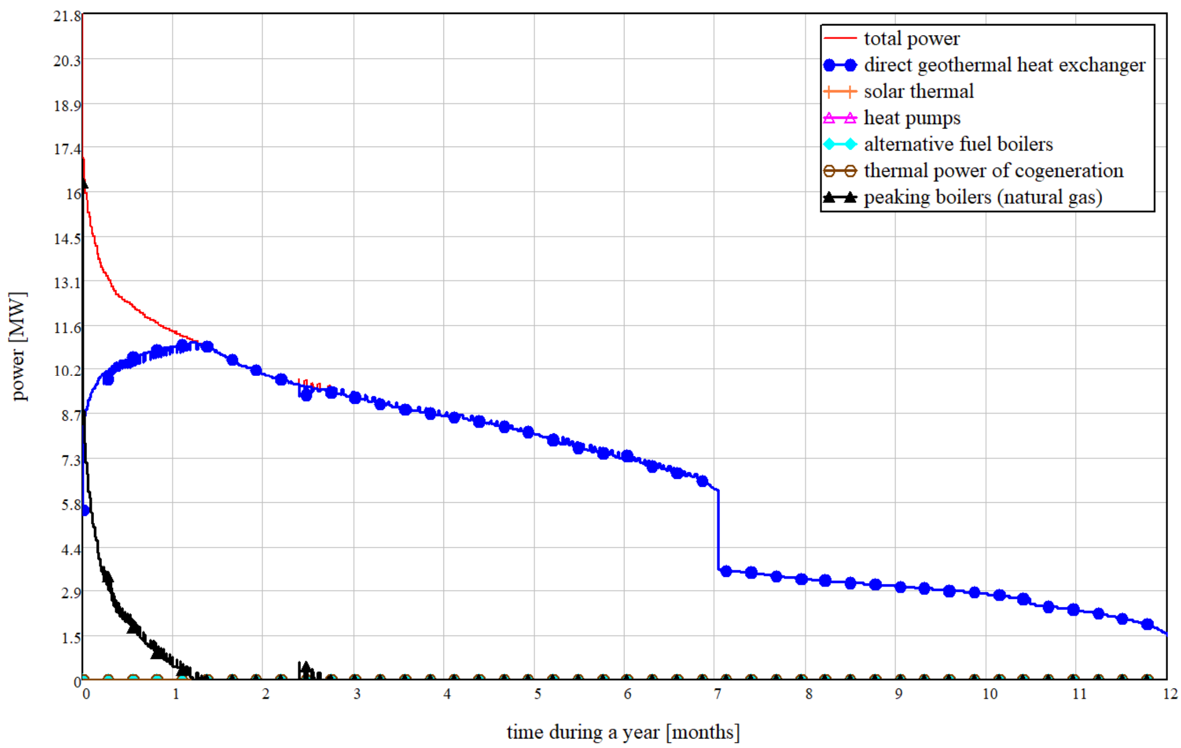


Fig. 5.4.4.3. A diagram of a source of energy operation in the Option with the extended user after retrofitting of radiators and the tap hot water preparation system

Table 5.4.4.1. Summary of the main technical and economic parameters characterising the analyzed Options for the town of Poddębice after retrofitting of radiators and the tap hot water preparation system

Parameter	Wartość
Description of the variant	Wariant 3D: Jura Dolna, odbiorca duży
Maximal thermal power consumption [kW]	20117
Consumption of thermal energy consumed by the user [GJ/year]	177042
Annual value of the load factor [-]	0,279
Supply temperature (maximum = nominal) [°C]	73,6
Return temperature (maximum = nominal) [°C]	51,8
Nominal flow of working medium [m3/hr]	1142,2
Nominal geothermal water outflow [m3/hr]	0
Estimated length of main pipelines [m]	40000
Calculated maximum power losses on transmission [kW]	1661
Calculated energy loss during distribution [GJ/year]	30087
Net purchase price of natural gas [PLN/m3]	1,204
Net purchase price of electricity network [PLN/MWhr]	300
Selling price of electricity produced in thermal and current modules [PLN/MWhr]	250
----------- Description of energy sources ----------	
1. ----- Geothermal (direct use) -----	
1.1. Depth of geothermal horizon [m below ground level]	2063
1.2. Water temperature driven to evaporator of heat pumps [°C]	73
1.3. Water stream [m3/hr]	252
1.4. Assumed static water level [m bgl]	-30
1.5. Assumed unitary depression [m / m3/hr]	1
1.6. Production borehole status ('new', 'existing', 'reconstruction', 'no well')	existing
1.7. Injection borehole status ('new', 'existing', 'reconstruction', 'no well')	no well
1.8. Assembled borehole diameter [m]	0,244475
1.9. Maximal temperature reached on the production wellhead [°C]	72,2
1.10. Maximal power achieved on direct heat exchanger (without heat pumps) [kW]	11030
1.11. The amount of energy obtained from the direct heat exchanger [GJ/year]	200338
1.12. Nominal driving power estimatet for goethermal water pumps (exploitation and reinjection) [kW]	515
1.13. Electricity consumption by geothermal pumps [MWhr/year]	4510
2 .----- Solar collectors -----	
2.1. Surface area of ??solar collectors [m2]	0
2.2. Thermal efficiency of collectors [-]	0,55
2.3. Solar radiation absorption coefficient [-]	0,9
2.4. Emission factor [-]	0,8
2.5. Maximum operating medium temperature [°C]	96,16
2.6. The amount of heat input to the customer's installation [GJ/year]	0
3. ----- Heat pumps (low energz source: geothermal) -----	
3.1. Heating capacity installed (maximal used) [kW]	0
3.2. Maximal working medium temperature at evaporator outlet [°C]	103,5
3.3. Maximal allowable water temperature at evaporator outlet [°C]	20
3.4. Minimum temperature of water at evaporator outlet [°C]	34,57
3.5. Maximum value of COP (on heating side) [-]	1,4
3.6. The amount of heat generated by heat pumps [GJ/year]	0
3.7. Amount of used drive energy consumed to drive the heat pump [MWhr/year]	0
3.8. Amount of used electric power used to drive geothermal pumps [MWhr/year]	4510
4. ----- Thermoelectric units -----	
4.1. Thermal power of modules [kW]	0

4.2. Electrical power generated by modules [kW]	0
4.3. The amount of thermal energy generated by the thermoelectric modules [GJ/year]	0
4.4. The amount of electricity generated by the thermoelectric modules [MWhr/year]	0
4.5. Costs of obtaining biogas derived from gasification of waste [PLN/m3]	0,74
5. ----- Boilers for alternative fuels and biomass -----	
5.1. Maximum installed power (used) in alternative fuels and biomass boilers [kW]	0
5.2. The amount of heat generated in boilers for alternative fuels and biomass [GJ/year]	0
5.3. Cost of acquisition / purchase price of fuels and biomass (average) [PLN/Mg]	400
6. ----- Peak boilers for natural gas -----	
6.1. Maximum installed power (used) in gas boilers [kW]	16230
6.2. The amount of thermal energy produced in gas boilers [GJ/year]	6792
Estimated investment outlays for heat source [thousands PLN]	29174
- production well [thousands PLN]	13781
- well for reinjection [thousands PLN]	0
- direct heat exchanger [thousands PLN]	552
- installation of solar collectors [thousands PLN]	0
- heat pumps [thousands PLN]	0
- installation of gasification of waste together with thermal and current modules [thousands PLN]	0
- alternative fuels and biomass [thousands PLN]	0
- peak boilers for natural gas [thousands PLN]	9738
- connection pipelines and transmission lines [thousands PLN]	0
- energy source building [thousands PLN]	581
- cost of assembly, reserve for unexpected expenses [thousands PLN]	4523
Total annual operating costs [thousands PLN/year]	3509
- constant costs [thousands PLN/year]	1896
- flexible costs [thousands PLN/year]	1612
- depreciation of fixed assets [thousands PLN/year]	1459
- costs of maintenance and repairs [thousands PLN/year]	438
- costs of buying conventional energy carriers [thousands PLN/year]	1612
- incomes from the sale of electricity produced in combination by thermal current modules [thousands PLN/year]	0
Unitary costs of energy generation (excluding transmission losses) [PLN/GJ]	17
The price of energy for final customer (including transmission losses) [PLN/GJ]	20
Emission of pollutants emission related to the unit of generated heat [kg/GJ]	
- benzo (a) pyrene locally	0
- soot locally	0
- total dust locally	0
- CO2 locally	2,32
- CO locally	0
- NOx (recalculated to the NO2) locally	0,001
- SO2 locally	0
- aliphatic hydrocarbons locally	0,001
- aromatic hydrocarbons locally	0
- benzo (a) pyrene in global scale	0
- soot in global scale	0
- total dust in global scale	0,01
- CO2 in global scale	28,991
- CO in global scale	0,061
- NOx (recalculated to the NO2) in global scale	0,05
- SO2 in global scale	0,165
- aliphatic hydrocarbons in global scale	0,001
- aromatic hydrocarbons in global scale	0,003

Summary and conclusions

As a result of the assumed thermal modernisation of the existing radiators and hot utility water preparation system, measurable economic, energy, and ecological effects can be expected. The energy effect will consist in the shortening of the necessary peak-demand source operation from nearly 7 months (Fig. 5.4.3.12) to a bit more than one month. The final measure of the economic effect will consist in the reduction of the energy sale price offered to the final customer, from the level of 26–27 PLN/GJ (Table 5.4.3.1) to 20 PLN/GJ (Table 5.4.4.1). The ecological effect will be attained on both global and local scales and that results directly from the reduction of the peak-demand source operation time. The direction of modernisation of the existing district heating system can be determined as a recommended and optimum solution.

5.5. Sochaczew study case

5.5.1. Geological – hydrothermal conditions of Sochaczew area and prospects to obtain geothermal waters for space heating and other uses

5.5.1.1. Geological and hydrogeological conditions prevailing in the area of Sochaczew

In geological terms, the area analysed belongs to the Polish Lowlands and is located within the Warsaw Basin. This unit is located on the boundary of two large tectonic units: the Precambrian Baltic Shield and the Paleozoic Platform (Pożaryski, 1969). The formations that build the three main aquifers (Triassic, Jurassic and Cretaceous) are mainly sandstone-mudstone-limestone sedimentary rocks. The stratigraphic profile was determined on the basis of deep drilling; four wells (Skierniewice GT-1, Sochaczew 1, Sochaczew 2 and Sochaczew 3) are situated in the immediate vicinity of the study area (Fig. 5.5.1.1). The earliest formations reached with these wells are Carboniferous sediments (the Sochaczew 2 well).

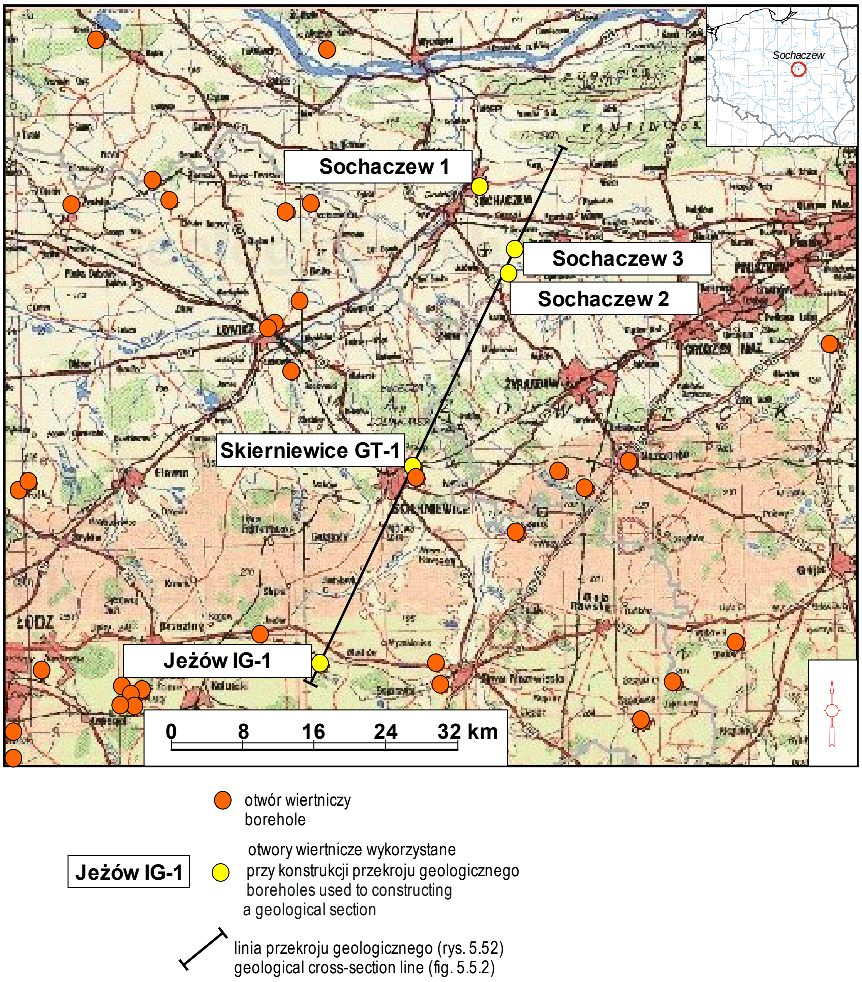


Fig. 5.5.1.1. Location of wells and the line of the geological cross-section in Fig. 5.5.1.2

Triassic formations consist of claystone and mudstone rocks, sandstones and less often limestones (Buntsandstein), limestones with sandstone inserts, claystones and marls (Muschelkalk), claystones and mudstones with sandstone and gypsum inserts (Keuper) and claystone-mudstone series with sandy-conglomerate inserts (Rhaetian). During the Lower Jurassic sedimentation (Lias), cyclically repeating strata formed composed of sandstones, claystones and mudstones. In the Middle Jurassic (Dogger), mudstone-sandstone series with dolomite interbeddings developed. The Upper Jurassic (Malm) level consists of marine formations that contain oolite and dolomitic limestones, sandy marls, marly mudstones with limestone inserts and anhydrites. Lower Cretaceous is present in the form of sandstone and mudstone rocks. On the other hand, Upper Cretaceous sediments are dominated by pelitic and marly limestones, marls and chalk.

Paleogene, Neogene and Quaternary sediments are present throughout the study area. These have the form of sands, tills, gravels and moraine formations.
The structural stage best studied from the tectonic point of view is the sedimentary Permian-Mesozoic cover. The generally weakly folded Permian and Mesozoic formations exhibit significant tectonic dislocations in places. These are folds, hinges and faults, which are usually accompanied by diapirs and other halotectonic forms. The Warsaw Basin is asymmetrical, with a very mildly sloped north-eastern limb that covers the study area and a steeper south-western limb (Fig. 5.5.1.2). Only Cretaceous formations retain a clearly synclinal pattern while in the older structural surfaces, the synclinal structure gradually disappears. Most deep dislocations run in the NW-SE direction, parallel to the axis of the Basin. There are also numerous deep latitudinal synsedimentary faults that result in changes in the thickness of Mesozoic rocks.

Hydrogeological and geothermal conditions
The hydrogeological conditions of the study area were determined on the basis of data from the wells drilled in the 1970s and 1980s and also at the turn of the century. The information used includes, *inter alia*, the results of water inflow testing and descriptions of the phenomena observed and tests conducted during drilling. Below, the hydrogeological parameters of the main geothermal reservoirs within the area studied, i.e. the Lower Cretaceous, Jurassic and Triassic aquifers, are presented on the basis of the documentation on results and catalogues of the aforementioned wells.

<u>Lower Cretaceous aquifer</u>

In the area under discussion, groundwaters in the Lower Cretaceous multiaquifer formation are geothermal waters contained in sandstone formations with clay inserts. Reservoir porosity determined by geophysical methods varies, ranging from a few percent to as much as 25%, and the water inflows observed exceed 60 m^3/h (Mszczonów IG-1 well). According to *Atlas zasobów geotermalnych formacji mezozoicznej na Niżu Polskim* ["Atlas of Geothermal Resources of the Mesozoic Formation in the Polish Lowlands"] (Górecki [ed.], 2006), maximum flow rates may reach up to 200 m^3/h.
Waters of the Lower Cretaceous multiaquifer formation in the area of Sochaczew were found at depths exceeding 1,000 m in the following deep research wells: Sochaczew 1, Mszczonów IG-1 and Mszczonów IG-2. In the Sochaczew-1 well, which is located within the town limits (Figs. 5.5.1.1 and 5.5.1.2), the sandstone Lower Cretaceous level was tested at depths ranging from 1,169 to 1,185 m; fresh waters were found there with temperatures of around 35–40°C and a flow rate of 20 m^3/h. Comprehensive information about the Sochaczew 1 well and about well testing results is presented in Fig. 5.5.1.4.

The thickness of the Lower Cretaceous complex decreases towards the SW, and in the Sochaczew area it reaches from 160 to 180 m. The reservoir is fed from the southwest along the edge of the Kujawy Swell and its floor reaches a maximum depth of about 1,700 m b.g.l. around 10 km SW from Sochaczew. Within town limits, the ceiling of the aquifer descends in a SW direction, starting at around 1,100 m b.g.l. and going down to 1,500 m b.g.l. Thus the variation in geothermal water temperatures at the top of the aquifer in this zone will be of the order of 10°C (35–40°C in the NE area of the town and 45–50°C in the SW area, Fig. 5.5.2). Temperatures of waters at the bottom of the aquifer will be approx. 5°C higher. The temperature distribution of waters in the Lower Cretaceous aquifer in the Sochaczew area is presented in Figure 5.5.3.

The Lower Cretaceous sandstone aquifer is used by geothermal plants in Uniejów and Poddębice and by the nearby geothermal plant in Mszczonów where the water exploited has the following parameters: t=42°C; Q=60 m^3/h, water table depth 50 m b.g.l. and mineralisation of approx. 0.5 g/dm^3.

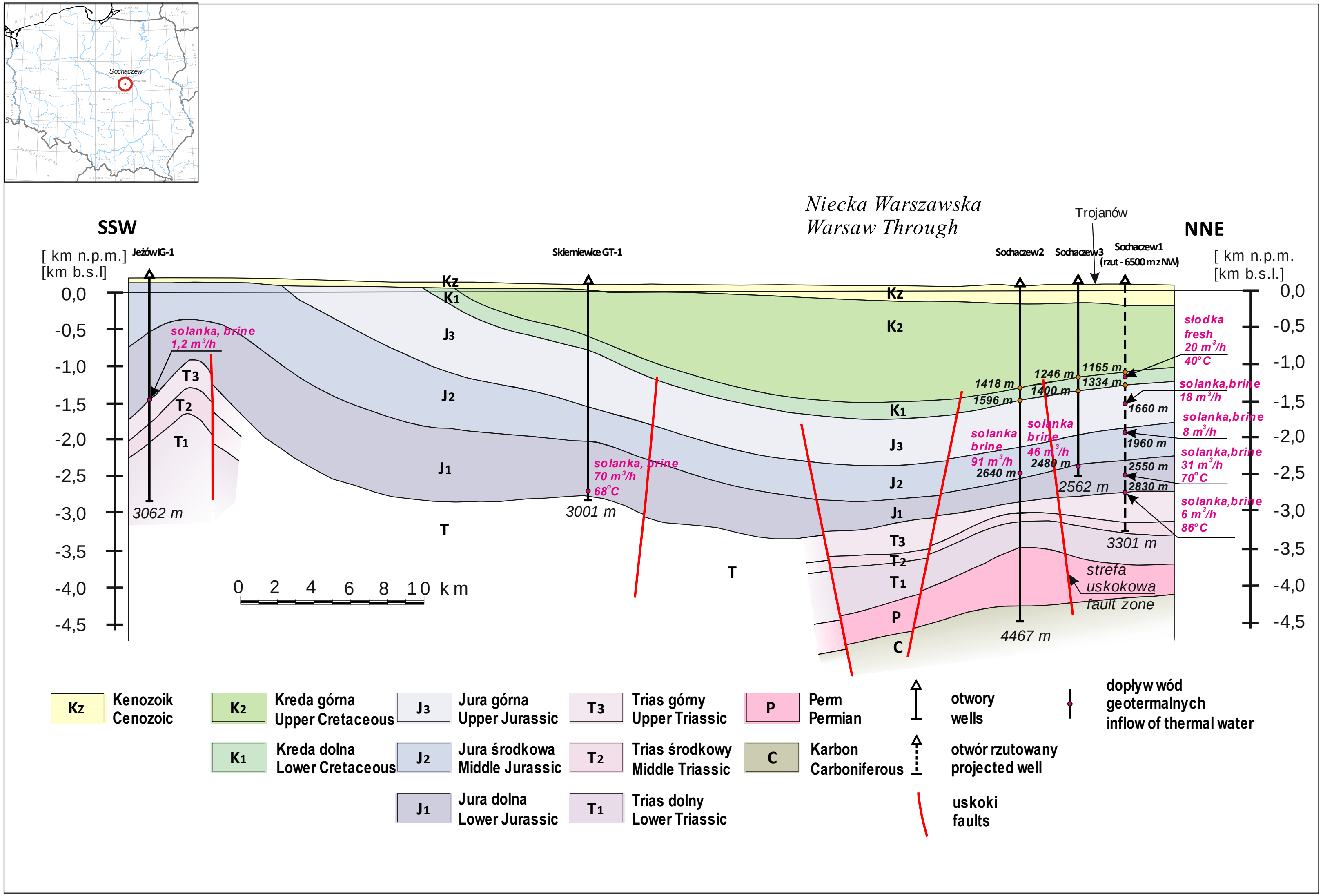


Fig. 5.5.1.2. Geological cross-section through the Skierniewice-Sochaczew region

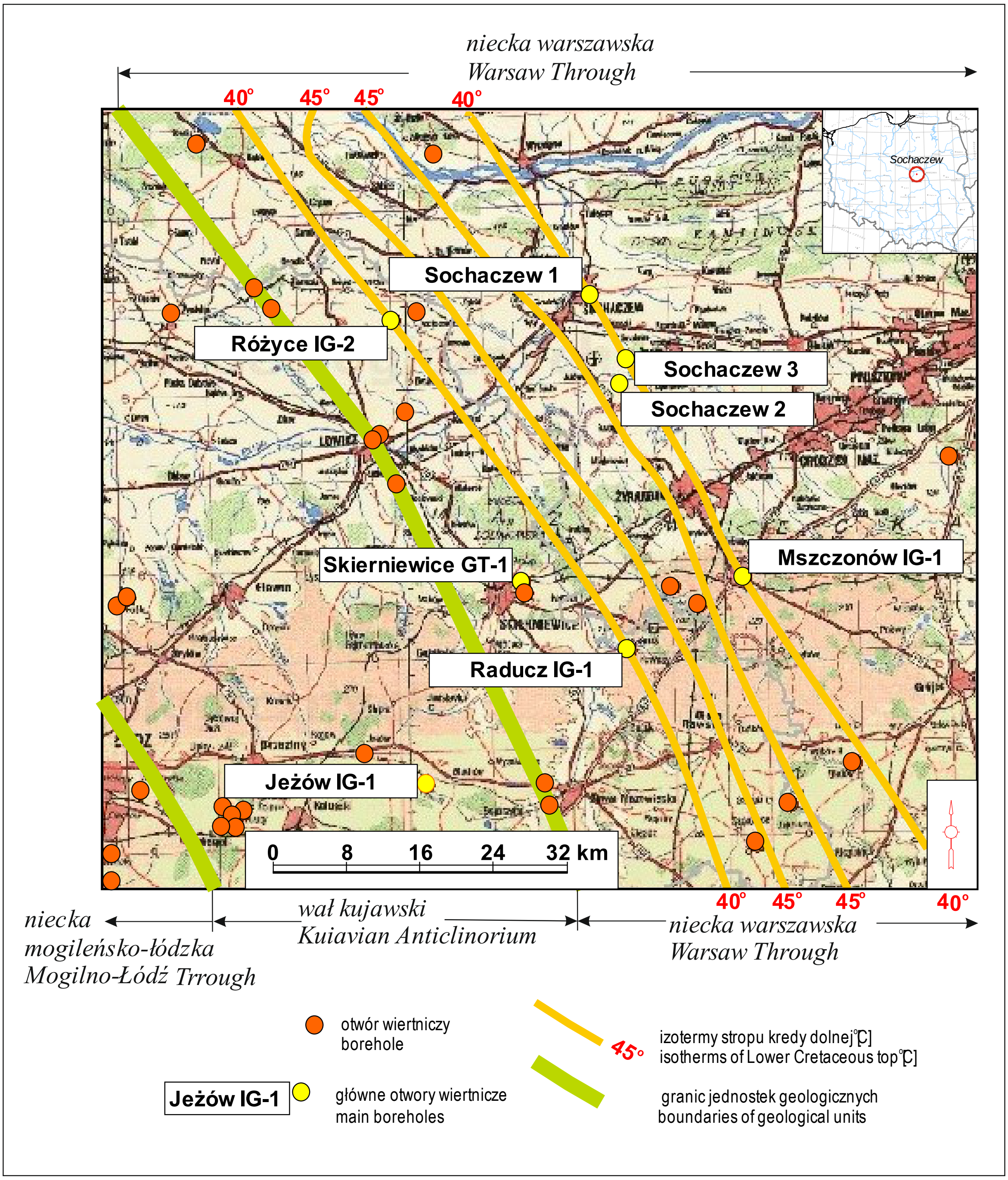


Fig. 5.5.1.3. Temperature distribution within the Lower Cretaceous aquifer in the Sochaczew area

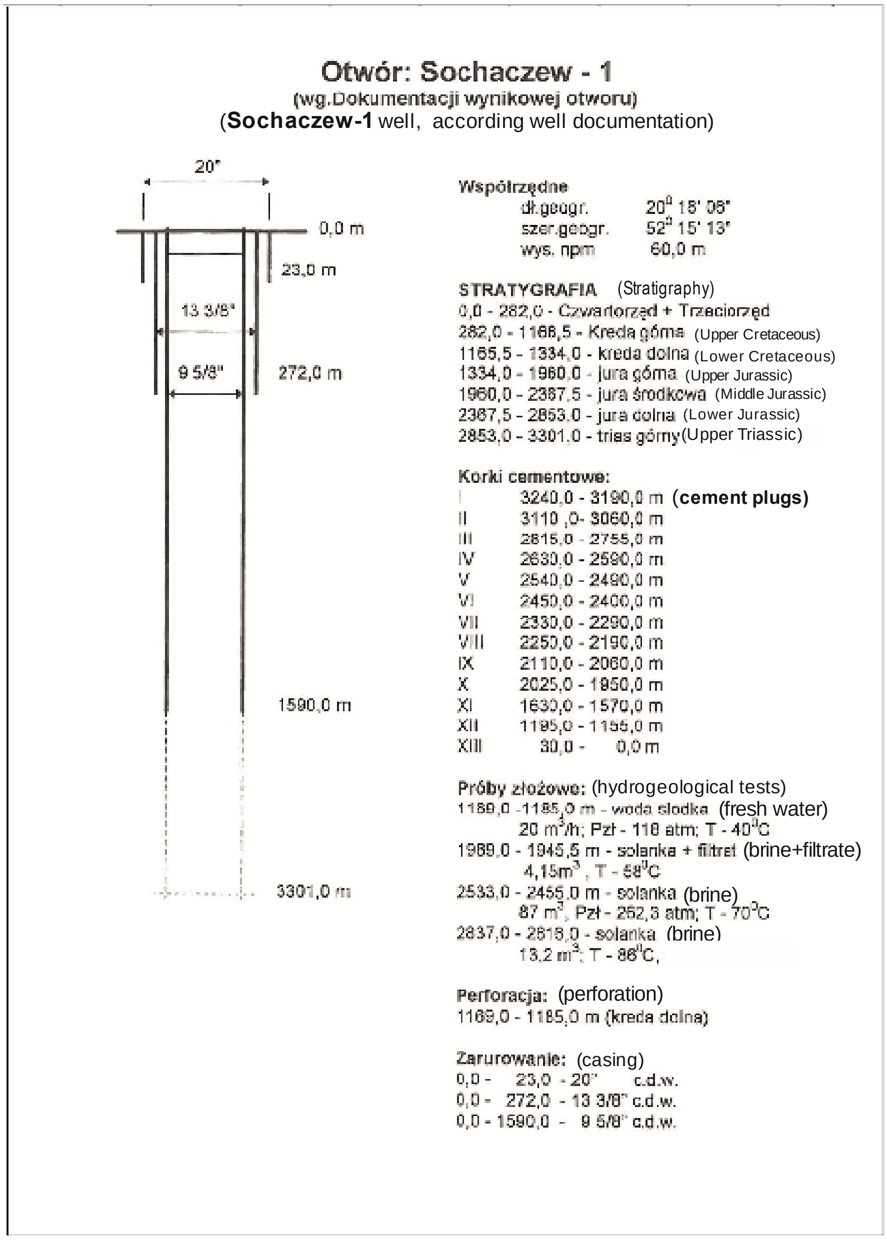


Fig. 5.5.1.4. Comprehensive information on the design of the Sochaczew 1 well and hydrogeological test results (opening year: 1972)

Jurassic aquifer

The Jurassic multiaquifer formation is characterised by favourable reservoir parameters, in particular in the Lower Jurassic level and in the lower part of the Upper Jurassic Level (Oxfordian).

Within the town limits, the aquifer found in the sandstone formations of the *Lower Jurassic* was tested using the Sochaczew 1, Sochaczew 3, Skierniewice GT-1, Jeżów IG-1, Raducz IG-1 and Różyce IG-2 wells (Fig. 5.5.3). Inflows of Cl–Na brines with mineralisation levels ranging from 95 g/dm^3 (Mszczonów IG-1, depth ca. 2,440 m, temperature ca. 66°C) to 124 g/dm^3(Różyce IG-2, depth 2,650 m, temperature 80°C) were found. In the Różyce IG-2 well, the temperature of brine with a mineralisation of 122 g/dm^3 was 90.9°C at a depth of 3,100 m. Water inflow rates vary, ranging from a few (Różyce 2 – 6.3 m^3/h) to several dozen m^3/h (70 m^3/h in the Skierniewice GT-1 well). In the Sochaczew 3 well, at a depth ranging from 2,460 to 2,503 m, an inflow of 46 m^3/h of chloride-calcium brine was found which had a mineralisation of 102 g/dm^3. Comprehensive information about the Sochaczew 3 well and about well testing results is presented in Fig. 5.5.1.5.

In the area of Sochaczew, the Lower Jurassic aquifer is fed along the edge of the Kujawy Swell (Fig. 5.5.1.3) and the depth of its ceiling ranges from 2,300 m b.g.l. (NE town area) to 2,700 m b.g.l. (SW town area, Fig. 5.5.1.2). In this area, the ceiling of the reservoir descends in a SW direction, so geothermal water temperature differences at the top of the aquifer in these two town areas will be of the order of 10°C (65°C in the NE part and around 75°C in the SW part of the town). Taking into account the thickness of the Lower Jurassic complex, which is on average 350 m, water temperature levels at aquifer bottom will be about 10°C higher. Owing to the numerous sandstone horizons and considerable thickness of the reservoir, it is difficult to determine particularly favourable drilling sites and the entire area analysed appears equally promising.

In lithological terms, *Middle Jurassic* formations are similar to those of the Lower Jurassic, but the claystone and mudstone fraction accounts for a greater part of the sediment profile. The porosity of these sediments is on average 10%. The Middle Jurassic aquifer was tested in the Sochaczew area in the Sochaczew 2, Łowicz IG-1, Mszczonów IG-1, Mszczonów IG-2 and Różyce IG-2 wells. This aquifer is characterised by inflows of brines with mineralisation levels ranging from 77 g/dm^3 (Mszczonów IG-1) to 116.8 g/dm^3 (Różyce IG-2) and wellhead temperatures ranging from 18°C (Żychlin IG-3 well) to 75°C (estimated for the Sochaczew 2 well at a depth of around 2,640 m). In the Różyce IG-2 well (15 km W of Sochaczew), the temperatures of brine in the reservoir amounted to 78.9°C and 86.9°C at depths of, respectively, ca. 2,600 m and 2,800 m.

Water inflows in the Middle Jurassic aquifer vary, ranging from a few to several dozen m^3/h (e.g. 91 m^3/h in the Sochaczew 2 well). In the Sochaczew 2 well, this aquifer is present at depths ranging from 2,290 to 2,700 m and from 2,620 to 2,656 m and it accumulates chloride-calcium Cl–Na waters with a mineralisation level of 107 g/dm^3. Comprehensive information about the Sochaczew 2 well and about the results of the tests conducted for this well is presented in Fig. 5.5.1.6.

Geothermal waters from this aquifer have also been found in the Sochaczew 1 well, where at depths ranging from 1,945 to 1,990 m brine inflows were observed with a rate of ~8 m^3/h and with a temperature of 58°C (Figs. 5.5.1.2 and 5.5.1.4).

In the Sochaczew area, the top of the Middle Jurassic aquifer lies at depths ranging from 1,900 m (NE part of the town) to 2,400 m (SW part of the town) and thus temperatures of geothermal waters in the top part of the reservoir will range from 55 to 70°C. Taking into account the thickness of the aquifer (around 400 m) the temperature in the bottom zones will be about 12°C higher.

Groundwater present in *Upper Jurassic* formations is associated with carbonate sediments. The most favourable reservoir parameters are found in the lower part of the Upper Jurassic profile (Oxfordian) where limestone porosity reaches up to 20%. The upper part of the profile, with a higher proportion of the clay fraction, is characterised by an average porosity of a few percent. Water inflows found in wells in this area are varied and range from 0.54 m^3/h (Raducz IG-1) to 32 m^3/h (Łowicz IG-1). In the Sochaczew 1 well, brine inflow was obtained from limestone formations at a depth of 1,644–1,685 m and with a flow rate of ~18 m^3/h (Fig. 5.5.1.2).

Upper Jurassic waters exhibit medium mineralisation, with levels ranging from 10.1 g/dm^3 (Raducz IG-1) to 31 g/dm^3 (Mszczonów IG-1), but in one case an inflow of brine with a mineralisation of 79.1 g/dm^3 was observed (Różyce-1). In the town area, the ceiling of this aquifer faults downwards in a SW direction, starting at around 1,300 m b.g.l. and descending to 1,700 m b.g.l. and thus geothermal water temperature differences at the top of the aquifer in this zone will be of the order of 10°C (40°C in the NE part and around 50°C in the SW part of the town). Given the thickness of the complex (~600 m), water temperatures in its bottom levels will be approx. 18°C higher. In the Sochaczew 1 well (NE part of the town): top levels as above (~40°C), bottom levels ~60°C and the zone where inflow was observed (at a depth of around 1,660 m) ~50°C (estimated).

Triassic aquifer

The Triassic multiaquifer formation in the neighbouring areas was tested using five deep research wells. The deepest aquifers within the Triassic multiaquifer complex were found in the *Buntsandstein* formations in the Kompina-2 (in the area of Łowicz), Mszczonów IG-2 and Różyce IG-2 wells. These are highly mineralised Cl–Na brines with mineralisation levels of up to 337.1 g/dm^3 (Kompina-2). However, we have no information about this level that would originate directly from the area of the town.

The *Upper Triassic* aquifer (Keuper/Rhaetian) was tested using the Kompina-2, Różyce-1 and Mszczonów IG-1 wells. Inflows of brines were observed with mineralisation levels ranging from 88 to 150 g/dm^3. Brine flow rates varied and ranged from 0.1 to 22 m^3/h in the Kompina-2 and to 8.3 m^3/h in the Mszczonów IG-1 well.

Water resources of the Triassic multiaquifer formation in the area studied have been determined to a degree that makes it possible to state that the most favourable reservoir parameters can be found in the Upper Triassic (Keuper/Rhaetian) level. The Triassic aquifer, which generally exhibits low intergrain porosity, is characterised by the presence of strongly cracked zones where the occurrence of groundwater is probably linked to discontinuous dislocation zones. However, there are problems with using these waters – their high salinity exceeding 300 g/dm^3 and the flow rates achievable for individual Triassic horizons, which are difficult to assess.

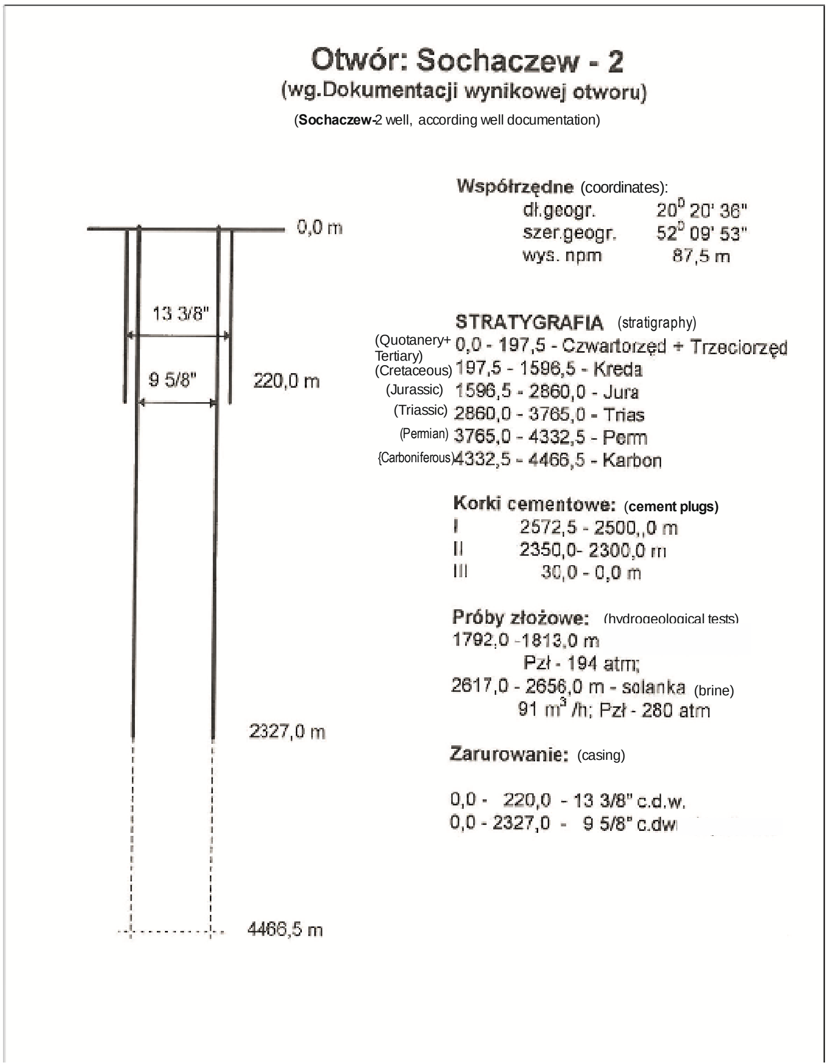


Fig. 5.5.1.5. Comprehensive information on the design of the Sochaczew 3 well and hydrogeological test results (opening year: 1972)

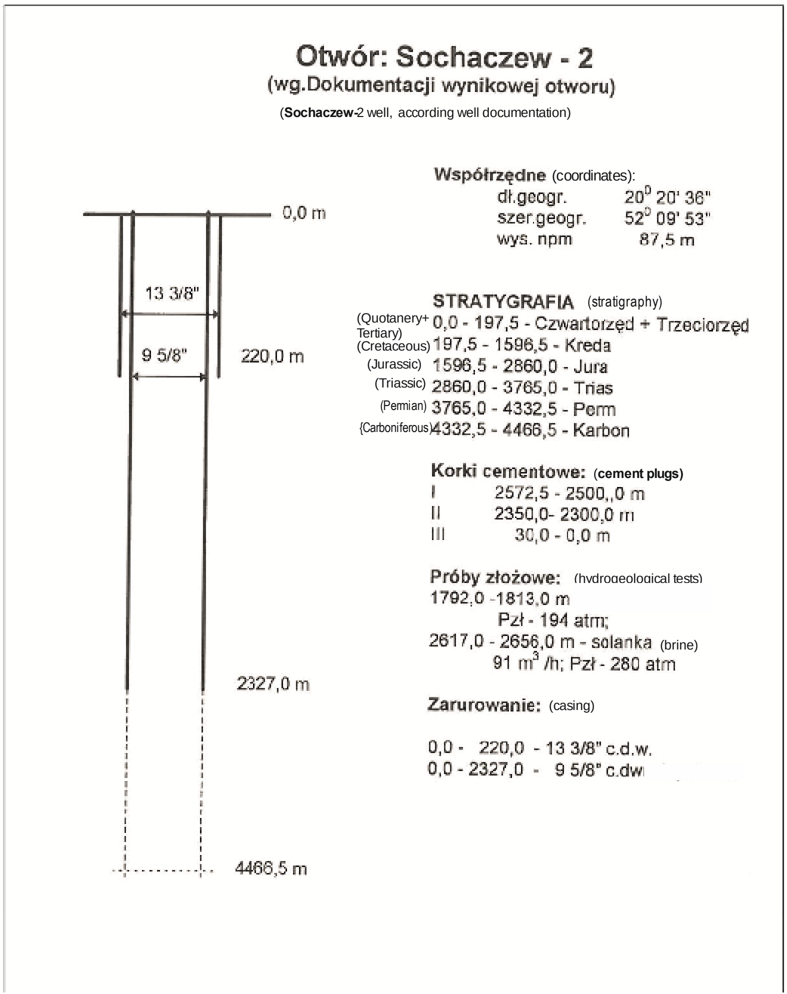


Fig. 5.5.1.6. Comprehensive information on the design of the Sochaczew 2 well and hydrogeological test results (opening year: 1972)

Physico-chemical characteristics of waters

Reliable data on water chemistry were only obtained in the case of *Lower Jurassic* waters in the Sochaczew 1 and 3 wells. These are as follows:

Sochaczew 1:

sampling depth: 2,465–2,533 m

mineralisation: 106.4 g/dm^3, density: 1.069 g/dm^3

main ion content:
- HCO_3 – 0.183 g/dm^3
- SO_4 – 1.043 g/dm^3
- Cl – 61.695 g/dm^3
- Ca – 3.256 g/dm^3
- Mg – 0.851 g/dm^3
- Na+K – 39.372 g/dm^3

Sochaczew 3:
sampling depth: 2,465–2,503 m
mineralisation: 102.09 g/dm^3, density: 1.069 g/dm^3

main ion content:
HCO_3 – 0.3051 g/dm^3
SO_4 – 0.4032 g/dm^3
Cl – 58.9472 g/dm^3
Ca – 2.9058 g/dm^3
Mg – 0.6682 g/dm^3
Na+K – 33.9486 g/dm^3

Iodine or bromine were not found in either well. Waters are of the Cl–Na type.
In turn, waters from the Lower Cretaceous aquifer in the Sochaczew 1 well were contaminated with drilling mud filtrate during sampling and were unsuitable for chemical testing. Their density was determined as 995 g/dm^3, so they were fresh waters. Their suitability for human consumption has not been established.

5.5.1.2. Potential energy resources related to geothermal waters in the Sochaczew area

Calculations of potential energy resources for the selected geothermal aquifers (Lower Cretaceous, Upper Jurassic, Middle Jurassic, Lower Jurassic, Upper Triassic) are based on the algorithm for determining exploitable resources. Literature on the subject contains a number of methods for determining energy potential, including available resources, disposable resources or exploitable resources, which are estimated here. Exploitable resources (understood as capacities and heat energy levels that can be obtained) are determined as the energy potential that can be extracted from a *single* well. Average temperatures (between the top and bottom of the reservoir in question) were used in the estimation, and flow rates were estimated using information from adjacent geological units in the Polish Lowlands. The energy assessments presented are therefore indicative and are intended, *inter alia*, as input for ranking the attractiveness of individual aquifers in the area.
For the aquifers selected, thermal capacity and the annual amount of heat that can be obtained were determined for the case where heat is extracted from geothermal water until it reaches a temperature of about 15°C, thus assuming the use of heat pumps.
Calculations were based on the following formulae:

Thermal capacity $$P_{term} \approx 0,0012 \cdot \Delta t \cdot Q \text{ [MW]}$$

where:
P_{term} – potential thermal capacity of a single well, MW
Δt – cooling, °C
Q – water flow rate, m^3/h
0.0012 – a coefficient accounting for the specific heat of water and unit conversions

It was assumed that water would be cooled to 15°C in the installations using heat pump systems:

Thermal energy [TJ/year] $$P_{term} = 0,0012 \cdot (t - 15) \cdot Q \text{ [MW]}$$
where:
P_{term} – thermal capacity of a single well, MW
t – temperature of thermal waters, °C
Q – estimated geothermal water flow rate, m^3/h
x = 0.3 – annual thermal capacity utilisation ratio
W_{term} – thermal energy from a single well, TJ / year
8,760 – number of hours per year
0.0036 – conversion coefficient (MWh to TJ)

Lower Cretaceous aquifer

On the basis of its depth range, the average temperature was assumed to be 40°C. Actual temperatures may range from 40 to 50°C (e.g. according to the data included in *Atlas zasobów geotermalnych formacji mezozoicznej na Niżu Polskim,* Górecki [ed.], 2006). Taking into account the data for the Mszczonów IG-1 well, the water flow rate was assumed to be Q=120 m^3/h (a more conservative estimatethan that in the *Atlas* where the flow rate from this zone was estimated at 200 m^3/h).

Thermal capacity*:*

$$P_{term} = 0,0012 \cdot (40 - 15) \cdot 120 = 3,6 \ [MW]$$

Thermal energy*:*

$$W_{term} = 9,46 \cdot P_{term} = 9,46 \cdot 3,6 = 34 \ \left[\frac{TJ}{year}\right]$$

Upper Jurassic aquifer

Based on estimated aquifer temperatures in the Sochaczew area, an average temperature of 50°C was assumed. Also taking into account data for the Sochaczew 1 well, it was assumed that after the inflow intensifies, a flow rate of Q~30 m^3/h will be achievable.

Thermal capacity*:*

$$P_{term} = 0,0012 \cdot (50 - 15) \cdot 30 = 1,26 \ [MW]$$

Thermal energy*:*

$$W_{term} = 9,46 \cdot P_{term}(t_{max}) = 9,46 \cdot 1,26 = 34 \ \left[\frac{TJ}{year}\right]$$

Middle Jurassic aquifer

On the basis of the data concerning the waters in the aquifer in the Sochaczew 2 zone (Fig. 5.5.2), a temperature of 60°C and a flow rate of 90 m^3/h has been assumed (it should be noted that in the area of Sochaczew 1, the much less favourable Middle and Lower Jurassic levels were tested).

Thermal capacity*:*

$$P_{term} = 0,0012 \cdot (60 - 15) \cdot 90 = 4,9 \ [MW]$$

Thermal energy*:*

$$W_{term} = 9,46 \cdot P_{term} = 9,46 \cdot 4,9 = 46 \ \left[\frac{TJ}{year}\right]$$

Lower Jurassic aquifer

On the basis of data on this aquifer in the area of the Skierniewice GT-1 well (Fig. 2), an average temperature of 70°C and a flow rate of 70 m^3/h have been assumed.

Thermal capacity:

$$P_{term} = 0,0012 \cdot (70 - 15) \cdot 70 = 4,6 \ [MW]$$

Thermal energy*:*

$$W_{term} = 9,46 \cdot P_{term} = 9,46 \cdot 4,6 = 44 \ \left[\frac{TJ}{year}\right]$$

In the zone analysed, the *estimated* parameters of geothermal waters contained in the aquifers present in the area are as follows (aquifers have been ordered in descending order according to their energy potentials):

- Middle Jurassic: temperature 60°C, flow rate 90 m^3/h, ceiling depth 2,000 m, mineralisation 100 g/dm^3
- Lower Jurassic: temperature 70°C, flow rate 70 m^3/h, ceiling depth 2,400 m, mineralisation 110 g/dm^3
- Lower Cretaceous: temperature 40°C, flow rate 120 m^3/h, ceiling depth 1,200 m, mineralisation 0.5 g/dm^3
- Upper Cretaceous: temperature 50°C, flow rate 30 m^3/h, ceiling depth 1,350 m, mineralisation 50 g/dm^3

5.5.1.3. Conclusions

After the analysis of available materials and the above estimates, it can be stated that in terms of their energy parameters, the Lower Cretaceous, Middle Jurassic and Lower Jurassic aquifers do not differ significantly with respect to their thermal capacity values, but there are considerable differences in their temperatures. This results in a wider range of potential applications for the geothermal waters present in Jurassic aquifers. However, this should not be considered the main factor determining the choice of the aquifer in question as the optimum one for development and exploitation. For example, the development of Jurassic aquifers, while attractive from the point of view of their energy potential, would involve high investment expenditure since these aquifers are found at depths below 2,000 m and contain highly saline waters. This means not only the need to drill deep wells but also the need to operate a doublet system (with two deep wells required).

In this context, the freshwater **Lower Cretaceous** aquifer, which can be exploited using a single well and where the cost of drilling the well would be much lower (with a ceiling depth of around 1,200 m), appears equally attractive. Moreover, the exploitation of these waters would not necessitate their reinjection into rock formations and thus there would be no problems with maintaining the absorption capacity of the injection well. The estimated flow rates and temperatures (of the order of 120 m^3/h and 40°C, respectively) of the Lower Cretaceous aquifer, which are close to the estimates provided in *Atlas zasobów geotermalnych formacji mezozoicznej na Niżu Polskim* (Górecki [ed.], 2006), indicate that it could be used directly for recreational and/or balneological purposes, while its use for heating purposes would necessitate the use of absorption or compression heat pumps.

Literature:

Bojarski L., Dadlez R. et al., 1973: Dokumentacja wynikowa otworu badawczego Raducz IG-1. Archiwum CAG PIG, Warszawa.

Borowska L., 2006: Opracowanie badań sejsmicznych z tematu „Skierniewice–Łowicz, rejon: Kompina, 2006 r." Archiwum IGSMiE PAN, Kraków.

Górecki W. (ed.) et al., 2006: Atlas zasobów geotermalnych formacji mezozoicznej na Niżu Polskim. Towarzystwo Geosynoptyków. Kraków.

Marek S., Feldman A., 1988: Dokumentacja wynikowa otworu badawczego Różyce IG-2. Archiwum CAG PIG. Warszawa.

Pożaryski W., 1969: Podział obszaru Polski na jednostki tektoniczne. Przegląd Geologiczny 2/1969.

Reicher B., Jarosz Z., 2006: Katalog otworów wiertniczych i studni głębinowych w utworach kredy dolnej i jury dolnej na Niżu Polskim.

5.5.2. Analysis and proposal for heat pump in geoDH in Sochaczew

Available resources

Assumptions concerning the geothermal parameters (Balcer, 2017):
-aquifer level: Lower Cretaceous

- borehole depth: 1,400-1,600 m under the ground level
- assumed maximum water flow rate: 120 m^3/h
- assumed annual average water flow rate: 80 m^3/h
- assumed geothermal water temperature: 40°C
- assumed maximum geothermal water cooling: from 40°C to 15°C
- assumed annual average geothermal water cooling: 20°C
- assumed maximum thermal capacity of the geothermal source: ~ 3.5 MW
- assumed annual average geothermal heat generation: ca. 37 TJ/y,
- water mineralisation will probably be below 1 g/dm^3which will allow for a single-well operation. Cooled water can be reused, e.g. as potable water (similarly to the system used in Mszczonów).

Existing infrastructure

The existing district heating network operates at full (quantitative and qualitative) control, providing the heating power delivered, design parameters for central heating (supply-return-external temperature-calculated external temperature:) 80/60/20/-20°C and for the hot utility water (in the summer) (supply-return:) 65/45°C.
Presently, the heating needs are satisfied by the existing four boiler houses with network natural-gas-burning boilers. The total thermal capacity installed is 15 MW. The total thermal energy generated by the energy sources is estimated at ~142 TJ/y (Balcer, 2017) to 152 TJ/y (Analiza, 2016b, p. 17).

Method of use

With reference to the Operator's assumption (Geotermia Mazowiecka S.A.), a geothermal power plant should rely on the absorption heat pumps supported by high-temperature natural-gas-burning boilers.

Effects

The total thermal power of the geothermal plant is 15 MW, including ~5 MW generated by the absorption heat pumps (1,86 MW from the geothermal source and 3.1 MW from high-temperature natural-gas-burning boilers driving the pumps). The peak-demand supporting boiler capacity will thus amount to ~10 MW.

Energy source model

Customer profile determination

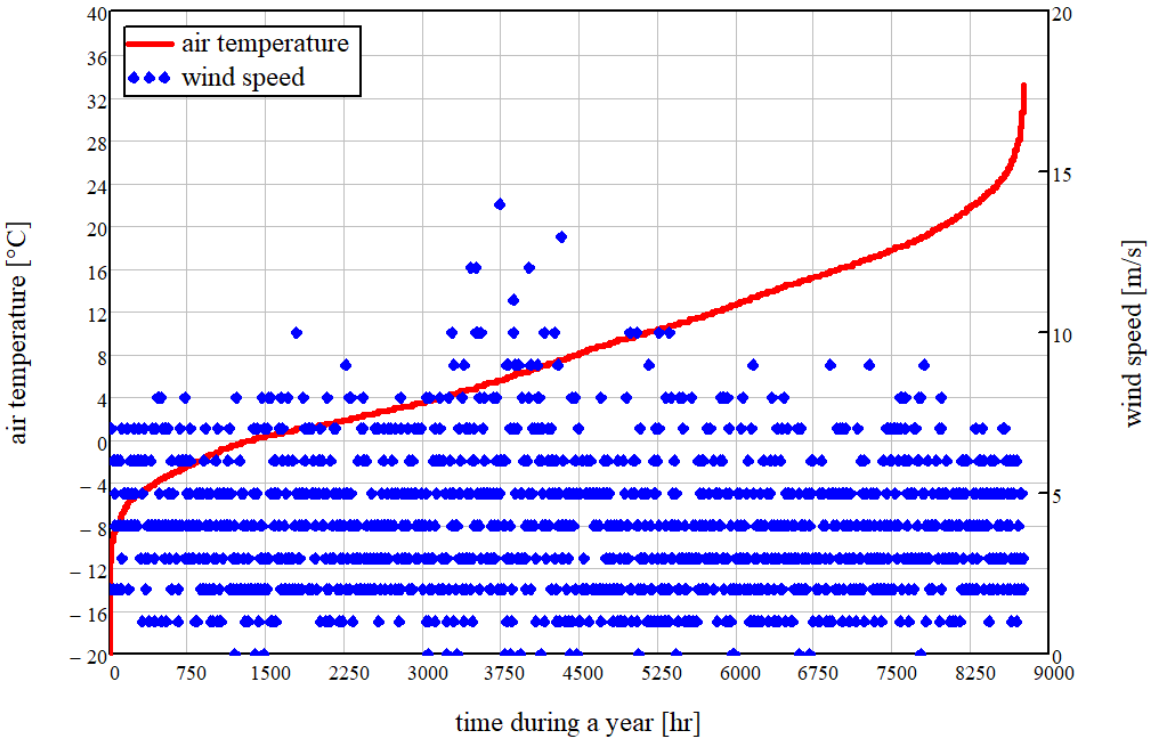


Fig. 5.5.2.1. Local weather conditions for the meteorological station in Warsaw (MIiB 2017)

The customer being currently served by the district heating system of Sochaczew is characterised by the maximum connection capacity of 15 MW, of which ca. 1 MW relates to the hot utility water preparation installation. Working temperature parameters of the customer are determined as 80/60/20/-20°C in winter (central heating + hot utility water) and 65/45°C in summer (hot utility water). The total annual heat energy generation is estimated at ca. 142 TJ/y.

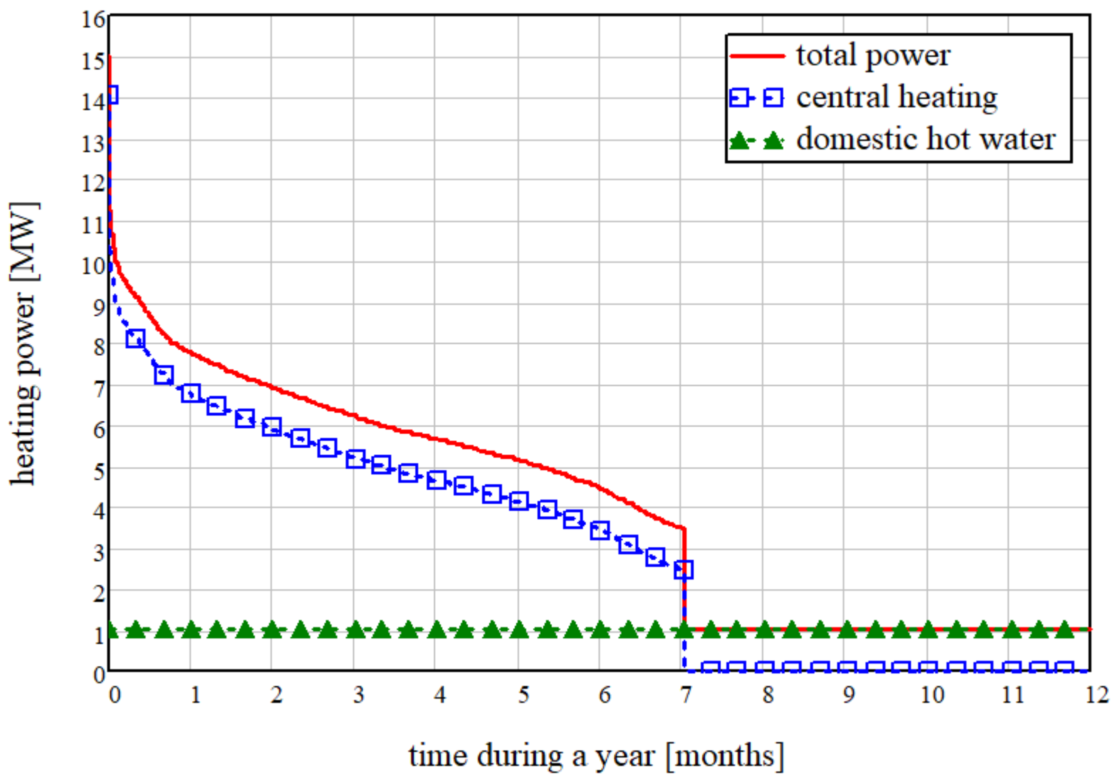


Fig. 5.5.2.2. Characteristics of the thermal power demand, for the recipient being currently served, vs. time

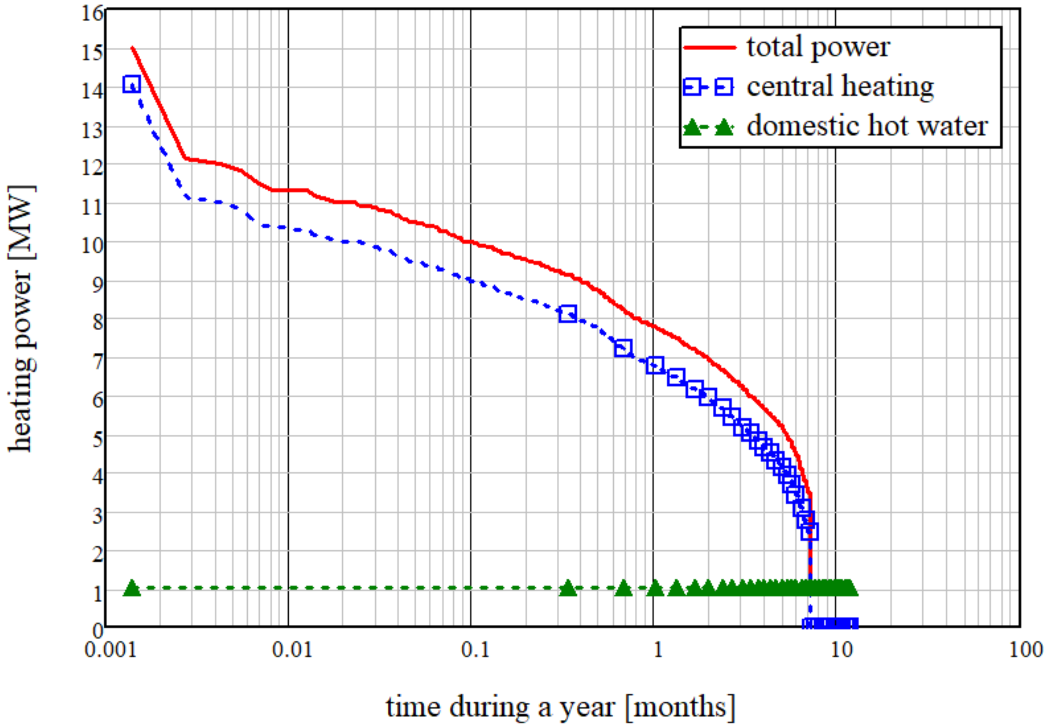


Fig. 5.5.2.3. Characteristics of the instantaneous power demand, for the recipient being currently served, as a function of time – logarithmic scale

Our analyses concerning the verification of the customer profile characteristics assume additional use of the energy originating from a geothermal source, by inclusion to the district heating network of the Aqua Park type of facility, with the water mirror surface area of ca. 1,250 m². The facility is characterised by the maximum demand for thermal capacity of 2,280 kW and the capacity for hot utility water preparation in a volumetric system at 340 kW. The total demand for energy by that facility is estimated at 35.8 TJ/y. The heating installation was designed as a low-temperature system (floor heating, with hot-air blow), with the parameters of 50/35/28/-20°C, and the hot utility water preparation system of 60/20°C.

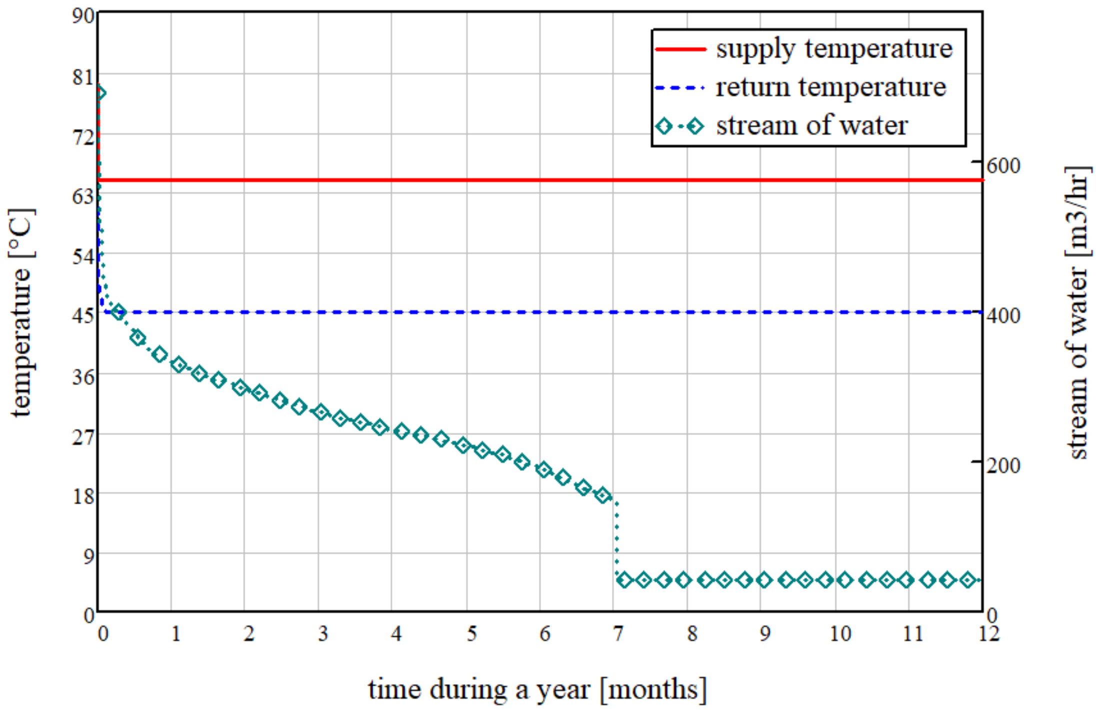


Fig. 5.5.2.4. Dynamic characteristics of the variation of the required flow temperature and the flow of the working fluid, as well as the return temperature obtained, for the customer being currently served by the system

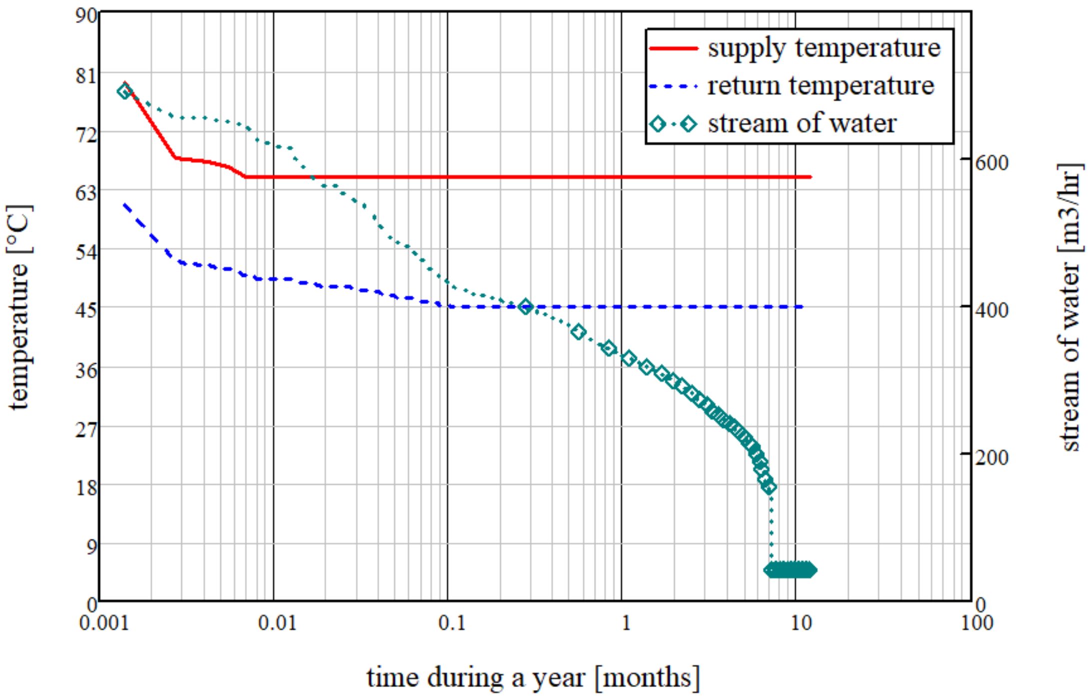


Fig. 5.5.2.5. Dynamic characteristics of the variation of the required flow temperature and the flow of the working fluid, as well as the return temperature obtained, for the customer being currently served by the system – logarithmic scale

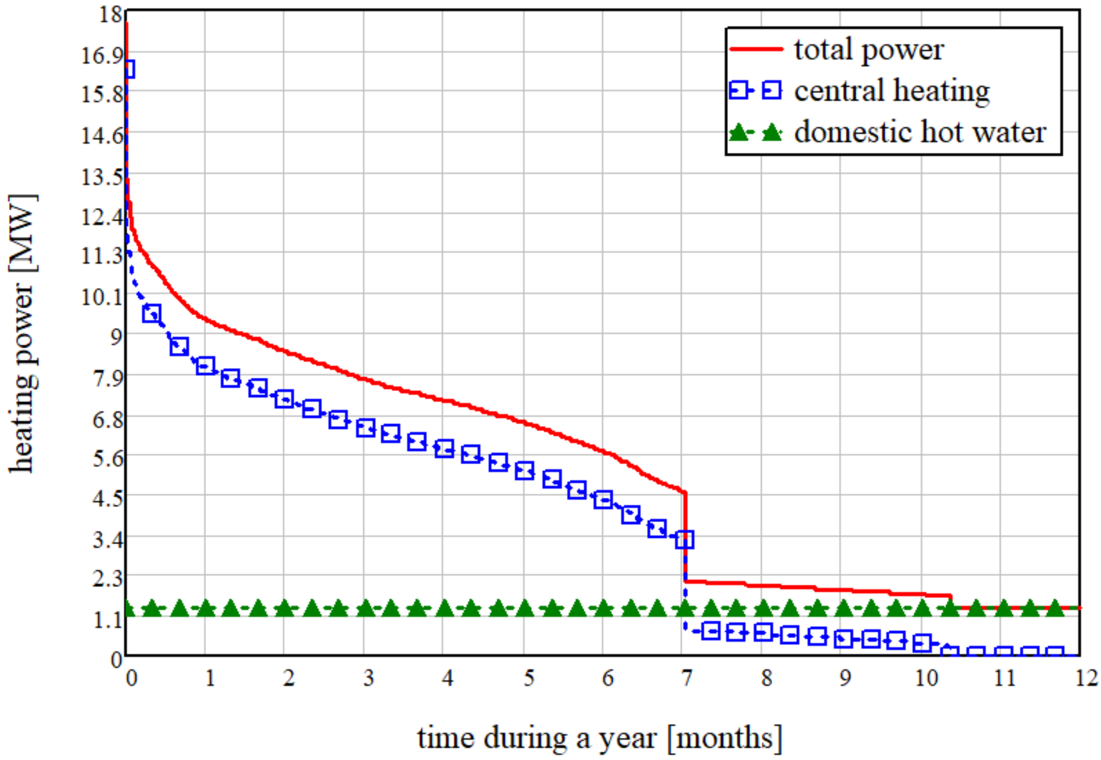


Fig. 5.5.2.6. Dynamic characteristics of the variation of the required flow temperature and the flow of the working fluid, as well as the return temperature obtained, for the “extended customer”

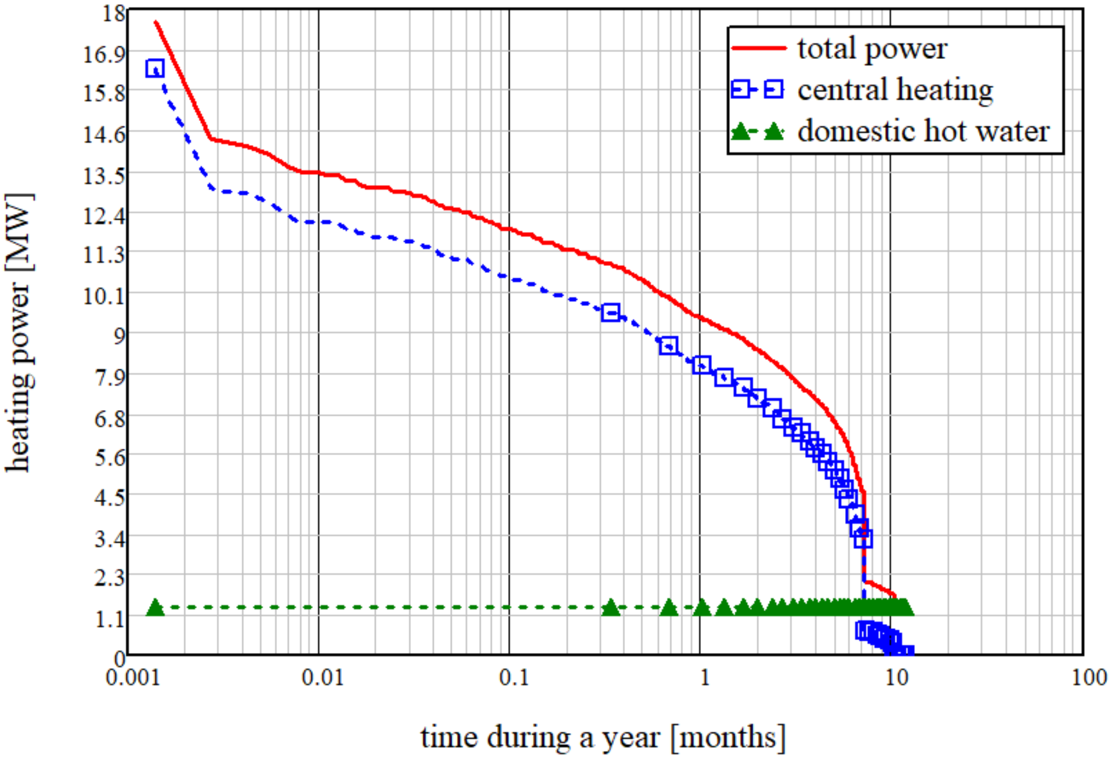


Fig. 5.5.2.7. Dynamic characteristics of the variation of the required flow temperature and the flow of the working fluid, as well as the return temperature obtained, for the “extended customer” – logarithmic scale

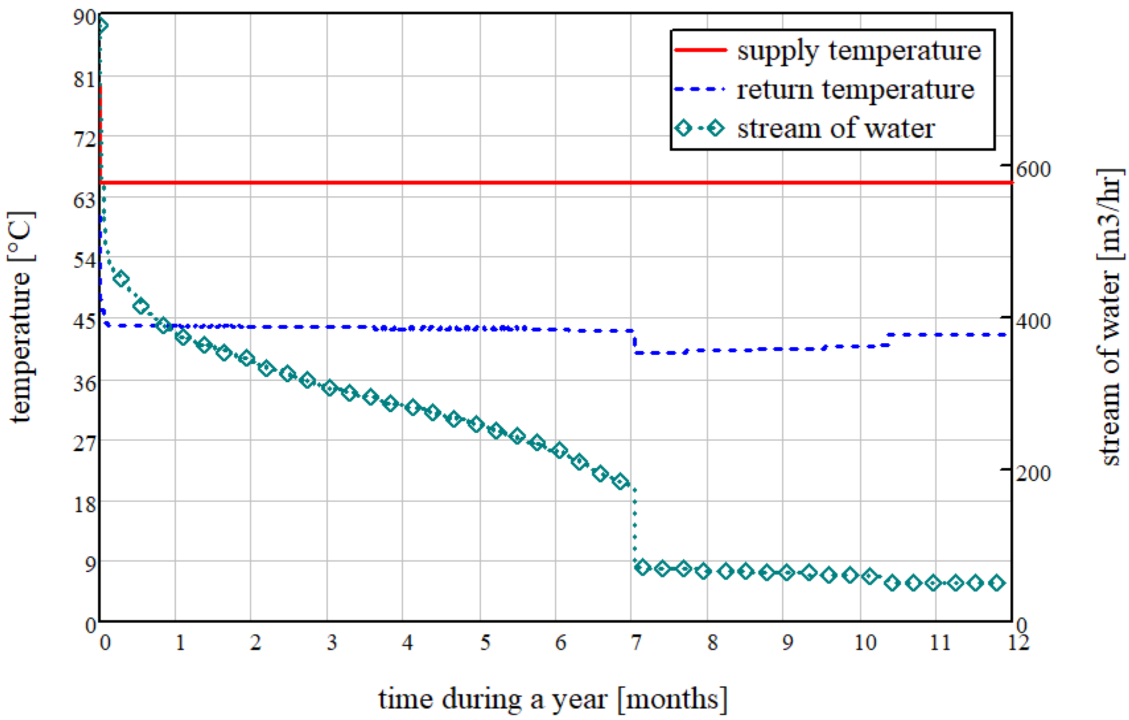


Fig. 5.5.2.8. Dynamic characteristics of the variation of the required flow temperature and the flow of the working fluid, as well as the return temperature obtained, for the “extended customer”

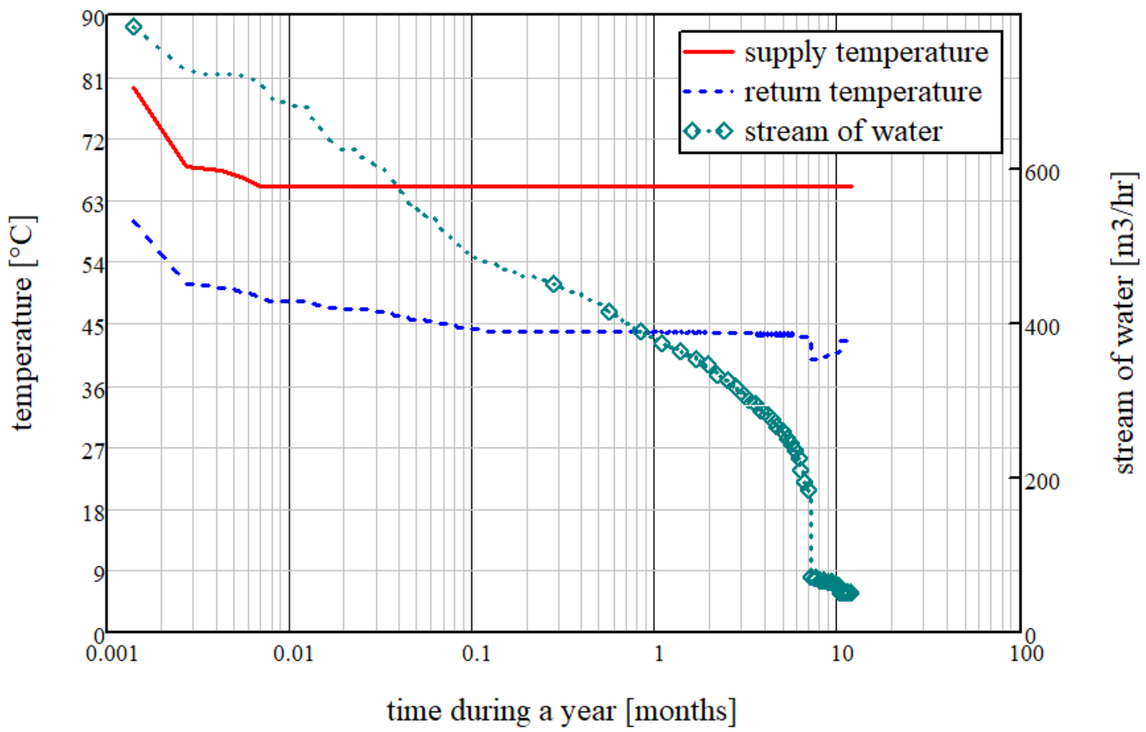


Fig. 5.5.2.9. Dynamic characteristics of the variation of the required flow temperature and the flow of the working fluid, as well as the return temperature obtained, for the "extended customer" – logarithmic scale

Power and economic calculations, as well as the estimations associated with the determination of the ecological effects, were carried out with the use of a mathematical model of the energy source, combined with the predefined customer. The energy source allowed for the possibility of analysing the effects of the operation of many integrated sources under a hybrid system. The general diagram of the source is presented in Fig.5.5.2.10.

The diagram was adjusted to the applicable requirements. The model contained the following elements: a direct geothermal heat exchanger, absorption or compression heat pumps (alternative solution, depending on the calculation option), and peak-demand boilers burning network high-methane natural gas. The following was excluded from analysis: solar collectors, heat-current modules, and alternative-fuel boilers. In the case of the compression heat pumps, our assumption concerned the use of the pumps allowing to obtain the condenser output temperature being higher than that of standard solutions (offering low capacity). That will require the application of high pressure for the condensation of the working medium and other special solutions available on the market.

The prices of the conventional energy media were assumed in accordance with the suggestions of the experts who know the Project and the local price market, as well as the availability of energy media. The prices were taken from the market offerings and they are current as of the second half of 2017. The net network natural gas purchase price was assumed at 110 PLN/MWhr (considering the gas-burning heat at the local area at the level of 39 MJ/m^3, the purchase price per volume will amount to ca. 1,204 PLN/m^3). The net grid electricity purchase price was assumed at 300 PLN/MWhr. The above purchase prices of conventional drive energy media can be recognised as favourable. To compare, the average net prices of those media, determined on the basis of standard settlement tariffs can be estimated at ca. 1.6-1.8 PLN/m^3 for natural gas (in respect of the gas volume , with the heat of combustion at the level of 39 MJ/m^3) and 400-480 PLN/MWhr for the grid electricity.

The level of capital investment expenditure needs to be discussed and clearly resolved. The proposed plant, mainly the heat pumps, are not in serial production or on sale. The purchase prices depend on the course of commercial negotiations. The proposed prices can be recognised as realistic, based on the experience of the authors of this study. As to the absorption heat pumps, the price will also comprise the expenditures spent on the purchase of high-temperature driving boiler and economiser.

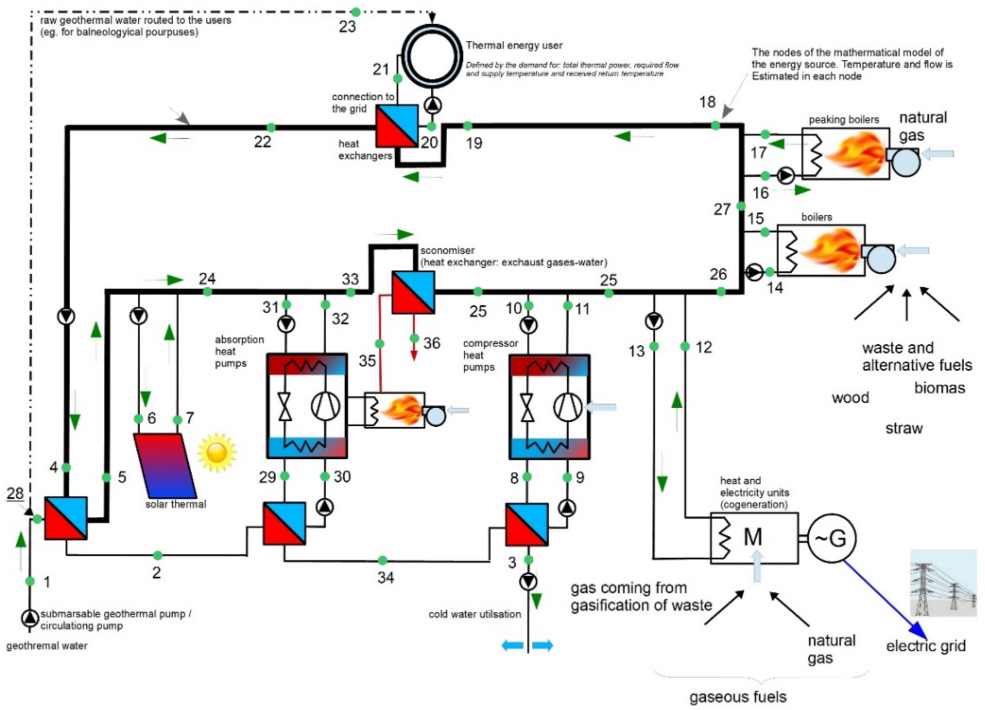


Fig. 5.5.2.10.A diagram of a hybrid energy source which was used for the estimation based on a mathematical model

The following options of using geothermal energy were analysed:

Option ngA (n-atural g-as A-ctual (current) user) – comparative option – references. The option assumed the use of natural gas to satisfy the heating demand of a currently served customer (connected to the district heating network) whose profile is presented in Figs. 5.5.2.2, 5.5.2.3, 5.5.2.4, and 5.5.2.5.

Option ngE (n-atural g-as E-xtended user) – comparative option, assuming that the system will satisfy the heating demand of the "extended customer" (upon connection of a new facility of the Aqua Park type); the customer profile is presented in Figs. 5.5.2.6-5.5.2.9; the peak-demand source consists in natural-gas-burning boilers.

Option ahpA (a-bsorption h-eat p-ump A-ctual (current) user) – this option assumes that the energy source will serve the customers who are currently connected to the network (Figs. 5.5.2.2-5.5.2.5). The energy source uses geothermal resources with the application of absorption heat pumps.

Option chpA (c-ompressor h-eat p-ump A-ctual (current) user) – this option assumes serving the customers who are currently connected to the network (Figs. 5.5.2.2-5.5.2.5), using geothermal resources with the application of compression heat pumps.

Option ahpE (a-bsorption h-eat p-ump E-xtended user) – this option assumes serving the "extended customer" (Figs. 5.5.2.6-5.5.2.9), using geothermal resources with the application of absorption heat pumps.

Option chpE (c-ompressor h-eat p-ump E-xtended user) – this option assumes serving the "extended customer" (Aqua Park), using geothermal resources with the application of compression heat pumps.

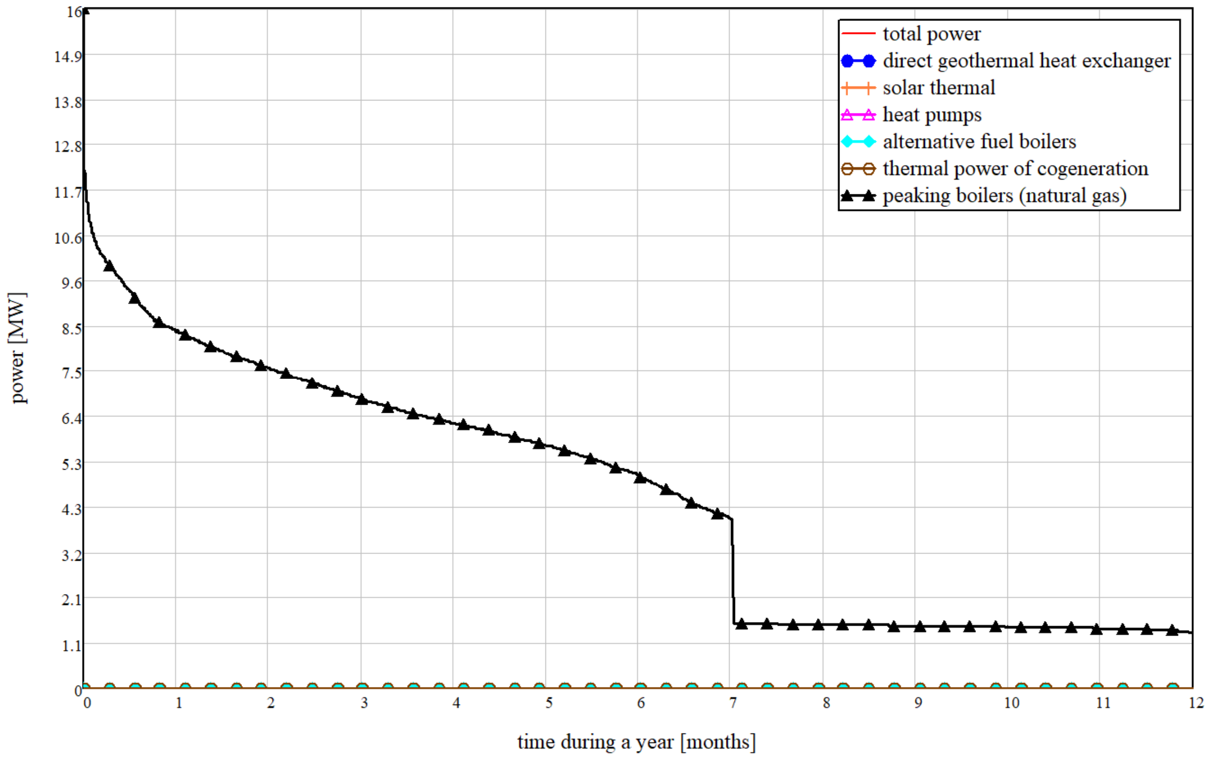


Fig. 5.5.2.11.A diagram of a source of energy operation in Option ngA

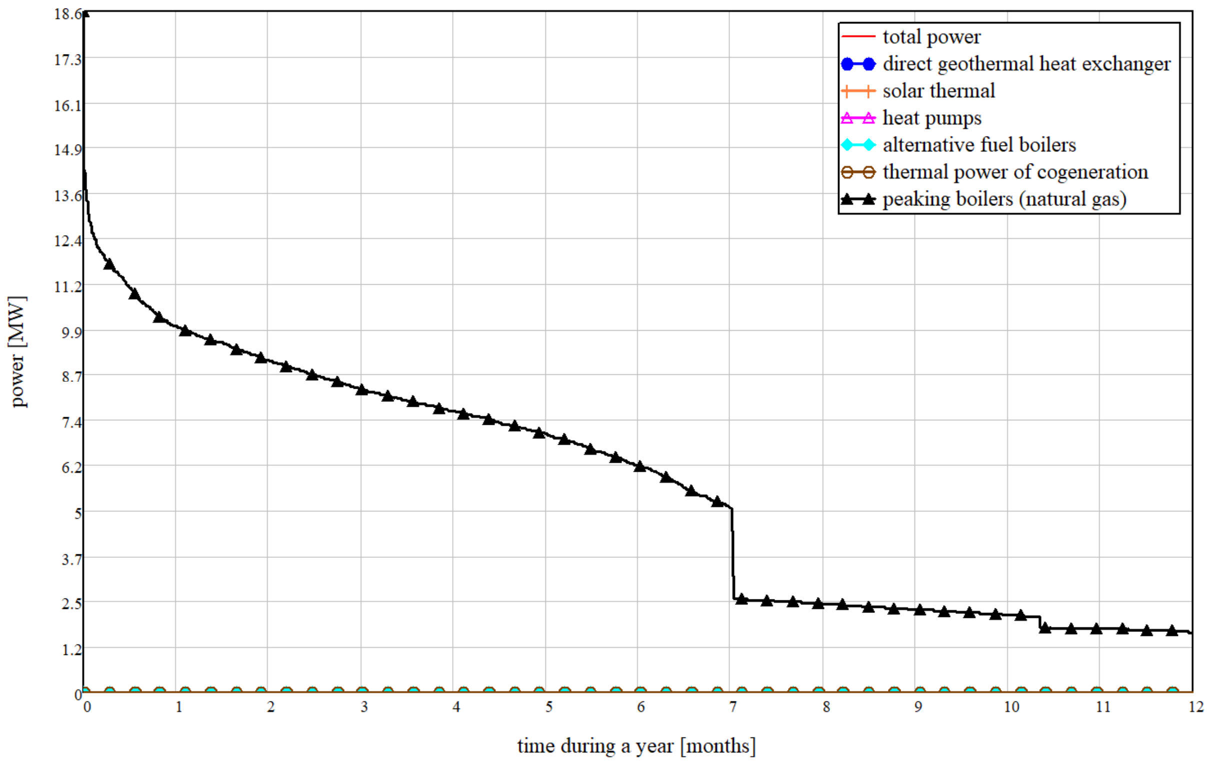


Fig. 5.5.2.12. A diagram of a source of energy operation in Option ngE

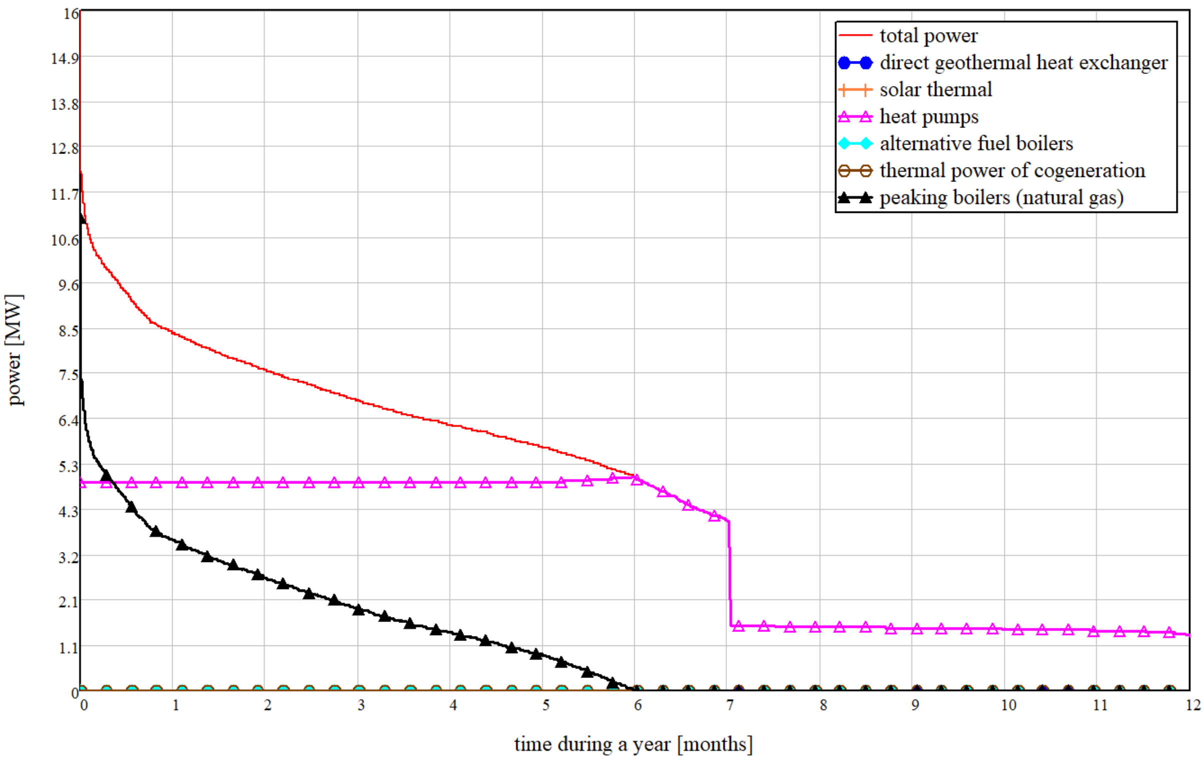


Fig. 5.5.2.13. A diagram of a source of energy operation in Option ahpA

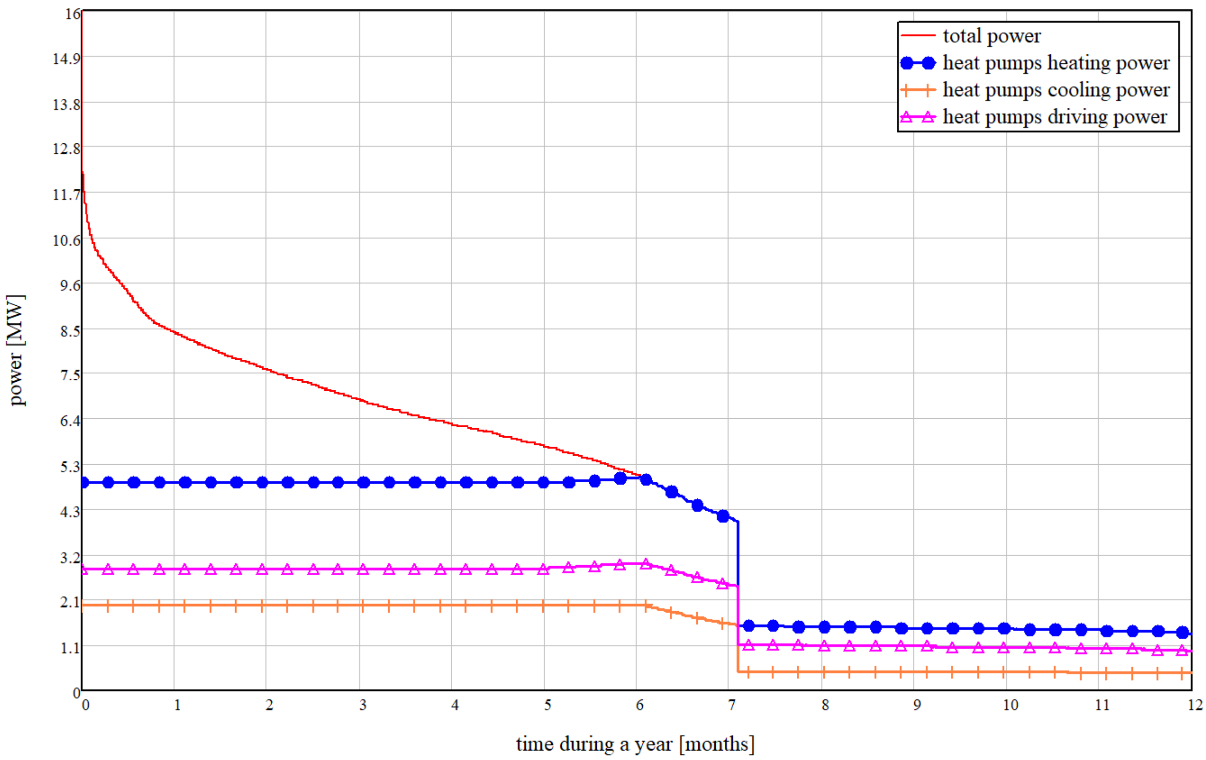


Fig. 5.5.2.14. Shares of cooling (geothermal) and drive power for heat pumps in Option ahpA

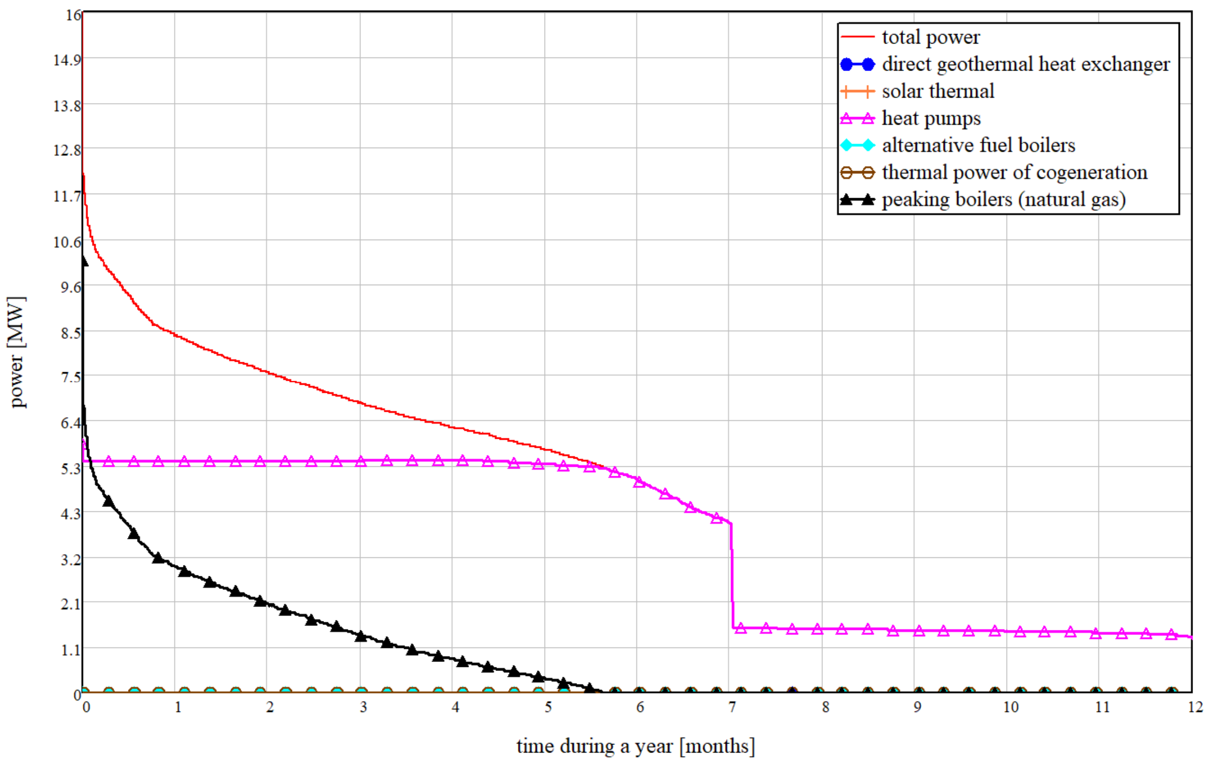


Fig. 5.5.2.15. A diagram of a source of energy operation in Option chpA

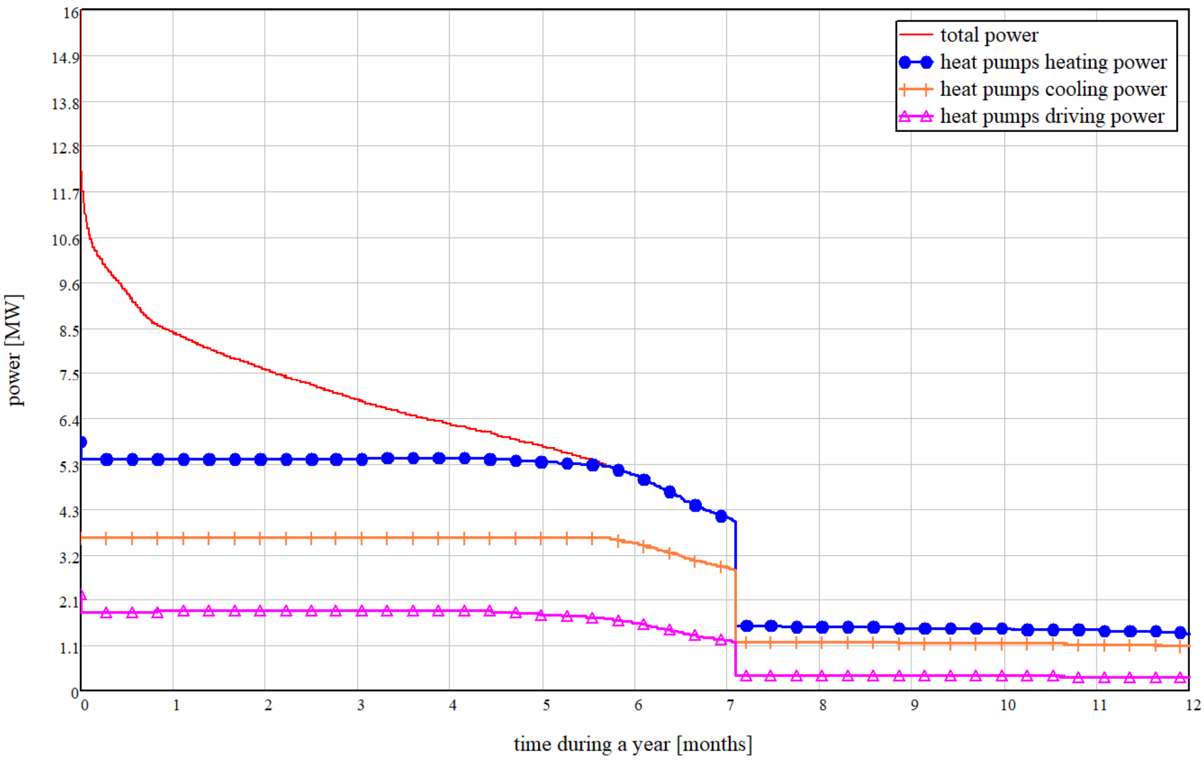


Fig. 5.5.2.16. Shares of cooling (geothermal) and drive power for heat pumps in Option chpA

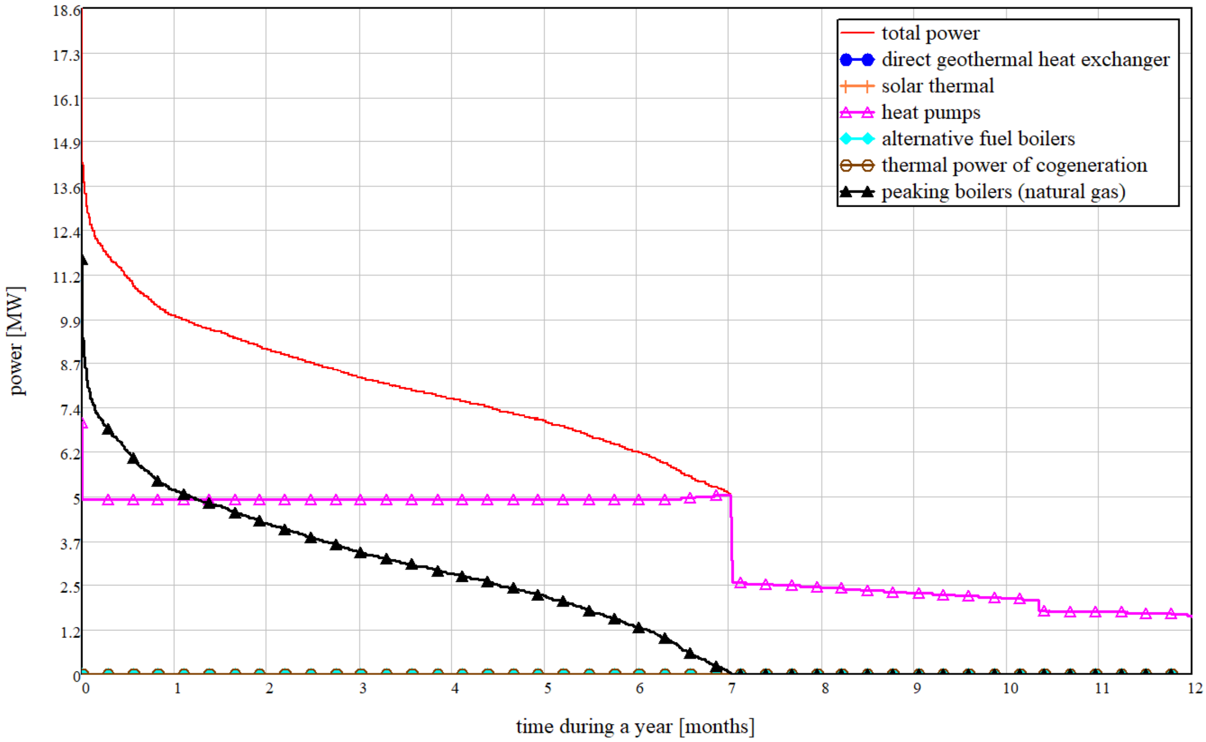


Fig. 5.5.2.17. A diagram of a source of energy operation in Option ahpE

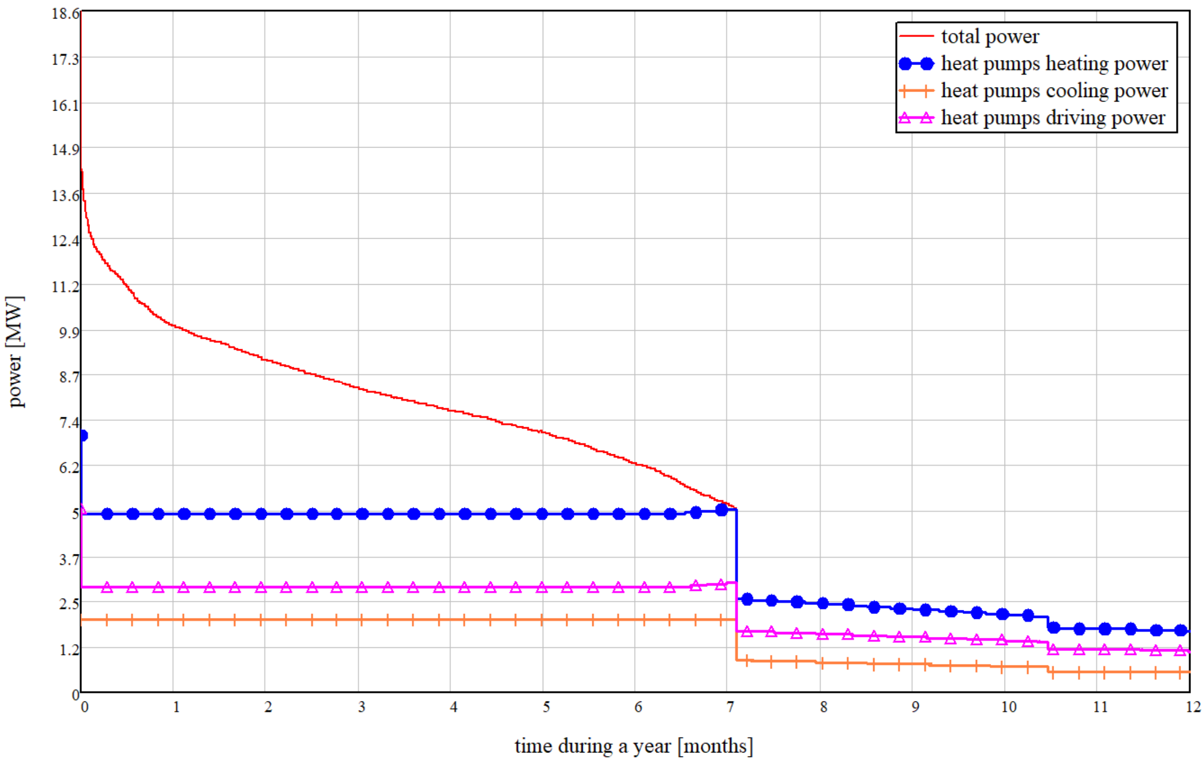


Fig. 5.5.2.18. Shares of cooling (geothermal) and drive power for heat pumps in Option ahpE

Table 5.5.2.1 contains the list of main technical, economic, and power parameters of the analysed Options. The estimated ecological effect was specified in two options:

- Local effect: referring to the forecast emissions of nine selected substances polluting the air. It does not take into account the emissions generated during the production of electricity used by the heat pump and circulation pump operation,
- Global effect (effect on a global scale): taking into account pollution emission generated by the power plant during the production of electricity used by the installation of the energy source analysed here.

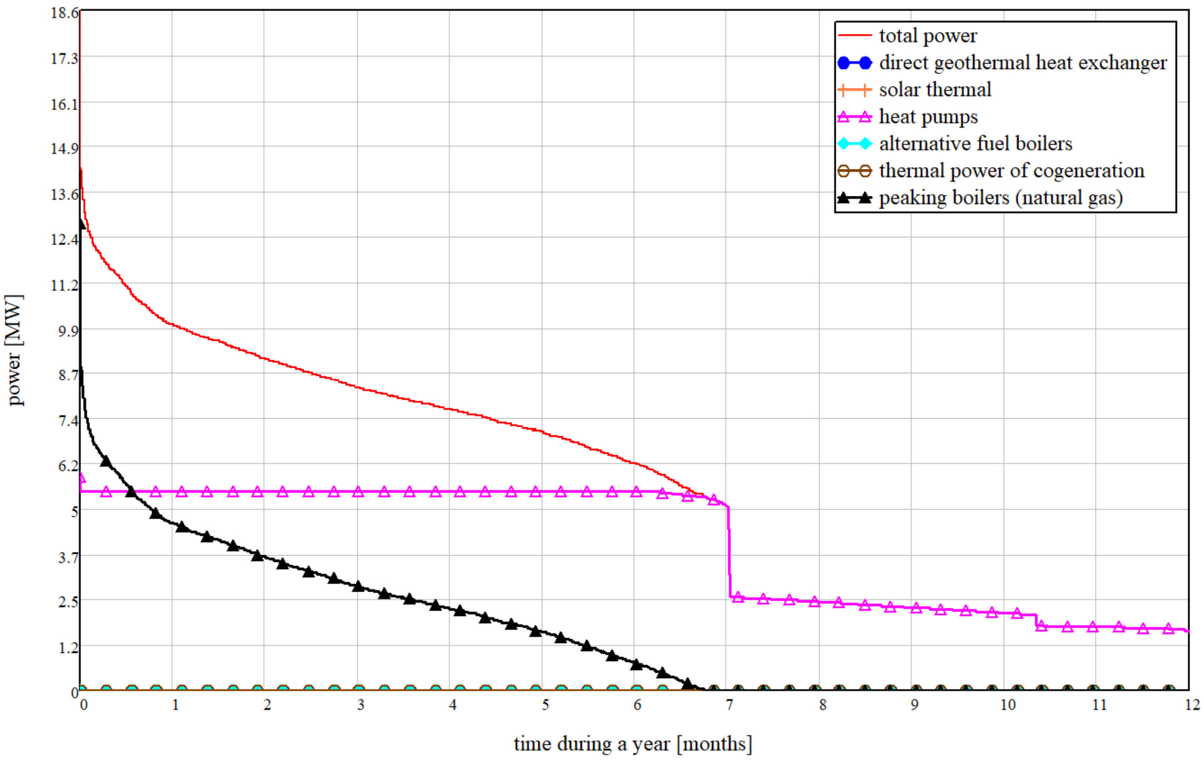


Fig. 5.5.2.19. A diagram of a source of energy operation in Option chpE

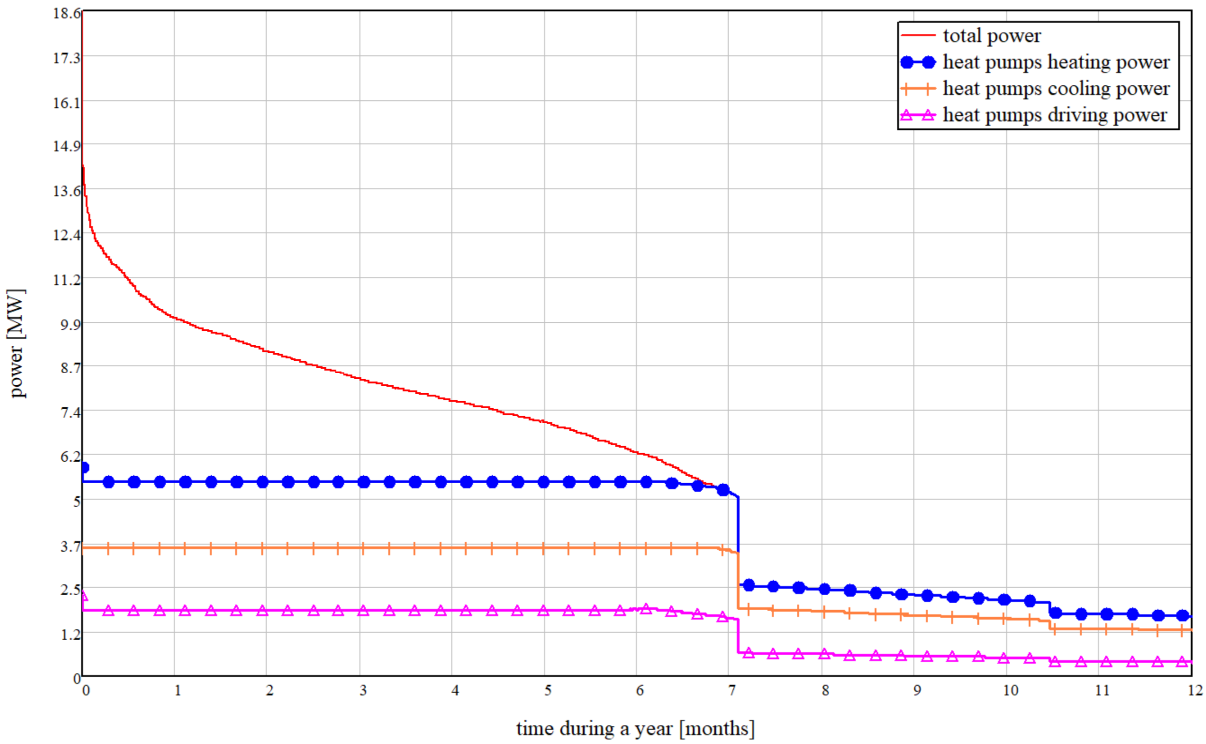


Fig. 5.5.2.20. Shares of cooling (geothermal) and drive power for heat pumps in Option chpE

Tale 5.5.2.1.Summary of the main technical and economic parameters characterizing the analyzed variants for the town of Sochaczew

Parameter	Values					
Description of the variant	ngA	ahpA	chpA	ngE	ahpE	chpE
Maximal thermal power consumption [kW]	15037	15037	15037	17651	17651	17651
Consumption of thermal energy consumed by the user [GJ/year]	126103	126103	126103	161932	161932	161932
Annual value of the load factor [-]	0,266	0,266	0,266	0,291	0,291	0,291
Supply temperature (maximum = nominal) [°C]	79,3	79,3	79,3	79,3	79,3	79,3
Return temperature (maximum = nominal) [°C]	60,7	60,7	60,7	60	60	60
Nominal flow of working medium [m^3/hr]	692,5	692,5	692,5	783,7	783,7	783,7
Estimated length of main pipelines [m]	20000	20000	20000	20000	20000	20000
Calculated maximum power losses on transmission [kW]	934	934	934	933	933	933
Calculated energy loss during distribution [GJ/year]	15981	15981	15981	15483	15483	15483
Net purchase price of natural gas [PLN/m^3]	1,204	1,204	1,204	1,204	1,204	1,204
Net purchase price of electricity network [PLN/MWhr]	300	300	300	300	300	300
Selling price of electricity produced in thermal and current modules [PLN/MWhr]	250	250	250	250	250	250
---------- Description of energy sources ----------						
1. ----- Geothermal (direct use) -----						
1.1. Depth of geothermal horizon [m below ground level]	0	1600	1600	0	1600	1600
1.2. Water temperature driven to evaporator of heat pumps [°C]	8	40	40	8	40	40
1.3. Water stream [m^3/hr]	0	90	90	0	90	90
1.4. Assumed static water level [m bgl]	0	100	100	0	100	100
1.5. Assumed unitary depression [m / m^3/hr]	1	1	1	1	1	1
1.6. Production borehole status ('new', 'existing', 'reconstruction', 'no well')	new	new	new	new	new	new
1.7. Injection borehole status ('new', 'existing', 'reconstruction', 'no well')	no well	no well	no well	no well	no well	no well
1.8. Assembled borehole diameter [m]	0	0,24448	0,24448	0	0,24448	0,24448
1.9. Maximal temperature reached on the production wellhead [°C]	8,3	39,1	39,1	8,3	39,1	39,1
1.10. Maximal power achieved on direct heat exchanger (without heat pumps) [kW]	0	0	0	0	0	0
1.11. The amount of energy obtained from the direct heat exchanger [GJ/year]	0	0	0	0	0	0
1.12. Nominal driving power estimatet for goethermal water pumps (exploitation and reinjection) [kW]	0	100	100	0	100	100
1.13. Electricity consumption by geothermal pumps [MWhr/year]	0	872	872	0	872	872
2.6. The amount of heat input to the customer's installation [GJ/year]	0	0	0	0	0	0
3. ----- Heat pumps (low energy source: geothermal) -----						
3.1. Heating capacity installed (maximal used) [kW]	0	4996	5825	0	7013	5825
3.2. Maximal working medium temperature at evaporator outlet [°C]	62,15	73,36	73,36	61,52	71,54	71,54
3.3. Maximal allowable water temperature at evaporator outlet [°C]	95	95	80	95	95	80

3.4. Minimum temperature of water at evaporator outlet [°C]	20	20	5	20	20	5
3.5. Maximum value of COP (on heating side) [-]	1,64	1,7	4,49	1,7	1,7	4,37
3.6. The amount of heat generated by heat pumps [GJ/year]	0	107764	115962	0	117514	127475
3.7. Amount of used drive energy consumed to drive the heat pump [MWhr/year]	0	18291	10229	0	19814	11321
3.8. Amount of used electric power used to drive geothermal pumps [MWhr/year]	0	872	872	0	872	872
6. ----- Peak boilers for natural gas -----						
6.1. Maximum installed power (used) in gas boilers [kW]	15971	11105	10146	18584	11570	12759
6.2. The amount of thermal energy produced in gas boilers [GJ/year]	142083	34319	26121	177415	59901	49940
Estimated investment outlays for heat source [thousands PLN]	12926	30004	32387	15041	34378	34501
- production well [thousands PLN]	0	9119	9119	0	9119	9119
- well for reinjection [thousands PLN]	0	0	0	0	0	0
- direct heat exchanger [thousands PLN]	0	0	0	0	0	0
- heat pumps [thousands PLN]	0	7494	9902	0	10520	9902
- peak boilers for natural gas [thousands PLN]	9583	6663	6088	11150	6942	7655
- connection pipelines and transmission lines [thousands PLN]	0	1000	1000	0	1000	1000
- energy source building [thousands PLN]	426	426	426	496	496	496
- cost of assembly, reserve for unexpected expenses [thousands PLN]	2917	5302	5852	3395	6300	6329
Total annual operating costs [thousands PLN/year]	6270	6040	6434	7758	7512	7809
- constant costs [thousands PLN/year]	840	1950	2105	978	2235	2243
- flexible costs [thousands PLN/year]	5430	4090	4329	6781	5277	5567
- depreciation of fixed assets [thousands PLN/year]	646	1500	1619	752	1719	1725
- costs of maintenance and repairs [thousands PLN/year]	194	450	486	226	516	518
- costs of buying conventional energy carriers [thousands PLN/year]	5430	4090	4329	6781	5277	5567
Unitary costs of energy generation (excluding transmission losses) [PLN/GJ]	44	43	45	44	42	44
The price of energy for final customer (including transimission losses) [PLN/GJ]	50	48	51	48	46	48
Emission of pollutants emission related to the unit of generated heat [kg/GJ]						
- benzo (a) pyrene locally	0	0	0	0	0	0
- soot locally	0	0	0	0	0	0
- total dust locally	0	0	0	0	0	0
- CO2 locally	68,145	48,04	12,528	66,263	49,014	18,652
- CO locally	0,012	0,009	0,002	0,012	0,009	0,003
- NOx (recalculated to the NO2) locally	0,044	0,031	0,008	0,043	0,032	0,012
- SO2 locally	0	0	0	0	0	0
- aliphatic hydrocarbons locally	0,037	0,026	0,007	0,036	0,027	0,01
- aromatic hydrocarbons locally	0,001	0,001	0	0,001	0,001	0
- benzo (a) pyrene in global scale	0	0	0	0	0	0

- soot in global scale	0	0	0,002	0	0	0,001
- total dust in global scale	0	0,003	0,034	0	0,002	0,029
- CO2 in global scale	68,145	55,284	104,702	66,263	54,655	97,497
- CO in global scale	0,012	0,025	0,212	0,012	0,022	0,183
- NOx (recalculated to the NO2) in global scale	0,044	0,044	0,176	0,043	0,042	0,155
- SO2 in global scale	0	0,045	0,57	0	0,035	0,487
- aliphatic hydrocarbons in global scale	0,037	0,026	0,007	0,036	0,027	0,01
- aromatic hydrocarbons in global scale	0,001	0,002	0,011	0,001	0,001	0,009

Summary and conclusions

The analyses of the effects of the use of geothermal energy for district heating purposes in Sochaczew, conducted on the basis of specific calculations, confirm a possibility of obtaining positive energy, economic, and ecological effects. Owing to the low temperature of geothermal waters, it will be necessary to apply heat pumps in the heating system. Two types of pumps were analysed: absorption pumps, driven by high-temperature natural-gas-burning boiler, and compression pumps, driven by electricity. The heat pump time operation, for both presently connected customers and after the group of customers has been increased by inclusion of swimming pools, was similar (Figs. 5.5.2.16-5.5.2.20). Unfortunately, the capital investments necessary for the implementation of the new energy source and low temperature of geothermal waters will not cause any reduction of the energy purchase price by the final user, in comparison to the price of energy generated by network natural-gas burning. A lower purchase price can be expected by the customers under the Options assuming the uses of absorption pumps. All the Options assuming the use of geothermal energy are characterised by a positive local emission reduction effect. Global emission reduction concerns the Options assuming the use of absorption heat pumps. Pollution emission reduction concerns mainly carbon dioxide (CO_2). That effect is much demanded, in the light of the necessity of CO_2emission limitation on a global scale.

Having considered the analysed economic and ecological effects, we can recognise that the use of absorption pumps will constitute the best option.

References:

Balcer M., 2017: Koncepcja geotermalnego uciepłownienia miasta Sochaczew.

Analiza uwarunkowań wykorzystania zasobów geotermalnych dla Gminy Miasto Sochaczew. Listopad 2016.

Ministerstwo Infrastruktury i Budownictwa Rzeczypospolitej Polskiej, 2017. Typowe lata meteorologiczne i statystyczne dane klimatyczne do obliczeń energetycznych budynków. Źródło: typowe lata meteorologiczne i statystyczne dane klimatyczne do obliczeń energetycznych budynków, dostęp 2017.09.11.

5.5.3. Energetic–economic optimisation of drilling a single production well to supply geothermal energy to existing district heating system (space heating, domestic hot water) in Sochaczew town

The energy and economic optimisation of drilling a single production borehole, to be used for district heating purposes in Sochaczew was intended to determine the feasibility of drilling more than one operating borehole.Considering the district heating network parameters, in reference to the geothermal water deposit parameters, we noticed that the main barrier that limited the use of geothermal energy consisted in lack of temperature coherence. The geothermal water deposit provides the temperature of ca. 40°C, and that is not adequate for the customers' requirements. The lowest return temperature is estimated at 45°C (Fig. 5.5.2.4).For that reason, the energy source operation always requires the uses of heat pumps. The increase of the number of boreholes within the system will cause increased streams and, consequently, the capacity that can be used, although the system head temperature will not change.The graphs presenting the diagram of covering the customers' thermal demand by the analysed energy sources (Figs. 5.5.2.13, 5.5.2.15, 5.5.2.17, and 5.5.2.19) indicate that the capacity obtained from heat pumps,with the use of geothermal water as the lower source,will meet the base capacity requirement. The use of the capacity installed in the heat pumps is even in time. The additional capacity installed in heat pumps can be replaced by peak-demand boilers.However, that can be done at the cost of a considerable increase of capital investments.

The answer to this question seems to be of key importance: Will the profit of reducing variable costs of electricity production cover the increased fixed costs, associated with the initial capital investments?All the Options assuming the drilling of an additional production borehole have been marked by adding: "(+1)" (plus one additional borehole) .

Figs. 5.5.3.1 – 5.5.3.8 present diagrams of the coverage of the peak demand, in the Option assuming the use of two production boreholes and heat pumps.The technical, economic, and ecological parameters of the energy source with modernised energy recipients are presented in Table 5.5.3.1.

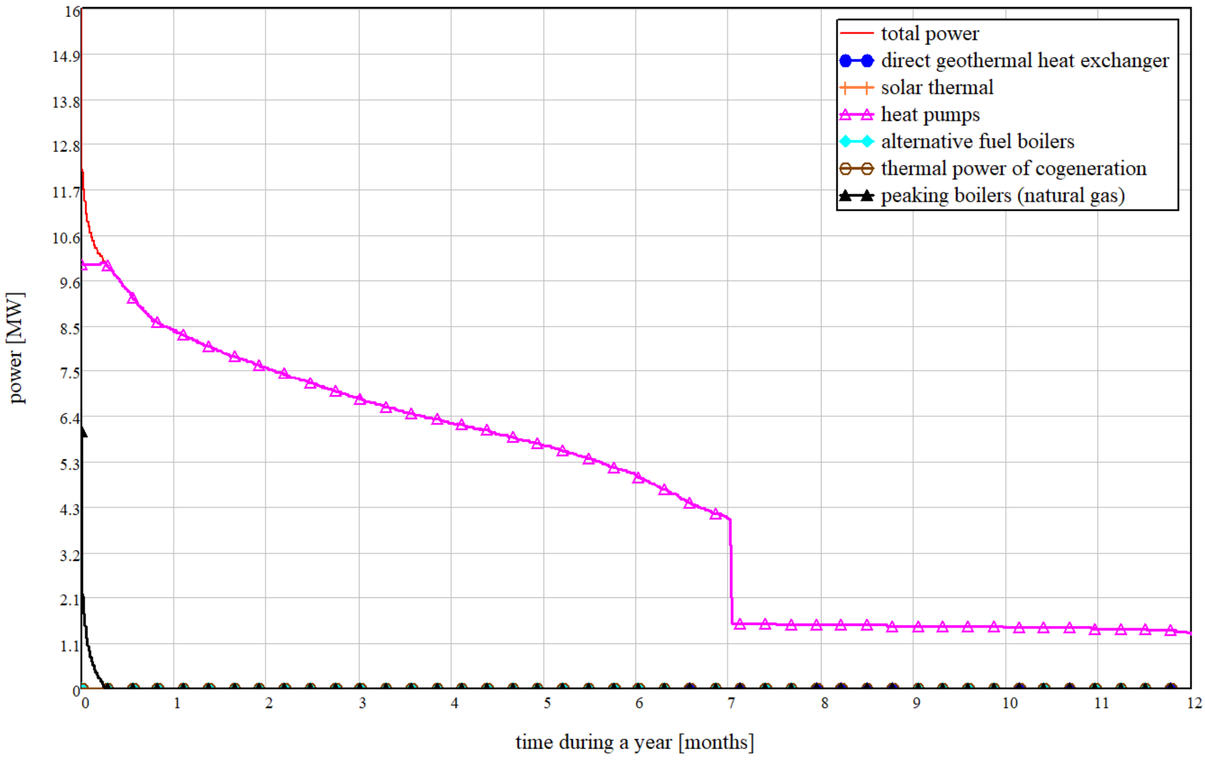


Fig. 5.5.3.1. A diagram of a source of energy operation in Option ahpA(+1), assuming geothermal operation with two production wells

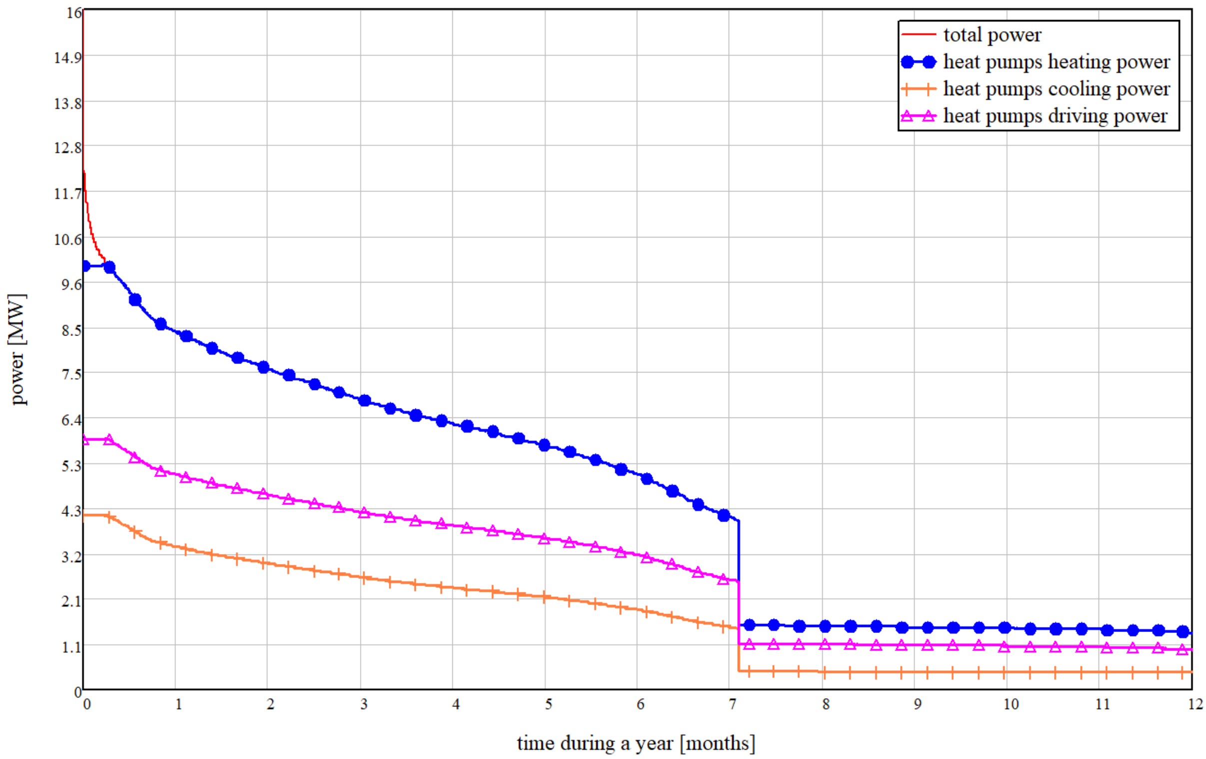


Fig. 5.5.3.2. Shares of cooling (geothermal) and drive power for heat pumps in Option ahpA(+1)

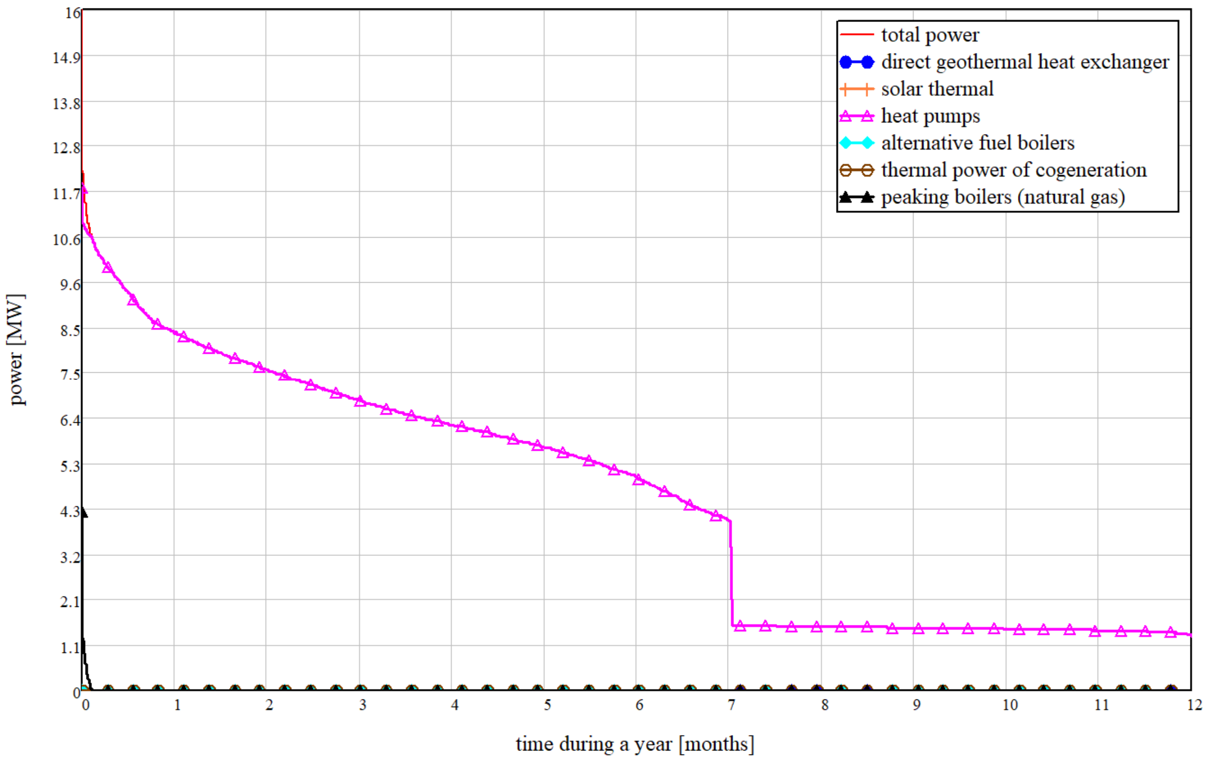


Fig. 5.5.3.3. A diagram of a source of energy operation in Option chpA(+1), assuming geothermal operation with two production wells

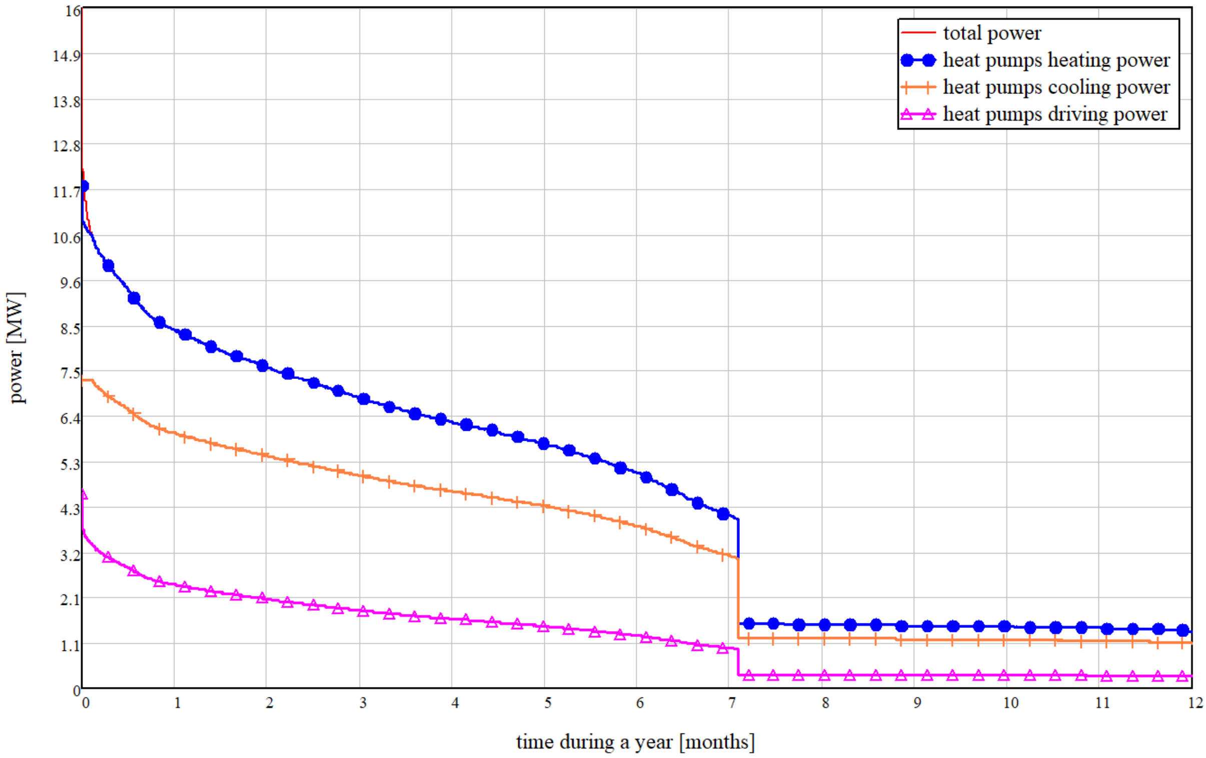


Fig. 5.5.3.4. Shares of cooling (geothermal) and drive power for heat pumps in Option chpA(+1)

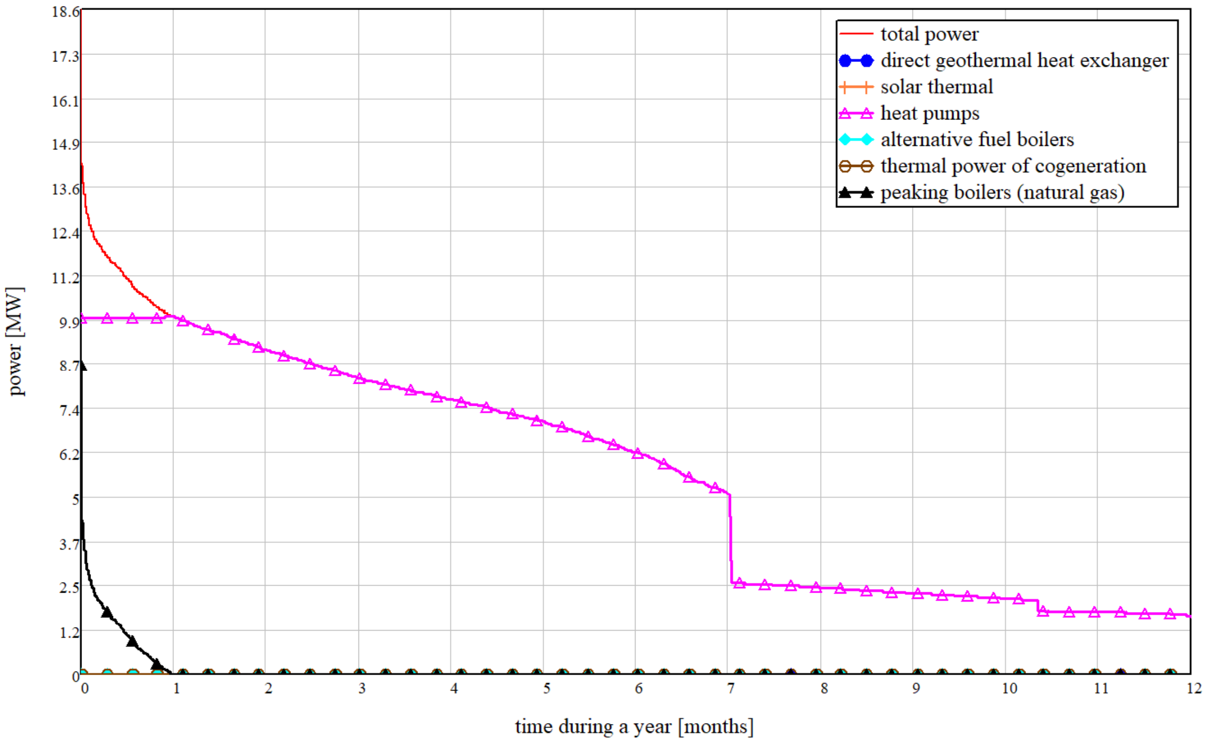


Fig. 5.5.3.5. A diagram of a source of energy operation in Option ahpE(+1), assuming geothermal operation with two production wells

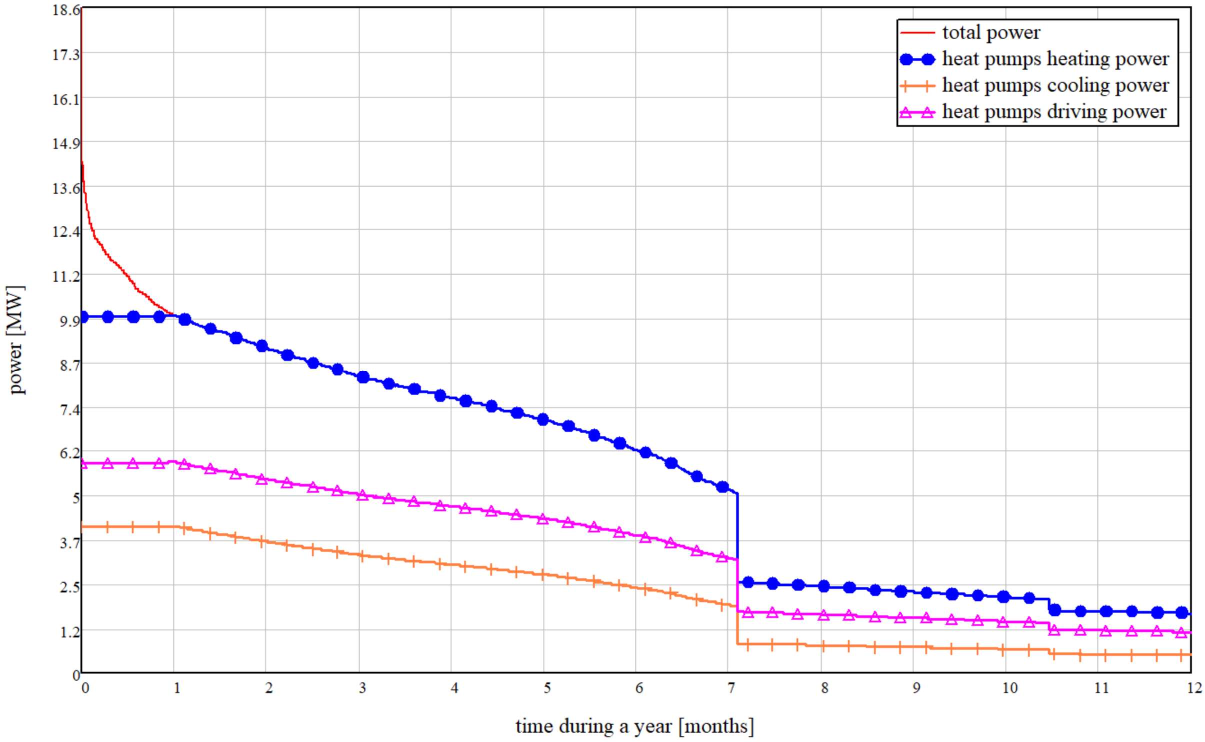


Fig. 5.5.3.6. Shares of cooling (geothermal) and drive power for heat pumps in Option ahpE(+1)

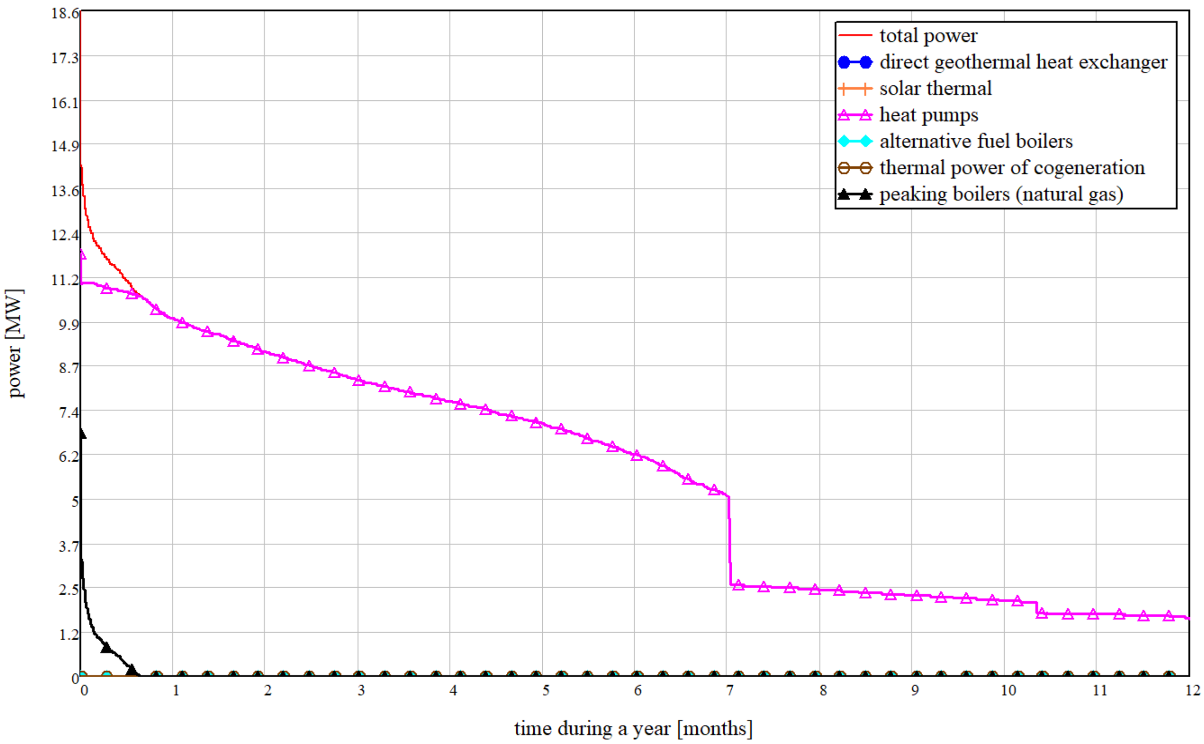


Fig. 5.5.3.7. A diagram of a source of energy operation in Option chpE(+1), assuming geothermal operation with two production wells

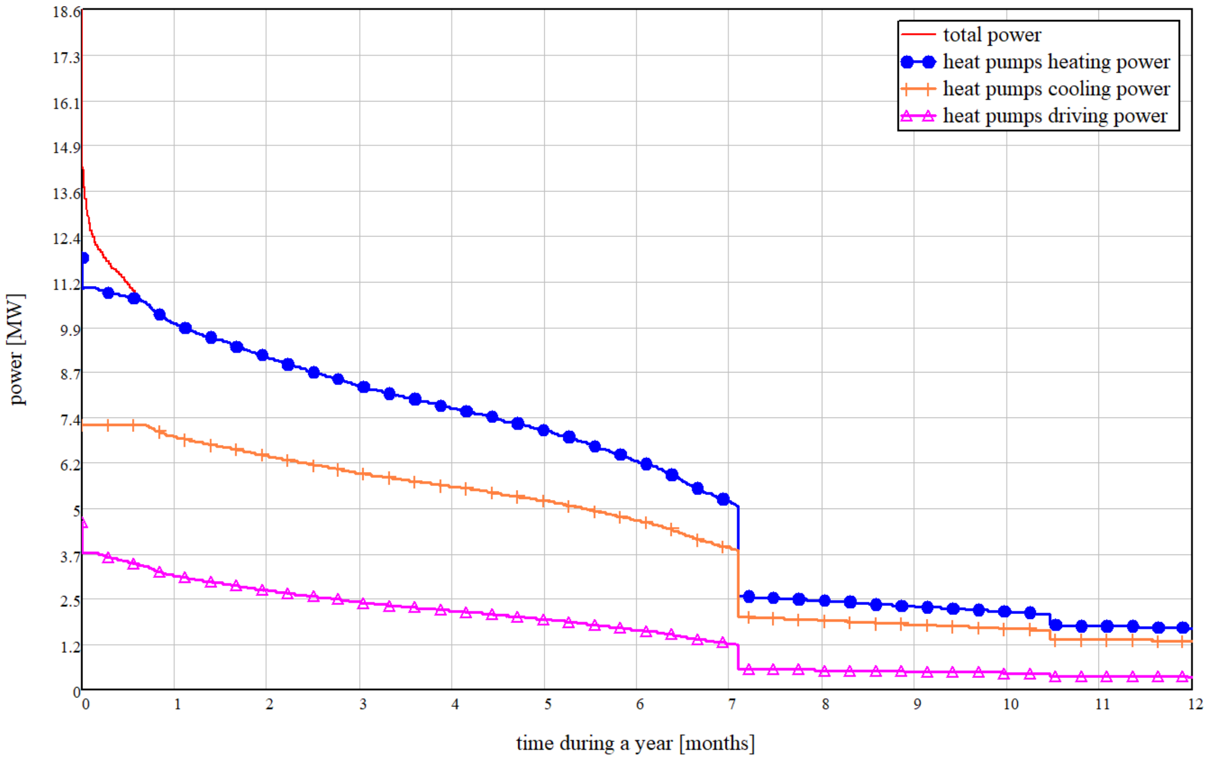


Fig. 5.5.3.8. Shares of cooling (geothermal) and drive power for heat pumps in Option chpE(+1)

Table 5.5.3.1. Summary of the main technical and economic parameters characterising the analysed Options for the town of Sochaczew

Parameter	Values					
Description of the variant	ngA	ahpA(+1)	chpA(+1)	ngE	ahpE(+1)	chpE(+1)
Maximal thermal power consumption [kW]	15037	15037	15037	17651	17651	17651
Consumption of thermal energy consumed by the user [GJ/year]	126103	126103	126103	161932	161932	161932
Annual value of the load factor [-]	0,266	0,266	0,266	0,291	0,291	0,291
Supply temperature (maximum = nominal) [°C]	79,3	79,3	79,3	79,3	79,3	79,3
Return temperature (maximum = nominal) [°C]	60,7	60,7	60,7	60	60	60
Nominal flow of working medium [m3/hr]	692,5	692,5	692,5	783,7	783,7	783,7
Nominal geothermal water outflow [m3/hr]	0	0	0	0	0	0
Estimated length of main pipelines [m]	20000	20000	20000	20000	20000	20000
Calculated maximum power losses on transmission [kW]	934	934	934	933	933	933
Calculated energy loss during distribution [GJ/year]	15981	15981	15981	15483	15483	15483
Net purchase price of natural gas [PLN/m3]	1,204	1,204	1,204	1,204	1,204	1,204
Net purchase price of electricity network [PLN/MWhr]	300	300	300	300	300	300
Selling price of electricity produced in thermal and current modules [PLN/MWhr]	250	250	250	250	250	250
----------- Description of energy sources ----------						
1. ----- Geothermal (direct use) -----						
1.1. Depth of geothermal horizon [m below ground level]	0	1600	1600	0	1600	1600
1.2. Water temperature driven to evaporator of heat pumps [°C]	8	40	40	8	40	40
1.3. Water stream [m3/hr]	0	180	180	0	180	180

1.4. Assumed static water level [m bgl]	0	100	100	0	100	100
1.5. Assumed unitary depression [m / m3/hr]	1	1	1	1	1	1
1.6. Production borehole status ('new', 'existing', 'reconstruction', 'no well')	new	new	new	new	new	new
1.7. Injection borehole status ('new', 'existing', 'reconstruction', 'no well')	no well	no well	no well	no well	no well	no well
1.8. Assembled borehole diameter [m]	0	0,244475	0,244475	0	0,244475	0,244475
1.9. Maximal temperature reached on the production wellhead [°C]	8,3	39,6	39,6	8,3	39,6	39,6
1.10. Maximal power achieved on direct heat exchanger (without heat pumps) [kW]	0	0	0	0	0	0
1.11. The amount of energy obtained from the direct heat exchanger [GJ/year]	0	0	0	0	0	0
1.12. Nominal driving power estimatet for goethermal water pumps (exploitation and reinjection) [kW]	0	337	337	0	337	337
1.13. Electricity consumption by geothermal pumps [MWhr/year]	0	2953	2953	0	2953	2953
2 .----- Solar collectors -----						
2.1. Surface area of ??solar collectors [m2]	0	0	0	0	0	0
2.2. Thermal efficiency of collectors [-]	0,55	0,55	0,55	0,55	0,55	0,55
2.3. Solar radiation absorption coefficient [-]	0,9	0,9	0,9	0,9	0,9	0,9
2.4. Emission factor [-]	0,8	0,8	0,8	0,8	0,8	0,8
2.5. Maximum operating medium temperature [°C]	93,68	93,68	93,68	93,68	93,68	93,68
2.6. The amount of heat input to the customer's installation [GJ/year]	0	0	0	0	0	0
3. ----- Heat pumps (low energz source: geothermal) -----						
3.1. Heating capacity installed (maximal used) [kW]	0	9990	11796	0	9990	11796
3.2. Maximal working medium temperature at evaporator outlet [°C]	62,15	74,5	76,79	61,52	72,43	74,46
3.3. Maximal allowable water temperature at evaporator outlet [°C]	95	95	80	95	95	80

3.4. Minimum temperature of water at evaporator outlet [°C]	20	20	5	20	20	5
3.5. Maximum value of COP (on heating side) [-]	1,64	1,7	4,9	1,7	1,7	4,86
3.6. The amount of heat generated by heat pumps [GJ/year]	0	141607	141944	0	174146	175915
3.7. Amount of used drive energy consumed to drive the heat pump [MWhr/year]	0	24579	10398	0	29740	13602
3.8. Amount of used electric power used to drive geothermal pumps [MWhr/year]	0	2953	2953	0	2953	2953
4. ----- Thermoelectric modules -----						
4.1. Thermal power of modules [kW]	0	0	0	0	0	0
4.2. Electrical power generated by modules [kW]	0	0	0	0	0	0
4.3. The amount of thermal energy generated by the thermoelectric modules [GJ/year]	0	0	0	0	0	0
4.4. The amount of electricity generated by the thermoelectric modules [MWhr/year]	0	0	0	0	0	0
4.5. Costs of obtaining biogas derived from gasification of waste [PLN/m3]	0,74	0,74	0,74	0,74	0,74	0,74
5. ----- Boilers for alternative fuels and biomass -----						
5.1. Maximum installed power (used) in alternative fuels and biomass boilers [kW]	0	0	0	0	0	0
5.2. The amount of heat generated in boilers for alternative fuels and biomass [GJ/year]	0	0	0	0	0	0
5.3. Cost of acquisition / purchase price of fuels and biomass (average) [PLN/Mg]	400	400	400	400	400	400
6. ----- Peak boilers for natural gas -----						
6.1. Maximum installed power (used) in gas boilers [kW]	15971	6020	4175	18584	8633	6787
6.2. The amount of thermal energy produced in gas boilers [GJ/year]	142083	476	139	177415	3269	1500
Estimated investment outlays for heat source [thousands PLN]	12926	45808	50958	15041	47921	53072
- production well [thousands PLN]	0	18239	18239	0	18239	18239
- well for reinjection [thousands PLN]	0	0	0	0	0	0

- direct heat exchanger [thousands PLN]	0	0	0	0	0	0
- installation of solar collectors [thousands PLN]	0	0	0	0	0	0
- heat pumps [thousands PLN]	0	14986	20054	0	14985	20054
- installation of gasification of waste together with thermal and current modules [thousands PLN]	0	0	0	0	0	0
- alternative fuels and biomass [thousands PLN]	0	0	0	0	0	0
- peak boilers for natural gas [thousands PLN]	9583	3612	2505	11150	5180	4072
- connection pipelines and transmission lines [thousands PLN]	0	1000	1000	0	1000	1000
- energy source building [thousands PLN]	426	426	426	496	496	496
- cost of assembly, reserve for unexpected expenses [thousands PLN]	2917	7546	8734	3395	8023	9211
Total annual operating costs [thousands PLN/year]	6270	7263	7323	7758	8217	8473
- constant costs [thousands PLN/year]	840	2978	3312	978	3115	3450
- flexible costs [thousands PLN/year]	5430	4286	4011	6781	5103	5024
- depreciation of fixed assets [thousands PLN/year]	646	2290	2548	752	2396	2654
- costs of maintenance and repairs [thousands PLN/year]	194	687	764	226	719	796
- costs of buying conventional energy carriers [thousands PLN/year]	5430	4286	4011	6781	5103	5024
- incomes from the sale of electricity produced in combination by thermal current modules [thousands PLN/year]	0	0	0	0	0	0
Unitary costs of energy generation (excluding transmission losses) [PLN/GJ]	44	51	52	44	46	48
The price of energy for final customer (including transimission losses) [PLN/GJ]	50	58	58	48	51	52
Emission of pollutants emission related to the unit of generated heat [kg/GJ]						
- benzo (a) pyrene locally	0	0	0	0	0	0
- soot locally	0	0	0	0	0	0

- total dust locally	0	0	0	0	0	0
- CO2 locally	68,145	42,667	0,067	66,263	41,208	0,56
- CO locally	0,012	0,008	0	0,012	0,007	0
- NOx (recalculated to the NO2) locally	0,044	0,028	0	0,043	0,027	0
- SO2 locally	0	0	0	0	0	0
- aliphatic hydrocarbons locally	0,037	0,023	0	0,036	0,022	0
- aromatic hydrocarbons locally	0,001	0,001	0	0,001	0,001	0
- benzo (a) pyrene in global scale	0	0	0	0	0	0
- soot in global scale	0	0	0,002	0	0	0,002
- total dust in global scale	0	0,009	0,04	0	0,007	0,039
- CO2 in global scale	68,145	67,183	110,921	66,263	60,301	107,602
- CO in global scale	0,012	0,063	0,252	0,012	0,051	0,243
- NOx (recalculated to the NO2) in global scale	0,044	0,072	0,202	0,043	0,061	0,195
- SO2 in global scale	0	0,152	0,685	0	0,118	0,662
- aliphatic hydrocarbons in global scale	0,037	0,023	0	0,036	0,022	0
- aromatic hydrocarbons in global scale	0,001	0,003	0,013	0,001	0,003	0,012

Summary and conclusions

An optimisation of the system of effects obtained from the application of an energy source by drilling additional boreholes, in view of the current customer base and the connection of a an additional swimming-pool complex (Aqua Park)is not feasible. Although the proportion of geothermal energy will be increased in the structure of total use of energy media, but that will be achieved by a considerable increase of capital investments. The heat pumps that will be necessary to be installed, owing to the geothermal water temperature, operate in more even manner in time than in the case of using one well in the system. The ecological effects obtained, especially those on a local scale are in fact higher, but the emission reduction problem concerns rather CO_2.

5.5.4. Analysis of geological and geophysical conditions for ATES/UTES in Sochaczew

5.5.4.1. General considerations related to ATES systems

The municipality of Sochaczew has approved the project entitled "GEOLOGICAL WORKS involving the prospecting and exploration of geothermal waters using the *Sochaczew GT-1* well in the town of Sochaczew, municipality of Sochaczew, Mazovia Province". The designated location for the project is the transport depot on the bank of the Utrata River, at the northern end of Okrężna street.

The use of an ATES (Aquifer Thermal Energy Storage) system could potentially contribute to the efficient production of heat using the Sochaczew GT-1 well.

ATES systems were operated in Shanghai, China as early as in 1960. In Europe, they have been particularly popular in the Netherlands and Sweden; they are also used to a lesser extent in Belgium, Denmark, Norway, Germany and in recent years in the United Kingdom as well (see Table 5.5.4.1: there are several large installations at the Oslo Gardermoen Airport in Norway, at the Reichstag building and neighbouring buildings in Berlin as well as installations in the United Kingdom, including a few that serve large residential complexes in London).

Table 5.5.4.1 Main areas where the ATES technology is used in Europe (based on IFTech, 2012; Godschalk & Bakema 2009; Desmedt et al. 2007)

Country	Number of ATES installations (approximate)	Type of aquifer	Main applications
Belgium	>15	sand/chalk	hospitals
Denmark	10	sand/gravel, chalk	industry
Netherlands	>1,000	sand	large buildings
Sweden	70	chalk, sand/gravel	large buildings

In 2004, *EU Commission SAVE Programme* and *Nordic Energy Research* estimated typical costs of heat storage in an ATES at EUR 100–200/kW and indicated other typical characteristics of these systems:

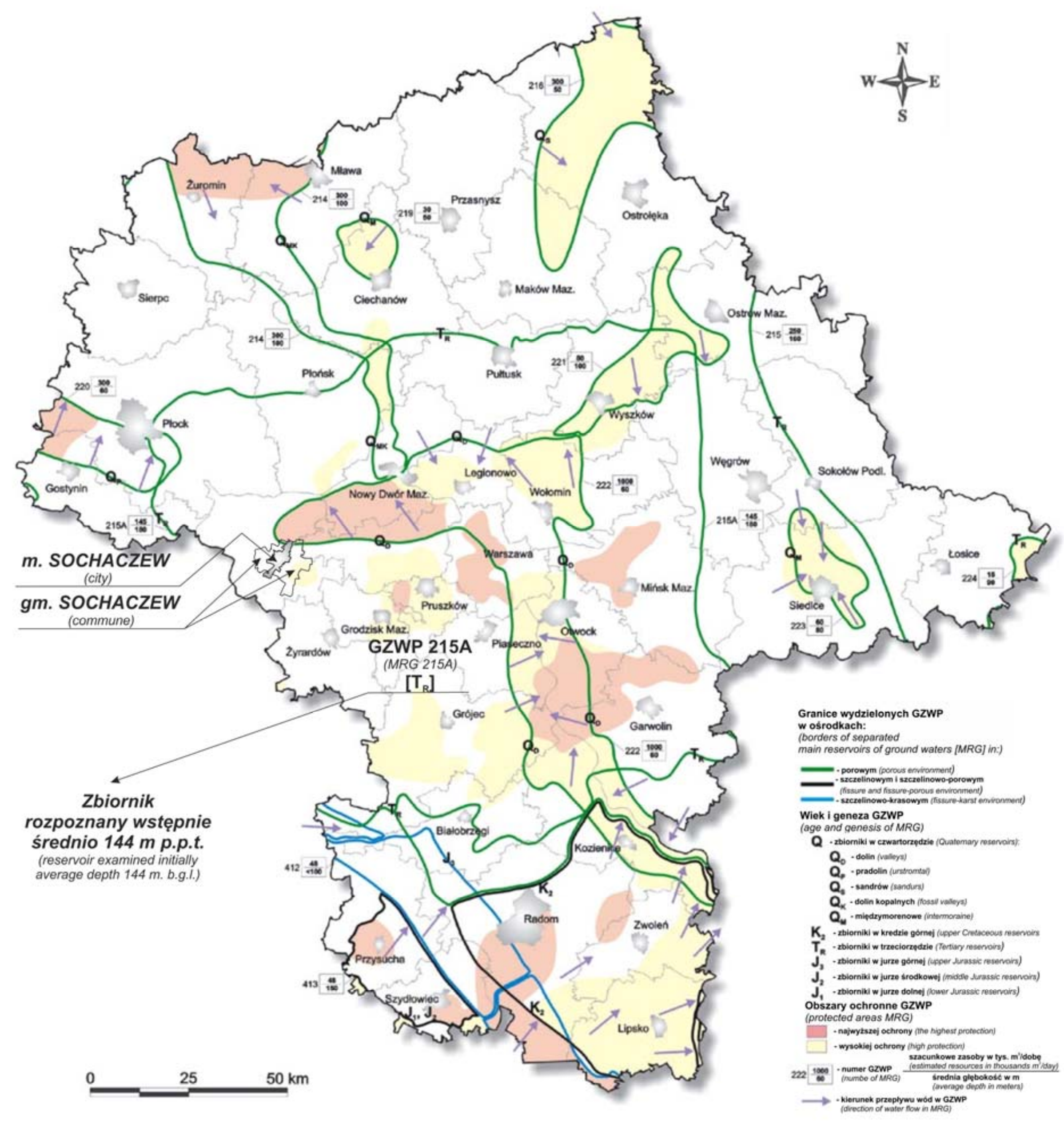
- production well discharge (water flow rate from the aquifer): 10–100 m^3/h;
- the amount of water reinjected into the injection well: 10–75 m^3/h;
- well diameter: 200–600 mm;
- well borehole depth: 10–300 m;
- minimum/maximum temperature during water reinjection: 3°C/80°C;
- aquifer permeability: from 10^{-3} to 10^{-4} m^2/s.

5.5.4.2. Hydrogeological conditions

Hydrogeological conditions have to be determined in order for an ATES system to be established.

The town of Sochaczew and the municipality of Sochaczew, which extends to the west and (separately) to the east of town limits, are located in the western part of the Mazovia Province. At the same time, these areas form part of a larger hydrogeological unit – the *JCWPd No. 81* groundwater body. This groundwater body is located in the south of the Warsaw Basin. It covers an extensive depression in Cretaceous formations, which was filled with Paleogene-Neogene and Pleistocene formations and subsequently covered with Quaternary ones. The area of the main strategic groundwater reservoir – *GZWP No. 222 – Middle Vistula Valley*, which is located in Quaternary formations within JCWPd No. 81, coincides with the northernmost suburbs of the town of Sochaczew and the northern part of the municipality of Sochaczew. On the other hand, the entire area of the town and municipality of Sochaczew coincides with the broader area of the main groundwater reservoir (*GZWP No. 215A – Central Part of the Warsaw Sub-Basin*) in Tertiary strata, which is another part of the JCWPd No. 81 groundwater body (Hydrogeologia…, 2007). The situation of the town and municipality of Sochaczew relative to the main strategic groundwater reservoirs (GZWP) is illustrated in Fig. 5.5.4.1.

In the area in question, useful freshwater aquifers are present in Quaternary, Neogene (Pliocene and Miocene) and Paleogene (Oligocene) sediments, i.e. down to a depth of approximately 220 m. The first usable aquifer typically occurs at depths ranging from 15 to 50 m. Locally, there may also be Paleogene-Cretaceous aquifers holding both fresh and mineralised waters.



Źródło (source):

http://docplayer.pl/35322-Raport-wojewodzkiego-inspektoratu-ochrony-srodowiska-w-warszawie-stan-srodowiska-w-wojewodztwie-mazowieckim-w-2006-roku.html

Fig. 5.5.4.1. Location of the town and municipality of Sochaczew relative to the map of the main strategic groundwater reservoirs (GZWP)

Fig. 5.5.4.2 shows the locations of wells drilled within the town limits and within the municipality of Sochaczew. The data, including well numbering, come from the PSH (Państwowa Służba Hydrogeologiczna – Polish National Hydrogeological Service) database. Information on the resources of individual aquifers is provided next to the numbers of selected wells. The location of the planned Sochaczew GT-1 well is also indicated. Figs. 5.5.4.3, 5.5.4.4 and 5.5.4.5 (based on PSH data) show the location of selected wells in the central part of the town of Sochaczew within three successive profiles along the SW-NE line. They also include information on the spatial distribution of the wells and the location of the Sochaczew GT-1 well (Fig. 5.5.5.5) as well as selected hydrogeological data (locations of free and confined aquifers, locations of well screen zones, water flow rates for aquifers from which water is being extracted).

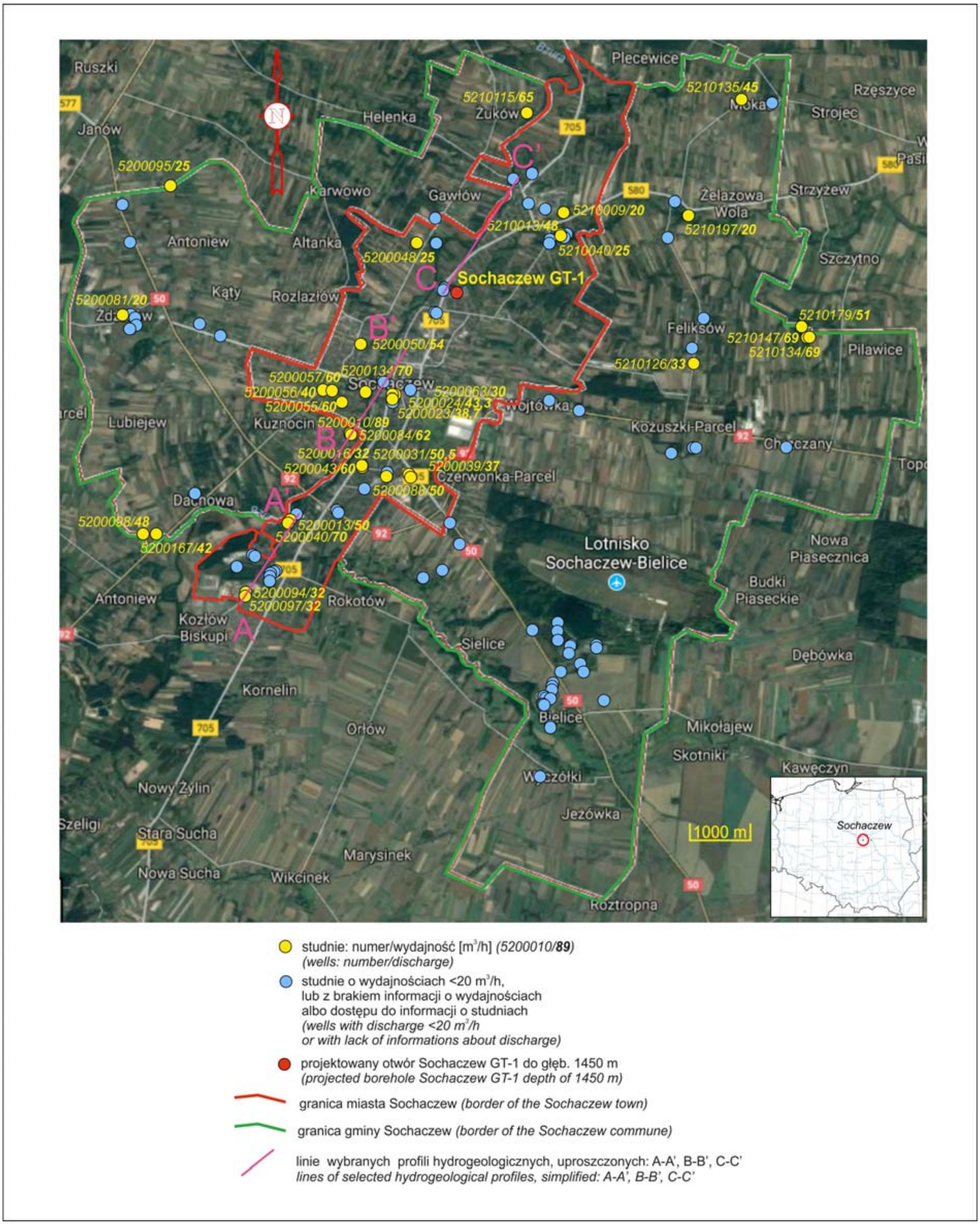


Fig. 5.5.4.2. Location of the wells included in the State Hydrogeological Service (PSH) database lying within the town and municipality of Sochaczew against the background of the orthophotomap https://www.google.pl

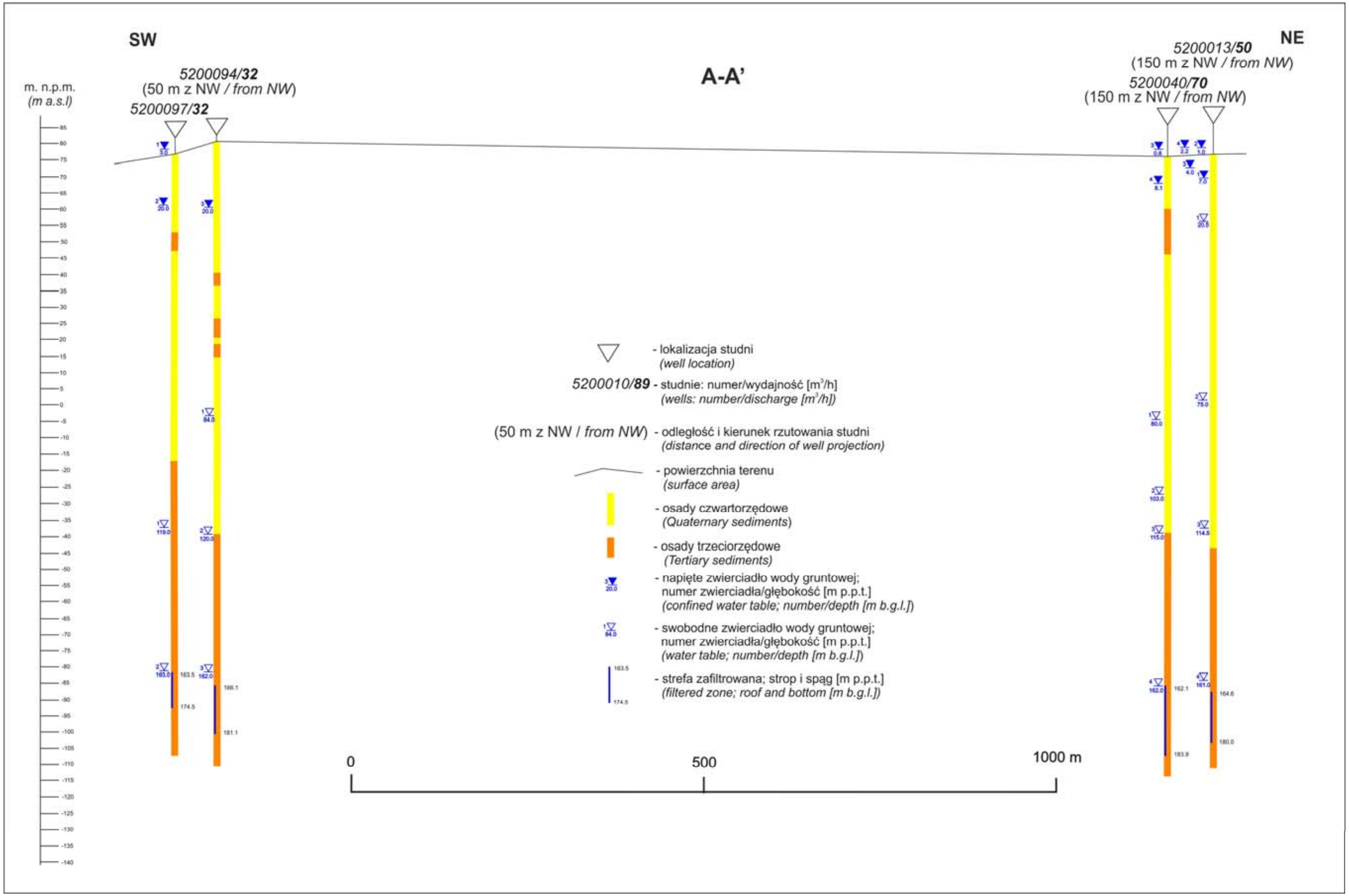


Fig. 5.5.4.3. Simplified hydrogeological profiles of selected wells from Fig. 5.5.4.2, projection along the A-A' line

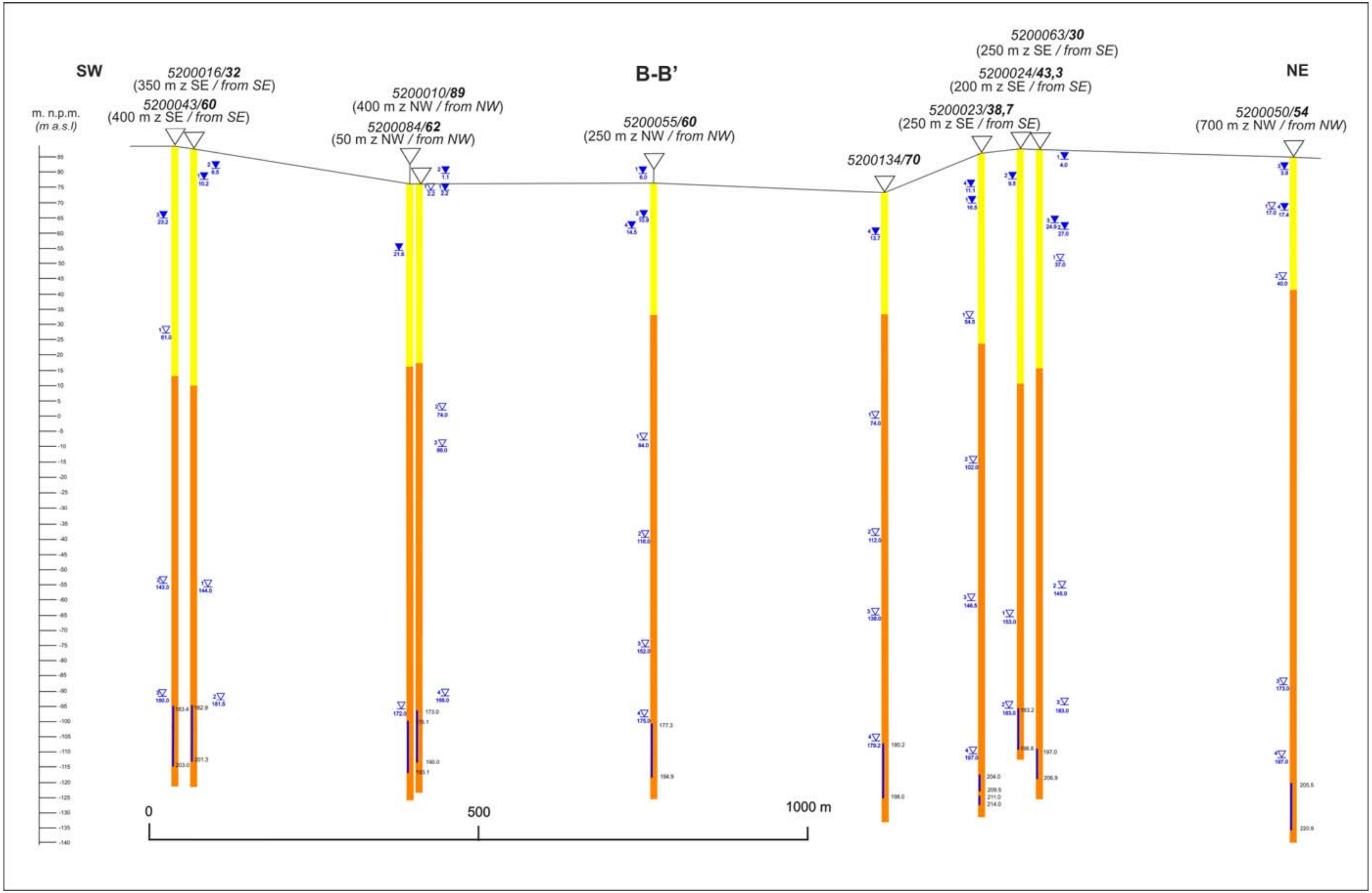
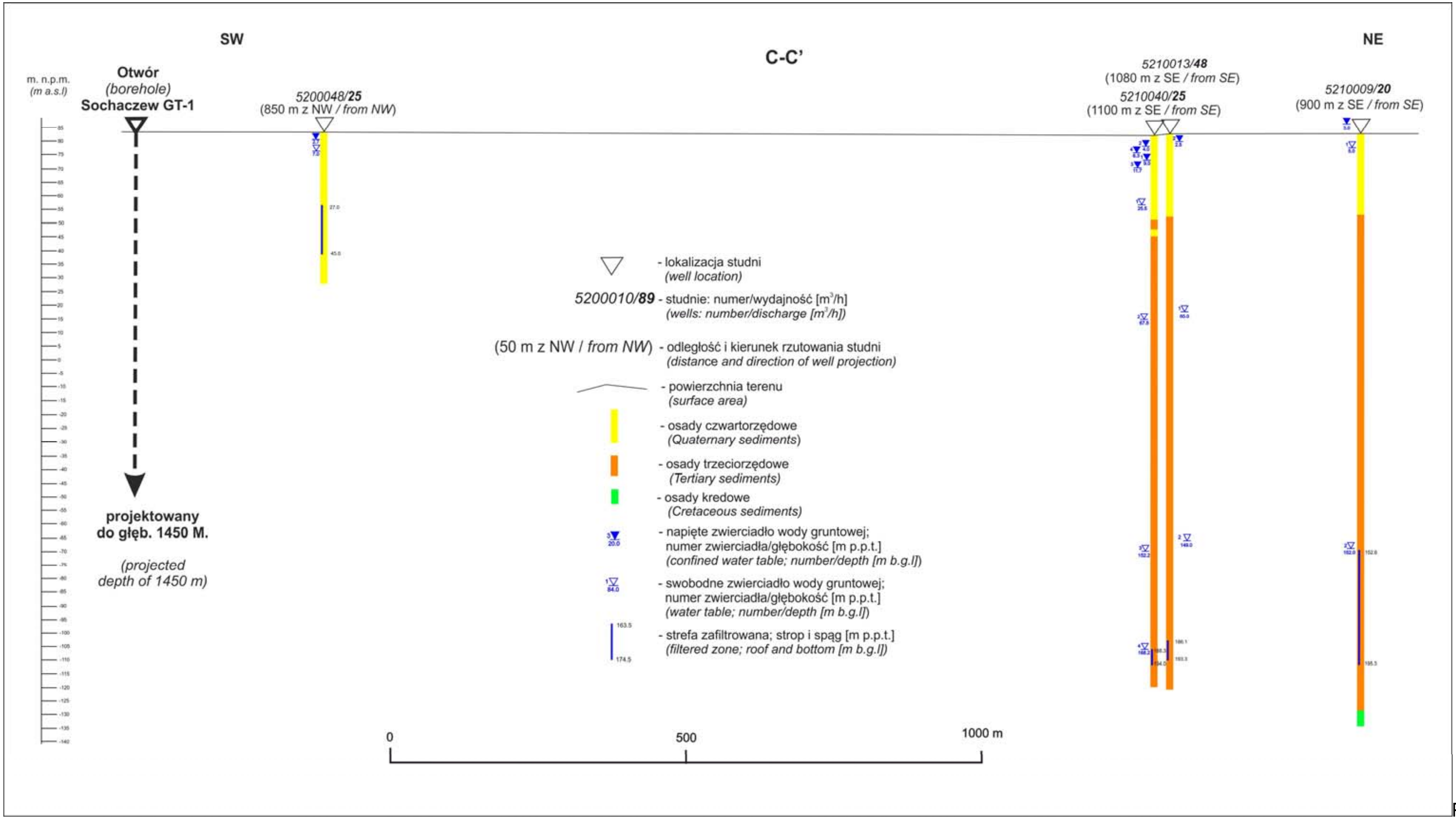


Fig. 5.5.4.4. Simplified hydrogeological profiles of selected wells from Fig. 5.5.4.2, projection along the B-B' line (legend as for Fig. 5.5.4.3)



Fi

Fig. 5.5.4.5. Simplified hydrogeological profiles of selected wells from Fig. 5.5.4.2, projection along the C-C' line

Quaternary multiaquifer formation

In the Sochaczew area, the *Quaternary multiaquifer formation* serves as the main useful aquifer. This is indicated by the presence of active well No. 5200048 in Karwów (Fig. 5.5.4.2). In most places, this multiaquifer formation consists of one to three aquifers separated by poorly permeable formations. The hydrogeological parameters of the aquifer are variable, mainly due to the varied morphology of its Pliocene substrate. On local plateaux, waters are present in sandy and gravelly formations (which are sometimes divided into multiple levels: the bottom level, the lower intermoraine level and the upper intermoraine level and/or near-surface level). Generally, however, there is a single level with a free water table at a depth of 15–20 m and with a thickness of 20–40 m, which is sometimes accompanied (at depths ranging from a few to around a dozen metres) by the near-surface level, also with a free water table and of limited thickness, lithologically diverse but susceptible to pollution (Hydrogeologia…, 2007).

Intramoraine levels occur at depths ranging from 20 to 60 m (the upper one) and from 50 to 100 m (the lower one), and the bottom level is located at depths of more than 60 m. These levels include gravels and coarse grained sands as well as fine sands and dust. The thickness of these formations ranges from a few to around a dozen metres. They are supplied with water by percolation from poorly permeable formations. Locally, in river valleys, infiltration may also be the source of water supply. Highly localised ascending supply from the Miocene or Oligocene levels also cannot be ruled out (Hydrogeologia…, 2007).

The Quaternary aquifer is fed primarily by infiltrating atmospheric precipitation (which also feeds useful lower aquifers as a result of percolation), and is drained by surface waterways. Average filtration coefficients for the main layer of this aquifer range from $1x10^{-4}$ to $3x10^{-5}$ m/s (Hydrogeologia…, 2007).

The three Tertiary aquifers in the area of Sochaczew are typically covered by layers of impenetrable formations (with thicknesses ranging from 11.0 to 32.5 m), and the lithological profiles of the wells and the pressures present in aquifers suggest that these aquifers are largely separate (Rudzińska-Zapaśnik, 2003).

Pliocene aquifer

The *Pliocene aquifer* has poor hydrogeological parameters and is not a useful aquifer. It occurs in small interbeddings, inserts or lenses of sand with thicknesses of up to 20 m. Rudzińska-Zapaśnik (2003) found that in the area of Sochaczew, it is only present in the well of the power substation on the NE periphery of town, at depths ranging from 61.1 to 79 m (with ceiling elevation of 19.5 m a.s.l.). These interbeddings are present in clayey, virtually impermeable Pliocene formations, which confine the aquifers situated below.

Miocene aquifer

The *Miocene aquifer*, fed by percolation and characterised by a confined water table, is locally hydraulically connected to the Oligocene aquifer.

Water from the Miocene aquifer is extracted using the three Kuznocin municipal intake wells in Sochaczew from a depth of around 160 metres (Figs. 5.5.4.2 and 5.5.4.4). Its waters are contained in fine-grained (sometimes dusty) brown sands with a thickness ranging from 18.4 m to over 25 m, interbedded with dusty formations, silt, clay, lignite or a considerable admixture of coal dust, i.e. formations that are usually present only locally (Rudzińska-Zapaśnik, 2003). However, in the vicinity of the Kuznocin municipal intake, the hydrogeological situation is a peculiar one. The elevation of the ceiling of these formations is the same as the elevation of the ceiling of the Oligocene aquifer, since Lower Miocene formations lie in the so-called "Kuznocin trough" (a depression around 40 m deep), which formed in the top layer of Oligocene formations and stretches towards Rozlazłów in a NW direction (Brzeziński, 1988). Lateral contact between the two aquifers results in a hydraulic connection between them and in this sense the aquifers are "continuous" (Rudzińska-Zapaśnik, 2003).

In the area of the Kuznocin municipal intake in the town of Sochaczew, a depression of several metres formed locally as a result of water being extracted (cf. e.g. wells Nos. 5200084 and 5200010, Fig. 5.5.4.4).

Paleogene (Oligocene) multiaquifer formation

In the Sochaczew area, the *Paleogene (Oligocene) multiaquifer formation* is the main useful aquifer (apart from the Kuznocin municipal intake). Its ceiling is located at depths ranging from 160 to over 200 m, and its thickness ranges from 11 m in the east to 64 m in the west of the area discussed. The confined water table of this multiaquifer formation stabilises at altitudes ranging from 75 to 145 m a.s.l. The generally uniform aquifer is present in fine- and medium-grained (sometimes coarse-grained) marine sands and gravels associated with the glauconite formation (Rudzińska-Zapaśnik, 2003). Locally, two water-bearing beds are present (well No. 5200023, Figs. 5.5.4.2 and 5.5.4.4), which are separated by a thin layer of clay, silt or dust. In the area of Sochaczew, no instances were found where this upper layer would coincide with Miocene waters or the lower one with the waters of the *Cretaceous-Paleocene multiaquifer formation* (which does not include useful aquifers, exhibits low hydrogeological values and the mineralisation of whose waters ranges from 2 to 3 g/dm^3, Hydrogeologia…, 2007).

5.5.4.3. Analysis of PSH data from the point of view of the needs of the ATES system in Sochaczew

The analysis covered 106 documented wells drilled within the town and municipality of Sochaczew. The data are sourced from the Polish National Hydrogeological Service (PSH) database. Most wells are located within the town limits (Fig. 5.5.2). For some of them, no information on water flow rates has been provided. The analysis has been narrowed down to 34 wells with recorded water flow rates higher than 20 m^3/h. The highest flow rate of 89 m^3/h was documented for well No. 5200010 of the Kuznocin municipal water intake (Figs. 5.5.4.2 and 5.5.4.4). Similarly high water flow rates were recorded in other wells of this intake: 5200134 (70 m^3/h), 5200084 (62 m^3/h), 5200055 and 5200057 (60 m^3/h each, Fig. 5.5.2). The following flow rates are also notable: the chemical plant intake (70 m^3/h, Fig. 5.5.4.2), the intake serving the rural waterworks system at Janaszówek (5210134 and 5210147 – 69 m^3/h each, Fig. 5.5.4.2), the Żuków municipal intake (5210115 – 65 m^3/h, Fig. 5.5.4.2) and Boryszew municipal intake (5200043 – 60 m^3/h, Fig. 5.5.4.2).

The potential ATES system should be located as close as possible to the planned Sochaczew GT-1 well. Two wells with depths of around a dozen metres are located in the immediate vicinity of the well,, and the two wells situated slightly farther away have similar characteristics (Fig. 5.5.4.2). These are used to extract Quaternary waters but have very low flow rates. Higher water flow rates have been documented for four other wells. At a distance of 1,000 m, at the nearest well No. 5200048 (Fig. 5.5.4.2) at the Radio Transformer Factory, which is several dozen metres deep, Quaternary waters are extracted with a flow rate of 25 m^3/h from a screened interval that ranges from 27 to 45 m in depth. A slightly confined water table is present in this well at a depth of 7 m b.g.l., which stabilises at 2.7 m b.g.l. (Fig. 5.5.4.5). Three other wells are around 2,000 m away from the planned well and enable the abstraction of water from the Oligocene confined aquifer. To the north-east, the following wells, which are situated close to each other, operate: No. 5210040 with a flow rate of 25 m^3/h and 5210013 with a flow rate of 48 m^3/h (Figs. 5.5.4.2 and 5.5.4.5). To the south-west, there is well No. 5200050 with a flow rate of 54 m^3/h (Figs. 5.5.4.2 and 5.5.4.4). The Oligocene water table in well No. 5210040 reaches -102 m a.s.l., while in well No. 5200050 to the south-west it is 4 m lower.

In view of the above, it appears that the vicinity of well No. 5200048 may be a convenient location for the ATES system (Fig. 5.5.4.6). It cannot be ruled out that two useful aquifers are present here. The first one is the documented Quaternary aquifer at depths ranging from around 25 to 45 m and with a flow rate of about 25 m^3/h, which is partly insulated from the ground level. The second one is an Oligocene aquifer, which is probably well insulated by a layer of impenetrable clay formations, with its top situated at a depth of approx. -104 m a.s.l. and with an assumed flow rate of ca. 30–40 m^3/h. However, water mineralisation may be a problem here since although well No. 5200048 is a freshwater one, Oligocene waters are strongly mineralised. Dry residue values are respectively 920 mg/dm^3 in well No. 5200040 (analysis of 12 August 1974) and 783 mg/dm^3 in well No. 5210050 (analysis of 27 January 1982).

The area indicated in Fig. 5.5.4.6, both with respect to the part included in the orthophotomap and with respect to both aquifers (the main Quaternary one and the Oligocene one), is interesting from the point of view of various ATES system solutions, but would require closer examination, e.g. detailed geophysical testing or the drilling of at least one test well that would reach below the Oligocene level.

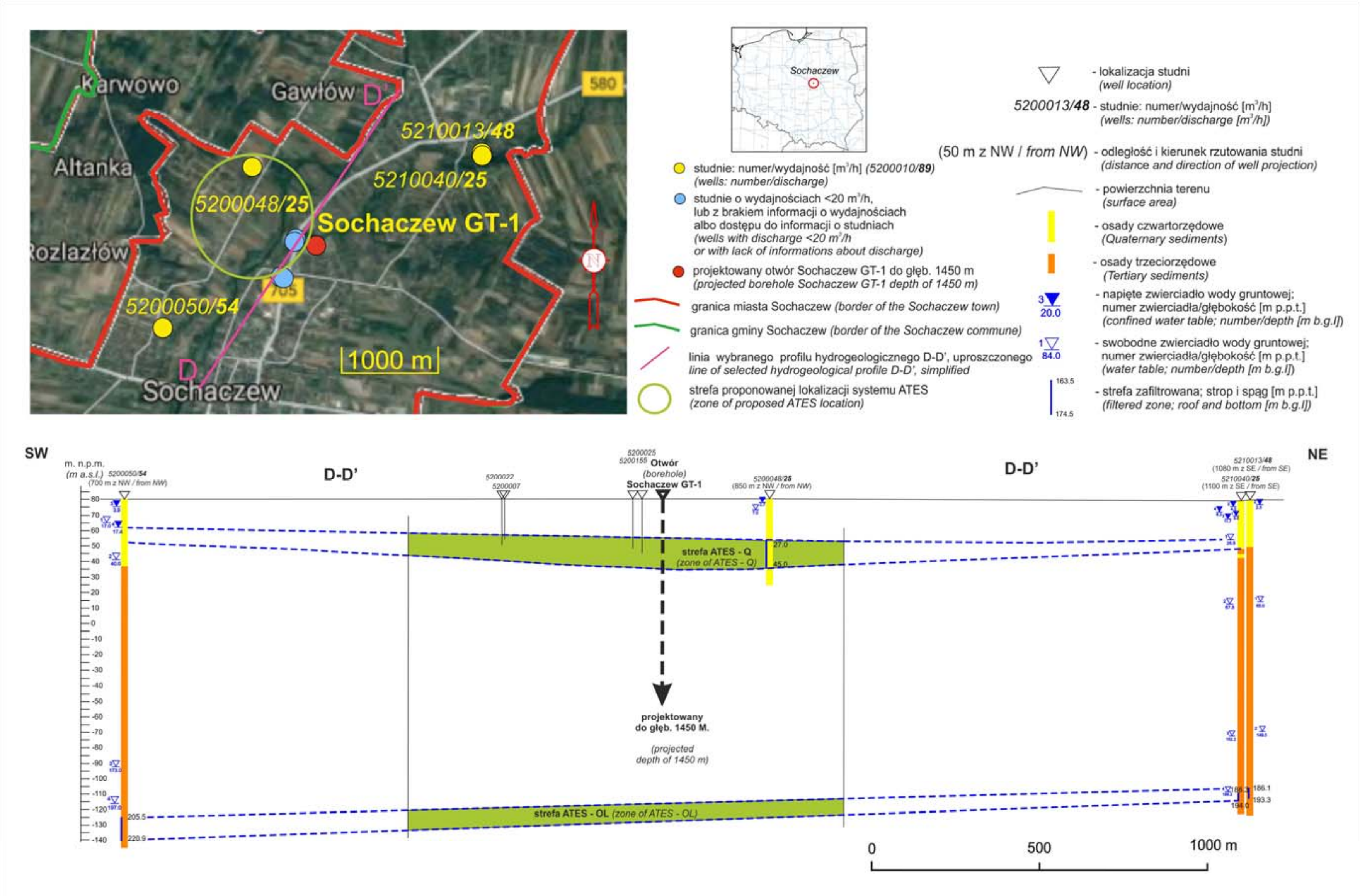


Fig. 5.5.4.6. Proposed location of the ATES system in Sochaczew

References:

Brzeziński M., 1988: Objaśnienia do Szczegółowej mapy geologicznej Polski w skali 1:50 000, Arkusz Sochaczew (520), Wyd. Geol., Warszawa.

Desmedt J., Hoes H., Lemmens B., 2007: Shallow geothermal applications in Belgium. Proceedings – European Geothermal Congress 2007. Unterhaching, Germany, 30 May–1 June 2007.

[in: https://pangea.stanford.edu/ERE/pdf/IGAstandard/EGC/2007/142.pdf].
EU Commission SAVE Programme and Nordic Energy Research, 2004: Table 4.2 [in: http://www.underground-energy.com/ATES.html].

Godschalk M., Bakema G., 2009: 20,000 ATES Systems in the Netherlands in 2020: Major step towards a sustainable energy supply. Proceedings Effstock 2009, Stockholm
[in: http://intraweb.stockton.edu/eyos/energy_studies/content/docs/effstock09/Session_10_3_Overviews/94.pdf].

http://docplayer.pl/35322-Raport-wojewodzkiego-inspektoratu-ochrony-srodowiska-w-wojewodztwie-mazowieckim-w-2006-roku.html

https://www.google.pl/maps/place/Sochaczew/

Hydrogeologia regionalna Polski, Vol. I – Wody słodkie. Ed. B. Paczyński and A. Sadurski. Państwowy Instytut Geologiczny, Warszawa, 2007. ISBN 978-83-7538-168-9.

IFTech, 2012: An Introduction to Aquifer Thermal Energy Storage (ATES). Rehau Workshop, 31.05.2012. http://www.icax.co.uk/pdf/IFTech_Presentation_Rehau_31May2012.pdf.

Projekt robót geologicznych na poszukiwanie i rozpoznawanie wód termalnych otworem Sochaczew GT-1 na terenie miasta Sochaczew, gminy Sochaczew, województwo mazowieckie. Kraków, September 2015. Materiały Pracowni Odnawialnych Źródeł Energii IGSMiE PAN Kraków.

Rudzińska-Zapaśnik T., 2003: Problemy występowania i izolacji mioceńsko-oligoceńskiego poziomu wodonośnego w rejonie Sochaczewa. Współczesne Problemy Hydrogeologii. Vol. XI, p. 1, Gdańsk, pp. 189–193.

System Przetwarzania Danych PSH, PIG-PIB Warszawa [in: http://spdpsh.pgi.gov.pl/PSHv7/].

https://www.google.pl

5.5.5. Proposal for ATES/UTES systems in Sochaczew

The aim of this study is to investigate and propose solutions for optimizing the use of geothermal energy in the Sochaczew area. In these solutions, UTES technology (ATES or BTES) should be used in conjunction with solar heat storage, one or more peak heat sources (biomass, gas etc.) and heat pump technology (absorption, VCC or combination between absorption and VCC). The proposed solutions should be based on modifying the existing energy management systems (district heating, domestic hot water).

It is of special interest to optimize use of geothermal water through sustainable exploitation by injection to shallow reservoirs (100-200 m below surface) for improvement of drinking water retention area. It is also of interest to determine economic and environmental effects of geothermal system variants.

A long-term strategy for the heat supply of the region is required, notably in terms of reducing the consumption of coal and oil for heating.

5.5.5.1. Current status

Sochaczew, a city of approx. 37 000 inhabitants, is located in central Poland, approximately 40 km west of Warsaw. The heating needs in the Sochaczew town are secured by a combination of local heating plants, individual boilers and district heating (DH) networks. Approximately 30-50% of the town is heated through DH networks, and the total heat demand of the part of the city covered by DH is estimated at 152 TJ/year. The DH network is not continuous, i.e. it consist of several separate networks that are not connected or overlapping (see section 0 for more details). The heating season lasts 222 days a year, which is slightly longer than the typical period from 15th October to 15thMay (212 days). The average heat demand during the heating season is assumed to be 7.9 MW.

No details as to a potential cooling demand has been given for the area, but it should be noted that cooling in summer can potentially improve the efficiency of an UTES in winter time.

5.5.5.2. Existing heating plants

The current heat sources are decentralized, there are several smaller plants that supplies relatively small DH networks, and the DH networks are not interconnected. Przedsiębiorstwo Energetyki Cieplnej Sochaczew (PEC Sochaczew), the heat supply company, currently holds five active heating plants, while Geotermia Mazowiecka and Boryszew S.A. facilitate two and one heating plants, respectively. The boilers installed vary in size and fuels, from smaller boilers of a few hundred kW to several MW. The DH heat suppliers use a combination of high methane natural gas, coal and biomass (wood chips, straw, hay). With respect to regulations, there is no obligations to connect to the DH grid, i.e. price is the only decision tool.

The design temperatures of the DH networks are 80/60°C (supply/return; according to the local DH company via Sweco questionnaire) and the temperature is controlled using a curve based on outdoor temperature, and the “summer temperature” is 65/45°C. Parts of the DH network may also be operated at 90/70°C, and the supply temperature is raised to approximately 110°C during peak load. Radiator systems in houses and other heated spaces are installed accordingly.

5.5.5.3. Geological and hydrothermal conditions and planned geothermal borehole

The ground consists of sandstone, gravel and clay, with identified geothermal sources at 1400 – 1500 m depth with temperature 40 °C (capacity of 80 – 120 m^3/h) and at 2500 m depth with temperature 70 °C.

It is planned to drill a well of depth 1400 m (±10%) in the Trojanów district of the town Sochaczew (see Fig. 5.5.5.1). The vertical borehole will be drilled into Cretaceous aquifer, with estimated water discharge of about 120 m3/h, outlet temperatures around 40°C. The water quality is described as good, with mineralization of less than 1 g/l. The assumed thermal power of the geothermal source is around 3.6 MW while heat production would reach approx. 45 TJ/year.

The proposed well is located within the undeveloped land with an area of 92.79 acres, fenced and equipped (sewerage, water supply). The area is characterized by a low level of urbanization. In the surroundings of the planned works, PEC Sochaczew is located along with some old industrial areas, which presently are not used.

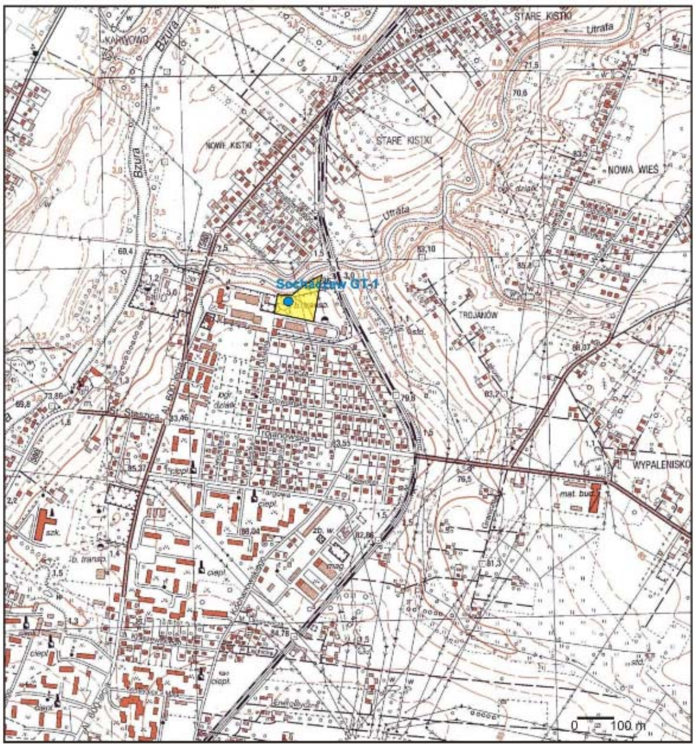


Fig. 5.5.5.1. Location of the planned geothermal borehole in Sochaczew

5.5.5.4 Recommendations for Sochaczew

Low-temperature heating systems

The geothermal source is located in an area that is not currently urbanized, but there are plans for development. This is an very good case for a low-temperature DH network, which can utilize geothermal heat in the temperature range 40 °C (source for planned test well at 1400 m depth) to 70 °C (deeper source at 2500 m depth, could be an option for future utilization) more efficiently than existing DH networks in Sochaczew which have design temperatures of 80/60°C. A low-temperature DH network will also make it more efficient to utilize other lower temperature renewable heat sources, such as solar thermal, biomass and waste heat from processes.

Utilization of a low-temperature DH is in line with development scenarios towards low-temperature DH suggested by (Walnum & Fredriksen 2017), Thermal Energy Systems in ZEN, 2017). The consumer substation should be designed with focus on lowering the return temperature to provide the DH network with a high temperature difference for supply and return. (Walnum & Fredriksen, 2017) suggest several examples of varying complexity that will help produce the low return temperature needed in a low-temperature DH network..

A low-temperature DH network should therefore be considered for the Sochaczew case. This should, however, be balanced with respect to the number of buildings to be covered with low-temperature heating system. Even for a low-temperature heating system there will be need for heat pumps, at least with the 40 °C source (see discussions in section 0), but a higher COP and lower usage of other energy sources can be achieved for the renewable heat sources with a low-temperature DH network.

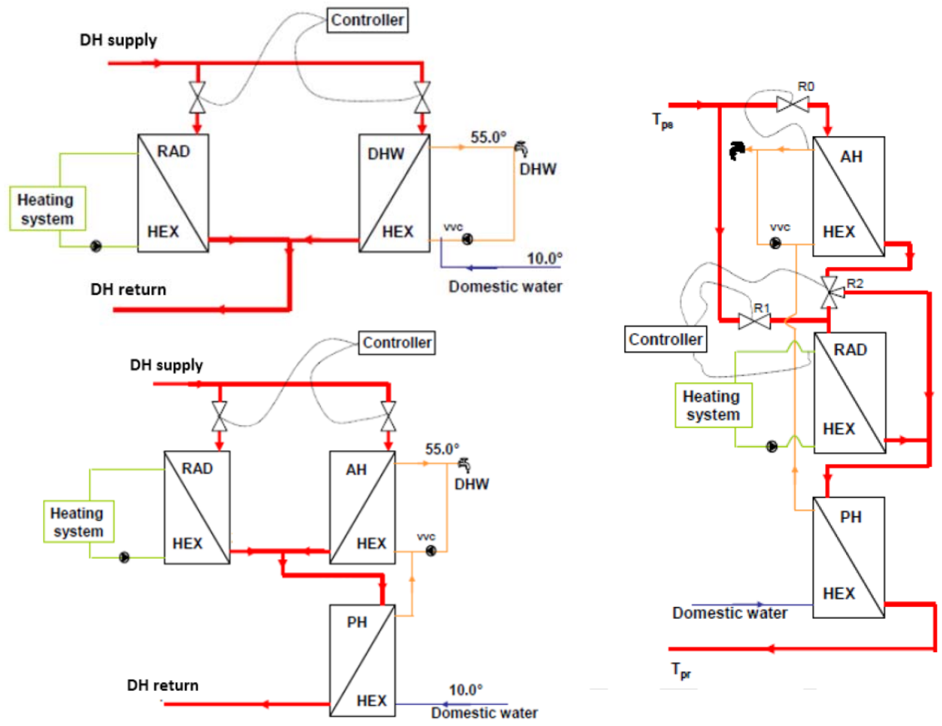


Fig. 5.5.5.2. Three different schemes for low return temperature in DHN, (Walnum & Fredriksen, 2017)

Possible utilization of ATES in the energy system

There are two scenarios for which an ATES would be a preferable solution for Sochaczew,

- If there is a cooling need, either comfort cooling or industrial cooling (including e.g. shopping malls and data centers, drying processes). In this case the upper aquifer should be used as a reservoir.
- If there is excess waste heat available with temperature above 40 °C. In this case the temperature in the 40°C aquifer can be increased, making it possible to run the heat pumps more efficiently, increasing the efficiency of the system.

Neither of these scenarios have not been specified as a requirement at this stage, therefore ATES is not recommended for Sochaczew at this stage. This recommendation should be further followed up and reevaluated in the future deveopment of the energy system. If one of these scenarios should be implemented, there is a need for simulations and investigations of the reservoir regarding temperature and water quality. Also, monitoring and follow-up with respect to reservoir temperature and water quality is important.

Successful implementation of geothermal heating

The temperature from the geothermal sources in Sochaczew is too low for direct implementation in a high temperature (80/60°C or 90/70°C) DH network. Using a heat pump installation, the temperature can be raised to adequate levels – 80-90°C. Note that the water quality should be analysed in more detail before final planning of the energy system.

Scenario 1

The local DH officials have suggested using a gas fueled absorption heat pump (GAHP) as 1st stage (estimated COP of 1.4) and a vapor compression cycle heat pump (VCCHP) as 2nd stage. The 1st stage will likely produce a hot side temperature in the range of 45-60°C depending on capacity and solution, whereas the 2nd stage will lift the temperature to approx. 80°C when needed. This would likely give a combined COP of around 1.0-1.1.

An alternative would be to use a VCCHP for both stages. A rough calculation indicate that a VCCHP would have to deliver heat at a COP of 3.75 or higher for the same conditions[1]. A VCCHP using conditions with 40/20°C and 45/50°C can maintain a COP higher than 4.5. If the hot side temperature is increased by 5°C, the COP would drop significantly to approx. 4.0 - 4.5, depending on choice of heat pump design. The combined COP of two VCCHP stages to a temperature of approx. 80°C is therefore likely to be around 3 - 3.5. These numbers depend on a large number of design choices, but can are easily obtained using commercial solutions.

As a VCCHP will outperform a GAHP, a VCCHP for the 1st heat pump stage is recommended as well. The preliminary calculations indicate that a two-stage solution based on a VCCHP design can achieve the needed temperature for the DH network. Further evaluation should consider an economic optimization of the heat pump installation. A solution using a boiler for peak load demand and heat pump energy coverage of 80-90% will likely be a feasible scenario.

Scenario 2

For the 40°C source, one option current high temperature DH network would be to concentrate on heating the return water from the distribution system, which is normally around 70°C. Since there is no electricity generation in the system, there is no cold end temperature to worry about, so heating of the return water from 70°C to perhaps 75-80°C would only lower the heat load of the fuel boilers. These fuel boilers operate at hundreds of degrees, so it makes no difference if water into the boilers is 70 or 80°C. The simple representation of such a system is shown in Fig. *5.5.5.2*, where all the geothermal water goes through a heat pump, which heats the return water in the distribution system and lowers the heat load on the boilers.

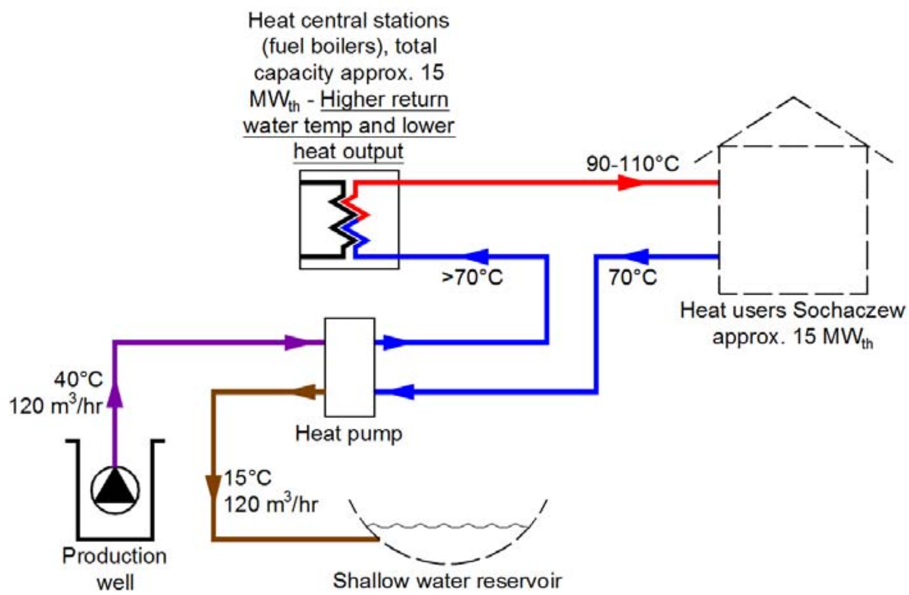


Fig. 5.5.5.2. Sochaczew low-temperature geothermal well and heat pump, schematic diagram

References:

Walnum & Fredriksen 2017: Thermal Energy Systems in ZEN, ZEN Report.

[1] Using the energy prices of 100 PLN/MWh for gas and 300 PLN/MWh for electricity

5.6. Konstantynów Łódzki study case

5.6.1. Geothermal conditions and heat demand in Konstantynów Łódzki – Łódź area

Geological and hydrogeological conditions

The study area is located in the central part of the Łódź Synclinorium (Łódź Basin), which borders on the Gielniów Anticlinorium to the east and on the Miechów Basin to the south (Fig. 5.6.1.1). The Łódź Basin area forms an asymmetrical syncline within which a number of secondary structures such as anticlines, horsts (e.g. the Radomsko Elevation), grabens (the Bełchatów Graben) and structures that formed spontaneously, such as salt pillows, can be distinguished. For the most part, these structures are not the result of orogenic movements but rather of salt tectonics. Larger salt structures are present to the NW of the area in question, e.g. around Damasławek and Mogilno. The geological complexes found there were dissected by the faults that formed during the Alpine orogeny, which involved Tertiary (Miocene) movements. As a result of these dislocations, a number of grabens and horsts were formed (Pożaryski [ed.], 1974).
The Łódź Basin, including the study area, is built of Permian-Mesozoic sediments. Apart from diapir zones, the Permian substrate usually occurs at depths of 3,000–5,000 m, which means that the Mesozoic complex achieves significant thickness here, locally reaching up to 5 km. A schematic geological cross-section through the area in question (cross-section location shown in Figs. 5.6.1.1 and 5.6.1.2) is presented in Fig. 5.6.1.3.
Owing to the unfavourable reservoir parameters of Palaeozoic aquifers, the study has been limited to the discussion of the Mesozoic complex and of the hydrogeothermal conditions present there.

Triassic complex

Lower Triassic formations (Buntsandstein, Röt) are a continuation of uppermost Zechstein sediments. Just as in the Permian period, terrigenous sedimentation still predominated in the area (pelitic-psammite arkose formations with oolite limestone and marly limestone inserts). Sedimentation took place in an inland water body, which was drying out in places, with locally marked effects of flowing waters (numerous ripple marks, hieroglyphs, traces of drying, organic debris). For a short time only, a weak marine influence caused the environment to become brackish. It is only the upper Buntsandstein formations that represent a shallow marine water body which temporarily lost connection with the open sea, and full marine sedimentation occurred in the uppermost Röt, just as in the entire area of the Polish Lowlands (Marek, 1985).
Lower Triassic formations include red clays, sandstones, marls, limestones and dolomites.

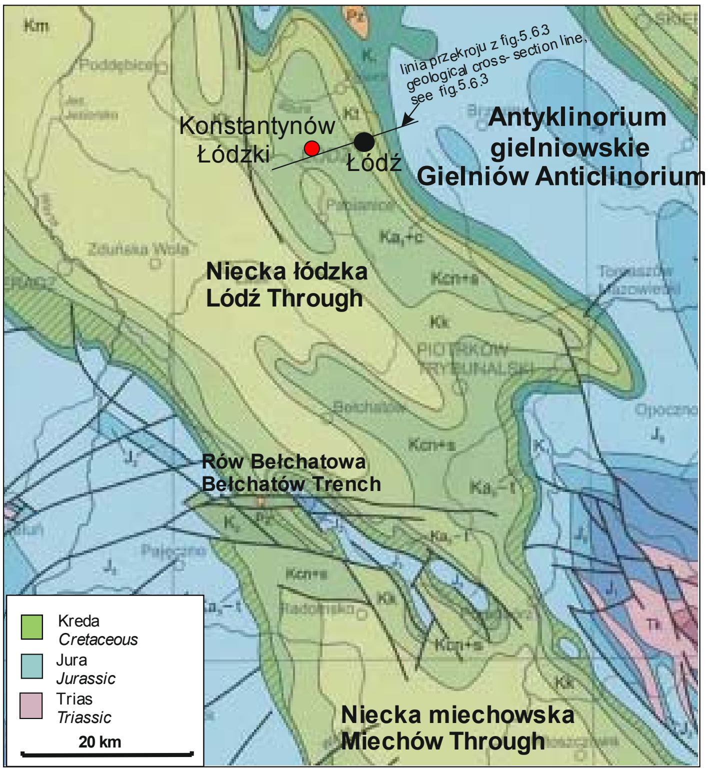


Fig. 5.6.1.1. Geological situation of the study area against the background of the „Geological map of Poland without Cenozoic formations" (after Dadlez et al., 2000)

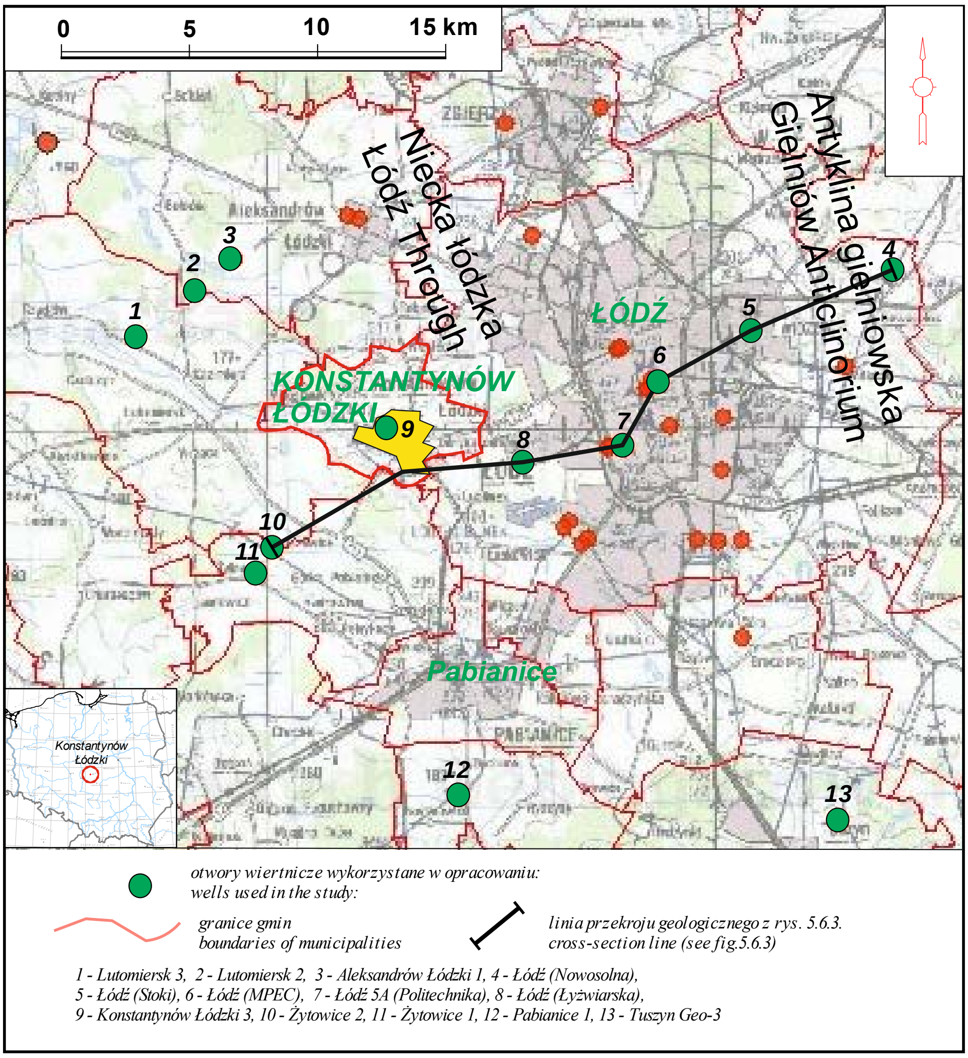


Fig. 5.6.1.2. Location of the wells analysed and the line of geological cross-section from Fig. 5.6.1.3 (base map after CBDG PIG-PIB Warszawa – online, September 2016)

The overlying *Middle Triassic lower and middle Muschelkalk* formations occur in the form of a generally uniform limestone-dolomite facies. Sulphates were precipitated in the middle Muschelkalk, while in the upper layer there are marly sediments and significant clay interbeddings. The sedimentation of Middle Triassic formations occurred during fairly stable bathymetric conditions but with an unstable substrate. This is evidenced by differences in sediment thickness: from 135.5 m in Kutno to around 500 m west of the city in the Krośniewice IG-1 well (Wojszyce structure), which indicates intensive salt tectonics taking place at that time. As a result of secular and widespread substrate movements, water regressed at the end of the Middle Triassic and the water body became an isolated inland one (Marek, 1985). Middle Triassic formations have the form of limestones, marls, claystones, dolomites, limestones with anhydrite and wavy-bedded limestone inserts. These are usually grey and brown-grey limestones, which are hard and compact. The Zgierz IG-1 well drilled through these formations at a depth interval from 3,575 m to 3,953 m.

Within the Łódź Basin, they were only occasionally tested for the presence of oil and natural gas. In the Gomunice 2 well (around 35 km S from Piotrków Trybunalski), an inflow of 13 m^3/h of bromine brine was observed in the 1,535–1,615 m interval, with chloride-calcium mineralisation (according to Sulin's classification) of 56 g/dm^3. Water mineralisation indicates a mixture of formation water with the drilling mud filtrate present in the well (the actual mineralisation level is probably higher). The formation temperature was high and was recorded as 51°C.

In the study area, this complex is presumably present at depths ranging from 3,300 to 3,500 m, and thus water near the top of the aquifer would exhibit a formation temperature of approx. 95°C. The flow rate is, however, difficult to assess and can only be estimated at around 20–30 m^3/h.

The <u>*Upper Triassic formations from the Keuper to the Lower Rhaetian*</u> were formed in brackish sedimentation conditions, while those in the Upper Rhaetian were formed in limnic sedimentation conditions. The isolated and increasingly freshening water body with clay and gypsum Upper Keuper sediments separated by Schilfsandstein (reed sandstone) found itself in a zone where individual substrate blocks became more mobile during the Late Keuper and Early Rhaetian. The brackish sedimentation of variegated shales in Rhaetian period was caused by redeposition of Keuper sediments, and limnic sedimentation of grey Rhaetian period marks the beginning of a new sedimentation cycle with increasingly damp formations.
In the Upper Keuper, and especially towards its end, there was intensive formation of salt structures of the Kutno block (with the particularly intensive formation of the Wojszyce salt structure – Rhaetian formations there overlie lower gypsum layers) and of the Rawa block (the Jeżowa salt structure with the Rhaetian overlying the Lower Keuper) (Marek, 1985).
Upper Triassic sediments of the Łódź Basin are mainly clay formations with sandstone inserts and in addition gypsum and anhydrite inserts in the top section. In the area in question, the Rhaetian is represented by grey claystones, variegated claystones (red and green), reddish brown dolomitic mudstones, light grey sandstones and conglomerates.

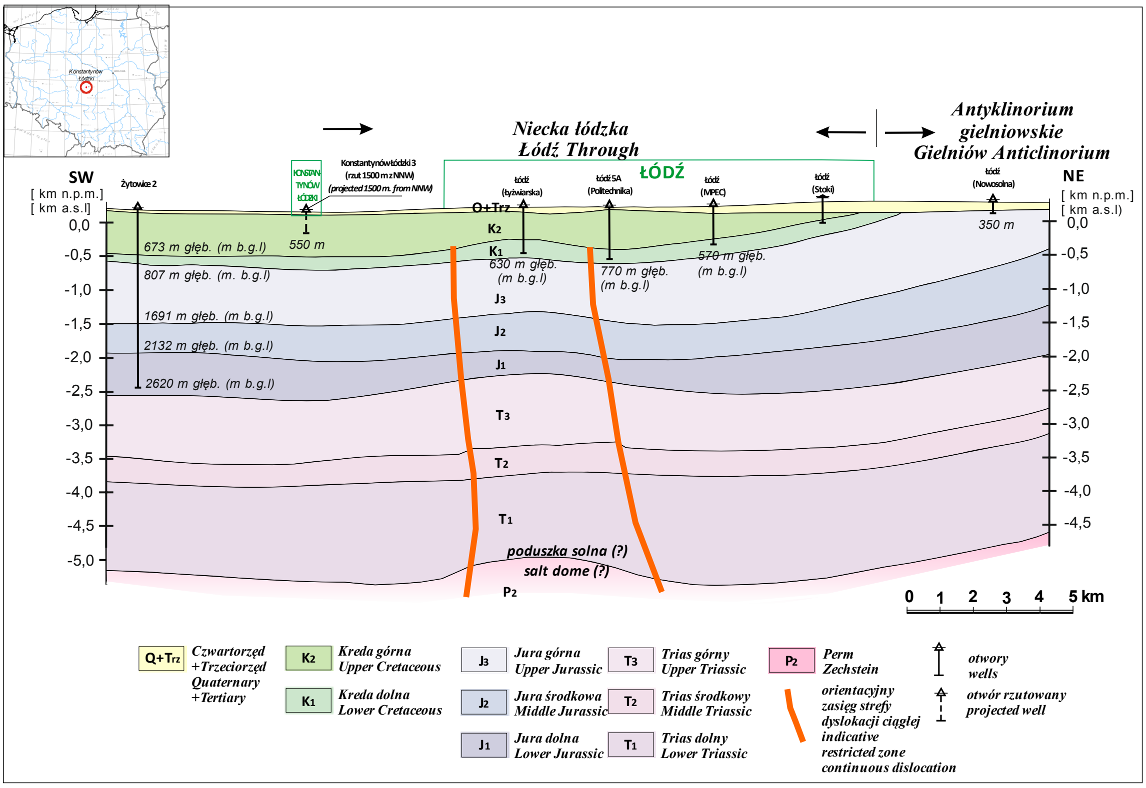


Fig. 5.6.1.3. Geological cross-section through Żytowice-Łódź (Nowosolna)
(according to the CBDG PIG-PIB Warsaw well data – online, September 2016)

The Żytowice 1 (with a depth interval of 2,481–2,531 m) and Lutomiersk 2 (2,532–3,204 m) wells were drilled into these formations (Fig. 5.6.1.2). Keuper formations are red claystones and mudstones, slightly marly with calcite and with gypsum and anhydrite layers. Sandstones occur within a series (a few dozen metres thick) of Schilfsandstein (reed sandstone) and Lower Keuper.
The main aquifer is considered to be the reed sandstone level of the Upper Keuper, which is usually saturated with formation water.
Flow rates of these waters have not been tested; the aforementioned *Atlas* (Górecki [ed.] et al., 2006) gives a maximum of the order of 100 m^3/h, but these are only indicative values. The ceiling of the Upper Triassic in the study area occurs at a depth interval of around 2,600 m hence the temperatures of waters present in these formations may range from 70 to 75°C.

Jurassic complex

The <u>*Lower Jurassic*</u> layer of the Łódź Basin is marked by alternating clay-mudstone-sandy deposits characteristic of the most heavily subsided parts of the Kujawy Furrow, with a thickness increasing from 1,125 m (Zgierz IG-1 well) to 1,318 m in the NW direction (Kutno 1 well). Triassic sedimentation continued in a freshened, limnic and isolated water body. Terrigenous formations were deposited there, with alternating predominance of clay-mudstone and sandy sediments. The clay sedimentation of brackish estuarine (Ciechocinek) layers only stabilised in the Toarcian to rapidly transform into sandstone sedimentation (Borucice layers) in the uppermost Toarcian. Salt structures in the Liasssic only formed to a small extent (Marek, 1985). The complex begins with brown and cherry claystones with conglomerate and limestone pebble inserts overlain by various types of sandstone. In the ceiling, there is a grey-green Estheria claystone series. In the area in question, the Lower Jurassic is represented by fine-grained fragile sandstones, mudstones, dark grey and black claystones with dolomite sandstone inserts and clayey siderite nests.

<u>Owing to its favourable reservoir parameters on the regional scale and significant water flow rates, the Lower Jurassic complex is considered to be the main geothermal aquifer within almost the entire area of the Polish Lowlands.</u>

The percentage share of aquifers in the entire Lower Jurassic profile in the Łódź region is estimated at around 50% of its total thickness (Górecki et al., 1995). The average filtration coefficient for the Łódź Basin is $4.5 * 10^{-5}$ m/s, the average permeability is 1.1 D and the average effective porosity is around 20% (Górecki et al., 1995). The mineralisation of Lower Jurassic reservoir waters in this region is estimated at around 50 g/dm^3 in the top layers with a hydrogeochemical gradient of 3.0 g/dm^3/100 m. Thus these are brines, mainly of the Cl–Na type.

Locally the flow rates of Lower Jurassic waters may reach up to 300 m^3/h from an individual well (assuming that the optimum levels within the complex are developed and that the thickness of the sandstone formations is sufficiently great). However, it may be assumed more conservatively that the flow rate from an individual well in the study area will range from 100 to 150 m^3/h. It may also be assumed that the free water table will be situated around 50 m below ground level.

The temperatures of Lower Jurassic waters and formations are directly related to the depth and thickness of the aquifer. It is estimated that in the area of Konstantynów where the ceiling lies at a depth of around 2,100 m and the estimated thickness is around 500 m, the temperature of the Lower Jurassic formations and the water at the top of the aquifer may reach around 65°C. Thus the temperature of the bottom parts, in line with the geothermal gradient, which is estimated at 3.0°C/100 m here, and given the thickness of Jurassic layers of 500 m, would be around 75°C at a depth of 2,600 m.

Detailed data on the spatial distribution of ceiling depths, temperatures and mineralisation levels of waters in the Lower Jurassic aquifer in the region in question are presented in Fig. 5.6.1.4.

<u>Lower Jurassic</u> formations were initially sediments of a limnic water body, which was transformed into a marine one during the Aalenian. Black claystones and mudstones accumulated there, separated by sandstone layers. In the Bajocian and Bathonian, marine terrigenous sedimentation of alternating calcareous claystone-mudstone and sandstone complexes followed, and sedimentation of the oolitic-chamosite-ferruginous facies was also present to a lesser degree. Dolomite and limestone sedimentation with glauconite started in the Lower Callovian, which later continued in the Lower Oxfordian (Upper Jurassic). These formations are overlain by a nodular Upper Callovian layer (Marek, 1985).

Within the Łódź Basin, the ceiling of this aquifer lies at depths ranging from -750 m a.s.l. (in the area of the Rogóźno diapir) through -1,500 m a.s.l. in the area of Żytowice and Konstantynów (Figs. 5.6.1.2 and 5.6.1.3) to around -2,250 m a.s.l. in the Aleksandrów Kujawski municipality. Thus within the Łódź Basin, where the thickness of this complex is very variable (from 100 to 1,100 m), water temperatures within the complex may range from 25°C to more than 70°C.

Aquifers were found, *inter alia*, in the Lutomiersk 2 well (at depths ranging from 1,226 to 1,250 m, with a flow rate of 12 m^3/h and with a temperature of 44°C, freshened water), Lutomiersk 3 well (at depths ranging from 2,211 to 2,181 m, with a flow rate of 1.5 m^3/h, formation temperature of 65°C, freshened water) (Fig. 5.6.1.2) and the Żytowice 1 well (at depths ranging from 1,965 to 2,065 m, with a flow rate of 0.5 m^3/h, formation temperature of 81°C, freshened water). In the area of the town of Zgierz (Zgierz IG-1 well; Marek, 1985), in Lower Bajocian sandstones and mudstones (at depths ranging from 2,155 to 2,180 m), saline formation water inflow of 1.3 m^3/h was observed with a formation temperature of 68°C, and from Lower Kuyavian sandstones (at depths ranging from 1,915 to 1,930 m) an inflow of Cl–Ca brine was noted which contained flammable gas and which had a flow rate of 0.7 m^3/h. The brine exhibited high mineralisation (60 g/dm^3) and significant iodine content (28 g/dm^3), and the formation temperature was 67°C.

In the area in question, these formations are mainly light-grey sandstones that are fine-grained, fragile and porous, slates, black mudstones with siderites, beige-grey and dark-grey claystones with mica containing charred plant detritus, and in the upper (Callovian) part, limestone is also present.

Water flow rates for the Middle Jurassic level can be estimated at around 100 m^3/h per well, assuming a large thickness of sandstone formations (see the *Atlas* cited above, (Górecki [ed.], 2006). More realistically, it can be assumed that the flow rate of a well in the study area will be about 50 m^3/h. The approximate depth of the free water table may be assumed to be approx. 50 m below ground level (according to data for other wells in the Łódź Basin).

The temperatures of Middle Jurassic waters and formations are directly related to the depth and thickness of the aquifer. It is estimated that in the area in question, where the aquifer ceiling lies at a depth of around 1,700 m (Fig. 5.6.1.3), the temperature of the top formations and Middle Jurassic waters may be around 55°C, while the temperature of the bottom parts will depend on the thickness of the aquifer and will change according to the geothermal gradient, which is estimated at 3.0°C/100 m in this area. For example, for the Middle Jurassic aquifer thickness of 400 m (in line with the cross-section shown in Fig. 5.6.1.3), its bottom would lie at a depth of around 2,100 m and the temperature would be around 60°C.

During the Oxfordian, Upper Jurassic formations within the Łódź Basin were deposited as shallow-water formations of the marly carbonate facies. These are light-coloured nodular limestones and rocky limestones with flints, organodetritic limestones, chalky limestones and oolite-oncolite limestones. The sedimentation of limestones and marls with marly shale and mudstone inserts persisted in the Kimmeridgian and in the Lower and Middle Volgian. In the Upper Volgian, this was transformed into brackish sedimentation (limestones with oolite inserts, anhydrites and Purbeck gypsum).
In the study area, these formations are quite uniform in lithological terms – these are mainly limestones, often marly or sandy, or marls, sometimes with gypsum and anhydrite inserts. Glauconite sandstones are present as well.

The thickness of Upper Jurassic sediments in this area is considerable, exceeding 900 m (Fig. 5.6.1.3) and the estimated depth of the ceiling of the Upper Jurassic formations in the area starts at around 800 m, which means that waters in the aquifer will reach temperatures of 25°C in its top part, while in the bottom part the temperature will be around 55°C.
Flow rates of these waters were little examined and the only information about Upper Jurassic aquifers in this zone comes from Lutomiersk 3 well, where a brine inflow of 10 m^3/h and temperature of 54°C was observed at a depth of 1,597–1,648 m.

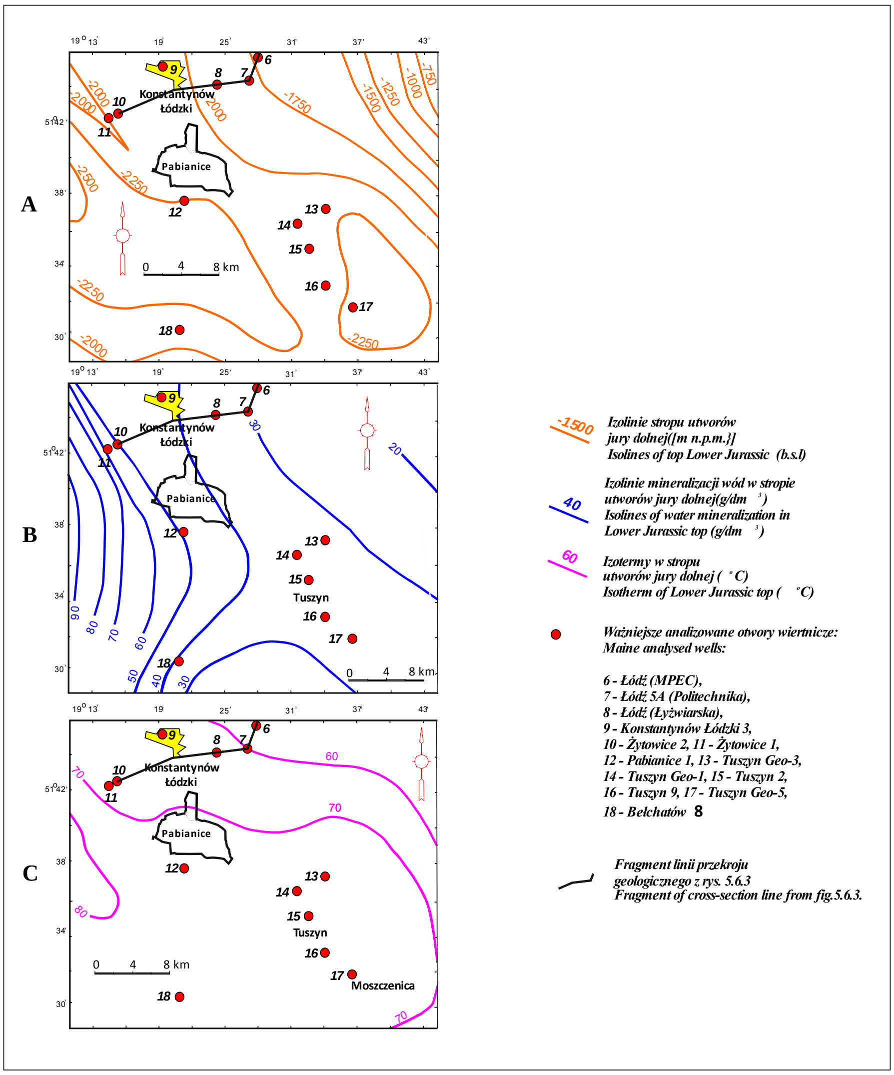


Fig. 5.6.1.4. Maps showing the locations of tops (A), water mineralisation levels (B) and temperatures of Lower Jurassic formations acc. to well data and the Atlas of Geothermal Resources in the Polish Lowlands (Górecki [sc.ed] et al., 2006)

Cretaceous complex

The *Lower Cretaceous* begins with shallow sea formations represented by claystone and mudstone series with siderite inserts. The upper part consists of sand and fine- and medium-grained sandstones, often glauconite ones with inserts that contain sandstone with ferruginous oolites.

In Lower Cretaceous formations, aquifers are present as a series of permeable sandy, sandy-marly and sandy-mudstone rocks from the Valanginian, Hauterivian and Barremian-Albian periods. The aquifer complex within the Łódź Basin is not a continuous one. Owing to tectonic rock dislocations, it is divided into several hydrostructural units with different aquifer formations and with no continuity of permeable and impermeable layers. The ceiling of the aquifer in the study zone is situated at a depth of around 650–700 m (Fig. 5.6.1.3), while the thickness of the entire complex is estimated at around 200 m and does not exceed 300 m. However, the percentage share of aquifers in the Lower Cretaceous profile is limited and estimated at around 85% here [5]. The average filtration coefficient for aquifers is $4.0 * 10^{-5}$ m/s, while the average effective porosity is 20% [5]. The mineralisation of waters in the Lower Cretaceous aquifer is estimated at about 0.3 g/dm^3 in this area, so these are fresh waters of the Na–Cl and Na–Cl–HCO_3 types (according to Altowski's classification).

Water flow rates from the Lower Cretaceous level can be estimated at 100–250 m^3/h per well, but actual flow rates will be dependent on local hydrogeological conditions and on production well design. Experience with the implementation of geothermal installations in nearby Mszczonów and with the tests conducted in wells in the area of Skierniewice indicates that real-world flow rates will be of the order of 60–150 m^3/h, although some hydrogeological data are more optimistic (Table 5.6.1.1). The pressure conditions present here are subartesian, with the free water table occurring at depths of around 30–40 m.

The temperatures of Lower Cretaceous waters and formations are directly related to the depth and thickness of the aquifer. Given the depth of the ceiling, which is expected to range from 500 to 700 m in the study area, water temperatures at these depths will be of the order of 20°C (Fig. 5.6.3, Table 5.6.1.1).

Table 5.6.1.1. Summary of water exploitation data from the Lower Cretaceous horizon

Well no. on fig.2	Well location	Drilled interval of the Lower Cretaceous (m b.g.l)	Water flow rate (m^3/h)	Temperature of water (°C)	Mineralization (g/dm^3)
2	Lutomiersk	91 – 267	1	13	0,2
3	Aleksandrów Łódzki	253 – 452	-	-	-
5	Stoki (Łódź)	~200 – (312>)	~150	14	0,35
6	MPEC ul. Tuwima (Łódź)	510 - (572>)	~100	~17	0,3
7	Politechnika (Łódź)	630 – 770	170	~18	0,2
8	ul. Łyżwiarska (Łódź)	~500 – (694>)	220	17	0,2
10, 11	Żytowice	673 – 807	-	20	-
13	Tuszyn	730 – 850	-	22	-

In the *Upper Cretaceous*, deep-sea sediments formed, mainly belonging to the marly facies with limestone, *opoka* (gaize) and chert inserts. The highest layer of the Upper Cretaceous consists of grey gaizes with sandy marl inserts that include glauconite grains and sponge needles.

In the northwestern zone of the Łódź Basin, Upper Cretaceous formations may reach a thickness of about 1,250 m within the 50–1,300 m interval. Due to its shallow deposition, this complex is uninteresting from the geothermal point of view, but is the main reservoir of groundwater intended for human consumption.

Cenozoic complex

Marine *Tertiary* formations were deposited unconformally upon Upper Cretaceous formations in the form of a clastic Oligocene formation (Fig. 5.6.1.3). In the bottom layer, these are represented by sands and disaggregated sandstones with glauconite; higher up, they are superseded by muddy and clayey formations. After the Oligocene, the sedimentation changed to terrestrial, and in the Miocene it occurred in huge inland water bodies. In the ceiling of Miocene sediments, within sands and clays, there are lignite deposits formed as a result of the accumulation of large amounts of plant matter in vast backswamps (in the area of Konin, Turek and Bełchatów). Within the Bełchatów lignite field, there are lacustrine limestones

that contain a rich fauna of both freshwater and terrestrial molluscs. Overlying Pliocene formations are represented by variegated clays.
The *Quaternary* formations are the result of three glaciations, with Baltic Glaciation formations being the best developed. These are moraine tills, fluvial and fluvioglacial formations. Holocene formations are mainly fluvial accumulation deposits – alluvial soils and sands and, locally, peat.
Cenozoic formations do not play a role as geothermal water reservoirs, but instead they provide (together with the Upper Jurassic aquifers) the main aquifers with groundwater for human consumption in the area.

5.6.2. Summary of selected hydrogeothermal data for wells in the Łódź Basin area

Analyses of hydrogeothermal parameters obtained for the wells drilled in the area of the Łódź Basin (including in the vicinity of Konstantynów Łódzki) indicate that Mesozoic aquifers composed of Cretaceous, Jurassic and locally Triassic formations are of most importance from the geothermal point of view. Given their potential water flow rates, especially favourable parameters are exhibited by Lower Jurassic, Middle Jurassic and Lower Cretaceous aquifers, but owing to the low water temperatures in the Lower Cretaceous aquifer in the Konstantynów area, its importance as a geothermal resource is limited. The Lower Jurassic aquifer exhibits the most favourable characteristics.
Information about geothermal conditions in the area discussed is very modest and thus it was supplemented with regional data from more distant wells. Below is a synthesis of relevant information on geothermal conditions according to data from selected wells in the vicinity of Konstantynów and in neighbouring areas (Głowacki et al., 1971; Bojarski, 1996).
The town of Pabianice (10 km S from Konstantynów Łódzki, cf. Fig. 5.6.1.2) has been adopted as the reference point for the locations of selected wells that are outside the boundaries of the map in Fig. 5.6.1.2.

Wartkowice 2 well (47 km NW from Pabianice)

The following formations were drilled through: Quaternary, Tertiary, Upper Cretaceous, Lower Cretaceous, Upper Jurassic, Middle Jurassic, Lower Jurassic, Upper Triassic and Lower Triassic; the well ends in Zechstein formations at a depth of 3,087 m.
Drill stem testing:
Upper Jurassic 1,549–1,566 m – brine inflow with gas (5 m^3/h), mineralisation 80 g/dm^3. Drilling fluid escape in Cretaceous formations.

Wartkowice 3 well (44 km NW from Pabianice)

The following formations were drilled through: Quaternary, Tertiary, Upper Cretaceous, Lower Cretaceous, Upper Jurassic and Middle Jurassic; the well ends in Lower Jurassic formations at a depth of 2,475 m.
Drill stem testing:
Upper Jurassic 1,715–1,718 m – an inflow of water with a mineralisation of 109 g/dm^3;
Middle Jurassic 2,142 m – an inflow of water (13 m^3/h) with a mineralisation of 114 g/dm^3;
2,298–2,324 m – an inflow of water (9 m^3/h) with drilling mud filtrate;
Middle and Lower Jurassic 2,398–2,350 m – an inflow of water (4.1 m^3/h) with a mineralisation of 76 g/dm^3;
Drilling fluid escape in Upper Cretaceous formations.

Poddębice IG-1 well (44 km NW from Pabianice)

Drill stem testing:
Upper Jurassic 2,545–2,572 m – an inflow of brine (3.5 m^3/h);
2,659-2,722 m – an inflow of brine (5 m^3/h).

Uniejów 1 well (47 km NW from Pabianice)

The following formations were drilled through: Quaternary, Tertiary, Upper Cretaceous, Lower Cretaceous, Upper Jurassic, Middle Jurassic, Upper Triassic, Middle Triassic and Lower Triassic; the well ends in Zechstein formations at a depth of 4,775 m.
Drill stem testing:
Lower Cretaceous 1,719–1,724 m – an inflow of formation water with a mineralisation of 21 g/dm^3.

Wilczyca 1 well (31 km NW from Pabianice)

The following formations were drilled through: Quaternary, Upper Cretaceous, Lower Cretaceous, Upper Jurassic and Middle Jurassic; the well ends in Upper Triassic formations at a depth of 3,217 m.
Drill stem testing:
Upper Triassic 2,359 m – gas inflow.
Drilling fluid escape in Upper Cretaceous formations.

Aleksandrów Łódzki 1 well

The following formations were drilled through: Quaternary, Tertiary, Upper Cretaceous, Lower Cretaceous, Upper Jurassic and Middle Jurassic; the well ends in Lower Jurassic formations at a depth of 2,318 m.
In Jurassic formations, loss of drilling fluid was observed.

Lutomiersk 2 well

The following formations were drilled through: Quaternary, Tertiary, Upper Cretaceous, Lower Cretaceous, Upper Jurassic and Middle Jurassic; the well ends in Lower Jurassic formations at a depth of 3,204 m.
Drill stem testing:
Middle Jurassic 1,226–1,250 m – an inflow of water (12 m^3/h) with formation temperature of 44°C;
In Upper Jurassic formations, drilling fluid escape was observed.

Lutomiersk 3 well

The following formations were drilled through: Quaternary, Upper Cretaceous, Lower Cretaceous, Upper Jurassic and Middle Jurassic. The well ends in Lower Jurassic formations at a depth of 2,506 m.
Drill stem testing:
Upper Jurassic 1,597–1,607 m – an inflow of brine (4.8 m^3/h); formation temperature 53°C;
636–1,648 m – an inflow of brine (5 m^3/h); formation temperature 55°C;
Middle Jurassic 2,211–2,181 m – an inflow of water (1.5 m^3/h) with formation temperature of 65°C.
Drilling fluid escape was observed in Upper Cretaceous and Lower Jurassic formations.

Żychlin IG-3 well (72 km NE from Pabianice)

The following formations were drilled through: Quaternary, Tertiary, Upper Cretaceous, Lower Cretaceous, Upper Jurassic and Middle Jurassic; the well ends in Lower Jurassic formations at a depth of 2,478 m.
Well testing:
Upper Cretaceous 100–110 m – after bailing, a weak inflow of water (around 0.02 m^3/h on average) was observed;
Upper Jurassic 1,208–1,220 m – no inflow was observed after bailing, the level was plugged at a depth of 620 m;
Middle Jurassic 1,875–1,885 m – after bailing, an artesian flow of mineralised water was observed (0.828 m^3/h, 5 m above ground level);
Lower and Middle Jurassic 2,203.4–2,478 m – brine inflow was observed (15 m^3/h) with mineralisation of 1.0716 g/dm^3. The hydrostatic level was 58 m b.g.l.

Kompina 2 well (69 km NE from Pabianice)

The following formations were drilled through: Quaternary, Upper Jurassic, Middle Jurassic, Lower Jurassic, Upper Triassic, Middle Triassic and Lower Triassic; the well ends in Zechstein formations at a depth of 4,570 m.
Drill stem testing:
Upper Jurassic 1,615–1,633 m – an inflow of brine (2.3 m^3/h); formation temperature 51°C, mineralisation 15.09 g/dm^3;
1,640–1,664 m – brine (0.2 m^3/h); mineralisation 48.9 g/dm^3;
Middle Jurassic 2,665–2,681 m – an inflow of brine (0.688 m^3/h); mineralisation 114.2 g/dm^3;
Lower Jurassic 2,760–2,765 m – an inflow of brine (3.34 m^3/h); mineralisation 94.1 g/dm^3;
Upper Triassic 3,110–3,125 m – an inflow of brine (22 m^3/h); mineralisation 129.6 g/dm^3;
3,545–3,585 m – an inflow of brine (0.177 m^3/h); mineralisation 96.57 g/dm^3;
3,620–3,635 m – an inflow of brine (0.106 m^3/h); mineralisation 145.25 g/dm^3;
3,644–3,656 m – an inflow of brine (0.34 m^3/h); mineralisation 148.5 g/dm^3;

Middle Triassic 3,910–3,920m – an inflow of brine (0.36 m3/h), mineralisation 164.76 g/dm3, temperature 97°C;
4,000–4,022 m – weak inflow, temperature 104°C;

Lower Triassic 4,024 m – artesian flow of brine, mineralisation 270.019 g/dm3;
4,110–4,115 m – artesian flow of brine, mineralisation 337.096 g/dm3;

During the drilling of the 3,395–3,884 m interval (Rhaetian-Keuper-Muschelkalk), continuous drilling fluid losses were observed (around 825 m3), and in the 4,048–4,105 m interval (Buntsandstein) drilling fluid loss amounted to ca. 50 m3.

Łowicz IG-1 well (62 km NE from Pabianice)

The following formations were drilled through: Quaternary, Tertiary, Upper Cretaceous, Lower Cretaceous, Upper Jurassic and Middle Jurassic; the well ends in Lower Jurassic formations at a depth of 2,997 m.

Testing with a wireline logging tool:

Lower Cretaceous 425 m; 430 m; 437 m – no inflows;

Upper Jurassic 790 m; 895 m; 970 m; 1,093 m; 1,150 m – no inflows;

Middle Jurassic 1,400 m; 1,402 m; 1,415 m; 1,823 m – no inflows;
1,675 m – an inflow of brine (8 dm3);

Lower Jurassic 2,033 m; 2,225 m – inflows of brine (7 dm3).

Temperatures according to maximum thermometer measurements:

295 m – 19.5°C;
775 m – 24°C;
1,020 m – 28°C;
1,295 m – 31°C;
1,860 m – 41°C;
2,293 m – 51°C.

Raducz IG-1 well (73 km NE from Pabianice)

The following formations were drilled through: Quaternary, Upper Cretaceous, Lower Cretaceous, Upper Jurassic, Middle Jurassic, Lower Jurassic, Upper Triassic, Middle Triassic and Lower Triassic; the well ends in Zechstein formations at a depth of 3,864 m.

Lower Jurassic 2,625–2,655 m – water temperature was 42°C, with a flow rate of 36 m3/h and mineralisation of 101.5 g/dm3. An unstable water table was found at a depth of 122 m b.g.l.

Middle Jurassic 2,305–2,335 m – water temperature was 41°C, with a flow rate of 18 m3/h and mineralisation of 91.9 g/dm3. The hydrostatic level was found at a depth of 96 m b.g.l.

Drill stem testing:

Lower Cretaceous 1,157–1,180 m – inflow (35–40 m3/h) of water with a low level of mineralisation (1.142 g/dm3), hydrostatic level 29.6 m b.g.l., temperature 25°C;

Upper Jurassic 1,485–1,510 m – inflow (0.54 m3/h) of mineralised water (10.1 g/dm3), hydrostatic level 30 m b.g.l.

Jeżów IG-1 well (47 km NEE from Pabianice)

The following formations were drilled through: Quaternary, Middle Jurassic, Lower Jurassic, Upper Triassic and Middle Triassic; the well ends in Lower Triassic formations at a depth of 3,062 m.

Testing with a wireline logging tool:

Middle and Upper Jurassic, Upper and Middle Triassic – no inflows.

Drill stem testing:

Upper, Middle and Lower Triassic 2,190.5–2,225.5 m – no water inflow (an inflow of 7 dm3 of drilling fluid);
2,190.5–2,263.6 m – no water inflow (an inflow of 30 dm3)

Aquifer testing:

Lower Jurassic 1,635–1,657 m – an inflow of bicarbonate-sodium water was observed with a mineralisation of 2.66 g/dm3 (2–3 m3/h, at depressions of 76–118 m). The hydrostatic level was at 1.9 m b.g.l.

1,712–1,721 m – an inflow of chloride-calcium formation water with a mineralisation of 12.9 g/dm3 was observed (1.25 m3/h, at a depression of 38 m). The hydrostatic level was at 18.3 m b.g.l.

Upper Triassic 1,899–1,893 m – an inflow of chloride-calcium formation water with a mineralisation of 63.2 g/dm^3 was observed (0.056 m^3/h, at a depression of 38 m).
Middle Triassic 2,020–2,027 m; 2,060–2,064 m; 2,077–2,090 m; 2,110–2,116 m – no inflows;
Lower Triassic 2,306–2,322 m – no inflow.
Drill stem testing:
Upper Triassic 1,893–1,899 m – no inflow;
Middle Triassic 2,306–2,322 m – no inflow.

Rawa Mazowiecka 1 well (62 km NE from Pabianice)

Drill stem testing:
Lower Triassic 4,203–4,230 m – inflow of drilling fluid.
Żytowice 2 well

The following formations were drilled through: Quaternary, Upper Cretaceous, Lower Cretaceous, Upper Jurassic and Middle Jurassic; the well ends in Lower Jurassic formations at a depth of 2,619 m.
Drill stem testing:
Upper Jurassic 1,090–1,130 m – an inflow of drilling mud filtrate with signs of gas;
Middle Jurassic 2,418–2,513 m – an inflow of brine (0.7 m^3/h).
Drilling fluid escaping in the Upper Jurassic.

Żytowice 1 well

The following formations were drilled through: Quaternary, Upper Cretaceous, Lower Cretaceous, Upper Jurassic, Middle Jurassic and Lower Jurassic; the well ends in Triassic formations at a depth of 2,330 m.
Drill stem testing:
Upper Jurassic 1,347–1,365 m – an inflow of weakly mineralised water;
Middle Jurassic 1,965–2,065 m – an inflow of mineralised water (0.5 m^3/h) with a formation temperature of 81°C;
Lower Jurassic 2,481–2,531 m – an inflow of brine (0.7 m^3/h).

Niemirów 2 well (45 km SW from Pabianice)

Drill stem testing:
Lower Triassic 2,183–2,193 m – an inflow of brine (2.1 m^3/h).

5.6.3. Potential energy resources related to geothermal waters in the Konstantynów Łódzki area

Calculations of potential energy resources for the selected geothermal aquifers (Lower Cretaceous, Upper Jurassic, Middle Jurassic, Lower Jurassic, Upper Triassic) are based on the algorithm for determining exploitable resources. Literature on the subject contains a number of methods for determining energy potential, including available resources, disposable resources or exploitable resources, which are estimated here. Exploitable resources (understood as capacities and heat energy levels that can be obtained) are determined as the energy potential that can be extracted from a *single* well. In the estimation, average temperatures (between the top and bottom of the reservoir in question) were used and flow rates were estimated using information from adjacent geological units in the Polish Lowlands. The energy assessments presented are therefore indicative and are intended, *inter alia*, as input for ranking the attractiveness of individual aquifers in the area.
For the aquifers selected, thermal capacity and the annual amount of heat that can be obtained were determined for the case where heat is extracted from geothermal water until it reaches a temperature of about 15°C, thus assuming the use of heat pumps.
Calculations were based on the following formulae:

Thermal capacity

$$P_{term} = 0{,}0012 \cdot \Delta t \cdot Q \text{ [MW]}$$

where:

P_{term} – potential thermal capacity of a single well, MW

Δt – cooling, °C

Q – water flow rate, m^3/h

0.0012 – a coefficient accounting for the specific heat of water and unit conversions

It was assumed that water would be cooled to 15°C in the installations using heat pump systems:

$$P_{term} = 0{,}0012 \cdot (t-15) \cdot Q \ [MW]$$

<u>Thermal energy [TJ/year]</u>

$$W_{term} = P_{term} \cdot 8760 \cdot 0{,}0036 \cdot x = P_{term} \cdot 31{,}54 \cdot 0{,}3 = 9{,}46\ P_{term}\ [TJ/year]$$

where:

P_{term} – thermal capacity of a single well, MW

t – temperature of thermal waters, °C

Q – estimated geothermal water flow rate, m^3/h

x = 0.3 – annual thermal capacity utilisation ratio

W_{term} – thermal energy from a single well, TJ / year

8,760 – number of hours per year

0.0036 – conversion coefficient (MWh to TJ)

<u>*Lower Cretaceous aquifer*</u>

Based on the depth range of the aquifer, the maximum temperature was assumed to be 25°C (temperatures probably vary from 20°C to 25°C). Taking into account borehole logging data and forecasts from *Atlas zasobów geotermalnych formacji mezozoicznej na Niżu Polskim* ["Atlas of Geothermal Resources of the Mesozoic Formation in the Polish Lowlands"] (W. Górecki [sc. ed] et al., 2006) the flow rate was assumed to be 70 m^3/h.

<u>Thermal capacity</u>

$$P_{term} = 0{,}0012 \cdot (25 - 15) \cdot 70 = 0{,}84\ [MW]$$

<u>Thermal energy</u>

$$W_{term} = 9{,}46 \cdot P_{term} = 9{,}46 \cdot 0{,}84 \approx 8\ [TJ/year]$$

<u>*Upper Jurassic aquifer*</u>

Based on estimated aquifer temperatures according to the *Atlas* cited above in the Konstantynów area, an average temperature of 40°C and a flow rate of Q~30 m^3/h were assumed.

<u>Thermal capacity</u>

$$P_{term} = 0{,}0012 \cdot (40 - 15) \cdot 30 = 0{,}9\ [MW]$$

<u>Thermal energy</u>

$$W_{term} = 9{,}46 \cdot P_{term} = 9{,}46 \cdot 0{,}9 = 8{,}6\ [TJ/year]$$

<u>*Middle Jurassic aquifer*</u>

On the basis of borehole logging data and the data included in the *Atlas* cited above on the aquifer in the area of Konstantynów an average temperature of 55°C and a flow rate of 70 m^3/h were assumed.

<u>Thermal capacity</u>

$$P_{term} = 0{,}0012 \cdot (55 - 15) \cdot 70 = 3{,}4\ [MW]$$

<u>Thermal energy</u>

$$W_{term} = 9{,}46 \cdot P_{term} = 9{,}46 \cdot 3{,}4 = 32\ [TJ/year]$$

Lower Jurassic aquifer

On the basis of the same data on the aquifer in the Konstantynów area, an average temperature of 70°C and a flow rate of 130 m^3/h were assumed.

Thermal capacity

$$P_{term} = 0{,}0012 \cdot (70 - 15) \cdot 130 = 8{,}6 \text{ [MW]}$$

Thermal energy

$$W_{term} = 9{,}46 \cdot P_{term} = 9{,}46 \cdot 8{,}6 = 81{,}5 \text{ [TJ/year]}$$

Upper Triassic aquifer

Similarly, on the basis of the above data on the aquifer in the area of Konstantynów, an average temperature of 95°C and a flow rate of 30 m^3/h were assumed.

Thermal capacity

$$P_{term} = 0{,}0012 \cdot (95 - 15) \cdot 30 = 2{,}9 \text{ [MW]}$$

Thermal energy

$$W_{term} = 9{,}46 \cdot P_{term} = 9{,}46 \cdot 2{,}9 = 27{,}4 \text{ [TJ/year]}$$

The *estimated* parameters of geothermal waters contained in the aquifers present in the study area are as follows (aquifers have been ordered in descending order according to their energy potentials):

- Lower Jurassic: temperature 60–75°C, flow rate 100–160 m^3/h, depth interval from 2,100 to 2,700 m, mineralisation from 40 to 120 g/dm^3;
- Middle Jurassic: temperature 50–60°C, flow rate 60–80 m^3/h, depth interval from 1,700 to 2,200 m, mineralisation from 35 to 40 g/dm^3;
- Upper Triassic: temperature 75–120°C, flow rate 20–40 m^3/h, depth interval from 2,700 to 3,700 m, mineralisation from 120 to 169 g/dm^3;
- Upper Jurassic: temperature 25–50°C, flow rate 20–40 m^3/h, depth interval from 800 to 1,700 m, mineralisation from 15 to 35 g/dm^3;
- Lower Cretaceous: temperature 22–25°C, flow rate 40–100 m^3/h, depth interval from 700 to 800 m, mineralisation <1 g/dm^3.

In the area discussed, the **Lower Jurassic** aquifer exhibits the most favourable characteristics in terms of its energy parameters. However, this aquifer is found at depths below 2,000 m and contains highly saline waters. Thus two wells (a doublet system) of considerable depths would need to be drilled, resulting in high costs. Favourable Lower Cretaceous reservoir parameters (possible flow rates of up to 100 m^3/h) and the low mineralisation of water in this aquifer indicate that it could be used for heating purposes in combination with heat pumps or for leisure purposes using a cheaper single-well system.

Analyses of the hydrogeothermal parameters for the wells drilled in the area discussed and in its vicinity indicate that, from the point of view of geothermal use, Mesozoic (Jurassic and Cretaceous) aquifers are the most significant. Given their potential water flow rates, especially favourable parameters are exhibited by the Lower Cretaceous and Lower Jurassic aquifers, but owing to the low water temperatures in the Lower Cretaceous aquifer in this area, its importance as a geothermal resource is limited (it could potentially be used in combination with heat pump systems).

Waters of the Cl–Ca or Cl–Na hydrochemical types with elevated iodine and/or bromine content are present in this area (especially in Jurassic formations). The iodine content and temperature of waters in the Łódź Basin indicate that these waters in the Konstantynów area may exhibit therapeutic characteristics and could be used in balneotherapy and also for recreational purposes.

5.6.4. Heat demand in the Konstantynów Łódzki and Łódź area

The energy generated from the geothermal installation using the planned Konstantynów Łódzki GT-1 geothermal well could potentially be used to meet the heating needs of the housing stock that is currently connected to the district heating network of the city of Łódź. The operator of the district heating network is Veolia Energia Łódź. Veolia started connecting customers from Konstantynów Łódzki to its district heating system during the 2016/2017 heating season. Previously, the demand for heating in Konstantynów Łódzki was satisfied by the existing (although currently disused) district heating plant with an installed capacity of 10 MW. It produced around 51.8 TJ of thermal energy and consumed around 1.5 million m^3 of high-methane natural gas per year. This district heating plant is around 20 metres away from the location of the planned Konstantynów Łódzki GT-1 well. It provides a convenient opportunity to incorporate the well in the district heating system. The amount of power delivered was controlled with the use of a so-called adjustment table, through adjustments to the flow rate of water within the district heating network. The water flow rate in the network ranged from 90 to 130 m^3/h in winter and from 15 to 30 m^3/h in summer (for water heating purposes). The district heating plant has now been replaced by heat produced from coal (86.55%) and biomass (12.26%) with other fuels making up the rest. The total length of the district heating network in Konstantynów is 6.5 km, of which about 93% is pre-insulated. The power ordered by customers amounts to 7,873 kW, and heat sales are estimated at 45,234 GJ/year (source of information: Konstantynowskie Przedsiębiorstwo Komunalne Sp. z o.o.). The power delivered to customers who use district heating to heat water is estimated at 800 kW. The amount of power delivered is currently controlled on the basis of the parameters applicable to the Veolia Energia Łódź district heating network. Emission indicators for the energy sources used by Veolia Energia Łódź S.A. are stated below; these emissions refer to the energy used by customers but also take into account heat loss in transit (source: Veolia Energia Łódź):

- 107.524 kg/GJ for CO_2;
- 0.338 kg/GJ for SO_2;
- 0.191 kg/GJ for NO_X;
- 8.4 kg/GJ for total inhalable dust.

It is necessary to comment on the data received from the operator of the energy source, i.e. Konstantynowskie Przedsiębiorstwo Komunalne Sp. z o.o., regarding the utilisation of the installed capacity. Annual energy demand data have been averaged over the past three years (i.e. cover the 2012/2013, 2013/2014 and 2014/2015 seasons). This period was characterised by fairly high average annual temperatures and thus energy demand was not particularly high. Additionally, the share of customers in Konstantynów Łódzki who use district heat for water heating is not significant. The typical average annual contracted capacity utilisation ratio (defined as the ratio of the energy actually consumed by the customer to the energy that the consumer could potentially use if the maximum capacity contracted were utilised throughout the year) ranges from around 0.22 to 0.25. In the case study, this ratio was around 0.18 for the last three years, i.e. significantly lower than typical values. Fig. 5.6.5 shows an ordered capacity demand curve for the customers who use the district heating network of Konstantynowskie Przedsiębiorstwo Komunalne. The amount of instantaneous power used by customers was determined using typical meteorological years and data from the local meteorological station.

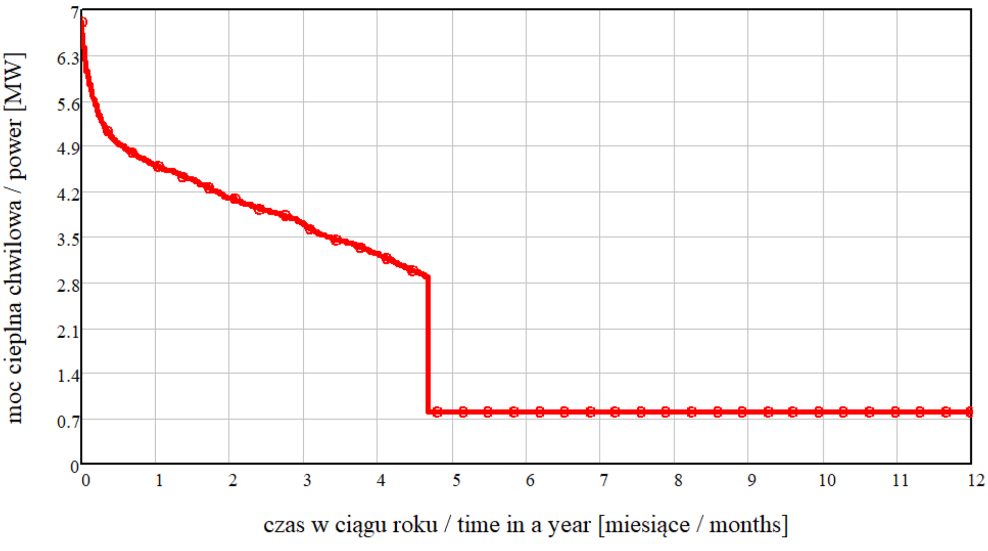


Fig. 5.6.1.5. Capacity demand curve (in decreasing order) for customers connected to the district heating system of the city of Łódź and of Konstantynów Łódzki

The diagram in Fig. 5.6.1.6 presents in simplified terms the integration of a geothermal source in the Konstantynów Łódzki district heating system. The Figure shows that the suggested method is to include the geothermal energy source in the district heating system so that it operates at the highest possible capacity throughout the year. The heat currently taken from the district network will serve as the peak load heat source.

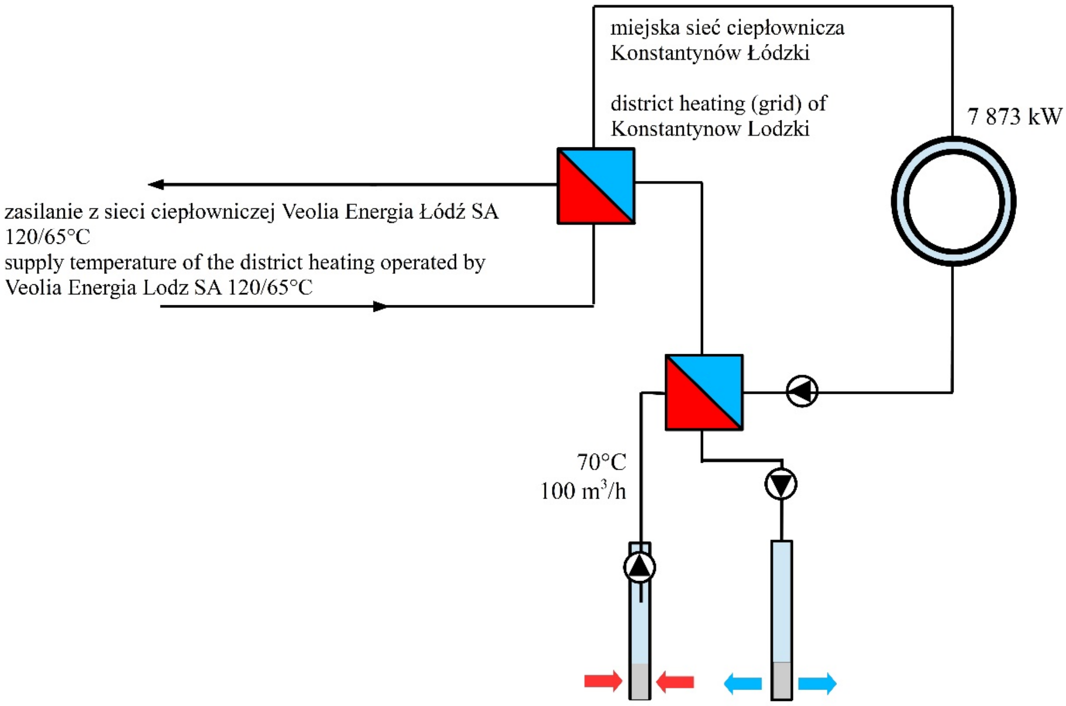


Fig. 5.6.1.6. Technological diagram related to the integration of the geothermal energy source in the district heating system in Konstantynów Łódzki

Fig. 5.6.7 presents a capacity demand diagram in decreasing order of the customers' demand for instantaneous power and the possibility of covering the demand for power using the geothermal source. The calculations, whose results are presented in the text, take account of a night (9 pm to 6 am) reduction in nominal capacity, using a factor of 0.7.

Based on the assumptions presented, the total capacity demand of the customers connected to the district heating network of Konstantynowskie Przedsiębiorstwo Komunalne Sp. z o.o. was estimated at ca. 65 TJ/year. This results in an average annual installed capacity utilisation ratio of 0.24. The amount of power that can be extracted from the geothermal source without the use of heat pumps (according to the diagram shown in Figure 5.6.1.6) is estimated at around 51.2 TJ/year. That means that geothermal covers about 78.8% of the total capacity demand of the customers connected to the district heating network in Konstantynów Łódzki. Based on Fig. 5.6.1.7, the maximum capacity can be estimated at approx. 3.5 MW.

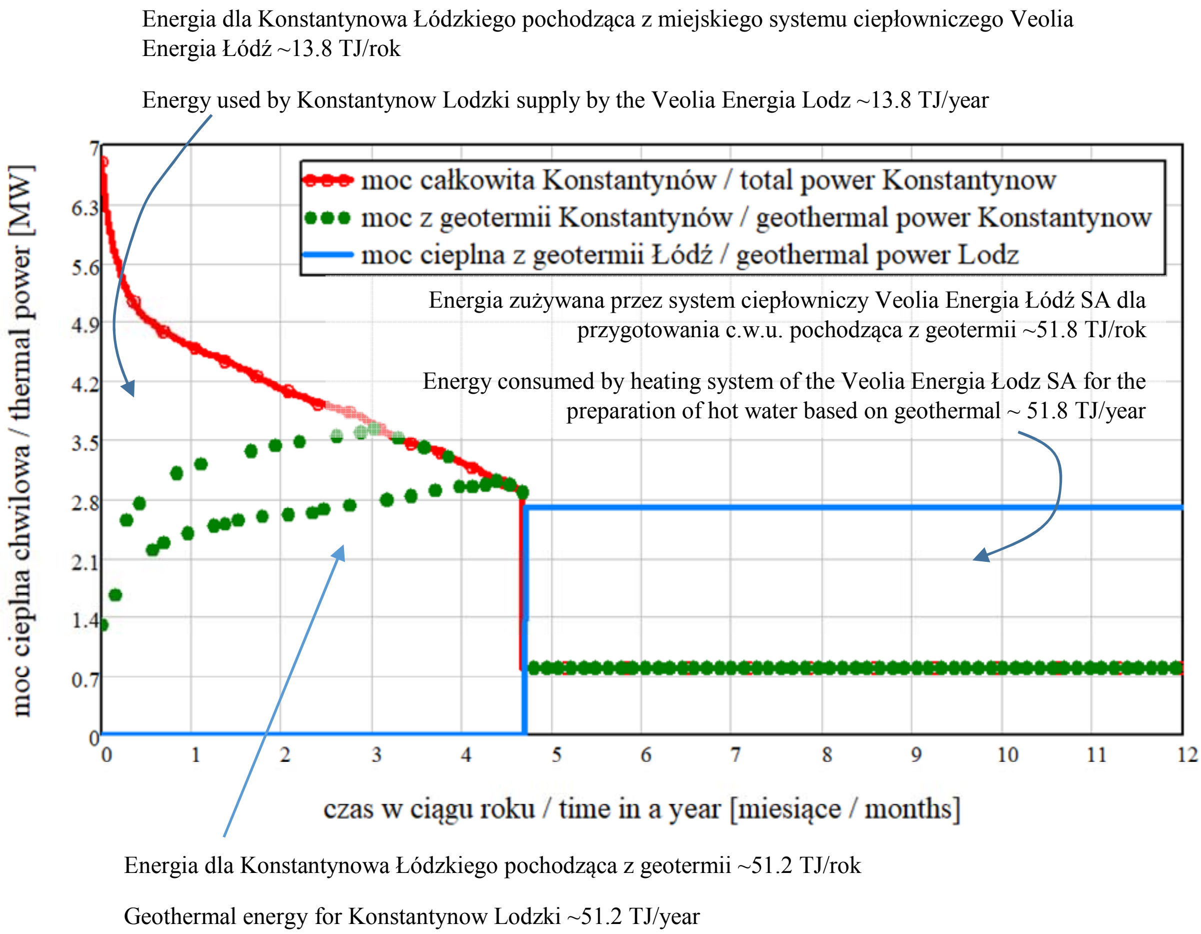


Fig. 5.6.1.7. Possibility of covering the heat demand of customers located in Konstantynów Łódzki with geothermal energy originating from the Konstantynów Łódzki GT-1 well – curves ordered in decreasing order of power supplied to customers. Energy use without heat pumps, as shown in Fig. 5.6.1.6

Using excess geothermal energy in summer to meet the needs of the Łódź district heating system could significantly increase the percentage share of clean renewable energy used. The Veolia Energia Łódź S.A. heating system operator has expressed interest in this solution as confirmed by the letter of intent enclosed with the application. With this solution, the potential amount of geothermal energy used would increase to around 101 TJ/year (51.8 TJ/year would be used by Veolia Energia Łódź in the city of Łódź and 51.2 TJ/year would be used in Konstantynów Łódzki).
Extracting this amount of energy would translate into an environmental effect of reducing the emission of pollutants from the energy sources operated by Veolia Energia Łódź S.A. by:

- 11,100 Mg/year for CO_2;
- 34.8 Mg/year for SO_2;
- 19.7 Mg/year for NO_X;
- 0.87 Mg/year for total inhalable dust.

The degree of utilisation of available energy resources in the case study can be considered very high. The available capacity of the geothermal installation is almost fully utilised throughout the year. This makes it possible to sell surplus energy in summer to a large additional customer – the district heating system in the city of Łódź.

The above assessment of real-world opportunities for using geothermal energy is limited to the simplest method of extracting it, exclusively using heat exchangers (Figure 5.6.1.6). Supplementing the energy source with heat pumps will enable a considerably greater amount of geothermal energy to be extracted. Given worldwide and domestic experience in the use of geothermal waters, geothermal water can be cooled by heat pumps (involving energy recovery) to less than 20°C. A relevant example is the Geotermia Mazowiecka installation in Mszczonów, which uses a cascade consisting of an absorption heat pump and a compression heat pump. In this case, the capacity of the installation using the planned Konstantynów Łódzki GT-1 well could increase to over 10 MW (the power generated from the geothermal source of ca. 8.3 MW and the power driving the heat pumps, depending on their type and efficiency). This would mean more than doubling the capacity compared to the solution based solely on heat exchangers (Fig. 5.6.1.6).

References:

Bojarski L., 1996: Atlas hydrochemiczny i hydrodynamiczny paleozoiku i mezozoiku oraz ascenzyjnego zasolenia wód podziemnych na Niżu Polskim 1:1 000 000. PIG Warszawa.

Dadlez R., Marek S., Pokorski J., 2000: Mapa geologiczna Polski bez utworów kenozoiku. PIG – Warszawa.

Głowacki E., Horn E., Wardęga A., Żurek E., 1971: Katalog wierceń naftowych w Polsce, T II, cz. 2. Min. Górn. i Energii, Warszawa.

Górecki W. [sc. ed], Hajto M. et al., 2006: Atlas zasobów geotermalnych na Niżu Polskim. Zakład Surowców Energetycznych, AGH – WGGiOŚ, Kraków.

Górecki W. [sc. ed], Reicher B., Jarosz Z., 1995: Katalog otworów wiertniczych i studni głębinowych w utworach kredy dolnej i jury dolnej na Niżu Polskim. Instytut Surowców Energetycznych AGH, Kraków.

Marek S., 1985: Najważniejsze wyniki wiercenia, rozdz. VI [W:] Dokumentacja wynikowa otworu badawczego Zgierz IG-1 (poz. pl. 1.3.4C). Praca zbiorowa Zakładu Geologii Regionalnej Obszarów Platformowych Instytutu Geologicznego Centralnego Urzędu Geologii. Warszawa.

Pożaryski W. [ed], 1974: Budowa Geologiczna Polski. T. IV, Tektonika Cz.1, Niż Polski. Wyd. Geol. Warszawa.

5.6.2. Analysis and proposal for heat pump in geoDH in Konstantynów Łódzki

5.6.2.1. Available resources

The projected operating parameters of the geothermal borehole, Konstantynów Łódzki GT-1:
- planned geothermal horizon: Lower Jurassic,
- planned depth interval: 2.200-2.770 m ugl (under the ground level),
- projected head temperature of thermal water: 60-75°C (70°C assumed in calculations). Water deposit temperature: 71°C,
- projected output: 100-160 m^3/h (130 m^3/h assumed in calculations),
- projected total mineralisation: 40-120 g/l (depending on the origin of the main influx of water: Lower Jurassic bottom or ceiling),
- static mirror level: 50 m ugl, dynamic: 180 m ugl (unit depression: 1 $m/m^3/h$).

5.6.2.2. Existing infrastructure

The energy obtained from the geothermal source, through the newly designed geothermal borehole, Konstantynów Łódzki GT-1,can be used for fulfilling the heating needs of the housing stock supplied from the network heat produced by the district heating facility in Łódź. Veolia Energia Łódź is the district heating network operator. Veolia included the customers from Konstantynów Łódzki to its district heating system in the heating season of 2016/2017. Earlier, the Konstantynów Łódzki customers had been supplied from the still existing but not operated any more municipal station, with the installed capacity of 10 MW. The station produced ca. 51.8 TJ of thermal energy a year and consumed ca. 1.5 mio. $m^3$of high-methane gas a year. The station is located ca. 20 m away from the site selected for the newly designed Konstantynów Łódzki GT-1 borehole. The site is suitable for the facility inclusion into the district heating system. The control of the supplied capacity was based on the so-called Control Table and by network water stream control. The network water stream control was changing from90 to 130 m^3/h in winter and from 15 to 30 m^3/h in summer (hot tap water preparation). Presently, the district heating station has been replaced by the network heat generated from: coal in 86.55%, biomass in 12.26%, and other fuels to the rest of 100%. The total length of the local district heating network of Konstantynów amounts to 6.5 km, of which ca. 93% is pre-insulated. The capacity ordered by the customers is 7,873 kW, and the heat sales are estimated at 45,234 GJ/yr (source: Konstantynowskie Przedsiębiorstwo Komunalne Sp. z o.o.). The capacity of the connected customers using the network heat to prepare hot tap water was estimated at ca. 800 kW. Presently, they apply the method of controlling the supplied capacity based on the parameters of the district heating network of Veolia Energia Łódź. Fig. 5.6.2.1 presents temperature graphs showing the supplied capacity control. The pollution emission indicators relating to the sources of energy used by the Veolia Energia Łódź SA are specified below. Those emission levels refer to the energy used by the customer, with taking into account the distribution heat losses (source: Veolia Energia Łódź):

- 107.524 kg/GJ; CO_2,
- 0.338 kg/GJ; SO_2,
- 0.191 kg/GJ; NO_X,
- 8.4 g/GJ; total particulate matter.

In the context of the utilisation of the installed capacity, it is necessary to comment on the data received from the energy source operator, the Konstantynowskie Przedsiębiorstwo Komunalne Sp. z o.o. The data relating to the annual energy demand are average data for the past 3 years (2012/2013, 2013/2014, and 2014/2015). That period was characterised by fairly high average annual temperatures, and that is why the energy demand was not high. In addition, the share of the Konstantynów Łódzki customers, using network heat to prepare hot tap water, was not high. The typical value of average annual coefficient of using ordered capacity by the customers (defined as the proportion of actually used energy to the energy the customer could have used had he used the maximum ordered power the whole year) was ca. 0.22-0.25. in the studied case. In the past three years, the value was 0.18, much less than typical figures. Aside of the relatively warm years' effect, we can conclude that the ordered capacity was overestimated by the customers, in respect to their actual needs. In the calculations presented below, the capacity demand and energy consumption was estimated on the basis of "Typical meteorological years and climatic data for energy calculation in buildings" (Polish Ministry of Infrastructure and Building, source: http://mib.gov.pl/2-Wskazniki_emisji_wartosci_opalowe_paliwa.htm), used by the meteorological station of Łódź Lublinek.

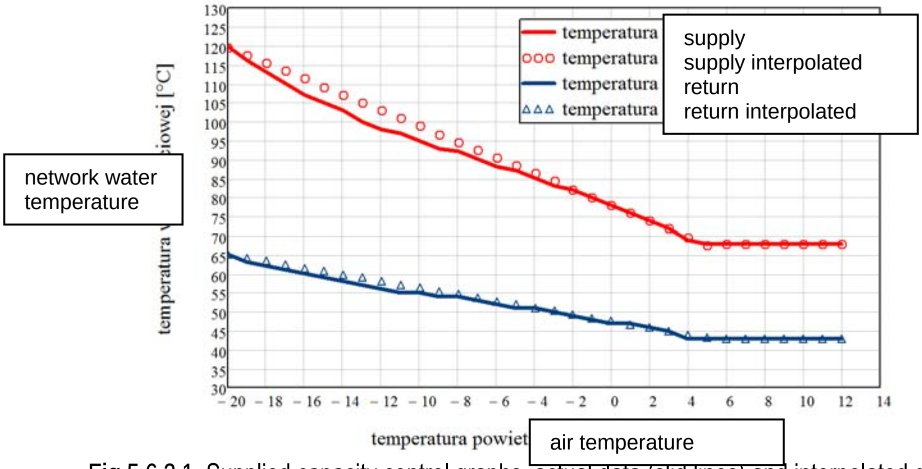


Fig.5.6.2.1. Supplied capacity control graphs, actual data (slid lines) and interpolated data (points used in further calculations), Veolia Energia Łódź SA

5.6.2.3. Options of using geothermal energy

Based on our recognition of geothermal conditions and local district heating infrastructure, as well as consultations with z local experts, representing the municipal district heating network operator (Veolia Energia Łódź), the following geothermal operation Options have been considered:

- Base Option dhA (dh – district heating, A– actual energy user).This Option shows the reference level; it describes the present conditions. It was assumed that the customer needs currently the total capacity of ca. 8.1 MW, of which 7.4 MW for central heating and 700 kW for hot tap water preparation. The customer (recipient) is connected to the district heating network of Veolia Energia Łódź.
- Option dhGeoA (dh – district heating, Geo – geothermal, A– actual energy user).This Option assumes the use of geothermal water supplemented by energy from the municipal district heating network. This Option describes the situation that would happen after the geothermal borehole has been completed in Konstantynów and it is used in peak demand periods from the district heating network as a peak demand source. It concerns presently connected customers of Konstantynów Łódzki.It was assumed that the required supply parameters are 90/70/20/-20°C.Source operating parameters are fitted to the customer's parameters, not to those of the municipal network, because the source supplies energy only locally in Konstantynów Łódzki.
- Option ahpEhw(ahp – absorption heat pumps, E– extended energy user, hw – hot tap water).This Option assumes expansion of the group of customers co-operating with the geothermal facility (the customers who are currently connected to the node in Konstantynów) by including the customers presently using the municipal district heating network in respect of hot tap water preparation in summer (outside the heating season).In summer, capacity losses associated with the distribution in the district heating network are quite high. For that reason, connecting the customers who are located far away from the energy sources (district heating plant), e.g. in and around Konstantynów Łódzki, would allow to limit heat losses. The capacity of additional customers in respect of hot tap water preparation was 890 kW, with the energy demand outside the heating season at 12 TJ/yr. The energy source represents the operating parameters that are fit to the district heating network, but only in summer (68/43°C), which basically is not a limitation.
- Option chpEhw (chp – compressor heat pumps, E– extended energy user, hw – hot tap water). That Option is identical with ahpEhw, although this one uses compressor heat pumps.
- Option ahpEhwCh (ahp – absorption heat pumps, E– extended energy user, hwCh – hot tap water and central heating). This Option assumes that, next to the customers who are currently connected to the heat node in Konstantynów, some customers of the Łódź city heating system will be connected to the geothermal plant, using absorption heat pumps. The customers' needs are satisfied in respect of central heating and hot tap water preparation. The total capacity of additionally connected customers is ca. 7,800 kW, of which 7.200 kW for central heating and 600 kW for hot tap water preparation. The source has to co-operate with the district heating network the whole year, and thus the operating temperature parameters are 120/65/20/-20°C in the heating season and 68/43°C outside.
- Option chpEhCh (chp – compressor heat pumps, E– extended energy user, hwCh – hot tap water and central heating). This Option is analogous to Option ahpEhwCh, although this one uses compressor heat pumps.

The customer characteristics depends on the type of heating installation: its design parameters and local weather conditions. The weather conditions have been described on the basis of typical meteorological years, as recommended by the Polish

Ministry of Infrastructure and Building to prepare energy calculations. The closest meteorological; station is that in Łódź (51.7500000 N, 19.4666667 E). Fig. 5.6.2.2 presents air temperature and wind speed distributions for that station. The parameter distributions shown on the graphs below are arranged according to increasing air temperature. The lowest recorded temperature in the respective meteorological years was -12.5°C. Polish Standard (PN-EN 12831) recommend the use of ambient calculation temperature for the zone in which Konstantynów Łódzki is located: -20°C.Consequently, the original file of the Typical Meteorological Years was revised by replacing -12.5°C with the temperaturę recommended by the Polish Standard. The graphs already contain that revision.

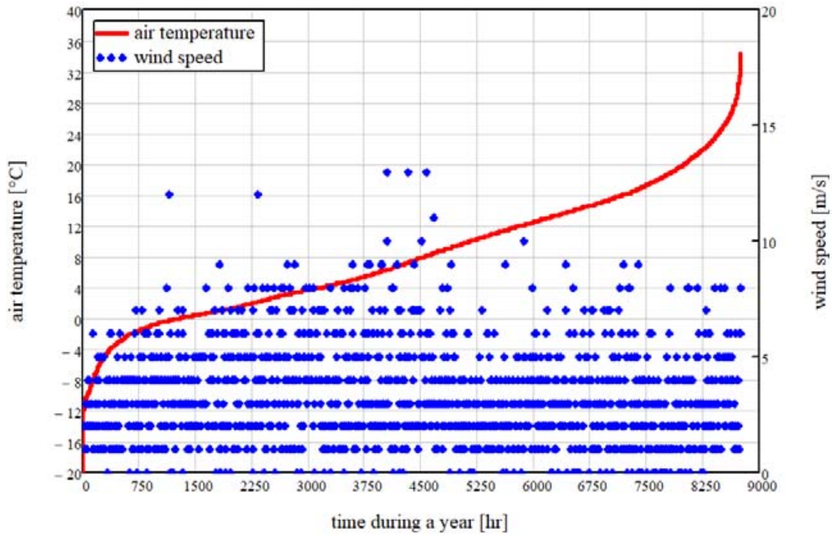


Fig. 5.6.2.1. Local weather conditions for the Łódź meteorological station (MIiB 2017)

Figs. 5.6.2.3 and 5.6.2.4below present the thermal characteristics of the customer who is currently connected to the node in Konstantynów Łódzki, – the customer for Options dhA and dhGeoA.

Figs. 5.6.2.5 and 5.6.2.6present the customer currently connected to the node in Konstantynów, supplemented by the additional summer customers, for whom the geothermal plant provides energy for the purpose of hot tap water preparation – customer for Options: ahpEhw and chpEhw.

Figs. 5.6.2.7 and 5.6.2.8 present the customer characteristics of the Option assuming inclusion of additional customers by the geothermal plant, in respect of heating and – Options ahpEhwCh and chpEchCh.

Well-visible interference in uniform demand for the working stream (for the time value of ca. 1 month) result from night-time temperature reduction in the heated facilities accounting for in our calculations. It was assumed that, from 7 p.m. to 6 a.m., the demand for capacity was lower than that suggested by the ambient temperature. Failure to account for the nigh-time temperature reduction would cause excessive thermal energy use, which would theoretically improve the result of the geothermal source operation. Unfortunately, such a result would not comply with the actual energy consumption.

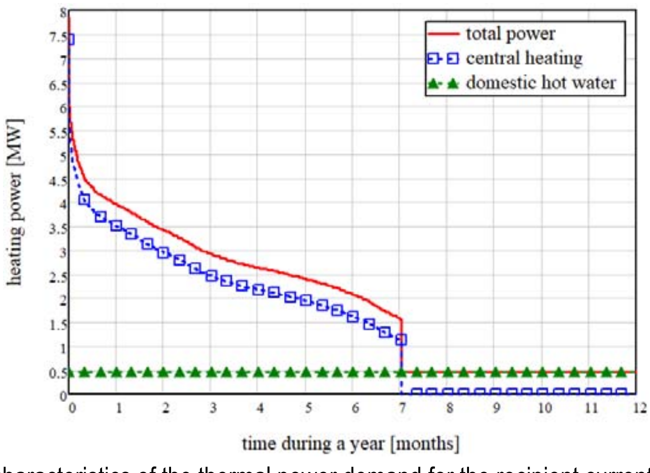


Fig. 5.6.2.3.The characteristics of the thermal power demand for the recipient currently served vs. time
(heat users in Options dhA and dhGeoA). Curve: ordered vs. total power

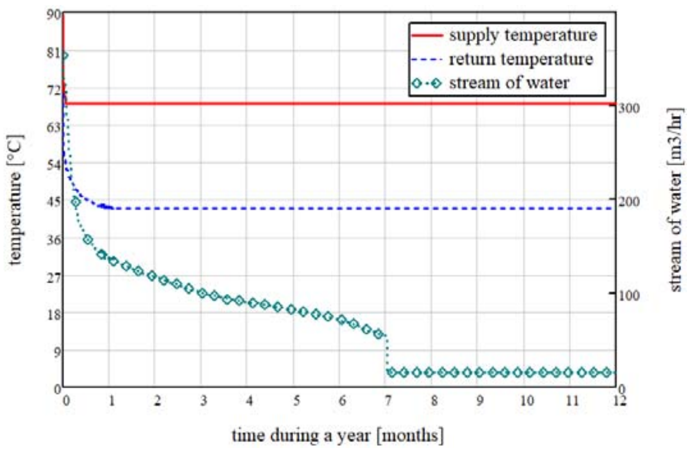


Fig. 5.6.2.4. The characteristics of instantaneous power demand for the recipient currently served as a function of time (heat user in Option dhA)

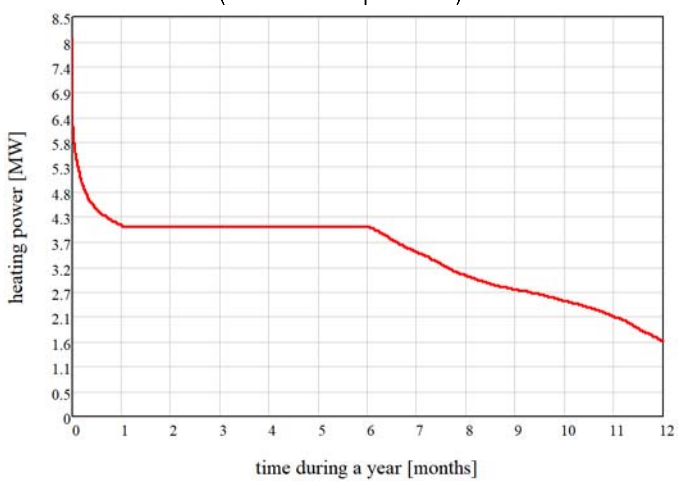


Fig. 5.6.2.5. The characteristics of the thermal power demand for the recipient currently served vs. time (heat user in Options ahpEhw and chpEhw). Curve: ordered vs. total power

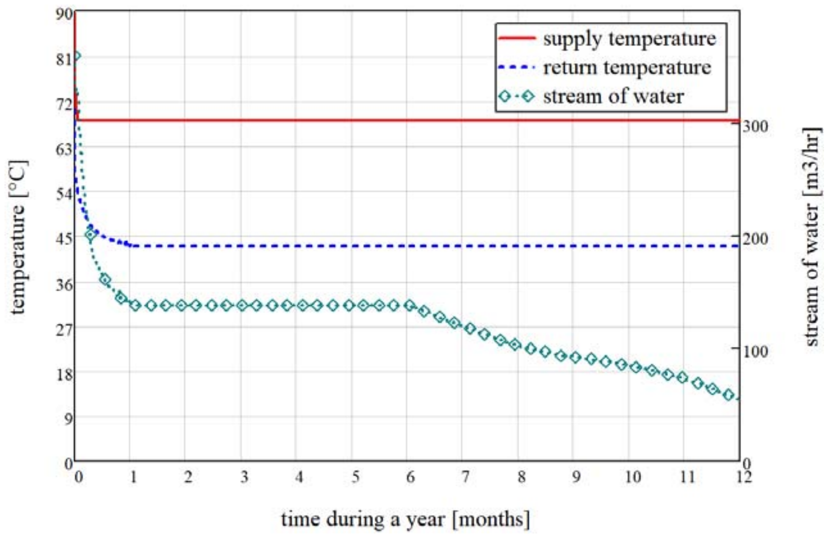


Fig. 5.6.2.6. The characteristics of instantaneous power demand for the recipient currently served as a function of time (heat user in Options ahpEhw and chpEhw)

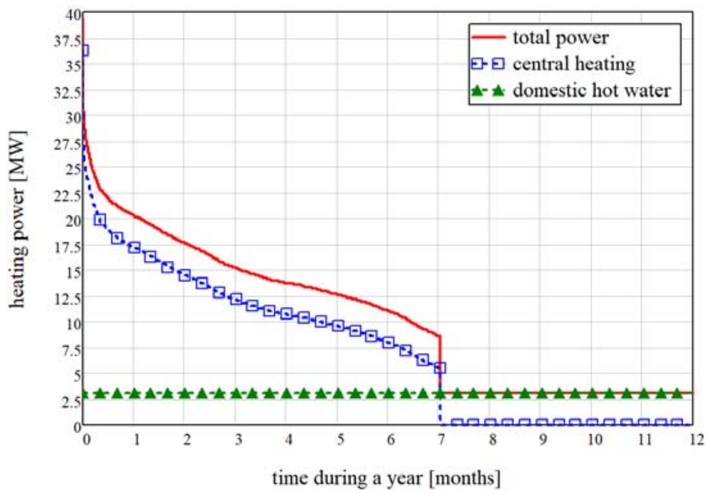


Fig. 5.6.2.7. The characteristics of thermal power demand for the significantly extended recipient base vs. time (heat user in Option sahpEhwCh and chpEhCh). Curve: ordered vs. total power

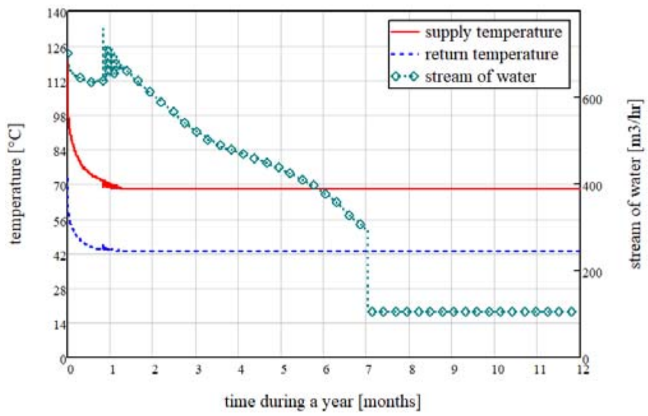


Fig. 5.6.2.8. The characteristics of instantaneous power demand for the recipient currently served as a function of time; logarithmic scale (heat user in Option sahpEhwCh and chpEhwCh)

5.6.2.4. Energy source model

The energy and economic calculations, as well as the estimations associated with the determination of the ecological effects, were carried out with the use of a mathematic model of the energy source, co-operating with the previously defined customer. The energy source allowed us to analyse the effects of operation of many sources co-operating jointly within a hybrid system. The general diagram of the source is presented in Fig.5.6.2.9. The diagram has been adopted to the specific requirements. The model contained the following elements: direct geothermal heat exchanger, absorption or compressor heat pumps (alternatively: depending on the assumed calculation option), and connection (of the heating node) to the district heating network of the Veolia Energia Łódź. The following were excluded from this analysis: solar collectors, thermal-current modules, and alternative-fuel boilers. In the case of compressor heat pumps, their use would allow to obtain the condenser output temperature that would be higher than those in standard (low power) solutions. However, high condensation pressure of the medium would be required, as well as special solutions that are commercially available.

The prices of conventional energy media have been assumed in accordance with the suggestions of the local experts who assist the heating system of the Veolia Energia Łódź. The net network heat purchase price was assumed, in accordance with the effective settlement tariff for the WPo Tariff Group (Veolia Energia Łódź S.A., *Heat Tariff*. Łódź 2016). Taking into account the regular and variable fees, applicable to both energy generation, supply, and distribution, the net network heat price for the WWo Group can be estimated at ca.48.38 PLN/GJ. The net grid electricity purchase price was assumed at the level of 350 PLN/MWhr (also upon suggestions of the local experts).

What is a controversial but still resolvable a question is the level of the required capital investment expenditures. The proposed equipment, mainly the heat pumps, are not in series production and commercially available. The purchase prices are negotiated. The proposed prices, based on the authors' experience, can be recognised as realistic. As to the absorption heat pumps, they also contain the expenses borne on the purchase of a high-temperature driven boiler and an economiser.

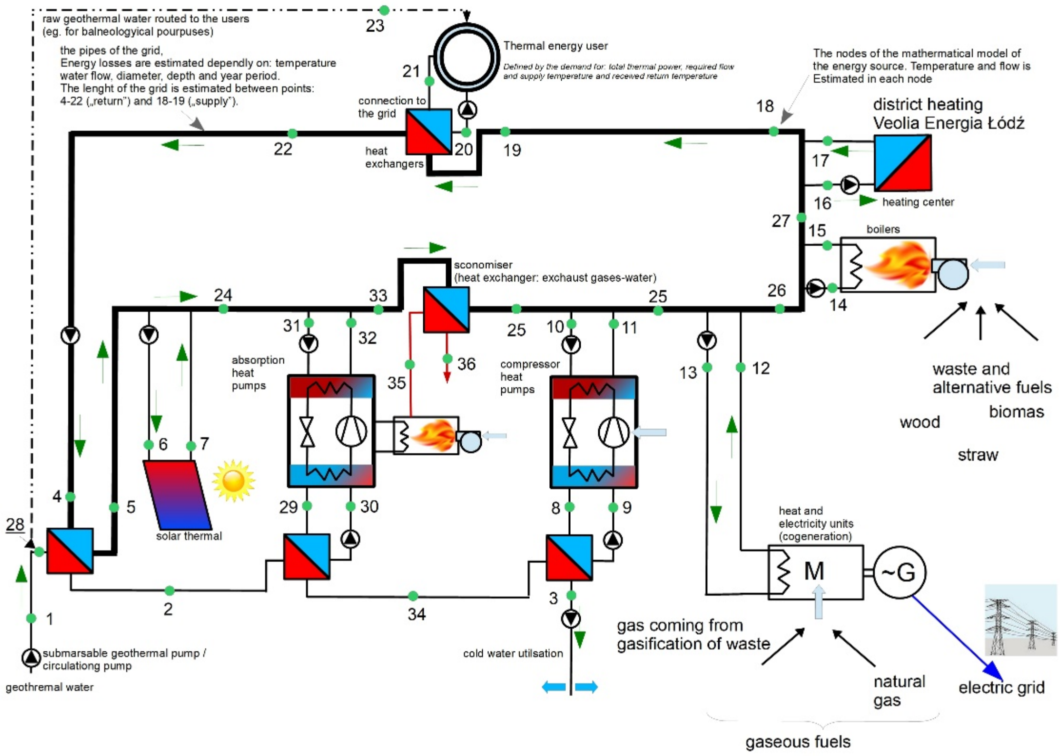


Fig. 5.6.2.9. Diagram of the energy source which was used in the mathematical model calculations

Based on the mathematical model of the installation and the customer characteristics, the energy source conditions and operating effects were estimated. The diagram of covering the capacity demand with various sources in the function of time is presented in Figs. from 5.6.2.10 to 5.6.2.18.

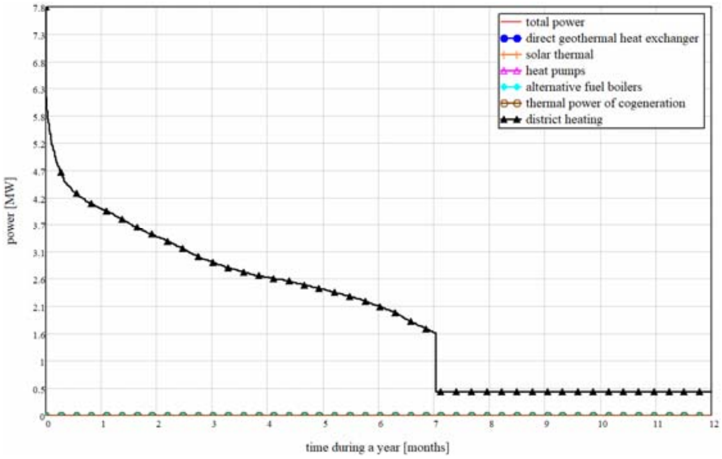


Fig. 5.6.2.10. Diagram of the source of energy operation in OptiondhA

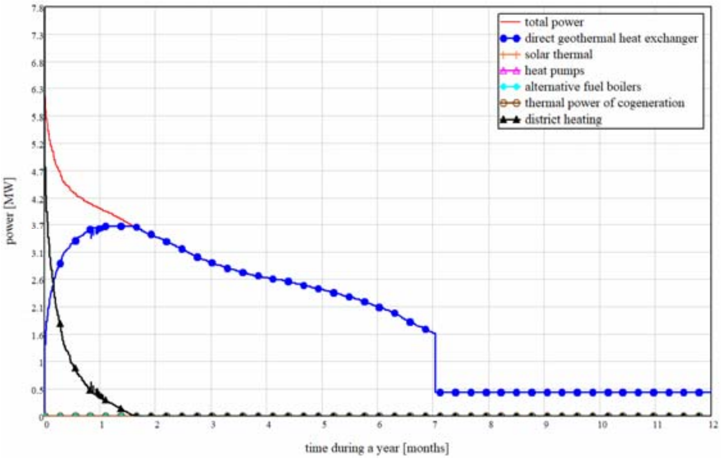


Fig. 5.6.2.11. Diagram of the source of energy operation in OptiondhGeoA

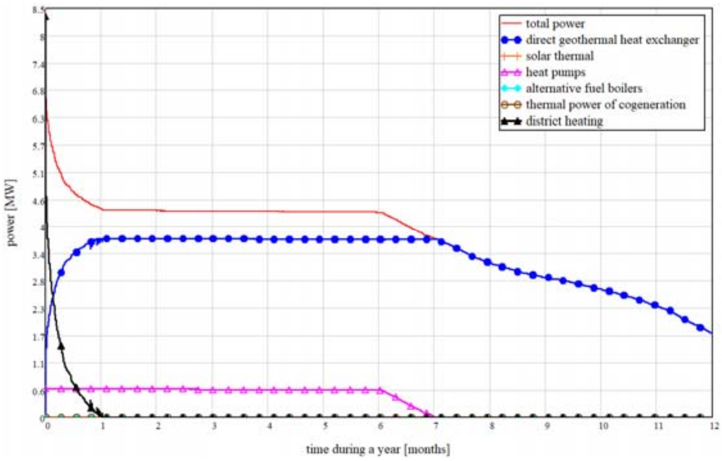


Fig. 5.6.2.12. Diagram of the source of energy operation in Option ahpEhw and chpEhw

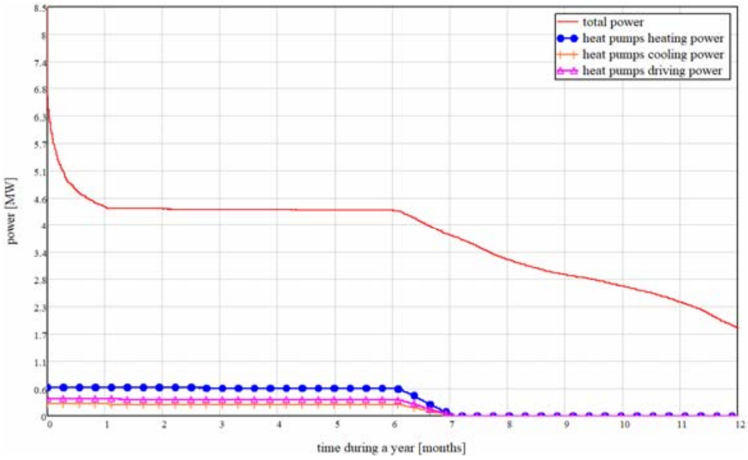


Fig. 5.6.2.13. Share of cooling (geothermal) and drive power; heat pumps in Option ahpEhw

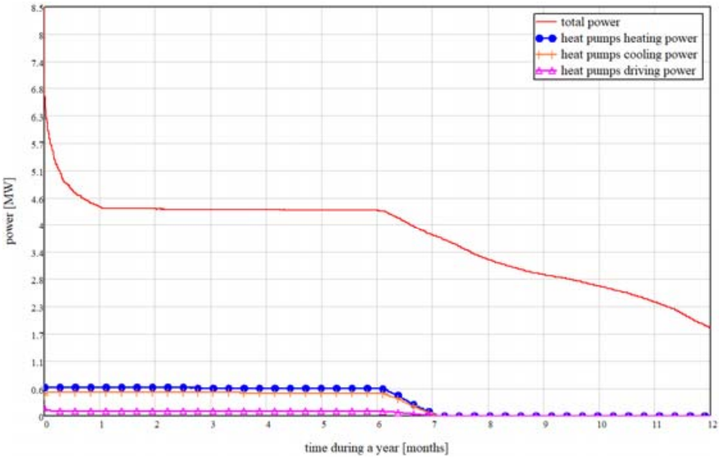


Fig. 5.6.2.14. Share of cooling (geothermal) and drive power; heat pumps in Option chpEhw

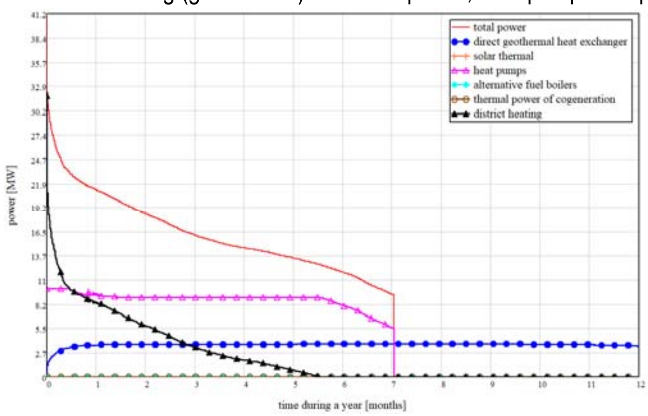


Fig. 5.6.2.15. Diagram of the source of energy operation in Option ahpEhwCh

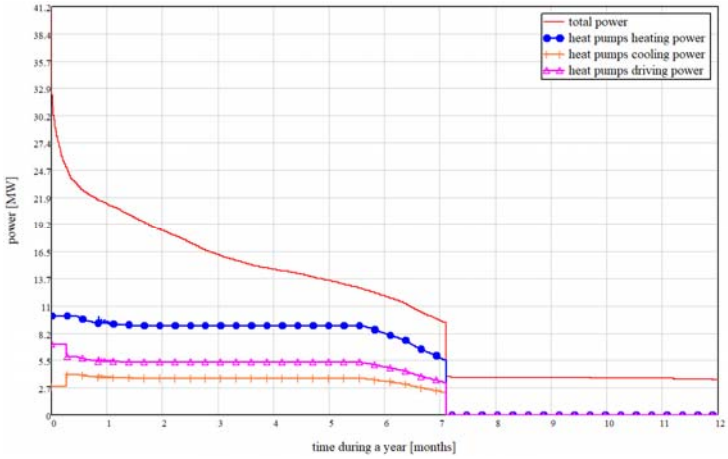


Fig. 5.6.2.16. Share of cooling (geothermal) and drive power; heat pumps in Option chpEhwCh

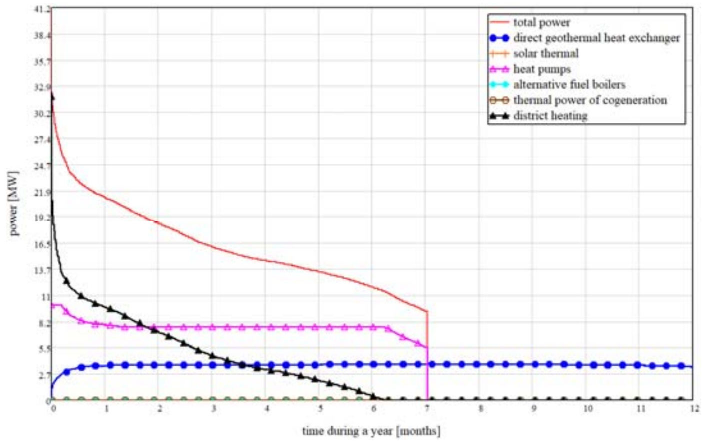


Fig. 5.6.2.17. Diagram of the source of energy operation in Option chpEhwCh

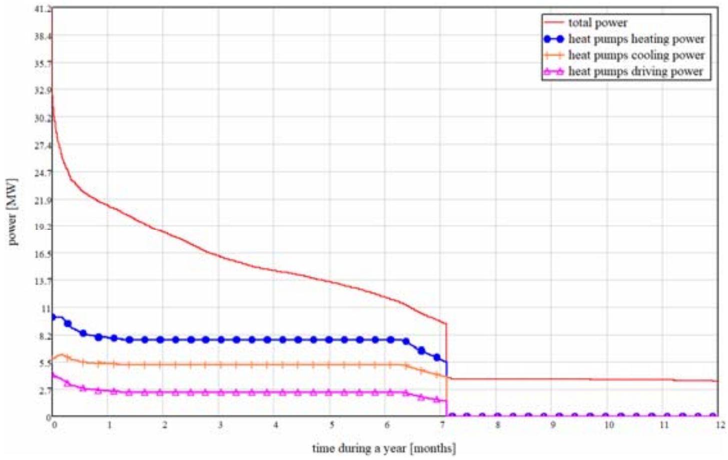


Fig. 5.6.2.18. Share of cooling (geothermal) and drive power; heat pumps in Option chpEhwCh

Table5.6.2.1 contains the list of main technical, economic, and energy parameters of the analysed Options. The estimated ecological effect is specified in two Options:

- local effect: referring to the projected emission of the selected nine air pollutants. This option does not take into account the emissions generated during the production of electricity consumed by the heat pumps and circulation pumps,
- global effect (global scale effect): this option takes into account the pollution emissions generated by the power plants for the generation of the electricity consumed by the installations of the energy source.

Evaluation was applied to the emissions of the selected pollutants, as declared by the Veolia Energia Łódź (CO_2, SO_2, NO_X and total particulate matter).

All the tabularised price or cost values are net values.

Table 5.6.2.1. Summary of the main technical and economic parameters characterizing the analysed Options for Konstantynów Łódzki

Parameter	Value	Value	Value	Value	Value	Value
Description of the variant	dhA	dhGeoA	ahpEhw	chpEw	ahpEhwCh	chpEwhCh
Maximal thermal power consumption [kW]	7844	7844	8035	8035	39308	39308
Consumption of thermal energy consumed by the user [GJ/year]	60565	60565	108571	108571	322794	322794
Annual value of the load factor [-]	0,245	0,245	0,428	0,428	0,26	0,26
Supply temperature (maximum = nominal) [°C]	89,5	89,5	89,5	89,5	120,6	120,6
Return temperature (maximum = nominal) [°C]	70,5	70,5	70,4	70,4	72,6	72,6
Nominal flow of working medium [m^3/hr]	353,6	353,6	360,2	360,2	758,4	758,4
Nominal geothermal water outflow [m^3/hr]	0	0	0	0	0	0
Estimated length of main pipelines [m]	0	0	10000	10000	30000	30000
Calculated maximum power losses on transmission [kW]	0	0	511	511	1844	1844
Calculated energy loss during distribution [GJ/year]	0	0	7823	7823	24289	24289
Net total purchase price of thermal energy form district heating [PLN/GJ]	48,38	48,38	48,38	48,38	48,38	48,38
Net purchase price of electricity network [PLN/MWhr]	350	350	350	350	350	350
Selling price of electricity produced in thermal and current modules [PLN/MWhr]	250	250	250	250	250	250
----------- Description of energy sources ----------						
1. ----- Geothermal (direct use) -----						
1.1. Depth of geothermal horizon [m bgl - below ground level]	0	2770	2770	2770	2770	2770
1.2. Water temperature driven to evaporator of heat pumps [°C]	8	71	71	71	71	71
1.3. Water stream [m^3/hr]	0	130	130	130	130	130
1.4. Assumed static water level [m bgl]	0	50	50	50	50	50
1.5. Assumed unitary depression [m / m^3/hr]	1	1	1	1	1	1
1.6. Production borehole status ('new', 'existing', 'reconstruction', 'no well')	no well	new	new	new	new	new
1.7. Injection borehole status ('new', 'existing', 'reconstruction', 'no well')	no well	new	new	new	new	new
1.8. Assembled borehole diameter [m]	0	0,244475	0,244475	0,244475	0,244475	0,244475
1.9. Maximal temperature reached on the production wellhead [°C]	8,2	69	69	69	69	69
1.10. Maximal power achieved on direct heat exchanger (without heat pumps) [kW]	0	3625	3733	3733	3799	3799
1.11. The amount of energy obtained from the direct heat exchanger [GJ/year]	0	56666	103526	103526	115401	115401
1.12. Nominal driving power estimated for geothermal water pumps (exploitation and reinjection) [kW]	0	166	166	166	166	166
1.13. Electricity consumption by geothermal pumps [MWhr/year]	0	1454	1454	1454	1454	1454
2 .----- Solar collectors -----						

2.1. Surface area of solar collectors [m^2]	0	0	0	0	0	0
2.2. Thermal efficiency of collectors [-]	0,55	0,55	0,55	0,55	0,55	0,55
2.3. Solar radiation absorption coefficient [-]	0,9	0,9	0,9	0,9	0,9	0,9
2.4. Emission factor [-]	0,8	0,8	0,8	0,8	0,8	0,8
2.5. Maximum operating medium temperature [°C]	96,16	96,16	96,16	96,16	96,16	96,16
2.6. The amount of heat input to the customer's installation [GJ/year]	0	0	0	0	0	0
3. ----- Heat pumps (low energy source: geothermal) -----						
3.1. Heating capacity installed (maximal used) [kW]	0	0	600	600	10000	10000
3.2. Maximal working medium temperature at evaporator outlet [°C]	72,47	71,18	72,22	72,22	85,06	85,06
3.3. Maximal allowable water temperature at evaporator outlet [°C]	20	100	100	100	100	100
3.4. Minimum temperature of water at evaporator outlet [°C]	45	45	42,66	41	20	10
3.5. Maximum value of COP (on heating side) [-]	1,4	1,7	1,7	6	1,7	6
3.6. The amount of heat generated by heat pumps [GJ/year]	0	0	9980	9980	161444	141902
3.7. Amount of used drive energy consumed to drive the heat pump [MWhr/year]	0	0	1631	470	26624	12740
3.8. Amount of used electric power used to drive geothermal pumps [MWhr/year]	0	1454	1454	1454	1454	1454
4. ----- Thermoelectric units -----						
4.1. Thermal power of modules [kW]	0	0	0	0	0	0
4.2. Electrical power generated by modules [kW]	0	0	0	0	0	0
4.3. The amount of thermal energy generated by the thermoelectric modules [GJ/year]	0	0	0	0	0	0
4.4. The amount of electricity generated by the thermoelectric modules [MWhr/year]	0	0	0	0	0	0
4.5. Costs of obtaining biogas derived from gasification of waste [PLN/m^3]	0,94	0,94	0,94	0,94	0,94	0,94
5. ----- Boilers for alternative fuels and biomass -----						
5.1. Maximum installed power (used) in alternative fuels and biomass boilers [kW]	0	0	0	0	0	0
5.2. The amount of heat generated in boilers for alternative fuels and biomass [GJ/year]	0	0	0	0	0	0
5.3. Cost of acquisition / purchase price of fuels and biomass (average) [PLN/Mg]	400	400	400	400	400	400
6. ----- Connection to the district heating -----						
6.1. Total maximal power of the connection [kW]	7844	8376	8378	8378	31873	31873
6.2. The amount of thermal energy supplied by district heating [GJ/year]	60565	3899	2887	2887	70239	89781
Estimated investment outlays for heat source [thousands PLN]	0	48221	49419	49419	68710	68710
- production well [thousands PLN]	0	21207	21207	21207	21207	21207
- well for reinjection [thousands PLN]	0	21207	21207	21207	21207	21207
- direct heat exchanger [thousands PLN]	0	181	187	187	190	190
- installation of solar collectors [thousands PLN]	0	0	0	0	0	0

- heat pumps [thousands PLN]	0	0	900	900	15000	15000
- installation of gasification of waste together with thermal and current modules [thousands PLN]	0	0	0	0	0	0
- alternative fuels and biomass [thousands PLN]	0	0	0	0	0	0
- peak boilers for natural gas [thousands PLN]	0	0	0	0	0	0
- connection pipelines and transmission lines [thousands PLN]	0	1000	1000	1000	1000	1000
- energy source building [thousands PLN]	0	209	228	228	1097	1097
- cost of assembly, reserve for unexpected expenses [thousands PLN]	0	4417	4690	4690	9008	9008
Total annual operating costs [thousands PLN/year]	2930	3832	4145	4025	13010	13778
- constant costs [thousands PLN/year]	0	3134	3212	3212	4466	4466
- flexible costs [thousands PLN/year]	2930	698	933	813	8544	9311
- depreciation of fixed assets [thousands PLN/year]	0	2411	2471	2471	3435	3435
- costs of maintenance and repairs [thousands PLN/year]	0	723	741	741	1031	1031
- costs of buying conventional energy carriers including district heating [thousands PLN/year]	2930	698	933	813	8544	9311
- incomes from the sale of electricity produced in combination by thermal current modules [thousands PLN/year]	0	0	0	0	0	0
Unitary costs of energy generation (excluding transmission losses) [PLN/GJ]	48	63	36	35	37	40
The price of energy for final customer (including transmission losses) [PLN/GJ]	48	63	38	37	40	43
Emission of pollutants emission related to the unit of generated heat [kg/GJ]						
- total dust locally	8,4	0,541	0,223	0,223	1,828	2,336
- CO_2 locally	107,524	6,922	6,129	2,859	41,355	29,906
- NO_X (recalculated to the NO_2) locally	0,191	0,012	0,007	0,005	0,053	0,053
- SO_2 locally	0,338	0,022	0,009	0,009	0,074	0,094
- total dust in global scale	8,4	0,55	0,228	0,23	1,83	2,353
- CO_2 in global scale	107,524	32,059	20,152	21,417	46,071	75,947
- NO_X (recalculated to the NO_2) in global scale	0,191	0,058	0,033	0,039	0,062	0,137
- SO_2 in global scale	0,338	0,177	0,096	0,124	0,103	0,379

5.6.2.5. Summary and Conclusions

Among the analysed Options of using geothermal energy in Konstantynów Łódzki, all the Options assuming the use of geothermal energy produced positive ecological effects (in the form of pollution emission reduction)on both local and global scales. Significant reduction concerned CO_2 emission. The poorest result in the Options assuming the use of geothermal energy (ahpEhwCh) showed the local emission unit reduction of that pollutant by more than 60%, in the best Option case (ahpE) the unit emission reduction of $CO_2$was estimated at ca. 94%.on a global scale, and the highest CO_2emission reduction was estimated at ca. 80% (Option ahpEhwCh), while the lowest one at ca. 28% (Option chpEhwCh).

As to the measures of energy effect and conventional energy medium reduction effect at the same time, it can be the quantity of thermal energy generated under particular Options by the direct geothermal heat exchangers (marked in Fig. 5.6.2.9, between points 1 and 2, on the geothermal water side, and points 4 and 5 on the network water side).

The savings of the primary conventional energy sources was estimated as follows: from 56.7 TJ/yr to 115.4 TJ/yr (line 1.11 in Table 5.6.2.1). The best effects can be expected in that respect wherever the capacity of the connected customers is significantly increasing, together with the energy consumed by them, that is under Options ahpEhwCh and chpEhwCh. Those Options assume that sine of the Łódź customers will be connected to Konstantynów (the capacity of the "captured" customers amounted to ca. 31 MW. That figure resulted from the difference between the total capacity of that Option and the capacity currently used in Konstantynów, line 3 of Table 5.6.2.1).

If we assume that the measure of the achieved economic effects of the energy source consists in the final price (including the fees for obtaining energy and its distribution), payable by the final user (customer), the best effects were obtained under Options ahpEhw and chpEhw. Those Options assumed the use of geothermal energy, supported by heat pumps of moderate capacity (600 kW) in Konstantynów Łódzki, with capturing of some of the customers currently supplied from the municipal district heating network, but only outside the heating season to prepare hot tap water. The energy source operation under those Options is presented in Fig. 5.6.2.12, showing a dominating quantity of energy originating from the direct heat exchanger, using geothermal energy, with a small quantity of energy originating from heat pumps. What was especially essential in that case was a very even capacity demand.

We can conclude that the use of energy in Konstantynów Łódzki is a very good example of the opportunities provided by the possibility of co-operation with a geothermal source and the z customers who are able to consume the energy source potential in the optimum manner.

Konstantynów alone (Option dhGeoA) is not able to use the energy available from the geothermal source evenly and efficiently (Fig. 5.6.2.11). The total capacity that can be obtained from a direct geothermal heat exchangers amounts to ca. 3.7 MW of which the capacity exceeding 3 MW can be used only during ca. 2 months. The best options from the economic viewpoint (ahpEhw and chpEhw) would allow to obtain geothermal capacity exceeding 3 MW during nearly 8 months (Fig. 5.6.2.12). The geothermal source placed in Konstantynów can become an attractive energy source for the Łódź district heating system, providing clean and inexpensive thermal energy (at least in respect of variable costs).

Extremely important for improving the efficiency of the entire heating system is the optimization of the return temperature. For this purpose, it is important to consider heating rooms with automatic controls the return temperature to maximize the cooling of the water on the heat exchanger. It is also appropriate to install telemetry systems in the individual heat distribution centres so as to have current control of this parameter and the possibility of remote control of the heating node. This should allow electively use of the building's accumulation – especially during the transition periods of spring and summer.

It is also advisable to change the local heat supply plan in order to introduce new requirements for indoor installations as low-latency buildings that enable cooperation with heat pumps or geothermal installations.

Another recommendation is to use heat from return pipelines to supply low-temperature district heating systems, which themselves can be the effective low temperature source for heat pumps in buildings with new low-temperature heating systems.

A cascade of such system solutions should definitely improve the efficiency of using geothermal heat and lower the price of heat for heat consumers.

The co-operation of the entities operating the geothermal source (Przedsiębiorstwo Komunalne Gminy Konstantynów Łódzki Sp. z o.o.) and the Łódź district heating system (Veolia Energia Łódź S.A.) will therefore be beneficial for both partners for economic and ecological reasons.

5.6.3. Energetic–economic optimisation of realisation of multi-wells' geothermal energy sourceto supply heat to the existing district heating systems in Konstantynów Łódzki and Łódź towns

Our calculations, based on a mathematical model of the energy source, using a constant customer characteristics, in respect of that specified in Section 5.6.2,suggested that it was not viable to increase the number of geothermal boreholes in the Konstantynów Łódzki plant. In neither of the cases, the thermal energy price dropped below the typical values for one double-well geothermal system (Table 5.6.2.1). In the case of a large energy customer – Options ahpEheCh and chpEhwCh – what turned out to be a barrier to the possibilities of generating a larger quantity of geothermal energy was rather a lack of coherence of the temperature parameters of the source and the district heating network. In the cases of Options ahpEhw and chpEhw,the quantity of energy generated from the geothermal source increased, but the quantity of energy generated from a heat pump dropped. Heat pump application was found to be unprofitable: a fairly high capacity installed produced very little energy. In the Option assuming operation of only the Konstantynów Łódzki district heating network, the proportional use of a geothermal plant increased considerably. In neither of the analysed cases, it was possible to cover the increased capital investment expenditures by the effects achieved, associated with the operation of two double-well geothermal systems.Those conclusions are confirmed by the graphs presented below.

Fig. 5.6.3.1 presents an operating diagram of two double-well geothermal systems for a customer being typical in respect of the needs identified in Konstantynów Łódzki, while the effects of operating one double-well geothermal system are presented in Fig. 5.6.2.11. One can notice increased capacity of the geothermal plant and the quantity of generated energy (increasing from 56.7 TJ/yto more than 60 TJ/y). Unfortunately, that increase does not cover the double increase of the required capital investment expenditures (increasing up to PLN 95 mio.). Finally, the net unit price of thermal energy, applicable to the final user, will increase from 64 to 134 PLN/GJ. That will be completely unprofitable considering the present price of 54.47 PLN/GJ.

Fig. 5.6.3.2 presents the energy sources chedule for the customer expanding the needs of Konstantynów by inclusion of hot tap water users in summer (Options ahpEhw and chpEhw). The thermal energy generated by the geothermal plant will be higher (from more than 103 TJ/yto nearly 116 TJ/y), but the capital investment expenditures will also increase (from ca. 49 to more than PLN 96 mio.).

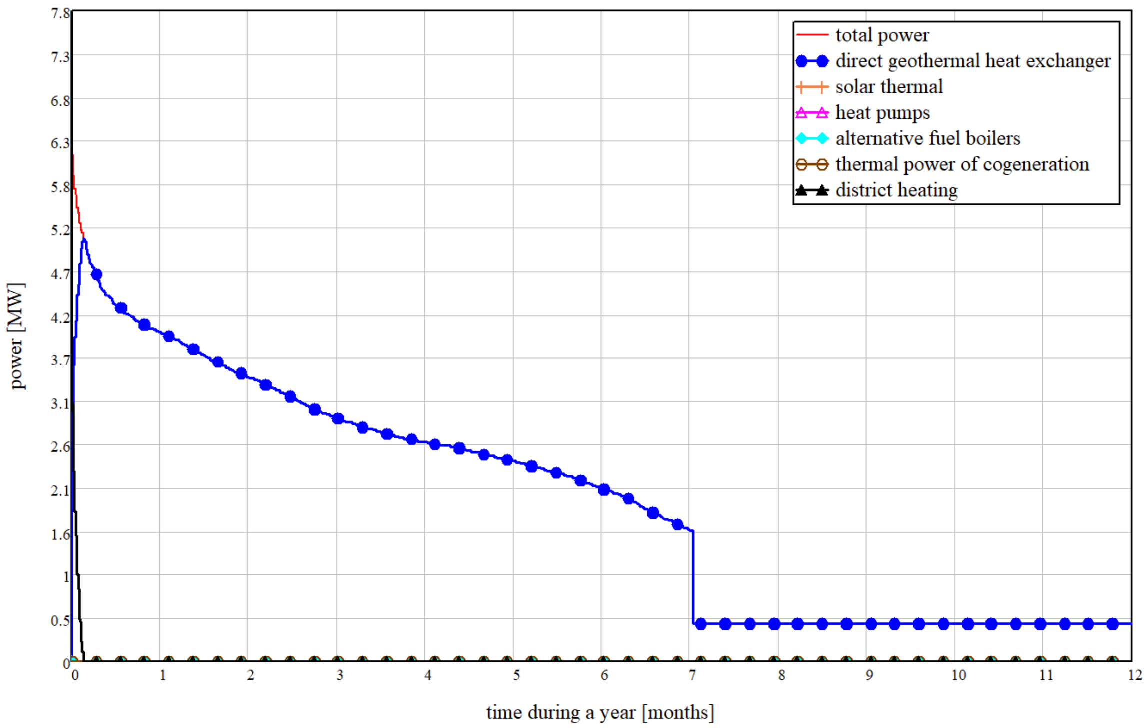


Fig. 5.6.3.1. Diagram of the source of energy operation in Option dhA, assuming operation of two double-well geothermal systems

The use of heat pumps becomes unjustified; one can see from the graph that the pumps generate little energy. Unfortunately, exclusion of heat pumps will reduce expenditures only slightly (down to ca. PLN 95 mio.). Finally, the net thermal energy price for the final user will amount to ca. 75 PLN/GJ, and still remain unattractive.

The co-operation of two double-well geothermal systems with the customer base that is considerably expanded (Options ahpEhwCh and chpEhwCh) will bring little positive effects, in terms of energy, economy, or ecology. The operating diagram of the source based on two double-well geothermal systems is presented in Fig. 5.6.3.3. In both cases, assuming the use of absorption and compressor pumps, the system is identical. In comparison to Figs. 5.6.2.15 and 5.6.2.17, we can notice the increase of energy obtained from a direct geothermal heat exchanger and the drop of energy obtained from heat pumps. The increase of the capital investment expenditures is, however, large: from more than PLN 68mio.to more than PLN 115 mio. The final total net unit price of energy purchase by the final user is similar to that when one double-well geothermal system is operated: ca. 44 (for absorption pumps) or 46 PLN/GJ (for compressor pumps). Consequently, the price has dropped in respect of the Options with one double-well geothermal system and is much lower than the current price. Some improvement can be reached by additional reduction of heat pump capacity down to the level of 5.5 MW: they will operate evenly in time and the capital investment expenditures will be lower. That will allow to reduce the energy purchase price by ca. 2 PLN/GJ (down to the level of 42-44 PLN/GJ).

The operation of two double-well geothermal systems in Konstantynów would allow for connecting a much larger additional customer. The effective capacity of the additional customer that can be connected to the district heating plant based on two double-well geothermal systems is estimated at 100 MW. Fig. 5.6.3.4 presents the operating schedule of the source under such an Option. The capital investment expenditures are estimated in that case at ca.PLN 137mio.The final net energy purchase price by the final user would amount to 45.6 PLN/GJ. Selected operating parameters of such an Option are presented in Table 5.6.3.1.

We can conclude that our calculations proved a considerable potential of the energy source, expanded by the use of the second double-well system, on the condition that efficient use is assured by energy supply to the customer demanding a proper capacity level.

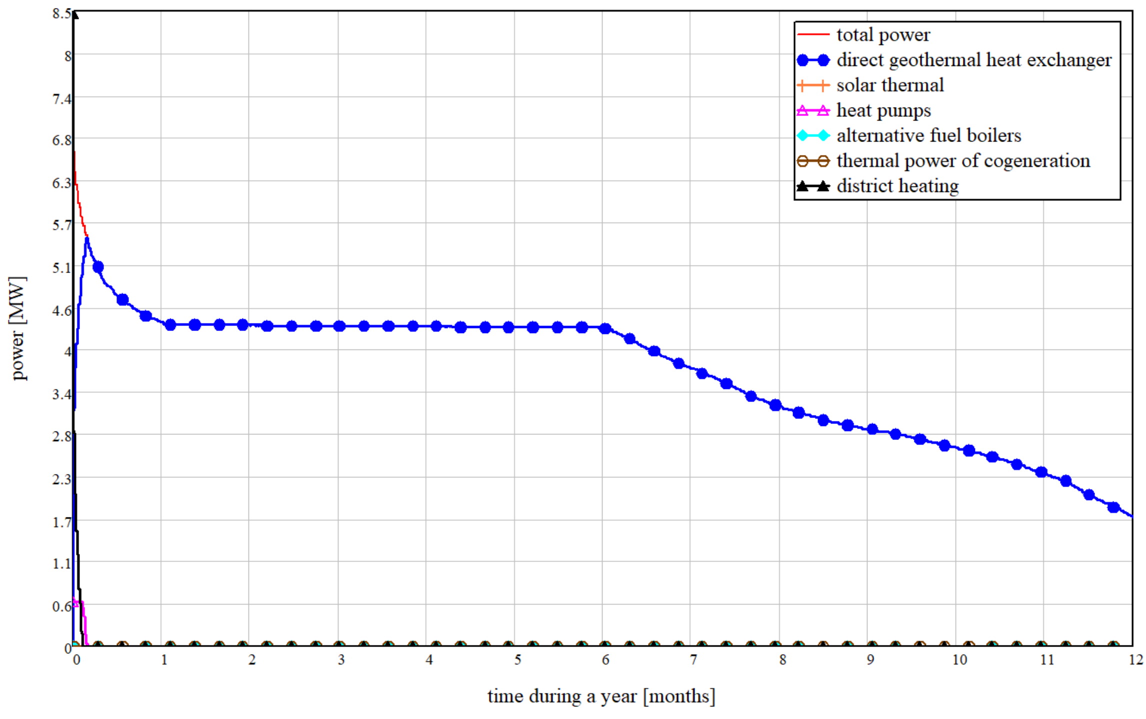


Fig. 5.6.3. 2. Diagram of a source of energy operation in Option ahpEhw and chpEhw, assuming two double-well geothermal systems

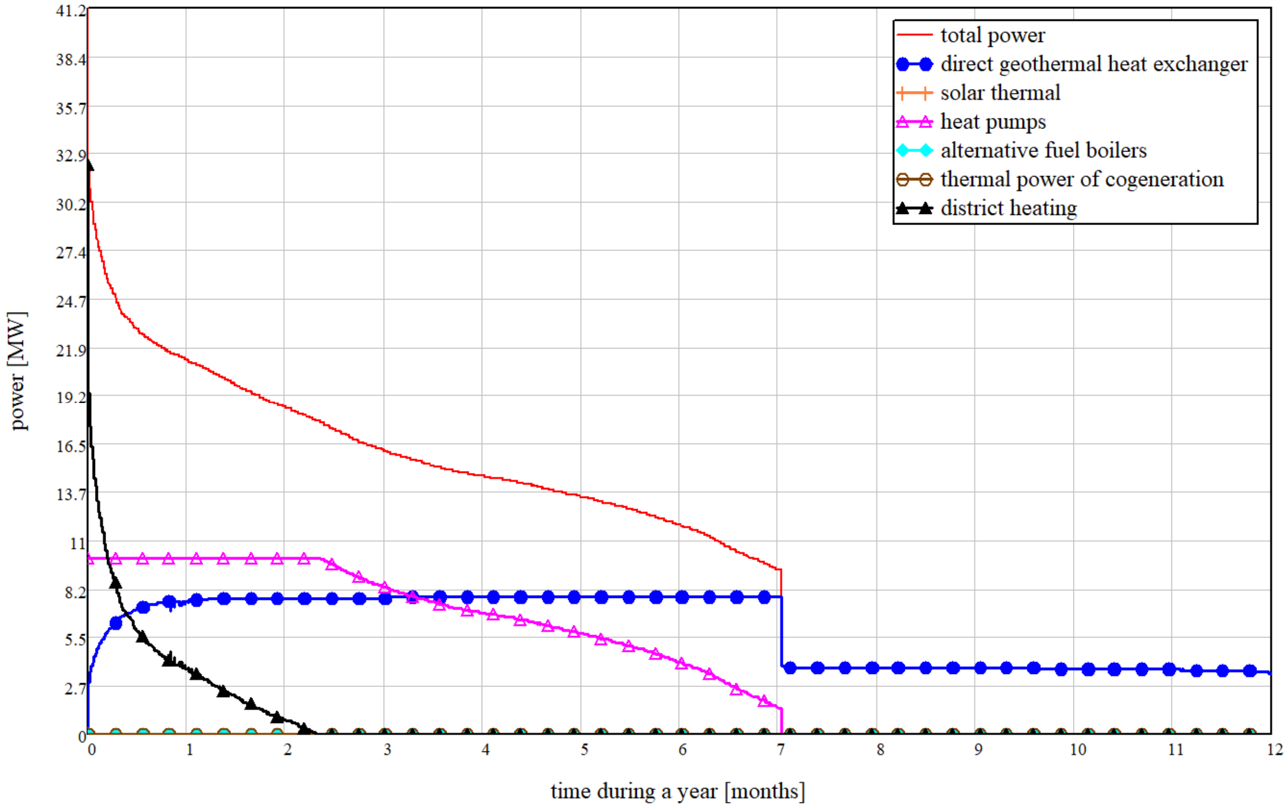


Fig. 5.6.3.3. Diagram of a source of energy operation in Options ahpEhwCh and chpEhwCh, assuming two double-well geothermal systems

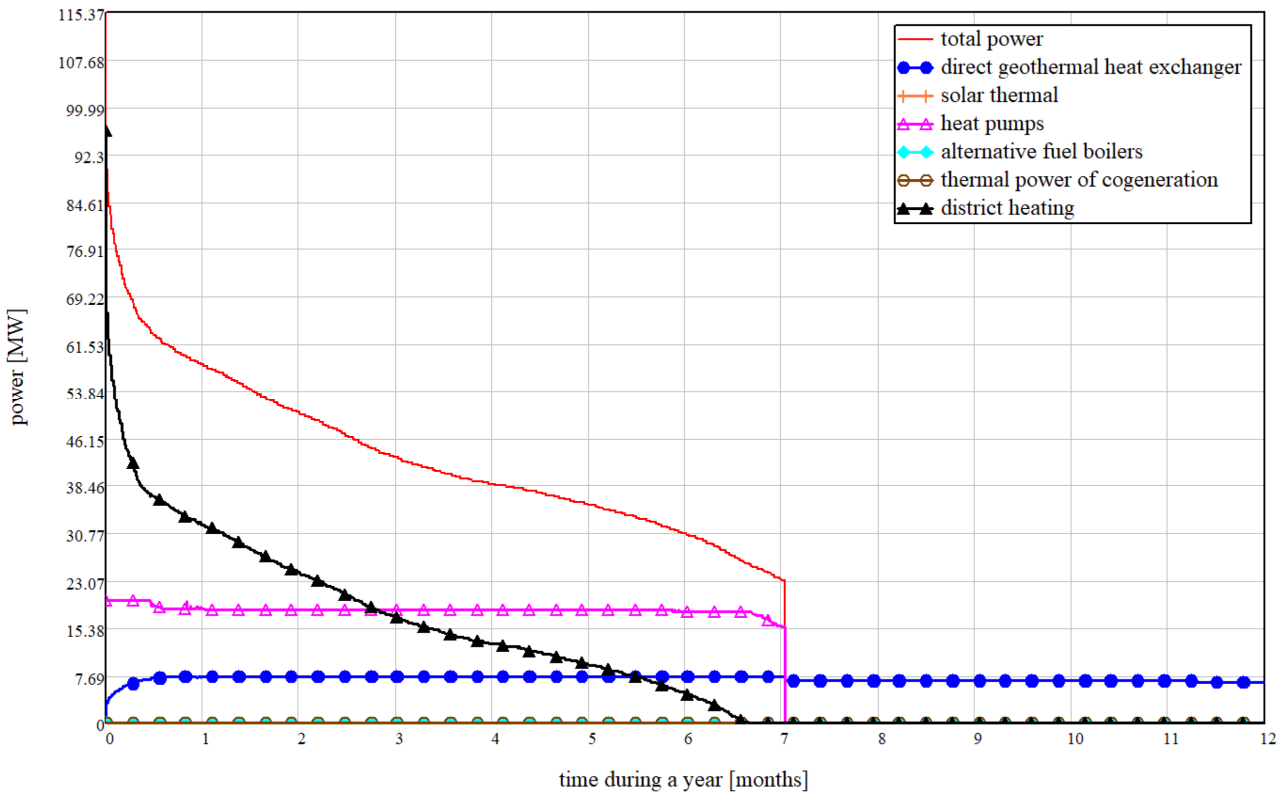


Fig. 5.6.3.4. Diagram of a source of energy operation in the Options with absorption heat pumps, assuming two double-well geothermal systems and an additional energy user, with the power demand of 105 MW

Table 5.6.3.1. Summary of the main technical and economic parameters characterising the analysed Options for the town of Konstantynów Łódzki

Parameter	Value
Description of the Option	Additional user, 105 MW and actual demand of Konstantynów. Absorption heat pump and two double-well systems
Maximum thermal power consumption [kW]	113509
Consumption of thermal energy consumed by the user [GJ/year]	866065
Annual value of the load factor [-]	0,242
Supply temperature (maximum = nominal) [°C]	122
Return temperature (maximum = nominal) [°C]	71,1
Nominal flow of working medium [m³/hr]	2044,1
Nominal geothermal water outflow [m³/hr]	0
Estimated length of main pipelines [m]	30000
Calculated maximum power losses on transmission [kW]	1862
Calculated energy loss during distribution [GJ/year]	24364
Net total purchase price of thermal energy form district heating [PLN/GJ]	48,38
Net purchase price of electricity network [PLN/MWhr]	350
Selling price of electricity produced in thermal and current modules [PLN/MWhr]	250
---------- Description of energy sources ----------	
1. ----- Geothermal (direct use) -----	
1.1. Depth of geothermal horizon [m bgl - below ground level]	2770
1.2. Water temperature driven to evaporator of heat pumps [°C]	71
1.3. Water stream [m³/hr]	260
1.4. Assumed static water level [m bgl]	50
1.5. Assumed unitary depression [m / m³/hr]	1
1.6. Production borehole status ('new', 'existing', 'reconstruction', 'no well')	2 x new
1.7. Injection borehole status ('new', 'existing', 'reconstruction', 'no well')	2 x new
1.8. Assembled borehole diameter [m]	0,244475
1.9. Maximum temperature reached on the production wellhead [°C]	70
1.10. Maximum power achieved on direct heat exchanger (without heat pumps) [kW]	7644
1.11. The amount of energy obtained from the direct heat exchanger [GJ/year]	227723
1.12. Nominal driving power estimated for geothermal water pumps (exploitation and reinjection) [kW]	620

1.13. Electricity consumption by geothermal pumps [MWhr/year]	5428
2 .----- Solar collectors -----	
2.1. Surface area of solar collectors [m^2]	0
2.2. Thermal efficiency of collectors [-]	0,55
2.3. Solar radiation absorption coefficient [-]	0,9
2.4. Emission factor [-]	0,8
2.5. Maximum operating medium temperature [°C]	96,16
2.6. The amount of heat input to the customer's installation [GJ/year]	0
3. ----- Heat pumps (low energy source: geothermal) -----	
3.1. Heating capacity installed (maximum used) [kW]	20000
3.2. Maximum working medium temperature at evaporator outlet [°C]	81,35
3.3. Maximum allowable water temperature at evaporator outlet [°C]	100
3.4. Minimum temperature of water at evaporator outlet [°C]	20
3.5. Maximum value of COP (on heating side) [-]	1,7
3.6. The amount of heat generated by heat pumps [GJ/year]	337689
3.7. Amount of used drive energy consumed to drive the heat pump [MWhr/year]	56024
3.8. Amount of used electric power used to drive geothermal pumps [MWhr/year]	5428
4. ----- Thermoelectric units -----	
4.1. Thermal power of modules [kW]	0
4.2. Electrical power generated by modules [kW]	0
4.3. The amount of thermal energy generated by the thermoelectric modules [GJ/year]	0
4.4. The amount of electricity generated by the thermoelectric modules [MWhr/year]	0
4.5. Costs of obtaining biogas derived from gasification of waste [PLN/m^3]	0,94
5. ----- Boilers for alternative fuels and biomass -----	
5.1. Maximum installed power (used) in alternative fuels and biomass boilers [kW]	0
5.2. The amount of heat generated in boilers for alternative fuels and biomass [GJ/year]	0
5.3. Cost of acquisition / purchase price of fuels and biomass (average) [PLN/Mg]	400
6. ----- Connection to the district heating -----	
6.1. Total maximum power of the connection [kW]	96218
6.2. The amount of thermal energy supplied by district heating [GJ/year]	325016
Estimated investment outlays for heat source [thousands PLN]	137292
- production well [thousands PLN]	42414
- well for reinjection [thousands PLN]	42414

- direct heat exchanger [thousands PLN]	382
- installation of solar collectors [thousands PLN]	0
- heat pumps [thousands PLN]	30000
- installation of gasification of waste together with thermal and current modules [thousands PLN]	0
- alternative fuels and biomass [thousands PLN]	0
- peak boilers for natural gas [thousands PLN]	0
- connection pipelines and transmission lines [thousands PLN]	1000
- energy source building [thousands PLN]	3077
- cost of assembly, reserve for unexpected expenses [thousands PLN]	18005
Total annual operating costs [thousands PLN/year]	36306
- constant costs [thousands PLN/year]	8924
- flexible costs [thousands PLN/year]	27382
- depreciation of fixed assets [thousands PLN/year]	6865
- costs of maintenance and repairs [thousands PLN/year]	2059
- costs of buying conventional energy carriers including district heating [thousands PLN/year]	27382
- incomes from the sale of electricity produced in combination by thermal current modules [thousands PLN/year]	0
Unitary costs of energy generation (excluding transmission losses) [PLN/GJ]	41
The price of energy for final customer (including transmission losses) [PLN/GJ]	42
Emission of pollutants emission related to the unit of generated heat [kg/GJ]	
- total dust locally	3.152
- CO_2 locally	54.436
- NO_X (recalculated to the NO_2) locally	0.081
- SO_2 locally	0.127
- total dust in global scale	3.155
- CO_2 in global scale	60.998
- NO_X (recalculated to the NO_2) in global scale	0.093
- SO_2 in global scale	0.167

5.7. Lądek Zdrój

5.7.1. Hydrogeothermal conditions in Lądek-Zdrój area and evaluation of possibility to gain geothermal water extraction for space heating and other purposes in the view of stable exploitation

5.7.1.1. Geothermal conditions in Kłodzko Land

In order to define the potential areas of thermal water occurrence, apart from assessing the possibility of extracting deep-circulation waters it is necessary to determine the geothermal field image of the investigated area.
The first synthetic analysis of geothermal conditions in the Polish part of the Sudetes and the Fore-Sudetic block was presented by B. Bruszewska (2000). Based on 51 selected measurement points, she drew maps of temperature distribution at depths of 500 m (from 18°C to 26°C), 1000 m (from 26°C to 38°C) and 1500 m (from 38°C do 50°C) (Fig. 5.7.1.1a, b, c).

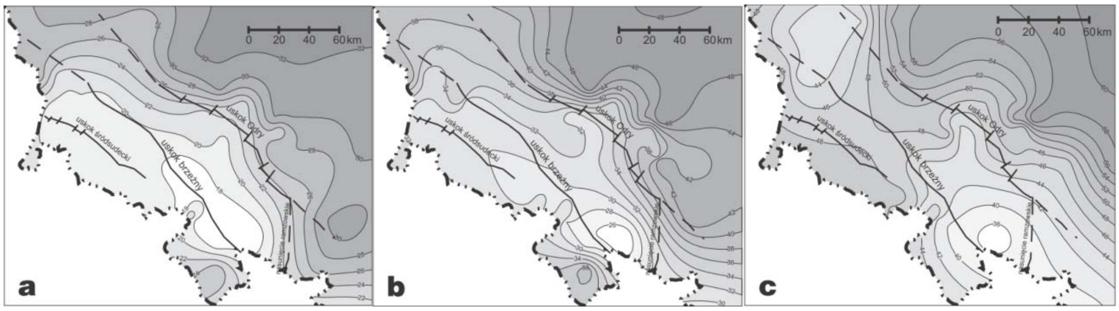


Fig. 5.7.1.1. Temperature maps [°C] at the depths: a — 500 m b.s.l., b — 1000 m b.s.l. , c — 1500 m b.s.l. (Bruszewska, 2000)

The uneven distribution of boreholes and their varied depths reduce the accuracy of the obtained results. Nevertheless, this is the first image of heat flow isolines in SW Poland (Przylibski ed., 2007). There is a clear temperature increase to the north-east, towards the Odra fault forming a natural border. Analogical conditions (temperature increase inside the orogen) can be observed to the south, in the areas of the Karkonosze and in Kłodzko basin. A similar pattern is visible in the isolines of temperature gradients of 2˚C/100m to over 3˚C/100m in the southern part of the discussed area (Fig. 5.7.1.2).

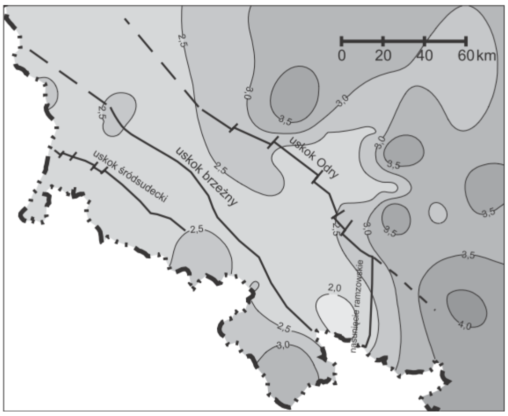


Fig. 5.7.1.2. Map of the average thermal gradient [°C/100 m] (Bruszewska, 2000)

An increase in the heat flow density (above 60 mW/m^2), likewise the demonstrated temperature increase, is observed towards the north-east along the Odra fault and southward in the area of the Karkonosze and in Kłodzko basin. The lowest values of heat flow density can be observed in the Fore-Sudetic block (50-60 mW/m^2). Higher values of this parameter have been found out in deep thermal waters intakes C-1 in Jelenia Góra-Cieplice Śląskie Zdrój (79 mW/m^2) and L-2 in Lądek-Zdrój (71.2 mW/m^2) (Dowgiałło, 2001; 2002; Liber and Kiełczawa, 2009). The biggest flow of endogenic heat (96 mW/m^2) was revealed by research conducted within the Bohemian Cretaceous massif in Tyniště (Dowgiałło, 2007).

The surface heat flow consists of the value of heat flow coming from the Earth's mantle and the radiogenic heat of rocks, as well as the heat related to endogenic, e.g. volcanic and tectonic processes. The distribution of heat flow density varies according to the specific thermal conductivity of the rock medium and the conductivity of crystalline rocks ranges from 1 to 4 W/m°C (Plewa, 1994). The Sudetic region is characterized by relatively high values of radiogenic heat of rocks, ranging from c. 2.0 to 5.1 μW/m^2 (Plewa, 1996). However, the research conducted by M. Plewa revealed that the high values of radiogenic heat of Sudetic rocks do not significantly affect the value of the surface heat stream (ranging from 45 to 64.73 mW/m^2). Both the heat stream density map developed by B. Bruszewska (2000) and the research by M. Plewa (1996) provide a generalized representation of geothermal conditions in the Sudetic region. In order to define potential areas of thermal water occurrence, at this stage of their recognition it seems essential to select permeable tectonic zones enabling the outflow of deep circulation thermal waters.

The hitherto best examined thermal water reservoir of Lądek-Zdrój, a town located in Kłodzko Land, was classified by E. Liber (2001) as a reservoir of very deep circulation fissure waters, whose outflows are related to deep tectonic fracture zones.

The conditions of thermal and naturally carbonated water occurrence, described by a number of authors including Fistek, 1977, 1989; Ciężkowski, 1990; Dowgiałło, 2001; Dowgiałło and Fistek, 2007; and Liber, 2001, confirm that tectonic zones are chief outflow paths of these waters and of carbon dioxide accompanying naturally carbonated waters. Particularly predisposed zones of thermal water outflow could be regional zones of tectonic fractures, which enable deep flow of these waters, allowing them to absorb heat from a higher temperature rock medium (Fig. 5.7.1.3).

The structure of the Bohemian massif and its margin, including the Sudetes, has been found to contain a number of deep fracture zones with a wide vertical range. The strike of these zones is not always consistent with the course of dislocations identified in surface zones. These fractures are identified directly with geophysical methods (Pożaryski, 1975; Cwojdziński et al., 1995). Indirectly, their presence can be inferred from belt-like pattern of ore mineralisation (Kanasiewicz, Sylwestrzak, 1970; Michniewicz, 1981), the occurrence of mafic and ultramafic rocks and areas with the occurrence of Cainozoic basaltoids (Cwojdziński and Jodłowski, 1982).

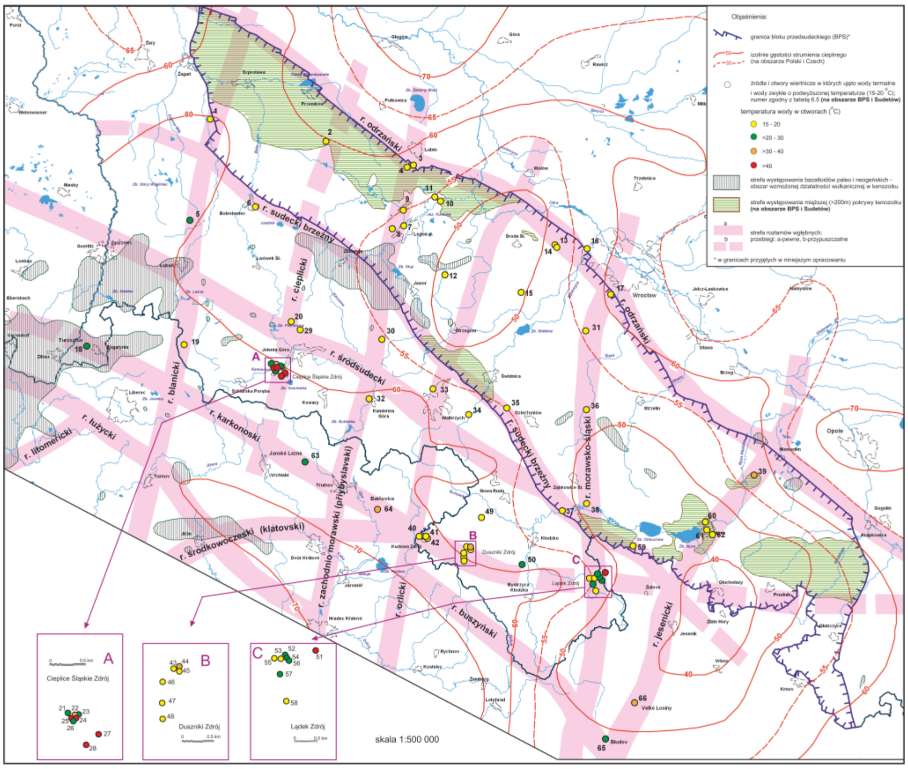


Fig. 5.7.1.3. Main tectonic zones in Sudety Mts. (Przylibski et al., 2007)

The occurrence of thermal springs in the Sudetes is related to the course of main tectonic zones, often consistent with the course of photolineaments (Bażyński et al., 1981, Doktór et al., 1985; Graniczny, 1994), which can also indicate the course of deep tectonic zones. A synthetic inventory of geofracture networks in the Sudetes and the adjacent part of the Bohemian massif was proposed by M. Michniewicz (1981). The strike of the Karkonosze fracture was later corrected and the new

Cieplice fracture was marked out for the purposes of predicting new occurrences of thermal waters in the area of the Fore-Sudetic block (Przylibski ed., 2007; Ciężkowski et al., 2011b).

Two fracture systems have been identified in the Sudetic province: one with NW-SE strike and the other – with NNE-SSW strike. When looking northwards, in Kłodzko Land (Fig. 5.7.1.4) one can distinguish a fracture system with NW-SE strike, forming two zones:

1. Buszyn fracture zone – whose fragment runs in the southern part of the upper Nysa Kłodzka graben. In the village Smreczyna, lying in this area, an occurrence of water type HCO_3-Na-Ca with an increased number of F ions has been found (Kiełczawa, 2001a, 2001b). In the Czech part of this zone, thermal waters type SO_4-Cl-Na occur in Bludov. They are characterised by the TDS of 526 mg/dm^3 and the temperature of 22–26°C (Dowgiałło, 1976).
2. The Karkonosze fracture zone, whose fragment crosses the southern boundary of the Sudetic province. It runs through Turoszów depression, then leaves the province (through Janské Lazně and Batňovice) to re-enter the Polish territory in Kudowa foredeep and then progress through Lądek-Zdrój as far as Prudnik. Within this fracture, one can find medicinal waters in Kudowa-Zdrój, Jeleniów and Duszniki-Zdrój, including naturally carbonated thermal waters of Jeleniów and Duszniki-Zdrój, as well as higher temperature waters in Gorzanów. Additionally, in a borehole drilled in Krosnowice, an artesian flow of thermal water type HCO_3-Na-Ca-Mg, with the temperature of 22°C and TDS of 1600 mg/dm^3 has been identified (Kiełczawa, 2001b). This village lies close to the fault zone of Pstrążna-Gorzanów, extending towards Kudowa along the strike of the Karkonosze fracture in this part of Kłodzko Land. The occurrences of thermal waters and carbon dioxide identified along this fault zone attest the deep and regional range of this fault.

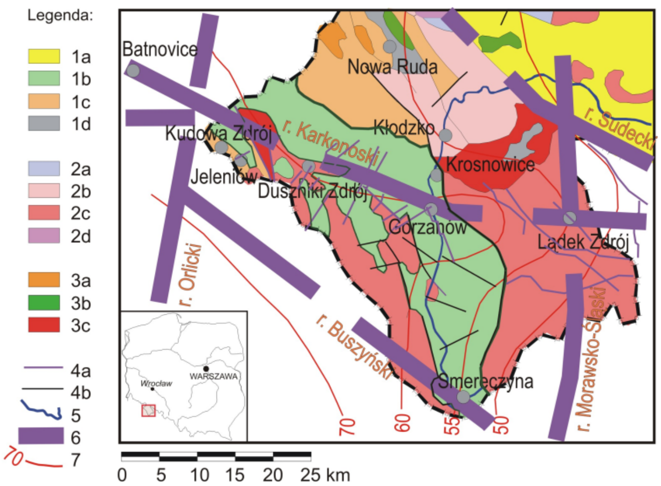


Fig. 5.7.1.4. Prospective areas of thermal water occurrence against the background of a simplified geological map of Kłodzko Land (Liber, Kiełczawa, 2009)

Explanation: 1 – sedimentary series: a – Tertiary, b – Cretaceous, c – Permian, d – Carboniferous; 2 – metamorphic series: a – Palaeozoic mylonites and cataclasites, b – Palaeozoic phyllites, siliceous schists and greenstones, c – Palaeozoic and Proterozoic mica schists and gneisses, Proterozoic gneisses, d – Proterozoic gneisses and migmatites; 3 – igneous rocks: a – Permian and Carboniferous volcanites, early Palaeozoic volcanites, c – late Palaeozoic granites; 4 – faults: a – with prospects of thermal water and higher-temperature water occurrence, b – other; 5 – rivers; 6 – deep fractures; 7 – isolines of heat flow density [mW/m^2]

The highest number of thermal water occurrences in the Sudetes is located in the Karkonosze fracture zone. The thermal waters of Lądek-Zdrój are linked to this fracture.

In connection with a growing demand for medicinal thermal waters, in 1969–1973 a number of measurements aimed at identifying the most propitious areas for the location of new intakes were carried out in and around Lądek-Zdrój. The results of measurements conducted at 53 shallow boreholes (with depths ranging from 25 to 30 m) Ciężkowski (1980) determined the values of near-surface geothermal degree and geothermal gradient to be 5.50,m/°C and 0.18°C/m respectively. Although, as he notes himself, the obtained image (Fig. 5.7.1.5) is not accurate, yet it represents the overall distribution of thermal anomaly in the investigated area.

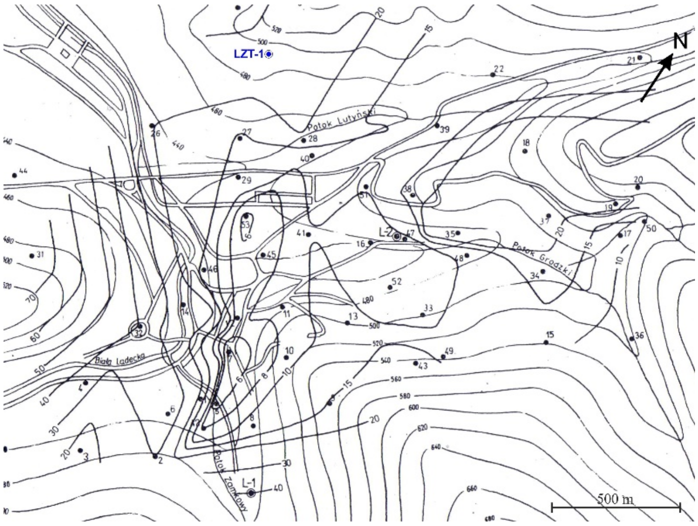


Fig. 5.7.1.5. Geothermal anomaly in Lądek region (Cieżkowski et al., 2016)
Explanations: solid line – geothermal degree

One can see a well-defined area with increased values of geothermal gradient in the central part of the town and east of the resort. In all likelihood, thermal water outflows are linked to the fault zone Lądek-Orłowiec-Karpno and the presence of thermal waters east of the town, in the area of Lądek-Orłowiec-Karpno and Raszowiec-Karpno faults, implies increased values of geothermal gradient. The relatively small range of this anomaly suggests that the thermal water flow is compact, i.e. showing no dispersal (Ciężkowski, 1978, 1980).

5.7.1.2. Geological coditions

The reservoir of medicinal waters in Lądek-Zdrój lies within the geological unit of the Lądek-Śnieżnik metamorphic complex, which is the easternmost tectonic unit of the Central Sudetes. The studied geological unit is delimited by Ramzova thrust in the east, upper-Carboniferous Kłodzko-Złoty Stok intrusion in the north and the upper-Cretaceous unit of the upper Nysa Kłodzka graben in the west. Lądek-Śnieżnik metamorphic complex is a piece of a larger tectonic unit referred to as Orlica-Śnieżnik dome (Żelaźniewicz, 2005).

The Lądek-Śnieżnik metamorphic complex is built of strongly metamorphosed rocks forming three Proterozoic-Palaeozoic complexes (Fig. 5.7.1.2.1a and 5.7.1.2.1b):

- mesometamorphic schists of the Stronie series, represented by mica schists with paragneiss, quartzite, marble, erlan and amphibolite insertions;
- Fine-blastic Gierałtów gneisses, more or less migmatitic, with amphibolite, eclogite and granulite insertions;
- Śnieznik gneisses with varied composition, mostly coarse-blastic, ocellar and lenticular.

All crystalline rocks of the Lądek-Śnieżnik metamorphic complex were formed as a result of polymorphic and polycyclic evolution of a supracrustal series.

In the Carboniferous, the Lądek-Śnieżnik metamorphic complex was penetrated by granitoid intrusions. Vein rocks of the Golden Mountains are related to them (Gierwelaniec, 1970, Żelaźniewicz, 2005).

Metamorphic rocks form fan-shaped fold elements, which dip and converge westward (Don, 1964). The folds form anticlinoria separated by synclinoria. In the area of the Lądek reservoir, one can identify:

- the Radochów anticlinorium, formed by Gierałtów gneisses surrounded by a blastomylonite zone;
- the Lądek synclinorium, built of rocks mica schists complex; the axes of these two structures dip in the SW direction;
- the Gierałtów anticlinorium, built of Gierałtów gneisses; the axis of this unit dips towards the north west;

The fold elements near Lądek-Zdrój are intersected by about a dozen transverse and a few longitudinal faults.

The strike of transverse faults is consistent with the so-called Sudetic direction (NW-SE). Their dips display a steep tilt towards NE (50°–61°). These faults were identified by Gierwielaniec (1970) as:

- Orłowiec-Wójtówka-Karpno fault (uOK, Fig. 5.7.2.1a) with a strike of 300° – 320°, along which one can observe a shift in beds of pegmatized Gierałtów and Śnieznik gneisses.
- Lądek-Orłowiec-Karpno fault (uLT, Fig. 5.7.2.1a) running in gneisses and mica schists from a disused basalt quarry "Lądek-Orłowiec" through Lądek-Zdrój to Trojak hill. It is also known as Lądek-Trojak fault. It has a strike of 290° –

320° and a throw amplitude of several hundred meters. In the resort area, this discontinuity is connected with Rasztowiec-Karpno dislocation by a short steep fault with a N-S strike. The intersection of these discontinuities is linked to outflows of thermal waters onto the surface.

- Rasztowiec–Karpno fault (uLZK, Fig. 5.7.1.2.1a), whose direction changes from 320° na 350° in the area of Lądek.
- Lądek-Zdrój–Królówka–Gierałtów fault (uLZG, Fig. 5.7.1.2.1a), a broad tectonic zone with the character of an inversion fault in Lądek and of an overthrust in Gierałtów.
- Lądek-Zdrój–Gierałtów fault running south of Lądek Zdrój–Królówka fault, parallel to it.

The dislocation zones in the area of Lądek are related to small occurrences of Neogene basalts (Birkenmajer et al., 2002). The presence and strikes of these dislocations were verified by geophysical investigations (Szarszewska, Madej, 1974). This research additionally discovered new tectonic discontinuities. In the Paleogene and the Neogene, the area of the Sudetes, including the Lądek-Śnieżnik metamorphic complex, was subjected to uplifting processes and well as erosion and accumulation action of rivers.

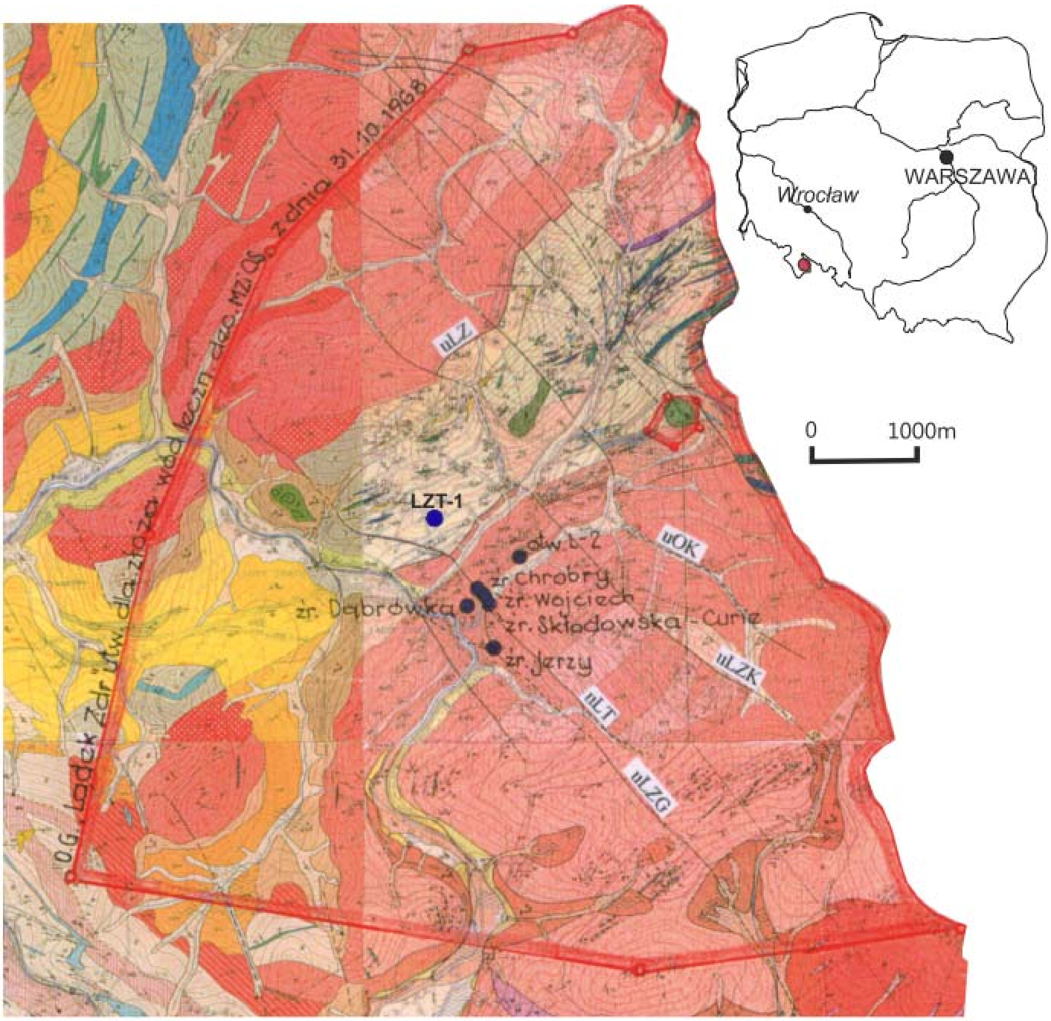


Fig. 5.7.1.2.1a. Location of thermal waters intakes in Lądek-Zdrój on the background of geology and mining area (based on Ciężkowski et al., 1996, geological map after Cwojdziński 1977, 1981, Cymerman & Cwojdziński 1984, Frąckiewicz & Teisseyre 1973, Gierwielaniec 1968a, Kasza, 1958)

Explanations: uLZ – Lądek-Zdrój fault, uOK – Orłowiec-Wójtówka-Karpno fault, uLZK – Rasztowiec–Karpno fault, uLT – Lądek-Zdrój–Orłowiec–Karpno fault, uLZG – Lądek-Zdrój–Królówka fault; LZT-1 – planned borehole

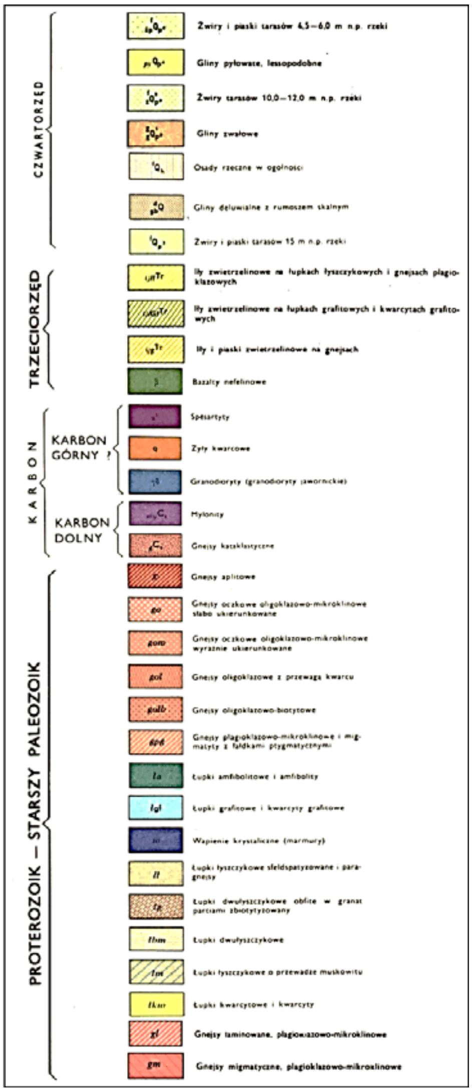


Fig. 5.7.1.2.1b. Explanation of the geological map

The Quaternary is represented in the described area by alluvia, waste rock sediments and slope debris

5.7.1.3. Hydrogeological conditions

In the area of the medicinal water reservoir in Lądek-Zdrój, one can identify two groundwater horizons: Quaternary, comprising waters in river and waste-rock sediments, and Palaeozoic-Proterozoic, comprising shallow and deep circulation fissure waters.

The occurrence of plain Quaternary groundwaters is related to Holocene sandy reservoirs filling valley floors and to gravels of river terraces. The Quaternary reservoir is recharged chiefly by waters from modern precipitation infiltration.
Groundwaters, playing the dominant role of the Palaeozoic-Proterozoic stage, are related to crystalline rocks and their waste mantles. In these rocks, two systems of water circulation occur – one shallow, related to the weathering zone, and the other, deeper, accompanying dislocation zones.

Shallow circulation fissure waters occurring in the crystalline bedrock are related to an exogenic fracturing zone reaching the depths of several to 15 metres, and locally even 30 metres. The abundance of water in this stage is relatively low. Around Lądek-Zdrój, such waters occur, among other places, on the nearby slopes of mountains Trojak and Królówka. The water-bearing reservoir of thermal waters of Lądek-Zdrój are diversely developed Gierałtów gneisses. These waters are classified as very deep circulation fissure groundwaters (Liber, 2001; 2009).

The medicinal thermal waters occurring here flow from large depths to the surface and out of the zone of Lądek-Zdrój fault. Natural outflows of thermal waters in the form of springs are connected with transverse faults intersecting the Lądek-Zdrój fault (Fig 5.7.1.2.1a). These are encased natural springs named Jerzy, Wojciech, Skłodowska-Curie, Dąbrówka and Chrobry.

In the zone of Lądek-Zdrój fault, at a larger depth, thermal waters are also captured from borehole L-2. Above the flow paths of thermal waters, there is an additional borehole L-1, capturing/which captured fresh waters (Ciężkowski et al., 2011a, 2011c, 2016; Liber-Makowska, 2011).

The planned borehole LZT-1 is located to the NW, at a small distance (c. 800 m) from the existing intakes of medicinal thermal waters and on the north-western border between the gneisses of Gierałtów anticlinorium and the schist Stronie series of Lądek synclinorium. This border is identical with the strike of Lądek-Zdrój fault identified by Gierwielaniec (1970). These thermal waters have very low TDS (about 0.2 g/dm^3) and are characterized by an exceptional chemical type – these are fluoride, sulphide and radon HCO_3–Na waters. Their slightly variable temperature averages from 20.3 to 28.3ºC in particular springs, and even 45ºC in the borehole (Ciężkowski, 1980). Additionally, thermal waters are characterized by high stability of their chemical composition. Based on small differences in TDS, one can order the waters from particular intakes according to their TDS – from the highest to the lowest respectively: L-2, Wojciech, Chrobry, Skłodowska-Curie, Dąbrówka, Jerzy and Stare (Ciężkowski, 1980, 1990).

The thermal waters of Lądek-Zdrój are of infiltration origin. The results of research into stable oxygen and hydrogen isotopes in thermal waters of Lądek-Zdrój indicate their recharge above the height of 700 metres, which has been confirmed by results of noble gas research. The underground flow time of these waters is about 5,000 years. The volume of water in the system can be estimated at $1.3 \cdot 10^9$ m^3 (Zuber et al., 1995).

The recharge area of Lądek waters lies about 10 km south-east of the drainage zone, within the Bialskie Mountains and the southern part of the Golden Mountains. After infiltration in the recharge area, waters flow at the depth of 2000–2500 m towards the resort (Ciężkowski, 1980, Ciężkowski et al., 1996). The thermal waters flowing out there are related to the hydrogeothermal anomaly of Lądek-Zdrój (Ciężkowski, 1980).

5.7.1.4. History of Lądek Spa

The water springs in Lądek are regarded some of the oldest in Lower Silesia. According to a legend, the first spring was discovered by a shepherd who came across it in a forest. He was surprised to find the water from the spring warm and unpalatable. What is more, it had a strange colour and smell. Nevertheless, local people came to check if the water could possibly help to cure their various ailments and when they found out about its beneficial effects, they enclosed the spring with a wall. It is not clear when exactly it happened but the first written records about Lądek springs date from the latter part of the 17th century. In 1683, dr G.H. Burghart, the author of a treatise about Lądek, wrote that Mongols returning after the Battle of Legnica in 1241 destroyed and burned the installations and the buildings around the spring. That spring was known as the Old Spring (later Georg or Jerzy). The next information, unfortunately also about the destruction of spring buildings, appears in records from the time of the Hussite Wars (1428 and 1431). The development of a spa resort in Lądek started when the land in which the springs are located became the property of the Poděbrad family. In 1498, they brought from Vienna a physician named Konrad von Berge, who carried out the first analysis of Lądek water and confirmed its medicinal properties.

The spring was encased again (in a larger ring than before), and lodgings for visitors and bathing facilities (Georgenbad) were built. The new name "Georg" was given to the spring to honour one of the Poděbrad brothers. In the following years, the changing owners of Lądek did not show much interest in the springs and the development of the resort. It was not until the latter part of the 16th century (1572) when the town bought the spring from private hands and started rebuilding the heavily neglected facilities (Brzeziński, 2000; Ciężkowski, 1998; Dębicki, 2000; Ostrowicz, 1881). In 1601, the town council published the first set of rules for resort users and three years later – the first 'advertising' brochure about it (Marsch, 2009). In 1619, a new spring was discovered and, in 1637, it was bought, together with the adjoining land, by the imperial counsel J.Z. Hoffmann. In 1677, the clearing of the land around the spring, named Friedrich (now Maria Skłodowska-Curie), started. During the work, another spring was discovered nearby. The workers found a tank cut out in stone and numerous tools (spades, hooks and water-drawing utensils). It turned out that the first of the discovered springs (Georg) was not the oldest spring in Lądek. Counsel Hoffmann enlarged the tank, commissioned a chemical analysis of both springs, and then, in 1678–1679, had new baths (Marienbad) built above them. The newly discovered spring was given the name 'New', later changed to "Marie" (now "Wojciech"). An inn was soon built near the springs, which started the development of a rival resort to Georgenbad (Ciężkowski, 1998; Marsch, 2009; Kincel, 1994).

The main form of treatment offered then were long-hour baths and every bather had his own bathtub (Ostrowicz, 1881). Water drinking treatments were introduced in the 1730s and peloid treatments – in 1849 (Ciężkowski, 1998). It was also at that time (1736) when the town council bought Marienbad from the descendants of Counsel Hoffmann, which put an end to competing activities between the owners of both resorts. In 1753, at the King's order, a new set of resort rules was published, but the following years started a period of stagnation deepened as a result of the Silesian Wars (Marsch, 2009;

Kincel, 1994). The situation of the resort changed in 1770–1807, when Count C.G.H. von Hoym, the Minister of Silesia, took over its management. He had both bathhouses connected by a larch-lined road, the area between them turned into a garden and a ballroom built, thus creating one spa resort.
The turn of the 18th century saw the development of resort architecture, not only in Lądek. It was characterized by the transformation of hitherto spontaneously developing construction around springs into compact resort complexes with a square in the centre.

In 1789, a Shower House was built in the square near Marie and Friedrich springs. A year later it was equipped with the region's first appliances for shower treatments (Ciężkowski, 1998; Dębicki, 2000; Marsch, 2009; Balińska, 2000). One must remember that baths were available only for upper-class guests. Poor patients had to wait until the baths were vacated and only then they had a chance to immerse in water. This situation changed in the late 18th century, when a separate bath for the poor was built (Kincel, 1994). In 1797, a specially appointed resort commission drew up a new set of rules, where their competency was specified. The rules were later confirmed by king Frederick William III (Kiełczawa, 2016). After 1811, every patient was obliged to have a card of residence, without which taking therapeutic baths was not possible. In 1814, a rescript by the royal administrative district in Wrocław introduced a ban on common baths for men and women (Ostrowicz, 1881; Kincel, 1994). In the 1830s, the inflow of visitors enforced the modernization of the casing of spring Marianne (now Dąbrówka) and the tapping of the Meadow Spring (now spring Chrobry) (Ciężkowski, 1998). Ostrowicz (1881) wrote that the date of the discovery of spring Marianne was unknown, but it is probably one of the springs discovered in the land owned by Counsel Hofffmann and its name is linked to the visit of Princess Marianne of the Netherlands in Lądek in 1838. However, Ciężkowski (1998) believes that the spring was discovered in 1679, during the construction of the church. The church was built nearby and the spring was captured. In 1795, a small pavilion was erected above it (rebuilt in 1828) and the water was reserved for drinking treatment. Between 1849 and 1935, waters from this spring were used in treatments administered in the Stone Bathhouse (pulled down in 1936). The other of the mentioned springs – the Meadow Spring – was exposed when the local stream flooded in 1829. It obtained its name in 1847, when the town took care of it (Ciężkowski, 1998). An important period in the development of the resort were years 1838-1861, when the office of the resort physician was taken by Dr F. Bannerth. Thanks to his efforts, an inhalation hall over spring Friedrich (1844), Albrecht's colonnade (1842–1845) (Fig. 5.7.1.4.1) and an orangery were built (Ciężkowski, 1998; Ostrowicz, 1881; Balińska, 2000).

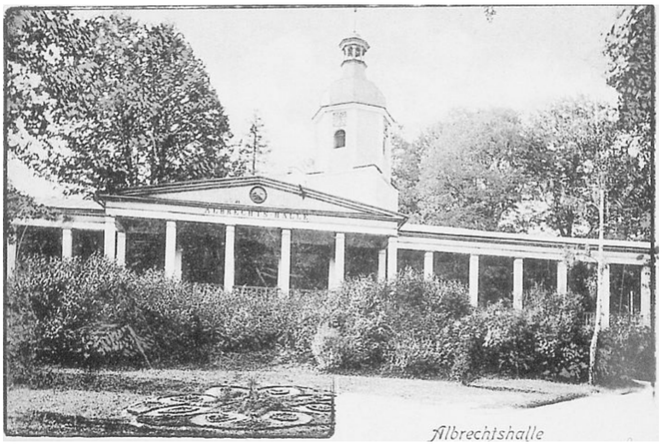


Fig. 5.7.1.4.1. Albrechts Hall (Wziątek, 1999)

In 1849, the construction of Steinbad (the Stone Bathhouse), designed for mineral and peloid baths, was completed (Ciężkowski, 1998; Ostrowicz, 1881). In the same period, marble bathtubs were fitted in 'Marie' bathhouse. White marble was also used for laying the pools in 'Georg' (1858) and 'Marie' (1860) bathhouses. In 1868, a military sanatorium (Militar Kurhaus) was built and in 1877 a specialist hydrotherapeutic bathhouse Thalheim was opened. It was equipped with a variety of showering appliances, a Roman-Irish bath and a Russian bath. It offered treatment with directional gravity showers, full and partial immersion baths, dousing, packing and inhalation (Ostrowicz, 1881). Between 1878 and 1880, the bathhouse 'Marie' was pulled down and replaced with a new building, still in existence today (Fig. 5.7.1.4.2). The bathhouse 'Georg' was modernized in 1917 (Ostrowicz, 1881; Marsch, 2009).

Fig. 5.7.1.4.2. Natural Treatment Centre "Wojciech" (source: Archives of Marshal Office of Lower Silesia, Regional Promotion Section, 2016)

An important year for the development of Lądek's therapeutics was 1904, when Jan Plesch carried out the first measurements of the radioactivity of waters from springs Marie and Georg (Dębicki, 2000). A few years later, in 1912, an emanation house adapted for providing radon treatments was opened. It operated until 1967. During World War II therapeutic activities in Lądek were targeted according to the needs of that period. After the war, treatments using Lądek waters were resumed in 1946 (Marsch, 2009). Practically all the time throughout the post-war period (from 1953 to 1994), the bathhouse complex 'Maria' repeatedly underwent multi-stage renovations and extensions and it was not until 1997 when the work was finally completed. Meanwhile, in 1853, the name of the complex was changed to Natural Treatment Centre 'Wojciech' (the treatment part), while the part providing accommodation was named 'Stefan' (Ciężkowski, 1998).

Until the end of 1998, the resort operated as a state-owned company supervised by the Ministry of Health and Social Care. It was commercialised by a statute of December 1998, which resulted in the creation of a company wholly owned by the State Treasury named Uzdrowisko (Health Resort) Lądek-Długopole S.A. The health resort is wholly owned by the Lower Silesian voivodeship (www.uzdrowisko-ladek.pl).

5.7.1.5. Geothermal reservoir description

Administratively, the reservoir of thermal medicinal waters in Lądek Zdrój is located in the south-eastern part of Lower Silesian voivodeship, in county Kłodzko. Slightly mineralized therapeutic fluoride, sulphide and radon thermal waters from the reservoir in Lądek-Zdrój, were declared medicinal by the Regulation of the Council of Ministers dated 14 February 2006, Item 417 § 2 section 2.27 (Journal of Laws No 32, Item 220, amended).

By the decision of the Marshal of Lower Silesian Voivodeship in 2012, a licence to exploit the medicinal water reservoir in Lądek-Zdrój for 30 years was granted to the Health Resort Lądek-Długopole partnership. Having got acquainted with a resort report submitted by the municipality of Lądek-Zdrój and written for the health resort, the Minister of Health confirmed the capacity of providing health-resort treatment in the area designated as the health resort Lądek-Zdrój and, based on the submitted certificates confirming the medicinal properties of natural materials and the climate, defined the following therapeutic profiles: orthopaedic-traumatic disorders, neurological disorders, rheumatological diseases, peripheral vascular diseases, osteoporosis, skin diseases and gynaecological diseases.

As early as 1968, the mining area "Lądek-Zdrój" of 41,075,000 m^2 was set up for the reservoir of thermal medicinal waters. The borders of the mining impact area "Lądek-Zdrój", established in 1983, correspond to those of the mining area (Fig. 5.7.1.5.1).

Fig. 5.7.1.5.1. Location of healing waters' intakes (red circles) and radon waters intakes (orange circles) (Krzonkalla-Maryniuk, 2015)

The mining area is mostly located within the town and commune Lądek-Zdrój, except for the south-western fragment encompassing a small part of village Gierałtów in commune Stronie Śląskie.

The health resort with its thermal water intakes is situated in the north-western part of town Lądek-Zdrój, about 2 km away from its centre (Fig. 5.7.1.5.1). Medicinal water intakes occur in this area along the Grodzki Potok – a right-bank tributary of the Biała Lądecka river.

The mining area and the mining impact area Lądek-Zdrój are located in the north-eastern part of Kłodzko Land, in the central part of the Golden Mountains and a small part of Śnieżnik massif (Krowiarki).

According to geographic regionalization of Poland by J. Kondracki (1998), the reservoir of medicinal waters in Lądek Zdrój lies in the megaregion of Central Europe, the province of Bohemian massif, the subprovince of the Sudetes with the Pre-Sudetic Foreland, the macroregion of the Eastern Sudetes and on the border between the Golden Mountains and the Śnieżnik Massif.

The area containing intakes of medicinal waters is located in town Lądek-Zdrój, within the Golden Mountains, at the height of 425 to 470 m asl /above the sea level. The town lies in the Biała Lądecka river valley. The resort lies on the southern slopes of the Golden Mountains, in the valley of the Grodzki Potok.

The recharge area of Lądek-Zdrój thermal waters lies about 10 km south-east of the drainage zone, within the Bialskie Mountains and the southern part of the Golden Mountains.

The recharge area lies outside the mining area of Lądek-Zdrój thermal waters. It is located within the borders of municipality Stronie Śląskie and is delimited by the state border in the east and the south. This area is forested and it is a part of the Śnieżnik Landscape Park.

In order to ensure the adequate protection of medicinal water intakes, it would be necessary to extend the mining area to comprise the whole medicinal water reservoir, including the recharge, flow and drainage zones. However, owing to the considerably long underground flow time (c. 5,000-10,000 years) of the medicinal waters of Lądek-Zdrój and the location of the recharge zone within the protected area of Śnieżnik Landscape Park, it can be accepted that there is very little threat to the quality and the resources of these waters, so the reservoir is being protected adequately.

In its north-eastern part, the mining area contains a small basalt deposit "Lutynia I" ("Szwedzkie Szańce") for which a mining area and a mining impact area "Lutynia I" of 75,889 m^2 and 841,501 m^2 respectively were created.

5.7.1.6. Intake description

Medicinal thermal waters in Lądek-Zdrój are extracted from six intakes, including five springs named Jerzy, Wojciech, Curie-Skłodowska, Chrobry and Dąbrówka, and one borehole L-2 (Zdzisław). One spring, named Stare, is not exploited currently (tab. 5.7.1.6.1).

Apart from medicinal thermal water intakes, the mining area also contains an unused borehole L-1 which captured fresh waters.

Table 5.7.1.6.1. Characteristics of geothermal healing waters' intakes in Ladek-Zdroj (based on: Ciężkowski and Ciężkowski, 1982/1983; Cieżkowski et al, 2011, 2016; Fistek, Szarszewska, 1975; Szarszewska, 1967; Szarszewska, Madej, 1974, Liber, 1997, 2001 and archival materials UZG). Intakes currently exploited are marked with a darker background

Name of the intake	**Admissible volume**	**Temperature of water**	**Water characteristics according to the resource documentation**	**Type of intake**	**Depth of intake**
	m^3/h	**°C**			**m**
Jerzy	17.08	27.1–29.5	0.02% HCO_3–Na, Rn, F, S	8 wypływów ujętych zbiornikiem 8 outflows captured with the tank	2
Wojciech	5.00	18.2–29.6	0.02% HCO_3–Na, Rn, F, S	7 wypływów ujętych studnią 7 outflows captured with the well	1.76
Curie-Skłodowska	3.79	22.4–34.7	0.02% HCO_3–Na, Rn, F, S	5 wypływów ujętych zbiornikiem 5 outflows captured with the tank	0.3-2
Dąbrówka	1.22	18.8–29.1	0.02% HCO_3–Na, Rn, F, S	studnia/ well	3.1
Chrobry	1.67	26.2–27.3	0.02% HCO_3–Na, Rn, F, S	studnia/ well	9.6
Stare	1.02	16.7–17.7	0.018% HCO_3–Na, F	wypływ obudowany zbiornikiem outflow captured with the tank	3.0
L-2 (Zdzisław)	30.0	44.1–45.1	0.02% HCO_3–Na, Rn, F	odwiert borehole	700.3

Spring Jerzy is located within the Old Natural Treatment Centre Jerzy built in 1498 (Fig. 5.7.1.2.1a, 5.7.1.5.1, 5.7.1.6.1). The spring is made up of 8 outflows captured with a tank, which is covered by a plate forming the bottom of "Jerzy" pool. Water flows out of fissures in tectonic breccia of the fault zone or at the contact with surrounding rocks – lithologically varied Gierałtow gneisses intersected with orthoamphibolite and leucogranite veins. The temperature of water from the intake oscillates between 27.1 and 29.5°C. This is a 0.02% therapeutic thermal slightly mineralized water containing fluorides, sulphides and radon (according to Dz.U. nr 196 z 2015 r.).

The water from this intake is transferred gravitationally, via a pipeline, to a reservoir in the New Natural Treatment Centre "Jerzy".

Fig. 5.7.1.6.1. Decorative casing of water outflow from George spring in the Centre "Nowy Jerzy" (phot. E. Liber-Makowska, 2017)

Spring Wojciech is situated inside the building of the Natural Therapy Centre "Wojciech" (Fig. 5.7.1.2.1a, 5.7.1.5.1, 5.7.1.6.2). It is captured with a 1.76 metre deep well covered with a plate forming the bottom of "Wojciech" pool. The spring is made up of 7 outflows related to Gierałtów gneisses with strong cleavage. The temperature of water from the intake oscillates between 18.2 and 29.6°C. This is a 0.02% therapeutic thermal slightly mineralized water containing fluorides, sulphides and radon (according to Dz.U. nr 196 z 2015 r.).

Fig. 5.7.1.6.2. Study Visit to Poland in Lądek-Zdrój, 2017 – lecture by prof. W. Ciężkowski in the pool over the Wojciech spring (photo E. Liber-Makowska, 2017)

Spring Dąbrówka is located in Lipowa Street (Fig. 5.7.1.2.1a, 5.7.1.5.1, 5.7.1.6.3). It is captured with a 3.1-metre deep well. Water flows out from strongly cracked and weathered fine-grained Gierałtów gneisses. This is a 0.02% slightly mineralized water containing fluorides, sulphides and radon. The water from this spring is conveyed only to a public outflow in the park.

Spring Skłodowska-Curie is located ca. 30 m east of spring Wojciech (Fig. 5.7.1.2.1a, 5.7.1.5.1). The intake is a brick tank with 5 water outflows, two of which are captured with a well. Water flows out of strongly fractured Gierałtów gneisses. Water temperature oscillates from 22.4 to 34.7°C, and it is a 0.02% therapeutic thermal slightly mineralized water containing fluorides and radon (according to Dz.U. nr 196 z 2015 r.).

Thermal water from intakes Wojciech, Skłodowska-Curie and L-2 is used in a therapeutic pool and for treatments provided at the Natural Treatment Centre 'Wojciech'.

Fig. 5.7.1.6.3. Decorative casing of water outflow from Dąbrówka spring in the Spa Park (phot. E. Liber-Makowska, 2017)

Spring Chrobry lies on the right bank of the stream Grodzki potok, near the Natural Treatment Centre "Wojciech" (Fig. 5.7.1.2.1a, 5.7.1.5.1, 5.7.1.6.4). It is captured with a 9.6-metre deep hexagonal well. The water flows out from shattered and strongly weathered Gierałtów gneisses, in a zone lying at the extension of Lądek-Orłowiec dislocation. The water temperature is 26.2–27.3°C. This is a 0.02% therapeutic thermal slightly mineralized water containing fluorides, sulphides and radon (according to Dz.U. nr 196 z 2015 r.).
The water from this spring is conveyed to a water outflow in the park.

Fig. 5.7.1.6.4. Stone casing of water outflow from Chrobry spring in the Spa Park (Krzonkalla-Maryniuk, 2015)

The Old (Stare) Spring lies near the Biała Lądecka river, at the crossroads of Nadbrzeżna street and M. Skłodowska-Curie square (Fig. 5.7.1.5.1). The spring flows out of several fissures in Gierałtów gneisses. Directly above the spring, there is a tank from which water is drained to the stream through an overflow channel. The spring is not exploited currently.
Borehole L-2 (Zdzisław) is located in Marzeń street, about 600 m NE of the Natural Treatment Centre "Wojciech" (Fig. 5.7.1.2.1a, 5.7.1.5.1, 5.7.1.6.5). Executed in 1972-1973, the hole reached the depth of 700.3 m and was drilled in Gierałtów gneisses with amphibolite intercalations and a lamprophyre vein surrounded by basalt veins. After drilling through this vein, at the depth of 577 metres, thermal waters were encountered. In order to isolate the inflow zones of cooler waters, the hole was walled up to the depth of 150 metres. After the completion of drilling, the hole was fitted with a wellhead.
The borehole has been cased as follows:

- 18''- diameter pipes to the depth of 8.8 m, cemented up to the surface;
- 14''- diameter pipes to the depth of 29.9 m, cemented up to the surface;
- 9 5/8''- diameter pipes to the depth of 150.0 m, cemented up to the surface;

Water flows out of the hole naturally and the pressure at the wellhead is 0.5 atm. The water temperature ranges from 44.1 to 45.1°C. This is a 0.02% therapeutic thermal slightly mineralized water, containing radon, fluorides, and sulphides (according to Dz.U. nr 196 z 2015 r.).
Water from the borehole is used for therapeutic treatments provided at the Natural Treatment Centres „Wojciech", Adam" and „Jerzy".

Fig. 5.7.1.6.5. The head of L-2 well (Zdzisław) (phot. E. Liber-Makowska, 2017)

The L-1 (L-600) borehole lies about 500 m NE of Jerzy spring. While drilling, no artesian flow was observed in it and the water table stabilized at the depth smaller than 25 m below ground level. It captures slightly mineralized radon and fluoride water with the temperature of 18.5˚C. The borehole is not in exploited and it acts as a piezometer.

5.7.1.7. Current exploitation conditions

All the intakes, both springs and the borehole, are exploited as artesian flow. The extraction is carried out under the supervision of the Resort Mining Division of Lądek-Długopole Resort.

The water flowing out of the intakes, either directly or through reservoirs, is distributed gravitationally by pipelines to natural treatment centres, drinking halls and water outflows in the Spa Park.

Owing to the low admissible volume of groundwater extracted from the springs and the artesian flow method of extraction, most medicinal groundwater intakes in Lądek-Zdrój have reservoirs where surplus water is collected. The water used for therapeutic treatments is extracted directly from intakes or collected in reservoirs.

For all the intakes of medicinal thermal waters in Lądek-Zdrój (with defined exploitable, industrial and non-industrial resources), apart from the disused Stare (Old) spring, stationary observations are conducted. The observations are carried out precisely and regularly by the Lądek-Długopole Resort Mining Division staff.

Regular measurements of reservoir parameters is essential for monitoring any changes occurring in the extracted reservoir. In order to control the volume and the quality of the extracted water, one should continue stationary observations. These observations comprise:

- flow rate (discharge) measurement at overflow level performed by volumetric method once a week for springs Jerzy, Wojciech, Skłodowska-Curie, Dąbrówka and Chrobry, and with a water meter and/or by volumetric method at overflow level, once a day for borehole L-2 Zdzisław;
- Water temperature measurement with an electronic thermometer, conducted once a week for springs Jerzy, Wojciech, Skłodowska-Curie, Dąbrówka and Chrobry, and once a day for borehole L-2;
- measurement of radon concentration in water conducted by scintillation method every three months for intakes Jerzy, Wojciech, Curie-Skłodowska, Dąbrówka, Chrobry and L-2.
- determination of H_2S content in water by iodometric titration, conducted every three months for intakes Jerzy, Wojciech, Curie-Skłodowska, Dąbrówka, Chrobry and L-2;
- bacteriological testing, conducted every three months for intakes Jerzy, Wojciech, Curie-Skłodowska, Dąbrówka, Chrobry and L-2;
- physico-chemical (so-called small) analyses, performed once a year for intakes Jerzy, Wojciech, Skłodowska-Curie, Dąbrówka, Chrobry and L-2, and full (so-called large) analyses – every 10 years.

All the springs are encased (Section 5.7.1.6.) with a well or a tank, with a possibility of collecting water and performing measurements at the overflow, at a stable defined level. Borehole L-2 is fitted with an extraction wellhead enabling the regulation and direct observations of water temperature and reservoir pressure as well as performing flow rate (discharge) measurements by volumetric method (there is an overflow tank installed beside the intake). Additionally, a water meter for measuring the volume of extracted water is fitted on the pipe.

The wellhead of L-2 borehole, together with measurement equipment, is locked in a secure building accessible only to the authorized staff of the Resort Mining Division.

Borehole L-2 (Zdzisław) captures the warmest slightly mineralized thermal water containing radon, fluorides and sulphides, with the temperature of about 44˚C. The water from this intake is transferred to natural treatment centres via a pipeline or it is stored in a 400 m^3 reservoir located near the borehole.

The current condition of the intakes, reservoirs and pipelines can be described as good. The used medicinal waters and waste peloid, after being used in natural treatment centres, are transmitted as waste to the municipal sewage system.

Waters are used chiefly for balneotherapeutic purposes – therapeutic treatments and baths in pools. A mixture of waters from various intakes is usually used. It is mostly the hottest water from borehole L-2 (with the largest exploitable resources) with added cooler water from springs Jerzy, Wojciech or Skłodowska-Curie. Medicinal water is also used in drinking halls of natural treatment centres "Wojciech" and "Jerzy". Additionally, there are publicly accessible outflows with waters from Chrobry and Dąbrówka springs in the spa park. In 2016, 185 963.66 m^3 of water were used for balneotherapeutic purposes.

Almost all the thermal waters flowing out of springs Chrobry and Dąbrówka are conveyed to water outflows in the form of small drinking places in the spa park. Additionally, about 30% of water from intake Chrobry (2790 m^3 in 2016) is used for therapeutic treatments at the Military Spa and Rehabilitation Hospital.

The balance of exploitation (production) and utilization presented in Table 5.7.1.7.1. demonstrates that waters from particular intakes are used to varying degrees. Given the total flow rate (discharge) of all the extracted intakes in relation to the amount of water used in balneotherapy in 2016, the percentage of water utilization was found to be 56.7%. The usage of thermal waters from springs Jerzy, Skłodowska-Curie and Wojciech amounts to about 15%, 22.6% and 38.5% of the extracted water respectively, while 100% of waters from borehole L-2 are put to use. It is also noteworthy that waters from intakes Chrobry and Dąbrówka are used to a small extent, although Table 5.7.1.7.1. specifies their usage as 100%. In this case, water flowing naturally out of springs is piped only to public drinking places in the park and then transmitted to sewers or to the river.

The presented balance sheet allows a conclusion that 43% of the exploited thermal water is not utilized at all. The heat of post-treatment waters and waters transmitted from public drinking places in the park is not reused. In the context of plans for the exploitation of thermal water heat from the new intake LZT-1, it would be advisable to design a system of reclaiming the already accessible heat from the existing thermal water intakes in Lądek Zdrój.

The overall extraction between 1.01.2016 and 31.12.2016 amounted to 327 856.22 m^3. The extraction from particular intakes ranged from 6 364.44 m^3/per year for spring Dąbrówka to 133 579.64 m^3 per year for borehole L-2.

Table 5.7.1.7.1. Balance of operating resources of thermal medicinal waters in Lądek Zdrój - production and utilization as of 31.12.2016 – therapy and drinking hall in the Park.

Intake name	Approved reserves	Production in 2016	UTILIZATION		
			Quantity	Percentage of production	Purpose
	m^3/year	m^3/year	m^3/year	%	
Jerzy	149650.00	118965.97	18078.15	15.20	balneotherapy
Wojciech	43800.00	30242.28	11635.00	38.47	balneotherapy
Skłodowska-Curie	33215.00	28933.42	6536.87	22.59	balneotherapy
Chrobry	14600.00	9770.47	9770.47	100.00	water drinking place in park
Dąbrówka	10950.00	6364.44	6364.44	100.00	water drinking place in park
Zdzisław (L-2)	262800.00	133579.64	133579.64	100.00	balneotherapy
Total amount	**515015.00**	**327856.22**	**185963.66**	**56.72**	

Currently, the volume of water that can be used by the „Uzdrowisko Lądek-Długopole" company largely depends on the range and the number of therapeutic treatments planned as services provided within three areas: those offered by the National Health Fund (health-resort treatment and hospital treatment, therapeutic rehabilitation), by the Social Insurance Company (rehabilitation treatment) and commercial services for individuals. As not all thermal water artesian flowing from all Lądek-Zdrój intakes is used for balneotherapeutic purposes, there are surpluses of several dozen percent of the total production, which can be further used, e.g. for heating.

Due to the artesian flowing manner of exploitation, it is not possible to control the extraction levels from springs. Also, borehole L-2 is exploited via artesian flow. In order to avoid adverse hydrodynamic changes in the reservoir, stable technical conditions of water extraction from intake L-2 have been maintained since the beginning of its exploitation. This is why, despite the possibility of regulating the flow rate with a valve on the wellhead, this option is not used. Extraction of thermal water from borehole L-2 and from other shallow intakes via artesian flow makes it possible to maintain stable exploitation conditions in the reservoir.

The current, correctly performed extraction of thermal medicinal waters of infiltration origin does not cause any significant changes in the quality or the quantity of underground or surface waters.

However, too intensive exploitation could result in a decrease in the flow rate (discharge) of all the exploited intakes of medicinal thermal waters and other groundwaters in the reservoir area. Possible threats to the medicinal thermal water reservoir of Lądek-Zdrój will be presented in the next section.

5.7.1.8. Potential threats to the stability of reservoir exploitation

The co-occurrence of different groundwater types within one reservoir of medicinal thermal waters may bring about changes in its hydrodynamic system. Observations conducted so far have demonstrated that intensive extraction of medicinal waters can cause changes in the dynamics of both these waters and fresh waters.

The area of medicinal thermal water reservoir in Lądek-Zdrój contains fresh and thermal (medicinal) fissure groundwaters. Thermal waters from large depths flow to the surface through Lądek-Zdrój fault zone. Medicinal water springs are related to transverse faults intersecting Lądek-Zdrój fault. Within this fault zone but at a distance from the springs and at larger depths, thermal waters are also captured from borehole L-2. Above the flow paths of thermal waters, there is also borehole L-1, which captured fresh waters. Currently, plans are being developed for drilling a new borehole LZT-1 in the same fault zone (Ciężkowski et al., 2016). The planned LZT-1 borehole is located to the NW, at a small distance (800 m) from the existing intakes of medicinal thermal waters and on the north-western border between the gneisses of Gierałtów anticlinorium and the schist Stronie series of Lądek synclinorium. This border is identical with the strike of Lądek-Zdrój fault.

Experience has proved that too intensive extraction of thermal waters from borehole L-2 causes a pressure drop in the thermal water reservoir, which is revealed by the decreasing flow rate (discharge) in springs and the lowered water table of fresh fissure waters captured not only from the closest borehole L-1, but also from other, more distant intakes (Ciężkowski, 1980).

Such a critical situation occurred in 1978, two years after the exploitation of borehole L-2 had been launched. Due to a fresh water shortage in Lądek-Zdrój, uncontrolled extraction from borehole L-1 started, reaching the volume of 330–360 m^3/day. The extraction of fresh waters from intake L-1 had a disadvantageous effect on the reservoir parameters of thermal waters. What was observed was a marked reduction in the flow rate (discharge) of shallow thermal water intakes (by 12 to 34%) and the deterioration of the chemical composition of water. Slightly though clearly, water temperature dropped, notably in the least productive intakes. Also, concentrations of radon and fluorine dropped by up to 40% and over 20% respectively. However, the biggest changes in the basic ion composition did not occur until 1982, i.e. four years after the inception and two years after the end of the exploitation of borehole L-1 (Ciężkowski, 1983, 1990). The observed changes are a proof of interaction between fissure thermal and fresh waters within the Lądek-Zdrój reservoir.

The drop in the reservoir pressure of thermal waters caused by medicinal water extraction from borehole L-2 initiated in 1976 brought about the lowering of the water table of fresh fissure waters. Additional extraction of fresh waters from L-1 borehole also led to a drop in the reservoir pressure in all the fissure groundwater system in Lądek-Zdrój.

The reactions of thermal water intakes in Lądek-Zdrój to extreme changes in the reservoir, like those described above, were confirmed by analysing correlations between the flow rate (discharge) of particular intakes. The highest correlation coefficients (0.8) were obtained when allowing for simultaneous and immediate reaction times (Liber, 2001). This proves a very strong and almost simultaneous reaction of particular intakes to changes occurring in the whole reservoir. It has also been confirmed by research into the modelling of these changes (Liber and Liber; 2003a and b; 2005, Liber, 2009).

Between April and July 2000, direct research was conducted on shallow thermal water intakes such as Skłodowska-Curie, Chrobry, Dąbrówka and Wojciech. The research proved that thermal springs in Lądek-Zdrój form one hydraulic system and they interact on the principle of communicating vessels. Particularly strong hydraulic connection was found between springs Wojciech and Skłodowska-Curie (Fig. 5.7.1.8.1). Additionally, it was demonstrated that variations in the level of water table in the pool over Wojciech spring cause changes in the flow rate (discharge) of springs (Liber, 2001, 2007, 2011).

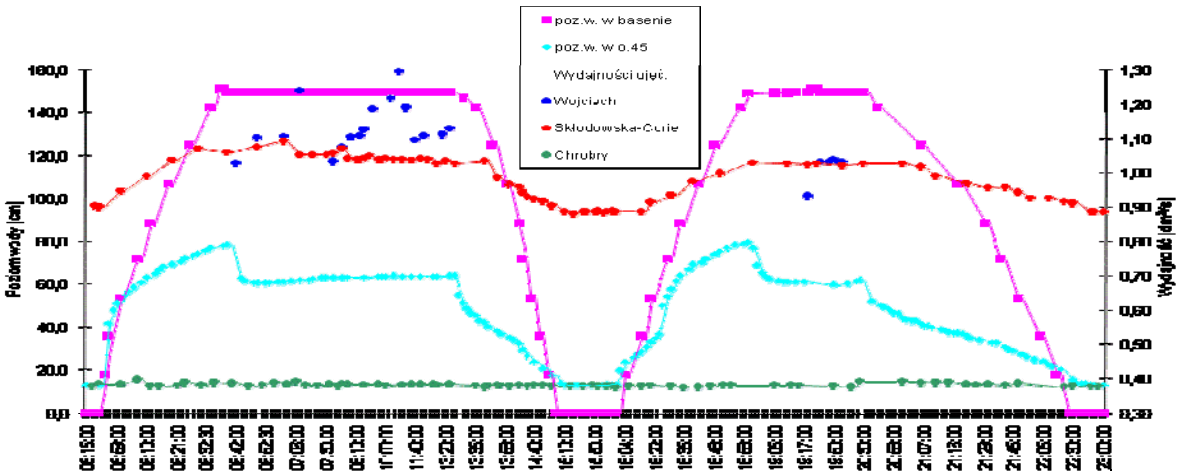


Fig. 5.7.1.8.1. The influence of water level in "Wojciech" pool on the water level in No. 45 borehole and on the flow rate (discharge) of thermal water springs in Lądek-Zdrój in 2-4.07. 2000 (Liber, 2001)

The existence of strong hydraulic connections between particular thermal water intakes indicates that all medicinal water intakes in Lądek-Zdrój are recharged from one fissure reservoir of very deep circulation waters (Liber, 2001). Hence, the total amount of water flowing out naturally from the reservoir should be almost constant.

Until 1973, the total flow rate (discharge) of all intakes of medicinal waters in Lądek-Zdrój was constant and amounted to 9.5 dm^3/s (820 m^3/d) (Ciężkowski, 1980). In order to increase the flow rate (discharge), a new deep thermal water intake, borehole L-2, was drilled in 1973. The operation of this borehole, initiated in 1976, brought about a distinct drop in the flow rates (discharges) of all shallow thermal water intakes. When considering the summative flow rate (discharge) of all the intakes, a distinct expotential character of this drop is observed.

Based on the results of stationary observations conducted by the Resort Mining Division during 27 months of exploitation, Ciężkowski (1980) estimated the stabilization of the summative discharge of all the intakes at 12.5 dm^3/s (1080 m^3/day).
In order to describe a model of emptying a reservoir of deep circulation fissure waters such as the medicinal water reservoir in Lądek-Zdrój, Liber (2009) used, for the first time, a modified Maillet's formula. The character of changes in the flow rates (discharges) of all the intakes was defined for the period of over 28 years of joint exploitation of the springs and borehole L-2. A better fitting of the employed Maillet's regression curve to real flow rate (discharge) changes in time was obtained after allowing for the basic inflow q (Fig. 5.7.1.8.2). This inflow determines the limit value, which defines the summative flow rate (discharge) of all the intakes that may be extracted during intake operation. This value can be equal to the summative admissible volume of extracted groundwater estimated in this way for the analysed intakes.

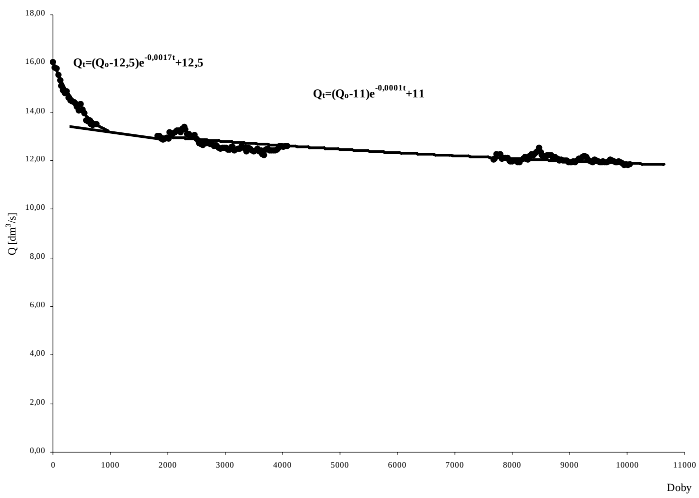


Fig. 5.7.1.8.2. Regression curve of total discharges of intakes of thermal water in Lądek-Zdrój in 1976-2004 (Liber, 2009)

The results of the performed calculations implied a distinct dual character of the process of emptying the reservoir, characterised by two representative straight lines with different tilt angles defined by various coefficients. One line, steeper and described by a regression coefficient of 0.0017, illustrates the initial stage of emptying the reservoir. It is related to a quick, substantial drop in the flow rate (discharge) of all thermal water intakes lasting from the beginning of the exploitation of borehole L-2 in 1976 to 1978 (from day 0 to day 761). The initial intensive water outflow from borehole L-2 (c. 8 dm³/s) and the rapid drop in the total flow rate (discharge) of all thermal water intakes (from 16 to 13.5 dm³/s) are the signs of emptying a water reservoir with a relatively small capacity but large permeability. In the rocks of Lądek-Śnieżnik crystalline massif, these can be zones with greater fissuring related to faults, or zones with weathering-related fissuring.

The other straight line, with a slight tilt, defined by a regression coefficient of 0.0001, characterizes a slow and gentle drop in the flow rate (discharge) of the studied intakes observed from April 1981 to 2004 (from day 1800 to day 10100) and related to the period of stabilizing the character of thermal water outflow. The calculated regression curve describing the model of emptying the very deep reservoir of Lądek-Zdrój fissure waters indicates that stabilization of the summative water discharge should occur at the value of 11 dm³/s, i.e. about (950 m³/d).

The calculated values of regression coefficients α and the corresponding flow rates (discharges) of intakes Q_o at the beginning of the regression period were used to calculate resource potential W defining the amount of water accumulated in the aquifer at the start of its emptying and stored above the drainage level. For the initial period of reservoir emptying, at α=0.0017 and q=12.5d m³/s, the calculated resource potential is 182 778 m³, and for the beginning of the slow discharge decline observed from 1981, at α=0.0001 and q=11 dm³/s, the resource potential is 1 741 528 m³ (Liber, 2009). At the start of the emptying process, the calculated aquifer capacity above the drainage level constitutes a small part (about a dozen ‰) of the total capacity of the whole thermal water reservoir in Lądek Zdrój, estimated with isotope research at about 1–1,6·10⁹ m³ (Zuber et al., 1995).

An important conclusion from the above model of emptying the thermal water reservoir in Lądek Zdrój is a strictly limited amount of thermal water flow rate (discharge) from one reservoir regardless of the number of intakes, as drilling another deep intake L-2 ultimately led to an increase in the mean summative flow rate (discharge) of all thermal water intakes by a mere 1.5 dm³/s, i.e. by about 16 %.

The current sum of total discharges of the studied intakes (in 2016) is about 904 m³/s and it is already smaller than the calculated value of long-term discharge (equal to the calculated basic inflow).

In spite of exceeding the long-term flow rate (discharge) estimated in 2009, drops in the discharges of particular Lądek intakes are now negligible (Fig. 5.7.1.8.3) and can be regarded as almost stable.

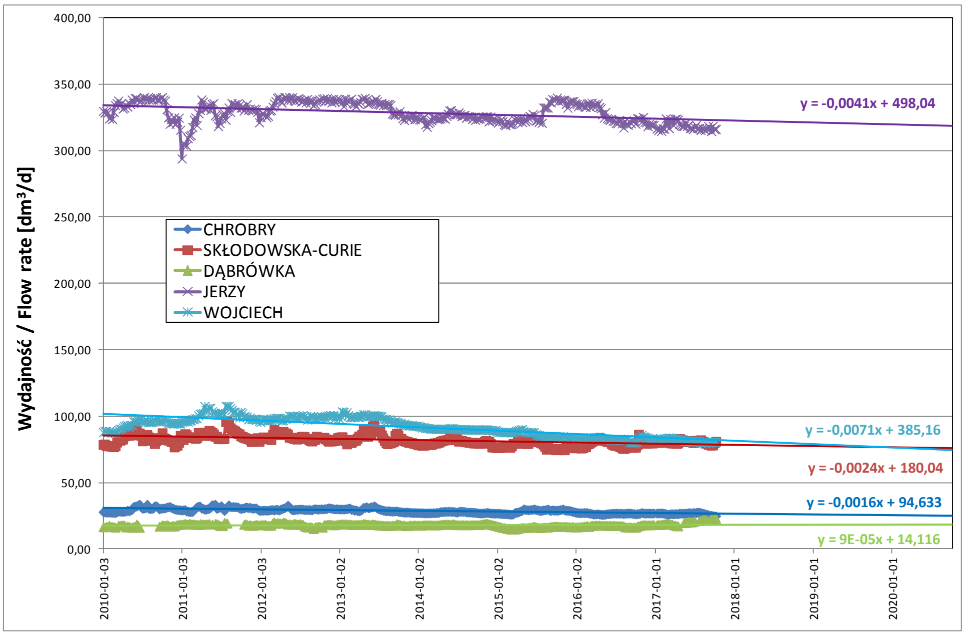


Fig. 5.7.1.8.3. Changes in the discharge of thermal water springs in Lądek-Zdrój in the last period of stable exploitation in 2010–2017

It could be even argued that a period of stabilized reservoir exploitation conditions has begun recently. These stable conditions can be disturbed by excessive extraction from borehole L-2 (when changing the technological conditions of water extraction or regulating outflow with a valve on the wellhead) or/and launching the operation of a new intake of thermal waters drawn from the same reservoir.
The hydrodynamical tests planned in the new borehole LZT-1, located close (c. 800 m) to the drainage zone of medicinal thermal water intakes, requires constant supervision and observation of changes in the flow rate (discharge), temperature and chemical composition of water in all the thermal water intakes exploited so far and in borehole L-1 extracting fresh water. Another issue concerning threats to the thermal water reservoir of Lądek-Zdrój is the appropriate protection of the whole reservoir encompassing the recharge, flow and drainage zones. Although the recharge area lies outside the mining area of Lądek-Zdrój thermal waters, it is a part of Śnieżnik Landscape Park protected area. Therefore it might be concluded that the reservoir is under appropriate protection now.

It is very likely that the newly planned borehole LZT-1 will be recharged with very deep circulation waters from the south-eastern direction, similar to that characteristic of medicinal thermal waters of Lądek-Zdrój, i.e. from the area of the Bialskie and the Golden Mountains.

5.7.1.9. Hydrochemical conditions

Lądek-Zdrój is one of the best known health resorts in Poland. Visitors have been coming here for medicinal purposes for centuries. According to Ciężkowski et al. (1996), the inflow of deep circulation waters occurs through deep tectonic zones whose strike is consistent with so-called Sudetic direction, i.e. NW-SE. In the areas of their intersection with secondary faults, artesian outflows of thermal waters occur.

One of the first detailed physico-chemical analyses of Lądek-Zdrój waters was carried out in the latter part of the 19th century. The next ones followed in the 1900s and in 1939. After World War II, analyses of Lądek waters, likewise those from other Lower Silesian resorts, were performed by the Balneotechnical and Microbiolgical Laboratory of the Design and Service Bureau of Resort Industry "Balneoprojekt" (Ciężkowski, 1978).

Based on the Geological and Mining Law (Dz.U. nr 196 z 2015 r.) and hydrochemical classification, the discussed waters can be categorized as HCO_3–SO_4–Na, F, Rn, S. However, one should note that periodically concentrations of sulphate ions in these waters are high enough to justify their designation as sulphate and siliceous waters (Tab. 5.7.1.9.1.). The total dissolved solids in the discussed waters range from 0.16 to 0.28 g/dm^3 (Fig. 5.7.1.9.1).

Table 5.7.1.9.1. Minimum and maximum contents of major ions and specific components expressed by the Kurłov formula (based on data 1970–2016)

Name of intake	Kurlov formula
Skłodowska-Curie	$F^{7-11}H_2SiO_3^{34-78}Rn^{8,1-12,8}H_2S^{0-2,6}M^{0,18-0,27}\frac{HCO_3^{28-83}SO_4^{18-36}}{Na^{82-91}}T^{22-26}$
Dąbrówka	$F^{5-11}H_2SiO_3^{36-58}Rn^{3,5-4,8}H_2S^{1-5,5}M^{0,17-0,25}\frac{HCO_3^{18-88}SO_4^{13-36}}{Na^{57-77}}T^{18-21}$
Jerzy	$F^{7-11}H_2SiO_3^{27-76}Rn^{29,1-362}H_2S^{1-2,8}M^{0,16-0,24}\frac{HCO_3^{23-53}SO_4^{8-24}}{Na^{78-98}Ca^{7-23}}T^{27-29}$
Chrobry	$F^{7-11,8}H_2SiO_3^{36-78}Rn^{3,4-8,8}H_2S^{0,3-3,7}M^{0,18-0,22}\frac{HCO_3^{21-64}SO_4^{11-28}}{Na^{87-92}}T^{22-27}$
Wojciech	$F^{5,5-12}H_2SiO_3^{37-78}Rn^{4,6-7,2}H_2S^{0,7-1,9}M^{0,18-0,27}\frac{HCO_3^{22-88}SO_4^{11-38}}{Na^{76-91}}T^{27,5-30}$
L-2	$F^{6,8-13}H_2SiO_3^{37-67}Rn^{2,9-4,9}H_2S^{2,6-5,1}M^{0,2-0,23}\frac{HCO_3^{17-100}SO_4^{12-23}}{Na^{82-91}}T^{41-44,7}$

anions, kations (% meq/L); F, H_2SiO_3, H_2S (mg/dm^3); Rn (nCi/L); M (g/dm^3); T (°C)

The highest value of this parameter is characteristic of waters from borehole L-2, followed by waters from springs Chrobry, Wojciech, Skłodowska-Curie, Dąbrówka and Jerzy (Tab. 5.7.1.9.1). One could observe a drop in TDS values in the exploited waters in the period from 2003 to 2009 (Fig. 5.7.1.9.1). The most likely reason for the observed changes was a variation in the inflow to the intakes of plain waters mixing through migration with waters of the deep circulation system. When studying Lądek waters in the 1970s and 1980s, W. Ciężkowski observed a drop in the concentrations of bicarbonates, sodium, fluorine and radon as a result of intensive exploitation of L-1 borehole (Ciężkowski, 1983). When analysing temporal variation in the concentration of HCO_3^- ions, one can observe that an increase in their number is accompanied by a decrease in the concentration of metasilicic acid in the discussed waters (Fig. 5.7.1.9.2).

Fig. 5.7.1.9.1. Variability of mineralization of thermal waters in Lądek-Zdrój

As mentioned above, the discussed waters are sulphide waters and the amount of H_2S dissolved in them varies from about 0.2 mg/dm³ (intakes Skłodowska-Curie and Chrobry) to the maximum of 5.1 mg/dm³ (borehole L-2). Waters from intake Skłodowska-Curie occasionally contain concentrations of this gas equal to or slightly higher than 1 mg/dm³. The dissolved H_2S content in waters form intakes Wojciech, Jerzy and Dąbrówka drops periodically even below the limit value for sulphide waters. Such a situation occurred in the 1970s and 1980s in intake Chrobry. In the 1990s, reduced H_2S concentrations were recorded in waters from all the mentioned intakes (Fig. 5.7.1.9.3).

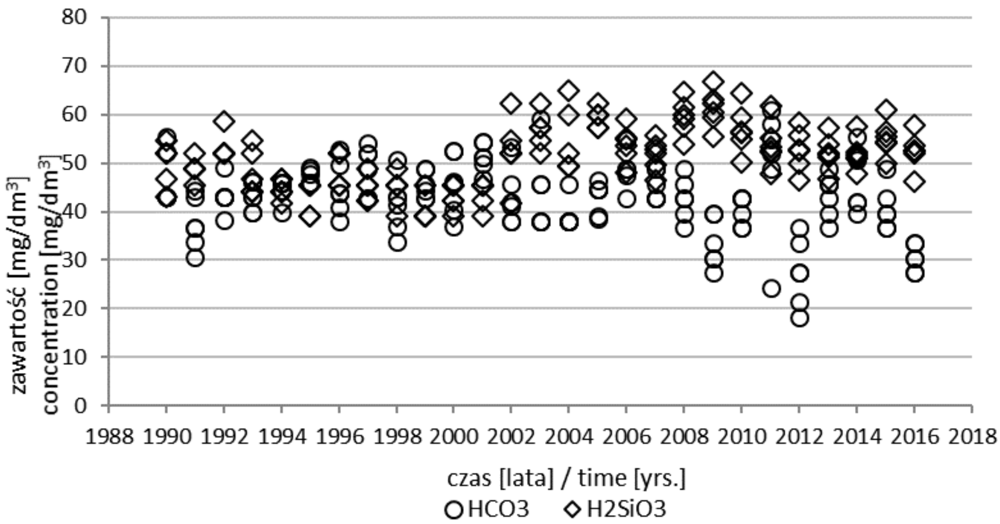


Fig. 5.7.1.9.2. Variability of HCO_3^- and metasilicic acid for Lądek-Zdroj healing waters

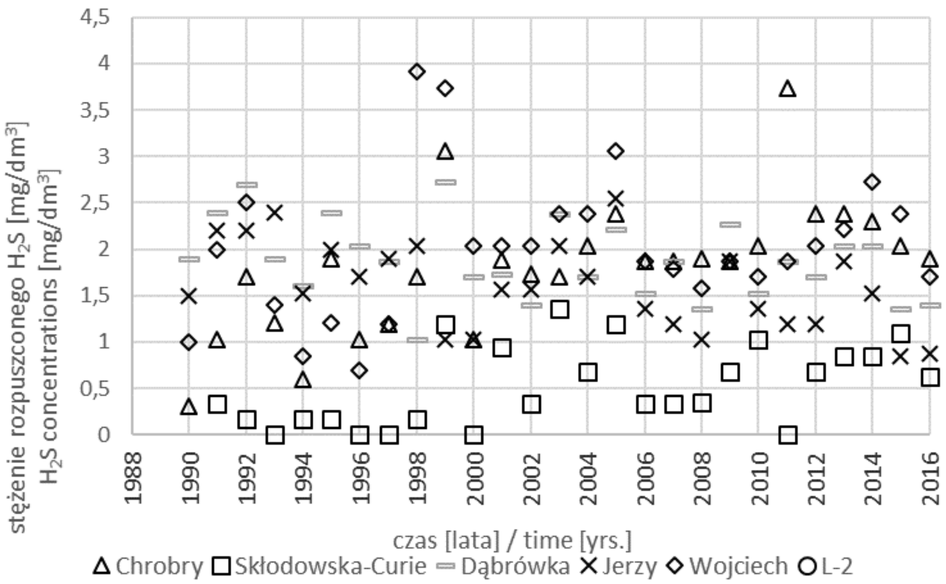


Fig. 5.7.1.9.3. Variability of dissolved H_2S

The analysed data were gathered from periodic measurements (conducted once a year), so it is difficult to assess the character of the observed changes (whether they occur temporarily, during the sampling, or if they are of long-standing character). Most likely, they are the result of changes in the dynamics of deep circulation water inflow.

While analysing the results of physico-chemical analyses of waters from particular intakes, one can observe large similarities in the proportions of major ions (Fig. 5.7.1.9.4).

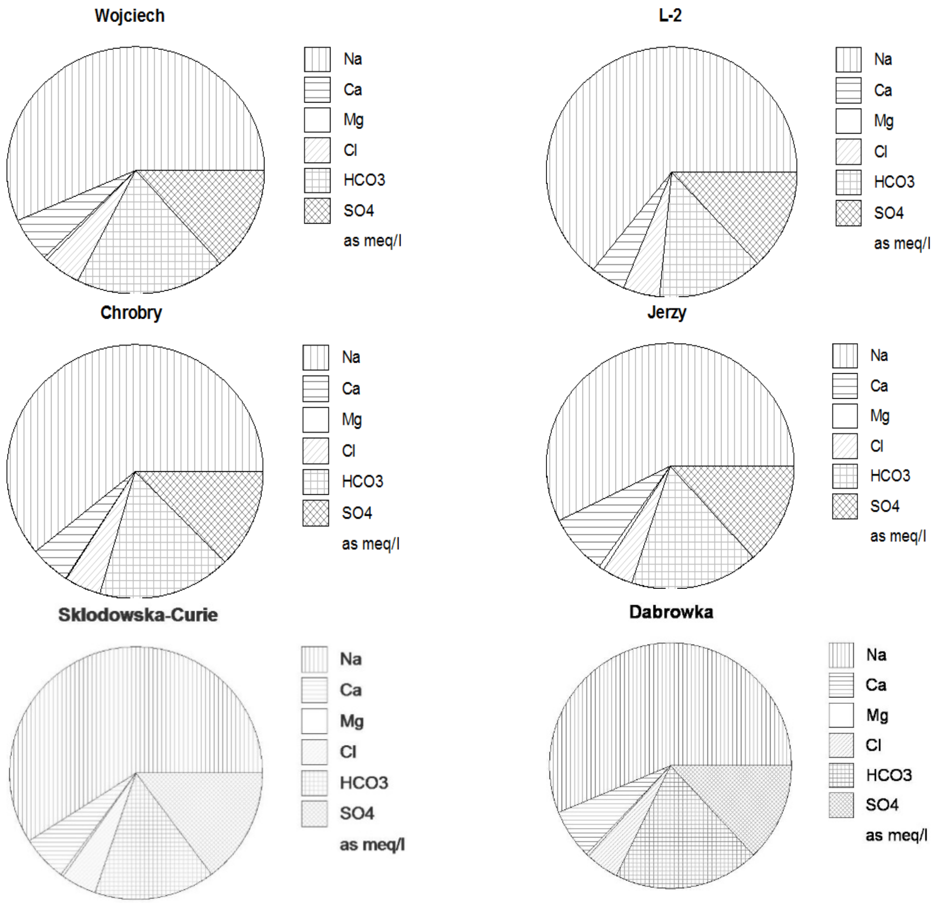
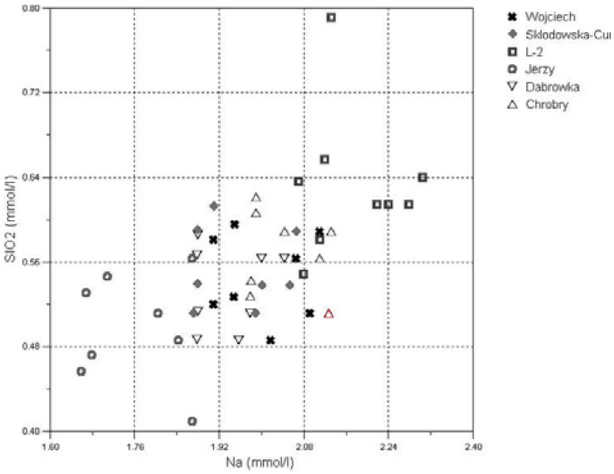
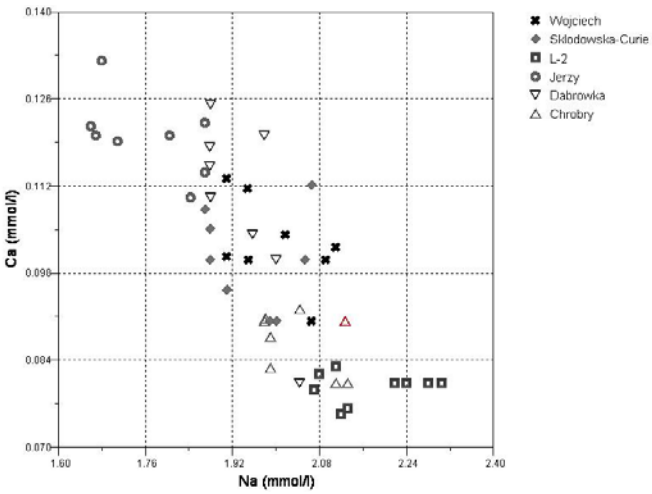


Fig. 5.7.1.9.4. Circle diagrams to display the participation of major ions (meq/l) in waters from particular intakes (based on 2016 data)

It has also been observed that a rise in the number of sodium ions is proportional to the rise in silica content (Fig. 5.7.1.9.5a). The inverse relationship takes place for sodium and calcium cations (Fig. 5.7.1.9.5b). A rise in the concentration of Na^{+} ions co-occurs with the reduction in the number of Ca^{+2} ions.



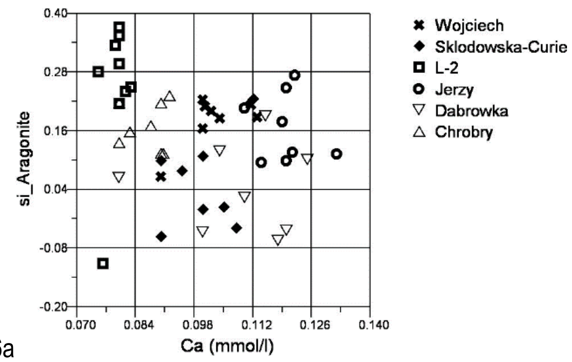
5a



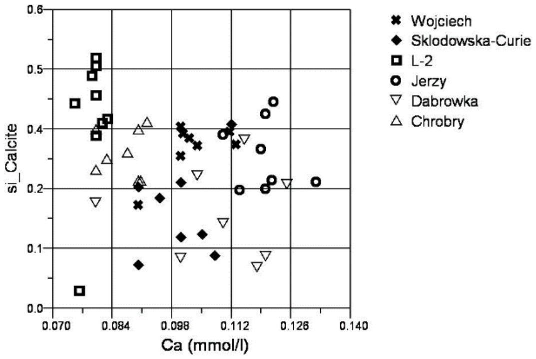
5b

Fig. 5.7.1.9.5. The relation between Na^{+} and silica (5a) and Na^{+} and Ca^{+2} (5b) concentrations for springs and well

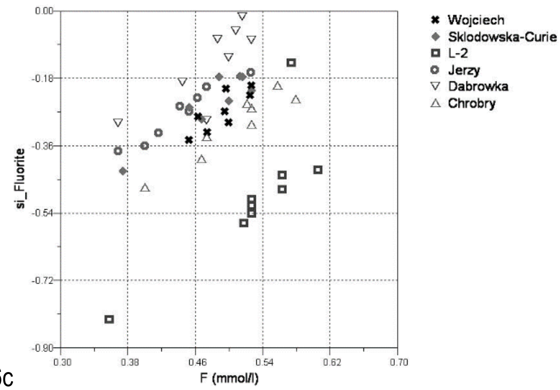
An attempt to define the group of processes determining the chemical composition of the discussed waters was first made by W. Ciężkowski (1978). The author pointed to weathering and hydrolysis of feldspars and to partial ion exchange as the principal processes shaping the chemistry of Lądek waters. The results of numerical modelling performed by Leśniak and Nowak (1993) and by Dobrzyński and Leśniak (2010) are generally consistent with Ciężkowski's hypotheses. The analysis of saturation indexes carried out as a part of the research revealed slight supersaturation or thermodynamic equilibrium with calcium carbonates (Fig. 5.7.1.9.6a, 5.7.1.9.6b), chalcedony quartzite and fluorite (Fig. 5.7.1.9.6c). Oversaturation is observed for hydrated magnesium silicate as well as iron oxides and hydroxides (Fig. 5.7.1.9.7).



6a



6b



6c

Fig. 5.7.1.9.6. Aragonite (6a), calcite (6b) and fluorite (6c) saturation indices as a function of total dissolved calcium and fluorine

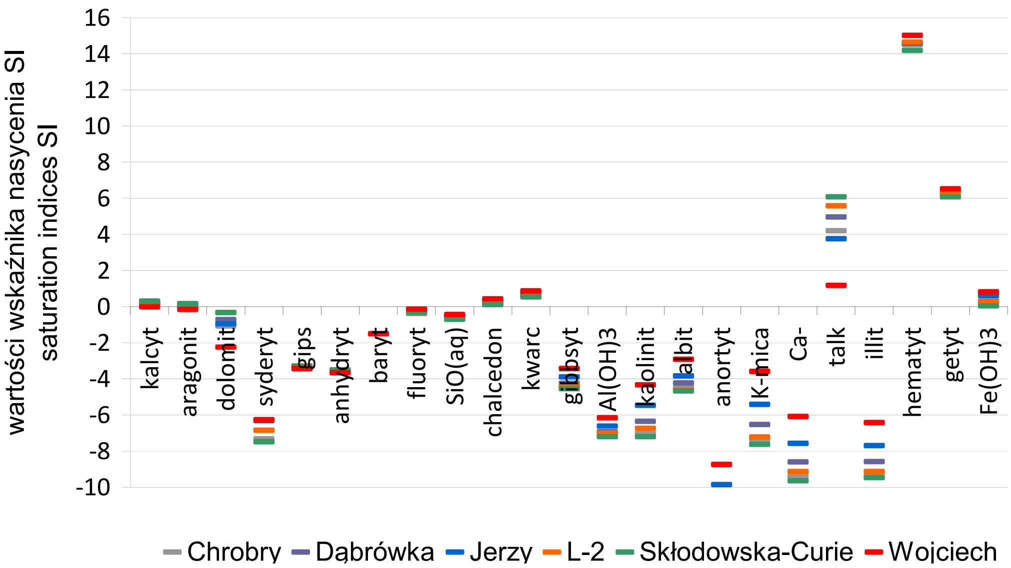


Fig. 5.7.1.9.7. Saturation indices for thermal waters of Lądek-Zdrój with respect to particular minerals (based on 2002–2015 data)

The results of the chemical analysis of the sample collected from geothermal well Zdzisław L-2 was used to calculate the *in situ* composition of deep aquifer at temperature of 43.9°C, and the saturation state of the fluid with respect to secondary minerals. The calculations were performed using the WATCH geochemical speciation code (Arnórsson et al., 1982; Bjarnason, 2010) and PHREEQC Version 3 geochemical computer code (Parkhurst and Appelo, 1999) and the standard phreeqc.dat database.

Table 5.7.1.9.2. The chemical composition of fluid from well L-2 in mg/L

Parameter	value
Temperature (°C)	43.9
pH/(°C)	9.5/20
CO_2	24
HCO_3-	33.6
H_2S	2.5
SiO_2	44.5
Na	48.3
K	0.77
Mg	0.18
Ca	3.13
NH_4^+	0.044
F	11
Cl	5.3
Br	0.04
I	<0.3
SO_4	20
NO_3	<0.02
NO_2	<0.02
Rn (Bq/l)	133
Al	0.021
As	n.a.
Ba	<0.003
B	0.04
Fe^{2+}	<0.02
Fe^{3+}	n.a.
Li	0.03
Mn	<0.003
Sr	0.031
TDS	206
Conductivity (mS/cm)/(°C)	0.235

The results of speciation calculations indicate that the water is only slightly undersaturated with respect to calcite at temperature of about 44°C but this undersaturation decreases with decreasing temperature (Fig. 5.7.1.9.8) and fluid becomes closer to equilibrium at 20°C with respect to this mineral. Although the calcite solubility increases with decreasing temperature (retrograde solubility), here the increasing pH with decreasing temperature dictates the saturation index evolution. Note the close correspondence between WATCH and PHREEQC models that supports the outcome of simulation.

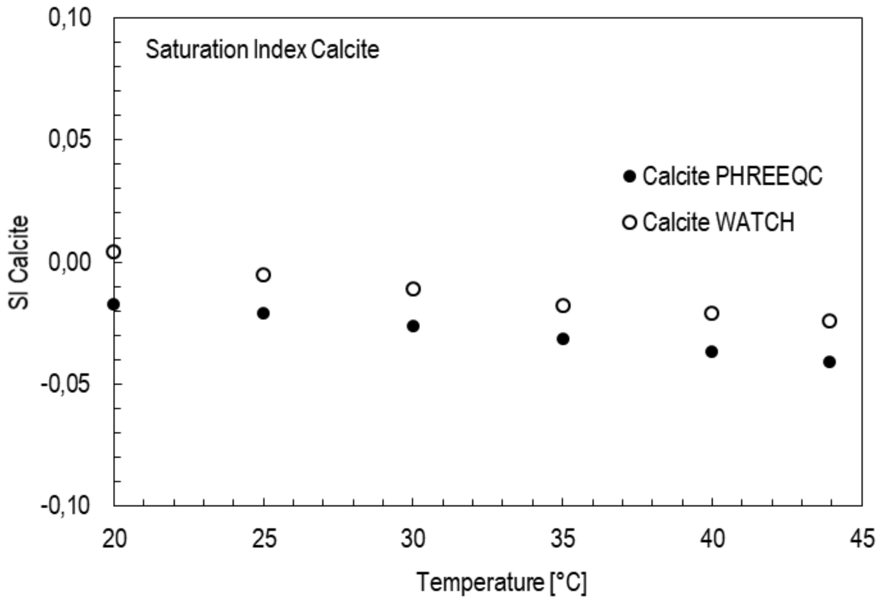


Fig. 5.7.1.9.8. The temperature dependence of the saturation state of the fluid with respect to calcite as calculated using WATCH and PHREEQC computer codes

The PHREEQC conductive cooling simulation reveals that saturation state of the fluid does not change substantially as the temperature decreases. At the deep fluid temperature of about 44°C the water is supersaturated with respect to several mineral phases such as quartz, chalcedony, clays here represented by talc and sepiolite (Mg-clay), chrysotile (Mg-phyllosilicate), and mackinavite (Fe-sulfide; fig. 5.7.1.9.7, 5.7.1.9.9). Although fluid is supersaturated with respect to quartz – its precipitation kinetics is very slow at low temperatures. The Mg-silicate scaling has been observed in several geothermal district heating systems in Iceland where heated fresh water after thermal deaeration reaches high pH and also when geothermal and fresh water are mixed (Gunnlaugsson et al., 2014). The L-2 water becomes supersaturated with respect to zeolites represented here by analcime at temperatures <40°C. The fluid is undersaturated with respect to other minerals such as Ca-montmorillonite, kaolinite, amorphous SiO_2, and gibbsite. To verify saturation state of sulphide minerals the concentration of Fe^{2+} used in the simulation was 0.02 mg/L which is the analytical quantification limit. The relatively high pH and presence of some dissolved Fe and H_2S indicates the potential of sulphides minerals scaling – however this type of scaling is not common in low salinity and low temperature geothermal waters. Low temperature and mineralization and high pH of the fluid indicates low risk of corrosion.

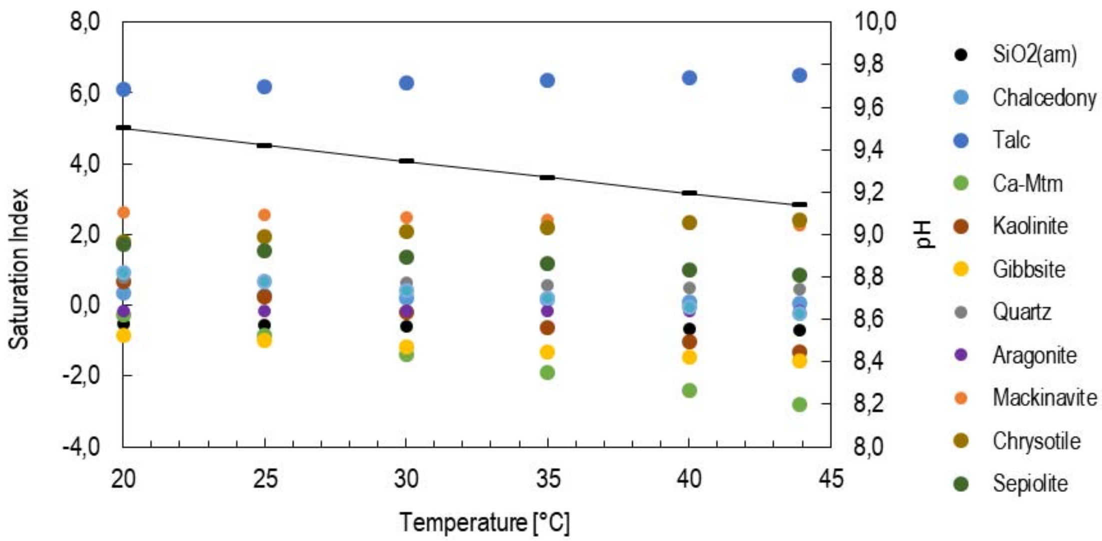


Fig. 5.7.1.9.9. The temperature dependence of the saturation state of the fluid with respect to selected mineral phases as calculated using PHREEQC computer code

The so called 'bubble point' calculations using WATCH reveals that degassing will proceed at pressures lower than 0.09 bars absolute. Because the partial pressure of CO_2 at all stages of cooling is lower than atmospheric it indicates no CO_2 diffusion from water at atmospheric conditions.

According to Zuber et al. (1995) and Ciężkowski et al. (1996), recharge areas of the medicinal water reservoir in Lądek-Zdrój, determined on the basis of isotope analyses, are situated in the Bialskie Mts south-east of the resort. These areas stretch in the elevation range from 700 to c. 1050 m a.s.l. Given the lithology of these areas and the results of chemical analyses of rock samples representing Lądek-Śnieżnik metamorphic complex, it can be concluded that, in all likelihood, the source of calcium ions in the discussed waters are pyroxenes, amphiboles and, to a lesser extent, plagioclases. The presence of sodium and potassium ions should be linked to the high proportion of microcline, orthoclase and sodium plagioclases (albite and oligoclase) in the mineral composition of the rock medium. Water enrichment in Na^+ ions and silica, resulting from the weathering of the mentioned aluminosilicates, is implied by the mutual quantitative ratios of these components (Fig. 5.7.1.9.5a). The development of calcium and sodium ion exchange processes suggested by Ciężkowski (1978) can be indicated by inverse relationship between the concentrations of these cations (Fig. 5.7.1.9.5b). Owing to secondary calcite crystallization, contributing to depletion of calcium ions from waters, the observed ratios could become more pronounced. Minerals such as plagioclases, potassium-magnesium micas, amphiboles and hydrated magnesium silicates are dissolved and equilibrium with carbonates, fluorite and silica (chalcedone) is observed. Oversaturation of waters with magnesium silicates is, in all likelihood, the result of the weathering of the abovementioned pyroxenes, amphiboles and olivines building basalt rocks.

Based on the results of studies of sulphur isotopes ^{34}S, Ciężkowski (1978) argues that decomposition of sulphides, in which in the Lądek-Śnieżnik metamorphic series abound, leads to enriching the discussed waters in hydrogen sulphide. This was confirmed by the observations by Gierwielaniec and Szarszewska (1978).

Ciężkowski (1980) distinguished several hydrochemical types among shallow and deep circulation fissure waters. Of these, the most represented are waters The hydrochemical background is formed by waters type SO_4-HCO_3-Ca-Na, while type HCO_3-Na, F is characteristic of thermal waters. The latter, while flowing through fissure and fracture zones, give rise to hydrochemical anomaly in close proximity to their outflows (Fig. 5.7.1.9.10).

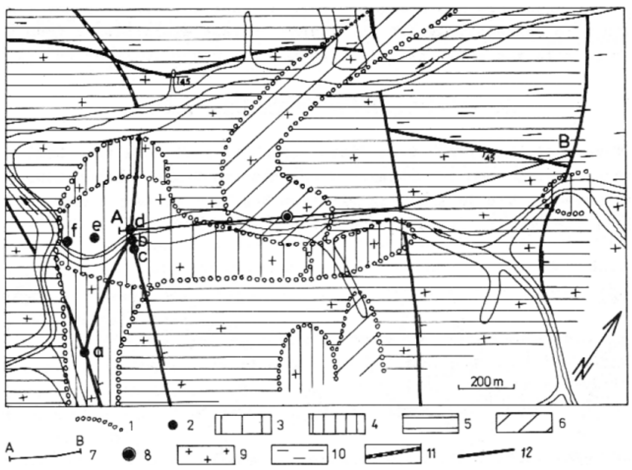


Fig. 5.7.1.9.10. Hydrochemical types of ground waters in Lądek-Zdrój area (after Ciężkowski, 1979)
Explanations: 1 - boundaries of the water types; water types: 2 – $C(F)^{Na}{}_{I}$, springs: a – Jerzy, b – Skłodowska-Curie, c – Wojciech, d – Chrobry, e – Dąbrówka, F – Stare; 3 – $C(S)^{Na}{}_{I}$; 4 – $C(S)^{Na(Ca)}{}_{I,\ II}$; 5 – $S^{Ca}{}_{I,\ II}$; 6 – $C^{Ca}{}_{I,\ II}$; 7 – hydrochemical cross-section; 8 – deep borehole L-2; 9 – gneisses; 10 – mica schists; 11 – lamprophyres; 12 – faults

The findings concerning the chemical composition of thermal waters from springs and deep boreholes L-1 and L-2 have been used to draw a diagram showing vertical zonation of particular water types. Waters in the near-surface zones, lowest in TDS, represent type HCO_3-SO_4-Ca-Na. When infiltrating deeper, due to reactions with the rock medium and inflowing deep circulation waters, the cation composition becomes dominated by sodium ions and the TDS increase. As mentioned before, deep circulation waters represent type HCO_3-Na, F (Fig. 5.7.1.9.11).

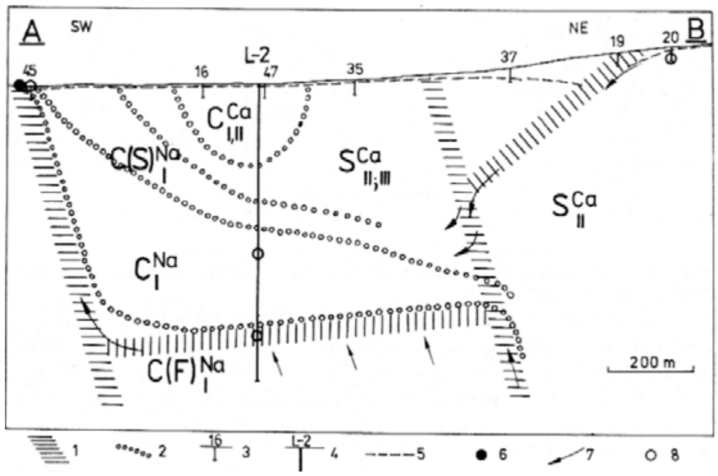


Fig. 5.7.1.9.11. Diagram of vertical variability of chemical types of groundwaters in Lądek-Zdrój area (Ciężkowski, 1979). Explanations: 1 – fault zones, 2 – boundaries of the water type, 3 – shallow boreholes and its numbers, 4 – deep borehole L-2, 5 – fissure water table, 6 – thermal waters springs, 7 – directions of water migration, 8 – depth of water sampling

Fluorine

Fluorine is a pharmacodynamic microelement and water containing no less than 2 mg of fluoride ions per litre is classified by the Geological and Mining Law as medicinal water (Journal of Laws No. 163, Item 981 dated 2011).

Generally speaking, the principal source minerals of fluoride ions in groundwaters are fluorite (CaF_2), fluorapatite ($Ca_5(Cl,F,OH)(PO_4)$) and cryolite (Na_3AlF_6). Other potentially fluorine-bearing minerals include amphiboles (hornblende and tremolite), micas (biotite, phlogopite and muscovite), tourmalines and topaz. It can be explained by the fact that the sizes of the ionic radii of the OH^- group and the F^- ion are comparable, so they can replace each other in the structures of the above minerals (Edmundson & Smedley, 2005).

Fluorine ion concentrations in waters from Lądek reservoir fall within the range from about 7 to about 13 mg/dm^3 at the most. According to Ciężkowski (1978, 1980), the hydrochemical background of F^- in shallow fissure waters and springs on the southern slopes of Śnieżnik does not exceed 0.5 mg/dm^3. Based on observations of waters from boreholes L-1 and L-2, he also noted that concentrations of this element rise with the depth at which water is drawn.

The long-time of being confined to a rock medium and a considerable depth of water circulation system can be inferred from a positive correlation between F^- ion content and water temperature (Chae et al., 2007). In the case of the discussed reservoir, one cannot definitively claim such a correlation (Fig. 5.7.1.9.12). This is confirmed by the results of research into stable isotopes of oxygen and hydrogen.

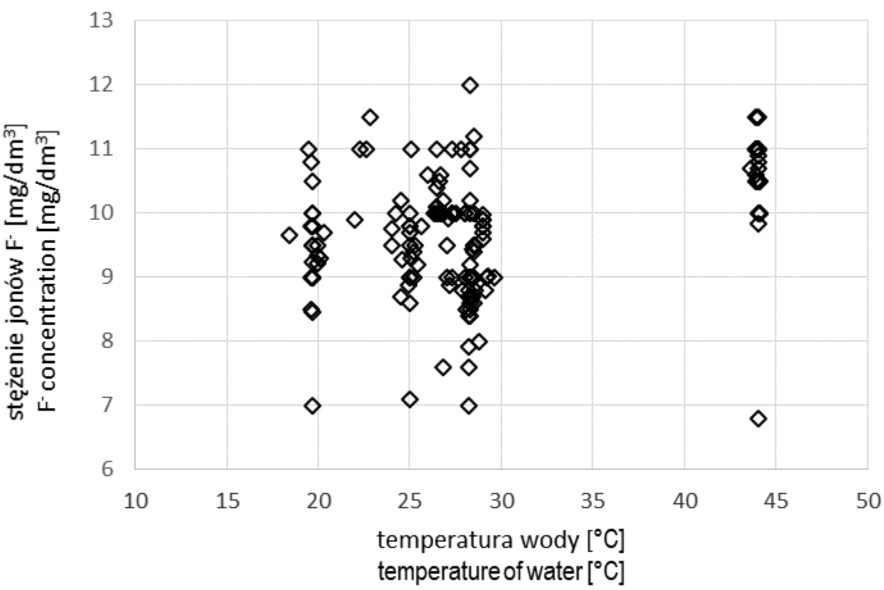


Fig. 5.7.1.9.12. Variation of F^- concentrations depending on water temperature

The correlation between the proportions of F^- and Ca^{+2} ions (Fig. 5.7.1.9.13) does not seem to point to fluorite as the source of their origin in the studied waters. The dissolution rate of this mineral depends on the concentration of Ca^{2+} ion content and a rise in this value can cause precipitation of secondary calcite. As the studied waters demonstrate a thermodynamic equilibrium with fluorite, the same amounts of this mineral can be dissolved and undergo secondary crystallization. On the other hand, dissolved silicates and aluminosilicates supply water with major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}), which enables the precipitation of secondary calcite, leading, in turn, to more intensive dissolution of fluorite.

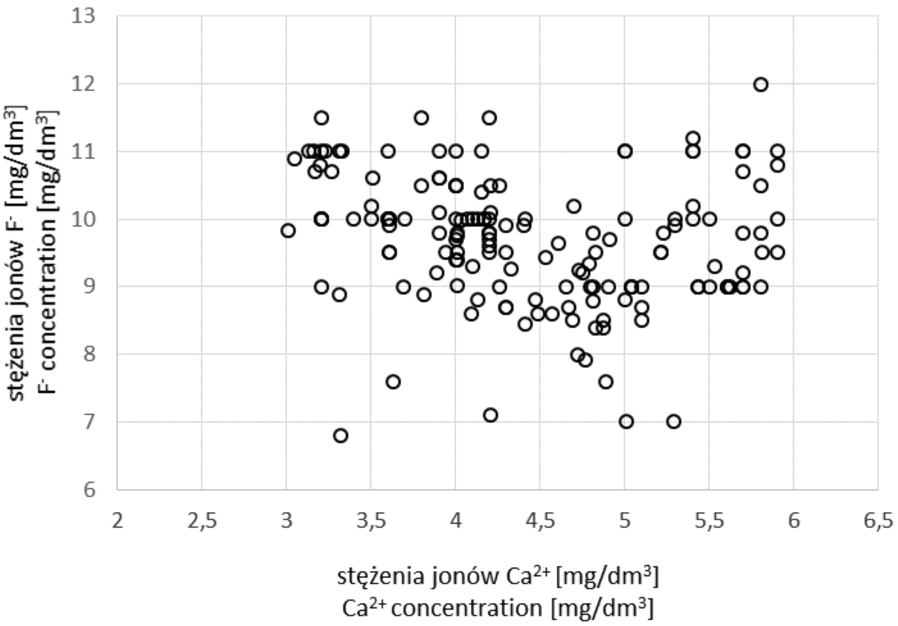
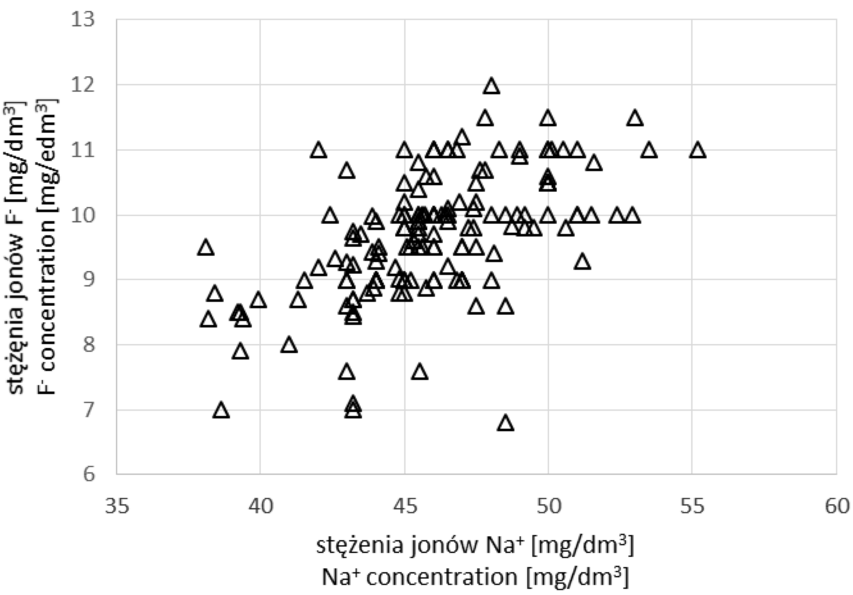


Fig. 5.7.1.9.13. Concentrations of F^- versus Ca^{2+} concentrations

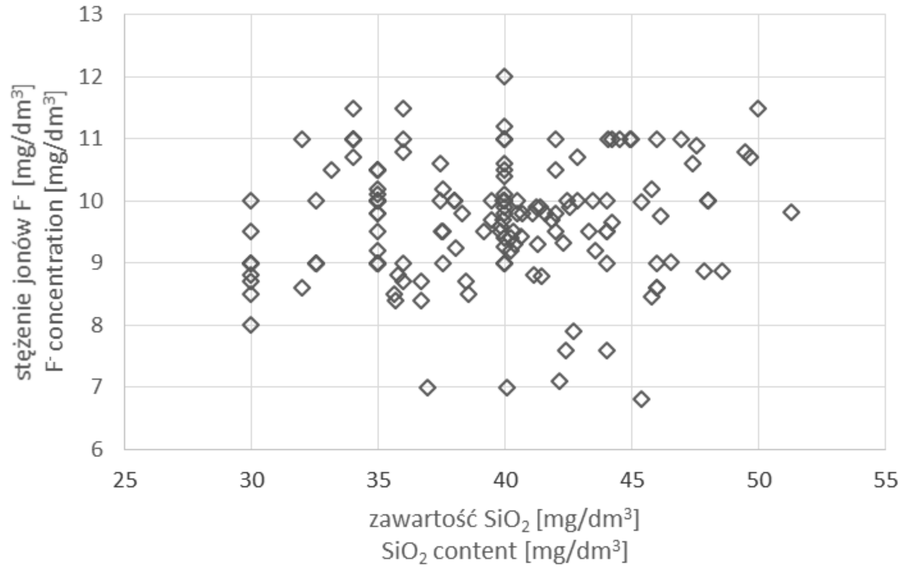
It must be noted, however, that fluorite has lower solubility ($K = 10^{-10,57}$), so no secondary calcite precipitation ($K=10^{-8,48}$) is possible until secondary fluorite appears (Appelo and Postma, 2007).

Additional calcium ions can be supplied by dissolved hornblende, apatite and plagioclases.

Although the discussed waters exhibit an equilibrium with fluorite, the correlation between the proportions of F^- ions, sodium ions (Na^+) (Fig. 5.7.1.9.14a) and dissolved silica (SiO_2) (Fig. 5.7.1.9.14b) points to silicate and/or aluminosilicate minerals as other possible sources of fluorine.



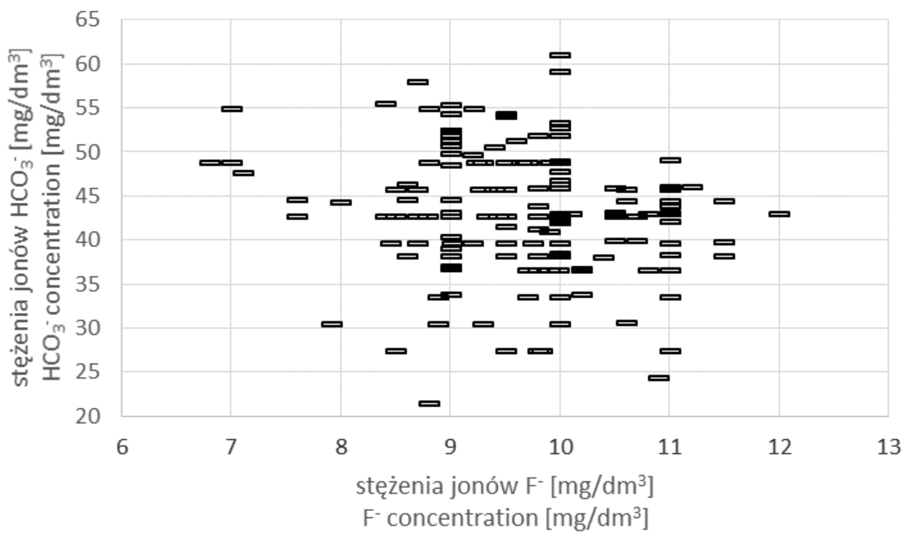
a



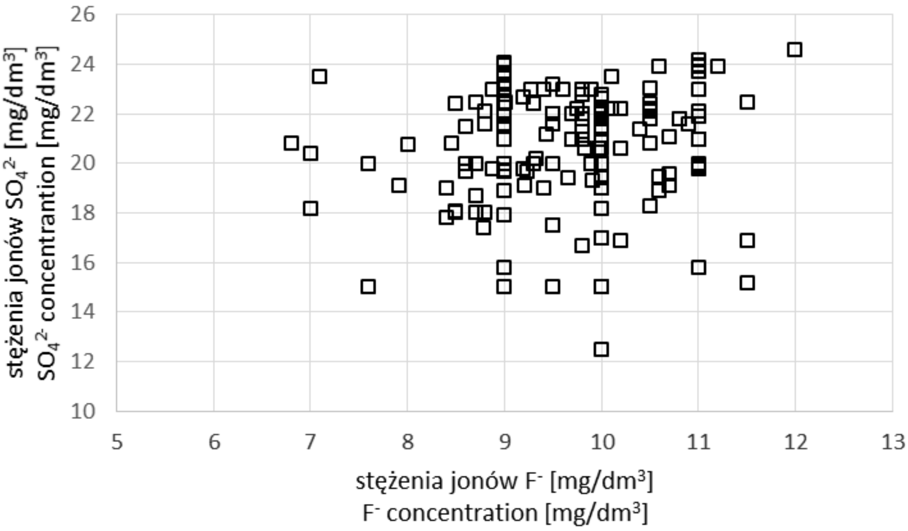
b

Fig. 5.7.1.9.14. Variation of F^- concentrations versus: a - Na^+, b – SiO_2 concentrations

It should be assumed, however, that these are micas (biotite, muscovite and lepidolite), hornblende and, secondarily, apatite – the minerals building mica and amphibolite schists as well as amphibolites (Polański, Smulikowski, 1969) that supply waters with this element. On the other hand, negative correlation between the concentrations of fluoride ions and bicarbonate ions (HCO_3^-) (Fig. 5.7.1.9.15a) implies a rather limited role of aluminosilicates as fluorine-bearing minerals (Chae et al., 2006; Jagadeshan et al., 2015).



a



b

Fig. 5.7.1.9.15. Concentrations of F^- versus: a - HCO_3^- and b - SO_4^{2-}

The correlation between the concentrations of sulphate (SO_4^{-2}) (Fig. 5.7.1.9.15b) and fluoride ions can indicate their relationship with the oxidation of sulphide minerals, which can, in turn, suggest the co-occurrence of fluorine and sulphide mineralization. Similar relationships were observed by Mroczkowska (1978), who analysed the occurrence of fluorine in waters in the area of Cieplice. It should be noted here that hydrothermal sulphide mineralization occurs within Lądek-Śnieżnik metamorphic complex both in dispersed form and in the form of deposits (Ciężkowski, 1978).

Gierwielaniec (1968b) suggested the origin of fluoride ions from the weathering of fluorite. However, the occurrence of this mineral is limited to the area of Kletno overthrust south of Lądek-Zdrój. Also, the origin of these ions as the product of apatite weathering seems unlikely due to the negligible occurrences of this mineral within gneiss series. Hence, it seems the most likely that the enrichment of Lądek waters in fluoride ions is the result of the weathering of micas and amphiboles being the main rock-forming minerals in Lądek-Śnieżnik metamorphic series.

Radon

The radioactive properties of waters from Lądek-Zdrój springs have been known since the early 20th century (1904). They result from the presence of radon (^{222}Rn) dissolved in these waters (Przylibski, 2005). Within the metamorphic series in the area of Lądek-Zdrój, values of local radon background determined from measurements performed on about 650 samples of plain groundwaters fall within the range between 0 and 92.5 Bq/L (2.5 nCi/L) at the most. A high emanation anomaly (of up to c. 25 nCi/L) was identified by Ciężkowski (1990) north of the town, in the zone of intensive tectonic involvement. Generally, the location of water outflows with increased radon concentrations (above 2 nCi/L) are consistent with the pattern of discontinuity zones. At the same time, the author observed that waters extracted from larger depths (600-700 m in intakes L-1 and L-2) are characterized by smaller radon concentrations (up to c. 4.9 nCi/L) compared to waters flowing from springs (even up to 41.6 nCi/L).

Przylibski (2005) observed that mean concentrations of ^{222}Rn are higher than 100 Bq/L (2.7 nCi/L), although the concentrations of the discussed gas in Jerzy intake are higher than 1000 Bq/L (27 nCi/L). Moreover, while analysing long-standing measurement results, he did not observe any trends concerning variation of radon concentrations in time. The distribution of concentration values of the discussed gas, characterised by slight skewness, is a sign of small variations in radon concentration rather than of inflow of waters from other recharge systems (mixing). These observations are consistent with the hypothesis of Zuber et al. (1995) about slight (up to 20-25%) mixing of waters from Lądek reservoir with those from shallow circulation systems.

Generally speaking, the amount of radon dissolved in these waters decreases with the depth of the extracted water level (Ciężkowski, 1980, 1990; Przylibski, 2005). Undoubtedly, the size of ^{222}Rn concentrations in waters is affected by the location of an intake (borehole or spring) in the fault zone or a tectonically involved zone, as it is in such areas where, due to the loosening of the rock medium, the likelihood of gas emanations increases (Ciężkowski, 1990; Przylibski, 2005). As Przylibski (2005) reports, there is no relationship between the amount of dissolved radon and weather conditions.

Geothermometers

Using several chemical geothermometres (quartz, chalcedony and Mg-Li) and isotope equilibriums of oxygen in SO_4-H_2O system, Porowski (2008) estimated the probable water temperatures for all Lądek-Zdrój intakes to range from ca. 30°C to ca. 91°C. However, since the examined waters contain H_2S originating from bacterial reduction processes, the use of an oxygen geothermometre in a SO_4-H_2O system produces unreliable results (Porowski and Dowgiałło, 2009). The two scholars corrected the temperature range of Lądek waters to about 48°C – about 57°C. While analysing variations in saturation indices relative to temperature changes, Dobrzyński and Leśniak (2010) determined the temperatures for the Lądek reservoir to be 80±5°C (Fig. 5.7.1.9.16).

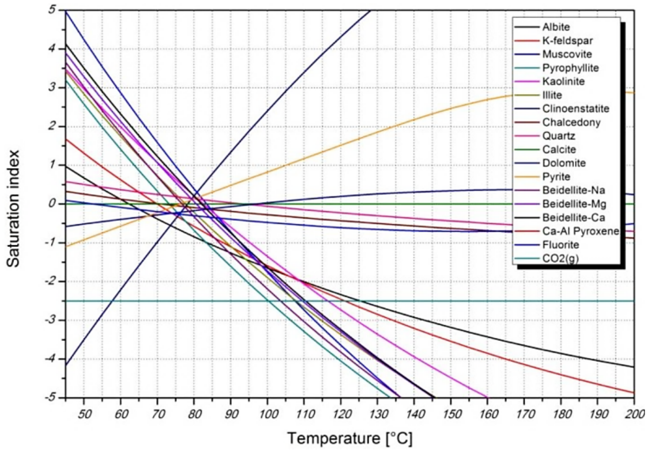


Fig. 5.7.1.9.16. Relationship between saturation indices (for main rock-forming minerals in Lądek-Śnieżnik methamorphic series) and the temperature of thermal water from L-2 intake in Lądek-Zdrój (Dobrzyński, Leśniak, 2010)

It should be noted that the most likely results obtained with chemical geothermometres are those for waters in the state of thermodynamic equilibrium with rock medium. The Lądek waters are characterised by undersaturation in relation to almost all rock-forming minerals of the rock medium through which these waters flow. Hence, when using geothermometres for waters exhibiting even partial equilibrium, one should be very cautious while drawing research conclusions (Dowgiałło, 2007; Leśniak and Nowak, 1993).

ISOTOPES

The composition of stable oxygen and hydrogen isotopes in groundwaters can point to the genesis of these waters on the one hand and provide information about the processes occurring along their flow path on the other. These issues were widely discussed in papers by Zuber et al. (2007) and other authors. The origin of these waters is significant for the adopted method of intake exploitation and protection of water reserves.

Interesting information of this kind includes facts about thermal waters flowing out of the Sudetic crystalline massif.

Table 5.7.1.9.3 presents the results of all isotope composition analyses of the discussed thermal waters of Lądek-Zdrój against the background of the other thermal water reservoirs identified in the Sudetes. Fig. 5.7.1.9.17 presents averaged results for particular water intakes plotted against the so-called global meteoric water line and local lines defined for the Sudetes, which provide separate characteristics of fresh groundwaters and carbonated waters.

The graph shows Lądek waters, originating in the early Holocene (Zuber et al., 1995; et al.), in the area between the World Meteoric Water Line and the local line for fresh Sudetic waters. Spreading the results along the δ^2H axis may suggest an influence of isotopic exchange between hydrogen atoms in water and in hydrogen sulphide occurring in Lądek waters. This issue requires further detailed investigations.

The studied ratios of isotopes $\delta^{34}S$ and $\delta^{18}O$ in sulphides point to the origin of SO_4^{2-} as a product of bacterial reduction activity. This hypothesis is confirmed by the presence of H_2S dissolved in these waters (Dowgiałło et al., 2005). The main mass of SO_4^{2-} ions found in the discussed waters is the product of sulphide oxidation (Dowgiałło, 1976).

Table 5.7.1.9.3. Results of isotopic studies of thermal waters in Lądek-Zdrój (after Ciężkowski et al., 1996)

Name of intake	$\delta^{18}O$ ‰	$\delta^{18}O_{avg}$ ‰	δD ‰	δD_{avg} ‰	Tritium TU	^{14}C pmc	$\delta^{13}C$ ‰	age thous. years
L-2	-10.52 ± 0.22	-10.52	-72.9 ± 1.7	-73.5	0.0 ± 0.5	17.8 ± 1.0	-15.0 -13.2	8.9
Chrobry	-10.56 ± 0.14		-74.4 ± 1.7		4 ± 3 0.0 ± 0.5	16 ± 5 26.6 ± 1.7	-9.8 -13.9	6.0
Wojciech	-10.44 ± 0.12		-72.4 ± 0.2		1 ± 3	24 ±8		
Skłodowska-Curie	-10.58 ± 0.10		-73.6 ± 1.0		1 ± 3	32 ± 25	-12.8	
Dąbrówka	-10.52 ± 0.14		-74.2 ± 1.1		3 ± 3 0.3 ± 0.5 0.4 ± 0.5	20 ± 6 27.7 ± 1.5	-16.2 -14.3	6.5
Jerzy	-10.50 ± 0.16		-73.7 ± 1.4		3 ± 3 0.7 ±0.5 0.3 ± 0.5	32 ± 7 34.9 ± 1.8	-15.0 -15.0	4.5

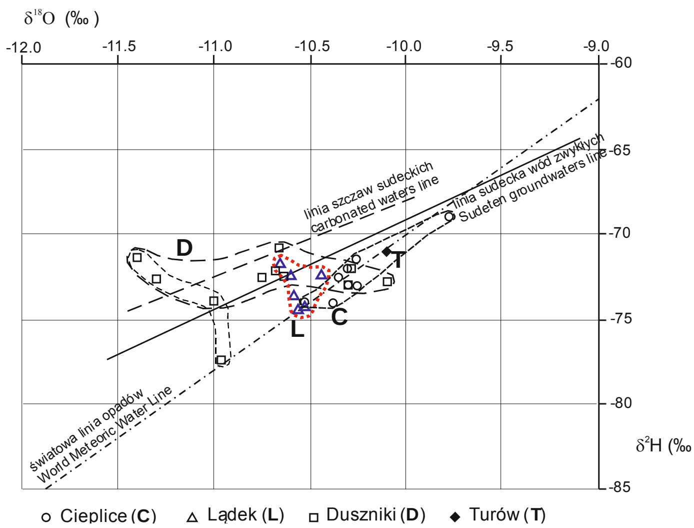


Fig. 5.7.1.9.17. Research results on the isotopic composition of Sudetic thermal waters. The lines of Sudetic carbonated waters and of plain waters by Ciężkowski (1990). The points mark medium isotopic composition for individual intakes

Recharge areas

The calculated location of probable recharge areas of Lądek thermal waters encompasses areas in the elevation range between 700 and 1000 m above sea level (Zuber et al., 1995; Ciężkowski et al., 1996). The morphology of the surroundings of Lądek-Zdrój and the significance of tectonic zones were taken into account. The spread of tectonic elements of Lądek-Śnieżnik unit and the strike of principal faults (mainly with NW-SE orientation) point to areas SE of the resort, on the peaks of the Bialskie Mountains above 700 m a.s.l. (Fig. 5.7.1.9.18) as the most likely recharge zones. Other directions of meteoric water inflow to intakes are considered to be less plausible, as they would be inconsistent with the strike of major dislocation zones conveying thermal waters to intakes. Recharge from the north-west, i.e. from the Golden Mountains, proposed by Dowgiałło (1976), is rather unlikely as the surface active/available for recharging the reservoir, lying at the elevation of more than 700 m a.s.l., is too small to be able to recharge the whole thermal water basin. On the other hand, inflows from areas lying south of the resort, i.e. from Śnieżnik massif, although satisfying the elevation criterion, also seem to be unlikely, as underground runoff from this massif is directed southward, towards the catchment of the river Morava in the Czech Republic.

Dowgiałło (1976) proposed the hypothesis of thermal water inflow to Lądek intakes from the NE while analysing the negative effect of L-2 exploitation (located to the NE from the springs) on the size of spring discharge and the absence of thermal waters in L-1 borehole located in the southern part of the resort.
Thus characterised recharge areas are located wholly within Śnieżnik Landscape Park. Moreover, they extend into Śnieżna Białka Forest – a forest-type nature reserve (Ciężkowski et al., 1996).
The results of research into stable oxygen and hydrogen isotopes in waters from particular intakes reveal their meteoric origin (Zuber et al., 1995; Dowgiałło, 1978; Porowski and Dowgiałło, 2009; Ciężkowski et al., 1996) Their high temperature is the result of deep infiltration, while deep circulation is possible thanks to systems of passable fault zones and fissures (Porowski and Dowgiałło, 2009).

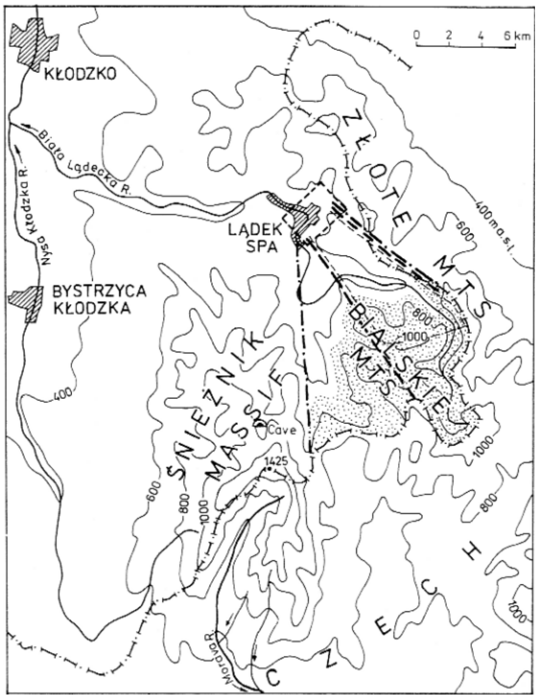


Fig. 5.7.1.9.18. Morphology of the eastern part of the Kłodzko Land with recharge areas (dotted) of thermal waters (Zuber et al., 1995)

Mixing
One method enabling the calculation of the percentage of modern infiltration waters in the analysed waters (e.g. thermal waters) is the determination of the amount of unstable hydrogen isotope – tritium (T) in these waters. The amount of this isotope is expressed in tritium units (TU). Zuber et al. (1995), Ciężkowski et al. (1996) and Dowgiałło claim that thermal waters of Lądek-Zdrój do not contain the amounts of tritium that would be indicative of the inflow of modern waters. These are Holocene waters. The observed slight changes in TDS values are the consequence of varying velocities of waters migrating inside the orogen. This, in turn, stems from the transport of these waters along paths with different flow time and at different depths. As a result, the duration and the extent of the interaction of these waters with rock medium varies, which results in the varying level of mineralisation and varied temperature of these waters. However, while analysing the variation of sodium (Na^+) and fluoride (F^-) ion content, Zuber et al. (1995) proposed that the mixing of waters from Lądek reservoir with waters with lower temperatures and mineralisation does not exceed 25%.

5.7.1.10. Current management of the geothermal reservoir

Thermal waters extracted in Lądek-Zdrój are currently used only for balneotherapeutic purposes. The treatments offered in Lądek-Długopole resort include bathing, peloid and thermal therapy, massages, showers, inhalations, light therapy, electrotherapy, kinesiotherapy, cryotherapy and water drinking treatment. These treatments require the usage of natural materials like medicinal waters and peloids. Thermal waters of Lądek-Zdrój are bacteria-free, so using them for bathing in pools or bathtubs and for drinking therapy does not require additional processing or treatment (Ciężkowski et al., 2011c, 2016).

The resort has a specific system of extraction and distribution of medicinal water to particular natural treatment centres and treatment sites. Water from intakes is distributed gravitationally and the system of intakes, tanks, their overflow channels and pipelines, which has been developed for centuries, enables almost full utilization of the total discharge of intakes. The water used for treatments is both water continuously extracted from flowing wells and that drawn from reservoirs, gathered in the afternoon and at night. All the reservoirs form a system of connected vessels, which enables daily filling of therapeutic pools and then replenishing them with fresh water as well as using medicinal waters for all types of bathtub treatments.
The water used for treatments is mostly the warmest water from borehole L-2, supplemented with cooler water from springs Jerzy, Wojciech or Skłodowska-Curie.

There are four natural treatment centres in Lądek-Zdrój. The biggest and the oldest one is the Natural Treatment Centre "Jerzy" built in 1498 directly above the spring with the same name. The Centre has a bathing pool and a radon emanation hall. In the early 20th century part of "Jerzy" Centre (so-called "New Jerzy") there is also a chain of bathtubs for therapeutic baths and underwater massages.
After an extensive renovation, the Natural Treatment Centre "Wojciech" is a gem of Polish health resorts. Built in 1678 over a medicinal water spring, it was modelled on a Turkish bath. It has a beautiful round thermal pool and 25 historical marble bathtubs from 1882, where patients are administered sulphide-fluoride and bubble baths (Fig. 5.7.1.10.1). In the Natural Treatment Centre "Adam", there is another pool with sulphide-fluoride water.
Used medicinal waters and waste peloid, after being exploited in natural treatment centres, are discharged as waste to the municipal sewage system.

Crenotherapy (drinking therapy) is a method supplementing the treatment of most illnesses in Lądek-Zdrój. A beautiful mineral water drinking hall is a part of the Natural Treatment Centre "Wojciech". Additionally, "Jerzy" Centre has a radon water drinking room. In the spa park, there are publicly accessible wells with sulphide-fluoride thermal waters – Chrobry and Dąbrówka (Ciężkowski et al., 2011c, 2016).
Due to medicinal properties, thermal sulphide-fluoride-radon waters of Lądek-Zdrój are used for curing numerous illnesses.

Fig. 5.7.1.10.1. The thermal water drinking room in Natural Treatment Centre „Wojciech"
(source: private collection of Z. Pilip, available at http://fotopano.pl)

The chief indications for treatment in Lądek are orthopaedic diseases, osteoporosis, rheumatic and orthopaedic-traumatic disorders, neurological diseases, skin diseases, endocrinological disorders, upper respiratory tract diseases and peripheral artery disease.

5.7.1.11. Plans for thermal water management

Lądek-Zdrój is one of the oldest health resorts in Poland. Considering the centuries-long tradition of health resort activity, it is particularly vital to preserve the therapeutic values of its thermal waters and to protect the cultural heritage of the town.
The specific character of the hydrotherapeutic activity of the resort, entailing large demand for water and heat, has provided an impulse for the local council to take steps aimed at broader and more detailed recognition of the thermal water reservoir in this region. In 2016, Lądek-Zdrój commune commissioned a prospection design aimed at searching for thermal waters in deeper parts of the Lądek-Śnieżnik metamorphic complex by drilling an exploratory hole with the planned depth of 2,500 m (Ciężkowski et al., 2016). Obtaining the expected water parameters from the designed borehole LZT-1 will enable sustained and multi-purpose exploitation of the Lądek reservoir. The estimated parameters will be able to satisfy most (probably about 65%) of the town's overall demand for thermal energy. It is estimated that geothermal waters will make it possible to launch a heat plant producing about 2 MW of energy, which is about 1/5 of the town's demand (converted to heat plant power). In order to fully satisfy the demand for useful heat in the winter season, plans are being developed to build a heat pump installation also using geothermal waters. Obtaining higher than estimated water parameters will enable managing its energy in a cascade system:

– Supplying heat and domestic hot water to individual (residents) and commercial (hotels, resort facilities, etc.) customers.,
– Balneotherapy and recreation,
– Agriculture (greenhouses for ecological food production) and industry,
– municipal engineering – maintenance of roads in the winter season

which will ensure optimal and effective energy management.

These actions will beyond doubt contribute to effective exploitation of geothermal water resources, considerably reducing emission of gases (CO_2, SO_2, NO_x), dust and other pollution having adverse effect on the natural environment. The outcome of the taken measures will be the improvement of not only the natural environment, but also of the energy security of Lądek-Zdrój, which will have a beneficial effect on the sustainable and ecological development of the resort.

5.7.1.12. Conclusions and recommendations

The medicinal thermal waters of Lądek Zdrój are recharged from one deep circulation fissure reservoir.

The total amount of water flowing naturally out of the reservoir is almost constant nowadays. This value can be taken as the summative admissible volume of extracted groundwater from all the intakes. Based on a correlation analysis, direct observations of intake response to changing extraction conditions and a model of intake flow rate (discharge) variation, the existence of strong hydraulic connections between particular thermal water intakes in Lądek-Zdrój has been demonstrated.

The extracted thermal waters are currently used only for balneotherapeutical purposes and as much as 43% of the drawn water is not used at all. The heat from post-treatment waters is not reused either. Currently, the reservoir is exploited in stabilized conditions. These conditions can be disturbed in the event of excessive exploitation of borehole L-2 and /or another deep intake such as the planned new thermal water intake.

There is a likelihood of the precipitation of small amounts of secondary minerals (magnesium silicates, chalcedony and iron sulphides), which can cause development of scaling in water transportation systems.

Because of high concentrations of ^{222}Ra, caution is required near intakes and it should be noted that increased concentrations of dissolved radon are characteristic of natural water outflows/springs. This is the result of the mixing of thermal waters from deep circulation systems with waters containing the mentioned gas, circulating in the shallow system. There is a strong likelihood that waters in the planned intake LZT-1 will contain much lower concentrations of ^{222}Rn or that this gas may even be absent from these waters.

An analysis of the effects of variations in H_2S concentrations on the values of SI coefficients in relation to major rock-forming minerals – i.e. changes in the pH of the extracted waters and, consequently, in redox conditions, bring about variations in the thermodynamic equilibrium of the solution, i.e. of the studied waters. Thus, changes in the concentration of the dissolved gas (H_2S) can lead to precipitation of secondary minerals, in this case sulphides or iron carbonates. In concentrations of particular ion and gaseous components. Therefore, it is essential to perform full chemical analyses of waters and gases and measure water temperature at the outflow, the pH, pressure at the wellhead, and intake discharge, as these data are crucial for thermodynamic modelling. Moreover, in order to predict reservoir response to possible injection of dumped waters, an analysis of the mixing of reservoir water with cool waters is also necessary.

References:

Appelo C.A.J., Postma D., 2007: Geochemistry groundwater and pollution, Balcema Publ., Leiden.

Arnórsson, S., Sigurðsson, E. and Svavarsson, H., 1982: The chemistry of geothermal waters in Iceland. I. Calculation of aqueous speciation from 0°C to 350°C, Geochimica et Cosmochimica Acta, 46, 1513-1532.

Balińska G., 2000: Kreacja przestrzeni uzdrowiska dawniej i dziś [in:] Ciężkowski W., Dębicki J., Gładkiewicz R.: Zdroje Ziemi Kłodzkiej. Historia, przyroda, kultura, przyszłość, Wyd. Uniwersytetu Wrocławskiego, 51-60.

Bażyński J., Fistek J., Graniczny M., Sławiński A., Wilczyński M., 1981: Interpretacja zdjęć satelitarnych w świetle badań hydrologicznych południowo-zachodniej części Ziemi Kłodzkiej. Technika Poszukiwań Geologicznych.Vol.20, nr 1, ss.14-16.

Birkenmajer K., Pecskay Z., Grabowski J., Lorenc M.W., Zagożdżon P.P., 2002: Radiometric dating of the Tertiary volcanics in Lower Silesia, Poland. II. K-Ar dating and paleomagnetic data from Neogene basanites near Lądek-Zdrój, Sudetes Mts. Ann. Soc. Geol. Polon., 72, 119-129.

Bjarnason, J.Ö., 2010: The speciation program WATCH, Version 2.4, user's guide. The Iceland Water Chemistry Group, Reykjavík, 9 pp., http://www.geothermal.is/software.

Bruszewska B., 2000: Warunki geotermiczne Dolnego Śląska. Przegląd Geologiczny vol. 48, nr 7, Państwowy Instytut Geologiczny, Warszawa.
Brzeziński T., 2000: Uzdrowiska Ziemi Kłodzkiej na tle historii światowej balneologii [in:] Ciężkowski W., Dębicki J., Gładkiewicz R.: Zdroje Ziemi Kłodzkiej. Historia, przyroda, kultura, przyszłość, Wyd. Uniwersytetu Wrocławskiego, 33-49.
Chae G-T., Yun S-T., Kwon M-J., Kim Y-S., Mayer B., 2006: Batch dissolution of granite and biotite in water: implication for fluorine geochemistry in ground water, Geochemical Journal, v. 40, ss. 95-102.
Chae G-T., Yun S-T., Mayer B., Kim K-H., Kim S-Y., Kwon J-M., Kim K., Koh Y., 2007: Fluorine geochemistry in bedrock groundwater of South Korea, Science of the Total Environment, No 385, ss. 272-283.
Ciężkowski W., 1978: Hydrogeologia i hydrochemia wód termalnych Lądka Zdroju. Inst. Geotech. Komunikat nr 284.
Ciężkowski W., 1979: Hydrochemical types of fissure waters from Lądek Zdroj. [in:] Hydrogeochemistry of mineralized waters, Proceedings of Conference of Cieplice Spa (Poland), Publ. By Geological Institute, p. 382-388.
Ciężkowski W., 1980: Hydrogeologia i hydrochemia wód termalnych Lądka-Zdroju. Problemy Uzdrowiskowe 4(150).
Ciężkowski W.,1983: Wody termalne Lądka Zdroju [in:] II Ogólnopol. Symp. Współczesne Problemy Hydrogeologii Regionalnej, Lądek-Zdrój, 30-40.
Ciężkowski W., 1990: Studium hydrogeochemii wód leczniczych Sudetów polskich. Prace Naukowe Instytutu Geotechniki Politechniki Wrocławskiej, 60.
Ciężkowski W., 1998: Lądek-Zdrój, Dolnośląskie Wydawnictwo Edukacyjne, 235.
Ciężkowski W., 2000: Wody lecznicze Ziemi Kłodzkiej [in:] Zdroje Ziemi Kłodzkiej, s. 77-93.
Ciężkowski W., 2011: Kierunki rozwoju i możliwości wykorzystania geotermii głębokiej na Dolnym Śląsku [in:] Ropuszyńska-Surma E., Szalbierz Z.: Strategia rozwoju energetyki na Dolnym Śląsku na podstawie metody Foresightowej Delphi. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław.
Ciężkowski M., Ciężkowski W.,1982/1983: Źródła Lądka Zdroju. Historia i badania. Balneol. Pol., t. XXVII, z. 1-4, 5-19.
Ciężkowski W., Doktór S., Graniczny M., Kabat T., Kozłowski J., Liber E., Przylibski T., Teisseyre B., Wiśniewska M., Zuber A., 1996: Próba określenia obszarów zasilania wód leczniczych pochodzenia infiltracyjnego w Polsce na podstawie badań izotopowych. Zał. 20. Złoże wód leczniczych Lądka-Zdroju. Zakład Badawczo-Usługowy „Zdroje", Wrocław.
Ciężkowski W., Marszałek H., Wąsik M., 2011a: Metody badawcze w poszukiwaniu i rozpoznawaniu złóż wód termalnych w sudeckim regionie geotermalnym. Technika Poszukiwań Geologicznych. Geotermia, Zrównoważony Rozwój nr 1-2/2011.
Ciężkowski W., Michniewicz M., Przylibski T.A., 2011b: Wody termalne na Dolnym Śląsku [in:] Żelaźniewicz A., Wojewoda J., Ciężkowski W. (red.): Mezozoik i Kenozoik Dolnego Śląska. WIND, Wrocław.
Ciężkowski W., Marszałek H., Wąsik M., 2016: Projekt robót geologicznych poszukiwania wód termalnych otworem LTZ-1 w Lądku-Zdroju, archiwum Urzędu Gminy Lądek-Zdrój.
Cieżkowski W., Liber-Makowska E., Ciekot B., Ogórek A., 2011c: Charakterystyka warunków występowania i eksploatacji wód termalnych Lądka-Zdroju. Technika Poszukiwań Geologicznych, Geotermia, Zrównoważony Rozwój. Zeszyt 1-2 (247-248), 61-70.
Cieżkowski W., Liber-Makowska E., Ciekot B., Ogórek A., 2016: Charakterystyka złoża wód leczniczych Lądka-Zdroju. Raporty Inst. Gór. Ser. PRE nr 5, Politechnika Wrocławska, Wrocław, 1-10.
Cwojdziński S., 1977: Szczegółowa mapa geologiczna Sudetów, 1 : 25000, ark. Trzebieszowice. Inst. Geol., Warszawa.
Cwojdziński S., 1981: Szczegółowa mapa geologiczna Sudetów, 1 : 25000, ark. Stronie Śląskie. Inst. Geol., Warszawa.
Cwojdziński S., Jodłowski S., 1982: „Plamowe" koncentracje bazaltowe masywu czeskiego i Dolnego Śląska. Biul. Inst. Geol., Nr 341, ss. 201-229.
Cwojdziński S., Młynarski S., Dziewińska L., Jóźwiak W., Zientara P., Baziuk T., 1995: GB-2A – pierwszy sejsmiczny profil głębokich badań refleksyjnych (GBS) na Dolnym Śląsku. Prz. Geol., Vol. 43, ss. 727-737.
Cymerman Z., Cwojdziński S., 1984: Szczegółowa mapa geologiczna Sudetów, 1 : 25000, ark. Strachocin. Inst. Geol., Warszawa.
Dębicki J., 2000: Uzdrowiska Ziemi Kłodzkiej do końca XVIII wieku [in:] Ciężkowski W., Dębicki J., Gładkiewicz R.: Zdroje Ziemi Kłodzkiej. Historia, przyroda, kultura, przyszłość, Wyd. Uniwersytetu Wrocławskiego, 13-32.
Dobrzyński D., Leśniak P., 2010: Two contrasting geothermal systems – towards the identification of geochemical reaction pattern and groundwater temperature, the Sudetes, Poland. Extendendabstracts – Groundwater Quality Sustainability, 12-17 September, Kraków.
Doktór S., Graniczny M., Wiśniewska M., 1985: Wykorzystanie badań teledetekcyjnych do poszukiwań wód termalnych i mineralnych na przykładzie masywu granitowego Karkonoszy. Prz. Geol., Vol. 33, No. 8, ss. 454-458.
Don J., 1964: Góry Złote i Krowiarki jako elementy składowe metamorfiku Śnieżnika. Geologia Sudetica, vol. I.
Don J., 1996: The Late Cretaceous Nysa Graben: implications for Mesozoic-Cenozoic fault-block tectonics of the Sudetes, Z. Geol. Wiss. 24(3/4) , Berlin, pp. 317-324.
Dowgiałło J., 1976: Wody termalne Sudetów. Acta Geologica Polonica, vol. 26, No 4.

Dowgiałło J., 1978: Mineral and thermal waters of the Sudetes against the geological background, Proceedings of Conference of Cieplice Spa (Poland), Publ. By Geological Institute, p. 21-27.
Dowgiałło J., 2001: Sudecki region geotermalny – określenie, podział, perspektywy poszukiwawcze. W: Współczesne Problemy Hydrogeologii, Vol.10, ss. 301-308.
Dowgiałło J., 2002: The Sudetic geothermal region of Poland. Geothermics 31.
Dowgiałło J., 2007: Stan rozpoznania zasobów termalnych regionu sudeckiego i perspektywy ich wykorzystania. Technika Poszukiwań Geologicznych. Geotermia, Zrównoważony Rozwój nr 2/2007.
Dowgiałło J, Fistek J, 2007: Prowincja sudecka [in:] Hydrogeologia regionalna Polski, tom. 2, Wody
Dowgiałło J., Hałas S., Porowski A., 2005: Isotope temperature indicators of thermal waters in South-Western Poland. Proceedings World Geothermal Congress 2005, Antalya, Turkey.
Dz.U. nr 196 z 2015 r.: Obwieszczenie Marszałka Sejmu Rzeczpospolitej Polskiej w sprawie ogłoszenia jednolitego tekstu ustawy – Prawo geologiczne i górnicze.
Edmunds M., Smedley P., 2005: Fluoride in natural waters [in:] Sellinus O. (red.) – Essentials of medical geology, impacts of the natural environment on public health, Elsevier Academic Press, US, ss. 301-329.
Fistek J., 1977: Szczawy Kotliny Kłodzkiej i Gór Bystrzyckich. Biul. Geol. UW, t. 22, ss. 61-111.
Fistek J., 1989: Rola uskoku Pstrążna – Gorzanów w kształtowaniu warunków hydrogeologicznych SW obrzeżenia synklinorium śródsudeckiego. Prace Nauk. Inst. Geotech. PWr, Nr 58, seria: Konferencje nr 29, ss. 362-368.
Fistek J., Fistek A., 1996: Problematyka poszukiwań nowych wystąpień wód termalnych na obszarze województwa wałbrzyskiego. Górnictwo Odkrywkowe, XXXVIII, nr 6, Wrocław.
Fistek J., Fistek A., 2002: Geotermia Dolnego Śląska – zasoby, wykorzystanie, koszty inwestycyjne [in:] Wykorzystanie odnawialnych źródeł energii na przykładzie Dolnego Śląska. Polski Klub Ekologiczny – Okręg Dolnośląski, Wrocław.
Fistek J., Szarszewska Z.,1975: Nowe ujęcie wody termalnej w Lądku Zdroju. Przew. XLVII Zjazdu Pol. Tow. Geol. Wyd. Geol., Warszawa, 259-262.
Frąckiewicz W., Teisseyre H., 1973: Szczegółowa mapa geologiczna Sudetów, 1 : 25000, ark. Międzygórze. Inst. Geol., Warszawa.
Gierwielaniec J., 1968a: Szczegółowa mapa geologiczna Sudetów, 1 : 25000, ark. Lądek Zdrój. Inst. Geol., Warszawa.
Gierwielaniec J.,1968b: Lądek Zdrój i jego wody mineralne. Kwart. Geol., T 12, No 3.
Gierwielaniec J.,1970: Z geologii Lądka-Zdroju. Pr. Nauk. Inst. Geotech. PWr. nr 5, Studia i Materiały nr 5, 1- 43.
Gierwielaniec J., Szarszewska Z., 1978: Lądek-Zdrój (Lądek springs), Proceedings of Conference of Cieplice Spa (Poland), Publ. By Geological Institute, p. 371-373.
Graniczny M., 1994: Strefy nieciągłości tektonicznych w świetle korelacji wielotematycznych danych geologicznych na przykładzie Żarnowca i Ziemi Kłodzkiej. PIG, Warszawa.
Gunnlaugsson, E., Ármannson, H., Thorhallson, S., Steingrímsson, B., 2014. Problems in geothermal operation – scaling and corrosion. Presented at the 'Short course VI on utilizatio of low and medium enthalpy geothermal resources and financial aspects of utilization organized by UNU-GTP and LaGeo in Santa Tecla, El Salvador, March 23-29, 2014.
Jagadeshan G., Kalpana L., Elango L., 2015: Hydrogeochemistry of high fluoride groundwater in hard rock aquifer in s part of Dharmapuri District, Tamil Nadu, India, Geochemistry International, vol. 503, No 6, ss. 554-564.
Kasza L., 1958: Szczegółowa mapa geologiczna Sudetów, 1 : 25000, ark. Nowa Morawa. Inst. Geol., Warszawa.
Kanasiewicz J., Sylwestrzak H., 1970: Zależność między przebiegiem głębokich stref tektonicznych a rozmieszczeniem złóż endogenicznych w Sudetach. Prz. Geol., Vol. 18, No. 5, ss. 219-221.
Kiełczawa B., 2001a: Wybrane zagadnienia chemizmu wód kredowego piętra wodonośnego rowu górnej Nysy Kłodzkiej [in:] Współczesne Problemy Hydrogeologii X, t. 1, Wrocław, ss. 321-327.
Kiełczawa B., 2001b: Wody zmineralizowane Gorzanowa. Praca doktorska, Wydział Górniczy PWr, Raporty Inst. Gór. Ser. PRE nr 9, Politechnika Wrocławska, ss.1-167.
Kiełczawa B.,2013: Charakterystyka hydrochemiczna wód termalnych Lądka-Zdroju, Technika Poszukiwań Geologicznych, Geotermia, Zrównoważony Rozwój, nr 2, 105-116.
Kiełczawa B., 2016: Zarys balneoterapeutycznego zastosowania wód termalnych, Wyd. Wydziału Geoinżynierii, Górnictwa i Geologii, 137.
Kincel R., 1994: Sławne kąpielami Landek [in:] U Szląskich Wód, Oficyna „Silesia", 16-37.
Kondracki J.,1998: Geografia regionalna Polski.
Krzonkalla-Maryniuk A., 2015: Hydrogeologiczne osobliwości Ziemi Kłodzkiej, praca dyplomowa, Archiwum PWr, 117.
Leśniak P., 1987: Some ionic equlibria of Sudetic thermal waters, Proceedings of Conference of Cieplice Spa (Poland), Publ. By Geological Institute, p. 389-394.
Leśniak P., Nowak D., 1993: Water-rock interaction in some mineral waters in the Sudetes, Poland: implications for chemical geothermometry. Annales Societatis Geologorum Poloniae, vol. 63.

Liber E., 1997: Charakterystyka wydajności ujęć wód termalnych Lądka Zdroju. W: Współczesne problemy hydrogeologii, T. 8, Wydaw. WIND, Wrocław, 357-360.
Liber E., 2001: Zmienność wydajności ujęć wód leczniczych eksploatowanych samoczynnie ze złóż sudeckich. Praca doktorska. Raporty Inst. Gór. Ser. PRE nr 3, Politechnika Wrocławska, Wrocław, 1-169.
Liber E., 2009: Charakterystyka opróżniania zbiornika wód szczelinowych głębokiego krążenia na przykładzie złoża wód termalnych Lądka-Zdroju. Biuletyn PIG, 436, 317-322.
Liber E., Liber A., 2003a: Modelowanie wydajności ujęć termalnych wód leczniczych eksploatowanych samoczynnie w Lądku Zdroju przy zastosowaniu sieci neuronowych. Modelowanie i symulacja komputerowa w technice. II Sympozjum, Łódź, s. 111-114.
Liber E., Liber A., 2003b: Analiza falkowa wydajności ujęć wód leczniczych w Lądku Zdroju. W: Współczesne problemy hydrogeologii, T. 11., s. 377-380.
Liber A., Liber E., 2005: Zmiany wydajności ujęć wód leczniczych w Lądku Zdroju i Szczawnie Zdroju w świetle nowych metod badań. W: Współczesne problemy hydrogeologii. T. 12, s. 453-460.
Liber-Makowska E., 2011: Dynamiczne oddziaływanie pomiędzy ujęciami wód termalnych Lądka-Zdroju. Technika Poszukiwań Geologicznych, Geotermia, Zrównoważony Rozwój. Zeszyt 1-2 (247-248), 71-80.
Liber-Makowska E., 2011: Geotermia w Lądku-Zdroju, Pryzmat nr 249, PWr, 26-27.
Liber E., Kiełczawa B., 2009: Wody termalne w rejonie Ziemi Kłodzkiej – wystąpienia udokumentowane i perspektywiczne. Technika Poszukiwań Geologicznych. Geotermia, Zrównoważony Rozwój nr 2/2009.
Marsch A., 2009: Kur- und Badeorte Schlesiens – einstundjetzt. Śląskie kurorty I zdroje – dawniej I dziś, Bergstadtverlag Wilhelm Gottlieb Korn, 167.
Michniewicz M., 1981: Próba interpretacji wczesnych etapów tektogenezy Sudetów w nawiązaniu do teorii diapiryzmu wgłębnego oraz koncepcji głębokich rozłamów. Geologia Sudetica, Vol. 16, No. 2, ss. 75-141.
Mroczkowska B., 1978: Występowanie fluoru w wodach sudeckich, Arch. PIG Oddz. Dolnośląski, Wrocław.
Ostrowicz A., 1881: Landek w Hrabstwie Kłockiem w Szląsku. Podręcznik informacyjny dla gości kąpielowych, 201.
Parkhurst, D.L., Appelo, C.A.J., 1999: User's guide to PHREEQC (Version 2) — a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. U.S. Geological Survey Water-Resources Investigations Report 99-4259, 312 pp.
Plewa S., 1994: Rozkład parametrów geotermalnych na obszarze Polski. Wyd. CPPGSMiE PAN, Kraków.
Plewa M. (red.), 1996: Badania ciepła radiogenicznego skał krystalicznych i osadowych obszaru sudeckiego. Prace Geol., nr 141, Kom. Nauk. Geol. PAN, Kraków
Polański A., Smulikowski K., 1969: Geochemia. Wyd. Geol., Warszawa, s. 662.
Porowski A., 2008: Sens i znaczenie badań geotermometrycznych w poszukiwaniach wód termalnych o niskiej entalpii. Technika Poszukiwań Geologicznych. Geotermia, Zrównoważony Rozwój 46(2).
Porowski A., Dowgiałło J., 2009: Application of selected geothermometers to exploration of low-enthalpy thermal water: the Sudetic Geothermal Region in Poland. Environ. Geol., 58, s. 1629-1638.
Pożaryski W., 1975: Interpretacja geologiczna wyników głębokich sondowań sejsmicznych na VII profilu międzynarodowym. Prz. Geol. Vol. 23, no 4, ss. 163-171.
Przylibski T.A., 2005: Radon. Składnik swoisty wód leczniczych Sudetów. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław.
Przylibski T.A. (red.), 2007: Studium możliwości rozpoznania nowych wystąpień wód zmineralizowanych, swoistych i termalnych na obszarze Bloku Przedsudeckiego. Instytut Górnictwa, Politechnika Wrocławska.
Szarszewska Z.,1967: Dokumentacja hydrogeologiczna złoża wód leczniczych Lądka Zdroju. PP OTU, Warszawa.
Szarszewska Z., Madej E.,1974: Dokumentacja hydrogeologiczna złoża wód leczniczych z utworów prekambru ujętych odwiertem L-2 (700 m) w Lądka Zdroju. B.P. i U.T.B.U. „Balneoprojekt", Warszawa.
Szewczyk J., 2007: Strumień cieplny a temperatura i mineralizacja wód podziemnych [in:] Paczyński B., Sadurski A. (red.): Hydrogeologia regionalna Polski, T. II, Państwowy Instytut Geologiczny, Warszawa.
Wziątek A.,1999: Uzdrowiska Ziemi Kłodzkiej na dawnej pocztówce. Die Kurorte der Grafschaft Glatz auf der alten Postkarte, Kolekcjoner, ss. 129.
Zuber A., Weise S.M., Osenbrück K., Grabczak J., Ciężkowski W., 1995: Age and recharge area of thermal waters in Lądek Spa (Sudeten, Poland) deduced from environmental isotope and noble gas data. Journal of Hydrogeology 167.
Zuber A., Różański K., Ciężkowski W. (red.), 2007: Metody znacznikowe w badaniach hydrogeologicznych. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław.
Żelaźniewicz A., 2005: Przeszłość geologiczna. W: Fabiszewski J. (red.), 2005: Przyroda Dolnego Śląska. PAN – Oddział we Wrocławiu, s. 61-134.

5.7.2. Exploration of hydrogeothermal conditions of crystalline massif in the area of Lądek-Zdrój on the basis of geophysical data re-interpretation

5.7.2.1 Introduction

A geothermal water reservoir in the area of Lądek-Zdrój occurs in specific geological conditions, which are quite different from the remaining areas of Poland, but they can be regarded as representative for the Sudetic region. It is of a fractured nature and it fills crystalline metamorphic formations of Lądek-Śnieżnik. The above-mentioned waters occur mainly in mesometamorphic and polymetamorphic Stronie formations, built mainly of crystalline schists with marble interlayers and paragneisses. Partially, the reservoir covers also infracrustal (probably catametamorphic and partially ultrametamorphic) Gierałtów formation, built in this area mainly of gneisses. Exploited aquifers are of pressurised character, which causes that the existing exploitation of both ground springs and one borehole (with the depth of ca. 700 m under ground level) has the nature of artesian outflows. A fractured nature of reservoir rocks is the reason of a certain concern among the representatives of the Management Broad of Lądek Resort, exploiting the aforementioned reservoir exclusively so far. Hydraulic connection of particular parts of the reservoir through the systems of fractures causes a very fast reaction of the existing intakes to the operation of additional intakes, which was experienced empirically in the past. The total flow rate of the intakes (operating as artesian outflows) remains at a stable (constant) level. Some concerns have been expressed that drilling of a new well and its potential exploitation would disturb the operation of the existing intakes used by the Resort. It is difficult to evaluate the appropriateness of the above comments on the basis of currently available data. The existing intakes, both surface (springs, wells) and borehole ones, reach down to the maximum level of ca. 700 m under ground level, whereas the goal of the borehole being designed is at the depth of about 2500 m under ground level Geophysical data (magnetotelluric sounding) indicate the presence of two levels (or zones) fractured and filled with mineral (geothermal) waters. Unfortunately, it is impossible to say whether the layer separating those levels with an elevated resistivity is not cut with fractures providing hydraulic connection between them, not it is possible to make a quantitative evaluation of such connection. A small scope of magnetotelluric data does not allow evaluation of a spatial distribution of aquifers and a potential isolation stratum. The characteristics of the geological conditions in which the hydrogeothermal reservoir occurs in the area of Lądek-Zdrój causes that it can be regarded as representative for the Sudetic region. The studies performed here and also future, more advanced, projects can be thus treated as pilot for this region. Chapter one of the report presented here reviews magnetotelluric tests in the Sudetic region in order to outline more widely the issues related to geophysical tests in its specific conditions.

The Sudetic region, including Sudetes and a Fore-Sudetic Block is characterised with diversified and often highly complex geological structure. At the same time, it is a very interesting area from the mineral point of view. Certainly, geothermal energy and mineral water resources are crucial from the economic and ecological point of view. A high degree of geological structure complexity is translated into difficulties in exploratory works or, more generally, in geological and geophysical deep prospecting studies. In particular, magma and metamorphic Sudetic orogen and crystalline substrate of its pre-frontier are a difficult area for the seismic method, being the main tool in structural studies of sedimentary complexes. In this situation, in exploratory works and in structural studies a new field opens to use other geophysical methods, and particularly elektromagnetic methods, with the most comprehensive variant being the magnetotelluric method (MT -1…,1996, Stefaniuk et al, 2011). In the Sudetic area MT studies have been performed within a small scope, although with good results (Fig. 5.7.1, 5.7.2. Examples of studies illustrating possibilities of this method in the geothermal domain in the aforementioned area are the subject of this study.

In studies of the Sudetic area, three basic methodological variants of the said method have been used: deep magnetotelluric probing in a wide scope of frequencies (MT/AMT), probing in the AMT audiomagnetotelluric band (high frequencies), continuous magnetotelluric and audiomagnetotelluric profiling, as well as probing and profiling with an artificial source of the primary field (CSAMT). As an illustration of using the magnetotelluric method in prospecting geothermal waters, studies conducted in the area of Cieplice, Polanica Zdrój and Nysa have been presented. The foregoing and other examples of studies carried out at the order of individual investors confirm the effectiveness of the MT method within the scope of a relatively deep (to 2-3 km) exploration of fault zones as prospective for the occurrence of geothermal waters and mineral waters (Stefaniuk et al., 2011).

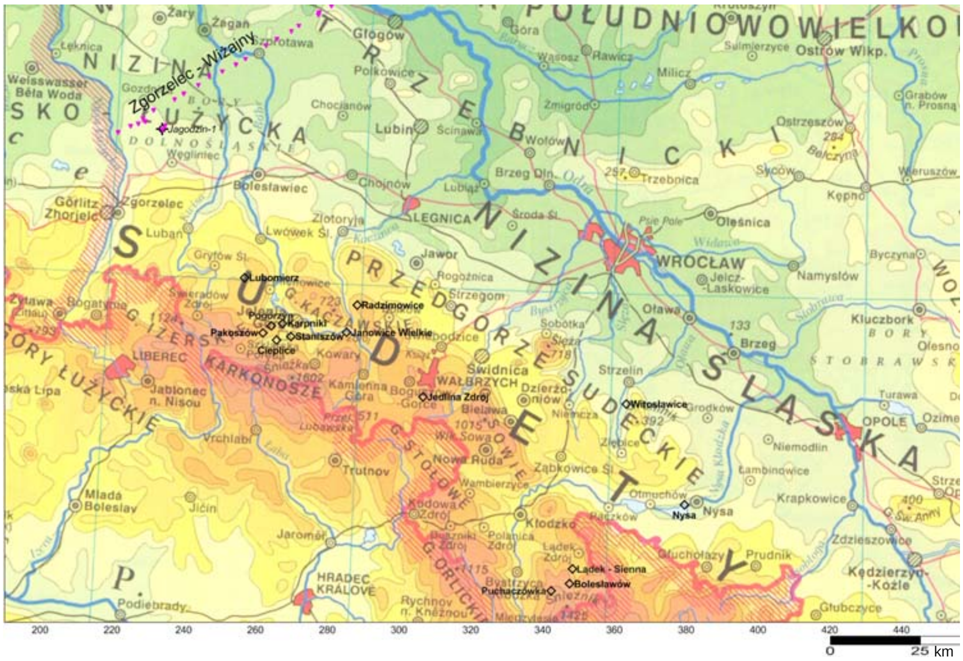


Fig. 5.7.1. Location of geo-electric studies in the Sudetic area on the physical map of Poland (acc. to Stefaniuk et al., 2011, supplemented)

5.7.2.2. Geothermal characteristics of the Sudetic region

Sudetes and the Fore-Sudetic Block substrate located in south – western part of Poland are built mainly from old crystalline rocks partially covered by younger sediments (Fig. 5.7.2.). Precambrian and Lower Paleozoic gneisses and metamorphic shales with marble interlayers were intruded in the Upper Carboniferous by acid granitoid magmas, which formed, e.g. Karkonosze–Izera Block and Kłodzko-Złoty Stok granitoid. In syncline structures, crystalline rocks are covered by Phanerozoic sedimentary rocks coming from different ages (from Silurian to Quaternary). The Tertiary period was marked with a spectacular vulcanism under the Earth's crust of the basaltoid kind, the remnants of which are cones and volcanic covers distributed throughout the region and creating the so-called Lower Silesian basaltoid formation (Stefaniuk et al., 2017). Geothermal waters occur in this region within crystalline formations. Most of fragmentary hydrogeothermal studies carried out in the Polish part of the Sudetes were limited to occurrence zones of geothermal waters used for medicinal purposes and to few areas where prospective studies were performed for this kind of resources (Dowgiałło, 2002, Ciężkowski, 2011). However, the Sudetic area is characterised by favourable thermal conditions. In Cieplice, water with the temperature of 86.7ºC was drilled at the depth of 2002.5 m. For this reason, the area of Cieplice, located in the Sudetic geothermal region has been selected for studies aimed at exploration of a prospective location of a HDR type intake, as well as a suitable location of binary systems (Wójcicki et al., 2013, Bujakowski et al., 2014).

5.7.2.3 Review of the applied geo-electric methods

Foundations of the magnetotelluric method

The magnetotelluric method (more properly magnetotellurics) is a set of geo-electric methods using harmoniously changeable electromagnetic field for exploring resistivity distribution in a geological medium (Stefaniuk et al., 2008, Stefaniuk et al., 2011). The basis of this method is the assumption of a source field in the form of a flat electromagnetic wave parallel to the Earth's surface (Berdichevsky, 1968). A genesis of a source field constitutes the basic for picking up basic variants of this. method. In the classical magnetotelluric method (MT-1…,1996), a source field with the frequency range of ca. 1 – 0.0001 Hz is generated by processes being the effect of a solar wind impact upon ionosphere. Propagation of an electromagnetic wave in the atmosphere, caused by distant lightnings is a source of a primary field in a high-frequency variation of the magnetotelluric method called Audiofrequency Magnetotellurics (AMT) (Wait, 1962, Strangway, 1973). In high-frequency shall applications, a suitably distant artificial source with specific geometric configuration is also used (Goldstein, 1975). This variant of the method is called Controlled Source Audiofrequency Magnetotellurics (CSAMT). The scope of frequencies of the so-called audiomagnetotelluric band ranges from ca. 1 Hz – 20 kHz.

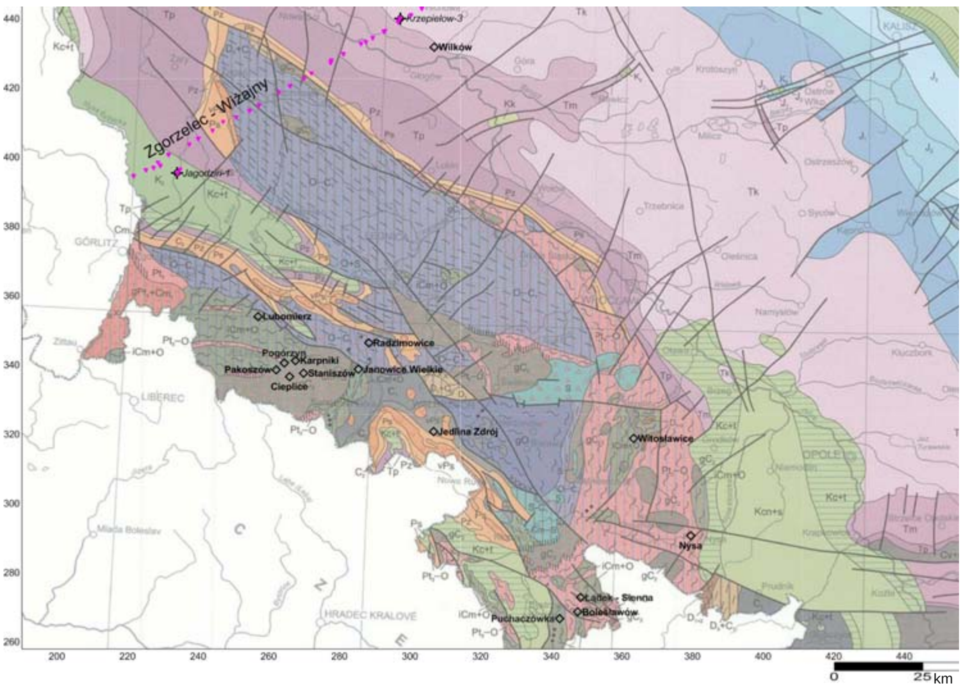


Fig. 5.7.2. Location of geo-electric studies in the Sudetic area on the geological map of Poland (Stefaniuk et al., 2011, supplemented, geological map acc. to Marks et al., 2006)

Theoretical foundations of the magnetotelluric probing method (MT-1…, 1996) for a one-dimensional medium have been developed independently by Tichonov (1950) (Tichonov, Ob…) and Cagniard (1953). The basic parameter designated in the magnetotelluric method is a combined impedance tensor (Z). In a general case, impedance binds elements of an electromagnetic field on the Earth's surface (Stefaniuk et al., 1996):

$$\begin{vmatrix} E_x \\ E_y \end{vmatrix} = \begin{vmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{vmatrix} \cdot \begin{vmatrix} H_x \\ H_y \end{vmatrix} \qquad (1)$$

Properties of impedance tensor elements reflect parameters of the geo-electric model of a geological medium and they depend on the degree of its complexity:

- in case of a 1D medium (resistivity variability only in one direction, e.g. vertical)

$$Z_{xx} = Z_{yy} = 0 \text{ oraz } Z_{xy} = -Z_{yx} \qquad (2)$$

- in case of a 2D medium ("x" axis of the measurement system is directed perpendicularly to the homogeneity axis, resistivity changeability distribution does not occur along the "y" axis – resistivity change in a plane)

$$Z_{xx} = Z_{yy} = 0 \text{ and } Z_{xy} \neq -Z_{yx} \qquad (3)$$

Therefore, two magnetotelluric field polarisations can be considered for a 2D medium:

- YX (electric polarisation), when we consider element

$$Z_{yx}=E_y/H_x \qquad (4)$$

- XY (magnetic polarisation), when we consider element

$$Z_{xy}=E_x/H_y \qquad (5)$$

In a 3D medium, where resistivity changes in all directions, all impedance tensor elements are different.

For such defined impedance, apparent resistivity curves are calculated on the basis of the following expressions:

$$\rho_{xy} = \frac{1}{\omega\mu} |Z_{xy}|^2 \qquad (6)$$

$$\rho_{yx} = \frac{1}{\omega\mu}\left|Z_{yx}\right|^2 \qquad (7)$$

and phase curves:

$$\varphi_{xy} = Arg Z_{xy} \qquad (8)$$

$$\varphi_{yx} - Arg Z_{yx} \qquad (9)$$

In the above expressions, ω - means angular frequency, μ - vacuum permeability.

Time waveforms recorded for mutually perpendicular elements of a horizontal and magnetic electric field enable determining impedance tensor elements. They are the functions of electromagnetic field frequency and location of the x, y measurement system in relation to the extent of geological structures, which specify the geometry of medium conductivity distribution. An impedance tensor includes e.g. information about the dimension and characteristics of geo-electric parameters of geological medium distribution (Swift, 1962, Simpson, Bahr, 2005, Wojdyła, Stefaniuk, 2011). Resistivity distribution in a geological medium is usually of complex three-dimensional nature. 1D and 2D models constitute simplification acceptable in certain conditions. Medium dimensionality determines the selection of MT data interpretation methodology.

Elements of magnetotelluric studies methodology and technique

The basic measuring system of magnetotelluric probing consists of two mutually perpendicular electric dipoles and three magnetic sensors (Fig. 5.7.3C). However, usually more complex modifications of that system are used (Stefaniuk et al., 2003). In magnetotelluric continuous profiling, the measuring system presented in Fig. 5.7.3B was used (Stefaniuk et al., 2003, Stefaniuk et al., 2008, Stefaniuk et al., 2011). In order to eliminate the impact of electromagnetic interference, measurements were made in two points with the so-called distant magnetic reference point (Goubau et al., 1978, Gamble et al., 1979).

Works with the use of the CSAMT method were performed by means of a scalar method (Yamashita, 2006, Zonge, Hughes, 1991). A diagram of the measuring system (transmission and receiving) has been presented in Fig. 5.7.4. The length of a transmission dipol A and B ranged from 600 metres to 4 km. The transmission system was located 3-8 km away from the measuring system. The measurement time for a single cycle was ca. 60 minutes, which enabled acquisition of high quality CSAMT curves in the frequency range of 10 kHz to 0.6 Hz. Yet, this frequency range was not the subject of geophysical interpretation in whole. Interpretation limitations result from the dependence between source field configuration (geometry) on the distance between a point of measurement and a current dipole (Fig. 5.7.4). Close to a current dipole, in the so-called near field, field geometry is complex and reflects mutual location of current electrodes. At a certain distance from a dipole, in the area surrounding a current dipole axis, an electromagnetic field achieves the geometry close to a flat electromagnetic wave falling perpendicularly to the Earth's surface. That area is called a far field.

Magnetotelluric studies are performed in different methodological variants. The most frequently used variant, used usually in regional and semi-detailed studies are series of probings distributed quite evenly along profile lines. Also, 3D probing is performed, i.e. in bundles of regular surface grids. In detailed studies, higher density of a probing grid is used or the so-called continuous profiling.

Continuous magnetotelluric profiling is a specific modification of magnetotellurics, the characteristic feature of which is suitably dense, spatial sampling of electric field elements, parallel to a measuring profile, in such a way that breaks in the distance between centres of measuring dipoles are equal or smaller than respective lengths of those dipoles (Stefaniuk et al., 2003, Stefaniuk et al., 2008). As a result, continuous coverage of a measuring profile by electric measuring dipoles oriented in parallel to it is acquired (Fig. 5.7.3A, B). Sampling of a magnetic field and electric field elements, perpendicular do a measuring profile, is usually much less dense in such method (Torres-Verdin, 1991). In calculations of magnetotelluric parameters, an electric field recorded by a series of electric dipoles is referenced to one centrally located pair of magnetic sensors. Measuring profiles are usually oriented perpendicularly to the extent of geological structures, so variability of electric element perpendicular to the profile is much less than elements parallel to it, which legitimises the possibility of sample it more rarely. The basis of the magnetotelluric method of continuous profiling has been developed as the so-called EMAP method (*Electro Magnetic Array Profiling*). This methodology, it is theoretical assumptions, is to ensure higher credibility of interpretation through eliminating the impact of a static shift phenomenon (Stefaniuk et al., 2011). This effect is caused by small surface nonhomogeneity with sizes comparable to the measuring system size. Continuous distribution of electric dipoles along the profile has enabled the application of spatial impedance filtration (Torres-Verdin, Bostick, 1992a, b). Since new ways of static shift elimination have been developed, continuous profiling is applied mainly in shallow studies, as high-resolution modification of MT.

As mentioned above, a joint feature distinguishing a group of magnetotelluric methods is characteristic configuration of a source field (Stefaniuk, Wojdyła, 2007). The assumption is that it is a flat electromagnetic wave falling from top, perpendicularly to the Earth's surface. Such an assumption simplifies excellently mathematical solutions, describing induced field distribution in a geological medium. It is relatively well fulfilled in case of classical magnetotellurics (MT) and Audiofrequency Magnetotellurics (AMT), in which natural sources are used. IN an audiomagnetotelluric band, similarly to a classical magnetotelluric band, there are frequency ranges, where natural field energy is low. As a result, the relation of the useful signal to interference deteriorates, thus generating high statistical scatter of measurement data. Such frequency ranges are referred to as dead band. They make it difficult to obtain high quality results and increase the costs of data acquisition (Stefaniuk, Wojdyła, 2007). An attempt at solving the issue of dead bands was made by introducing an artificial source of a magnetotelluric field, the parameters of which may be easily controlled. In this variant, referred to as the CSAMT method, the problem is still maintenance of suitable electromagnetic field geometry, meeting the magnetotelluric field criteria (Fig. 5.7.4). This is a necessary condition for using relatively simple mathematical solutions, adopted in magnetotellurics. As mentioned above, fields close to a flat horizontal electromagnetic wave appear in a far field, in a suitable long distance from the source (Fig. 5.7.4). A distance of a far field depends on field frequency, whereas electromagnetic signal is strongly attenuated in a geological medium, thus making it necessary to use a high-power transmitter. The above conditions limit the frequency range of the method down to relatively high frequencies, and thus, they limit its depth range.

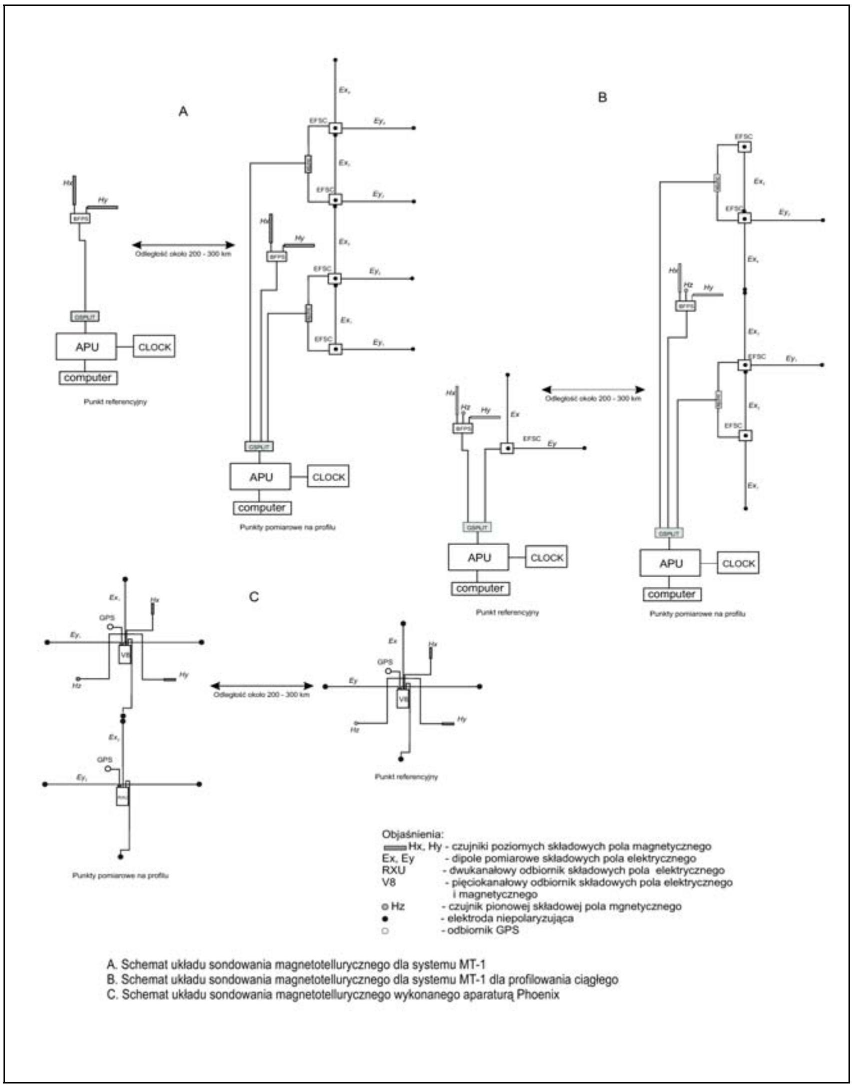


Fig. 5.7.3. Measurement systems used in magnetotelluric studies (Stefaniuk et al., 2011, amended)

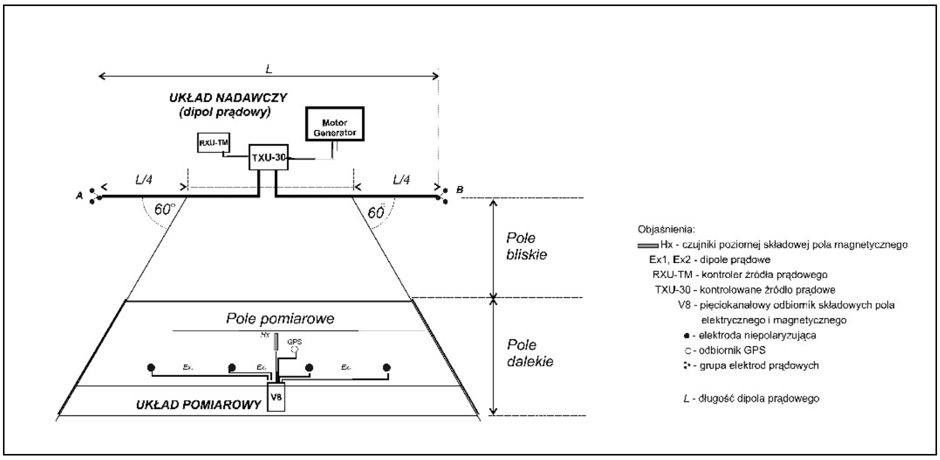


Fig. 5.7.4. Measuring system used in the CSAMT method in relation to the far and near field distribution for a current dipole (Stefaniuk, Wojdyła, 2007, modified)

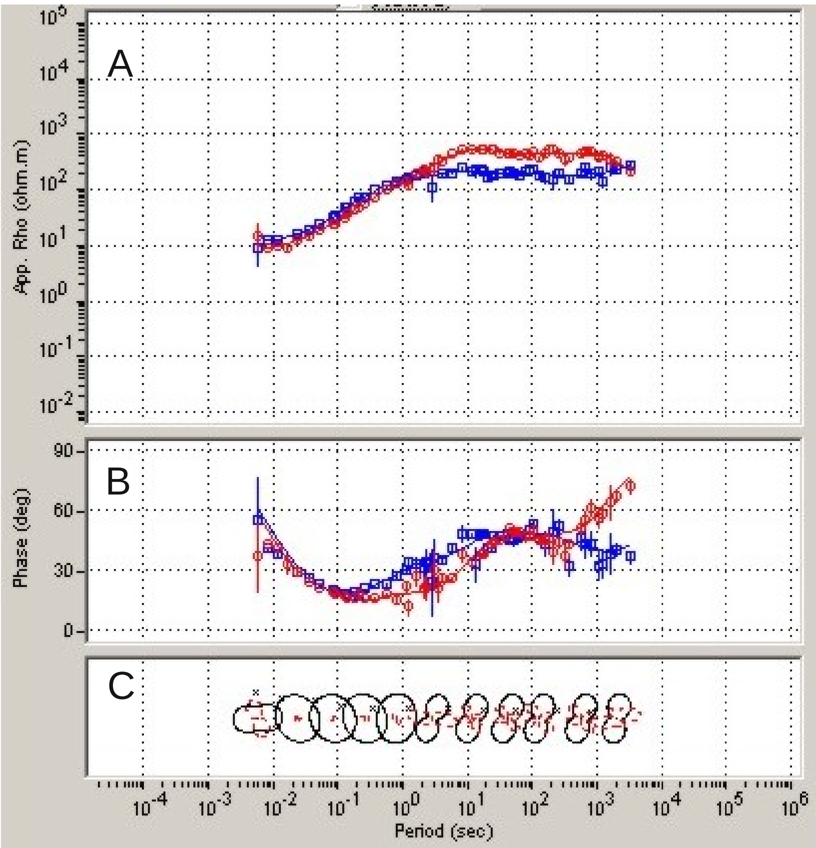


Fig. 5.7.5. Example of curved magnetotelluric probing and polar impedance diagrams. A amplitude curves, B phase curves, C polar diagrams

Measuring data processing

Recorded time waves were the subject of a multi-stage reference processing in order to eliminate interferences with variable spatial characteristics (Goubau et al. 1978). The result of calculations are impedance tensor elements: Z_{xx}, Z_{yy}, Z_{xy}, Z_{yx} binding electric field and magnetic variables on the Earth's surface (Sims, 1971). On their bases, the so-called impedance directional diagrams are indicated to illustrate dependence between the impedance tensor module and electric orientation of an element. Elements Z_{xy} and Z_{yx} are used to calculate amplitude and phase curves of magnetotelluric probings, whereas in case of a continuous profiling variant element Z_{xy} is used (Fig. 5.7.5). In the CSAMT method, data processing takes place, in fact, during measurements, which enables the operator to control the quality of recorded data up to date. Under measurement processing, field curves are edited. An example of a CSAMT measurement curve collated with an AMT curve for probings made in the same point and for an identical frequency range has been presented in Fig. 5.7.6. What draws attention is the quality of CSAMT data in relation to AMT data, particularly within the aforementioned dead band ranges of a natural field.

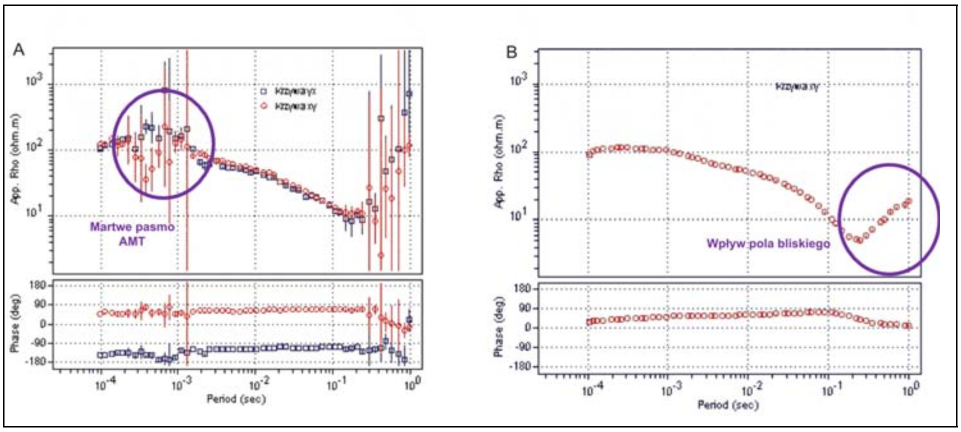


Fig. 5.7.6. Comparison of AMT and CSAMT probing curves (Stefaniuk, Wojdyła, 2007, amended)

Magnetotelluric data interpretation

Amplitude and phase probing curves and other magnetotelluric parameters are the subject of geophysical and geological interpretation. Inversion procedures with the use of 1D and 2D interpretation models were used for interpretation. Magnetotelluric data inversion consists in, generally, multiple performance of simple modelling, where in subsequent calculation cycles (iterations) new sets of interpretation model parameters are introduced. Changes in the above-mentioned parameters are controlled by optimisation procedures, aimed at minimising the so-called error function, describing discrepancies in sets of measured and calculated parameters. In 1D inversion, most frequently used are algorithms referred to as the “Occama” algorithm and an LSQ (*Least Square*) algorithm (Levenburg, 1994, Marquardt, 1963, Constable et al, 1987). Currently, algorithms for 2D inversion, most frequently encountered in interpretation practice are: Rodi and Mackie algorithm (Rodi, Mackie, 2001), abbreviated as NLCG (*Nonlinear Conjugate Gradients*) and the SBI (*Sharp Boundary Inversion*) algorithm (Smith et al., 1999). Initial geo-electric medium models, introduced into calculation procedures are treated as interpretation models. An interpretation model should determine both geo-electric medium geometry and resistivity distribution tested for that geometry.

A solution to the problem of inversion is ambiguous, i.e. there are a number of different models, which can be fitted into empirical data with satisfactory precision. In this situation, suitable imposition of bonding adjusting the acquired solution and suitable preliminary conditions in the form of starting model is crucial for proper program utilisation (Stefaniuk et al., 2011).

5.7.2.5. Examples of electromagnetic studies

Geo-electric studies performed in orthographical area of the Sudetes can boil down to the exploration of tectonic zones butting crystalline rocks, although the ultimate goal was to explore hydrothermal conditions, or potential presence of sulphide mineralisation. Tectonic zones in high-resistive crystalline complexes usually relate to resistivity decline, due to water filtration in fracture systems near faults or with metasomatic sulphide mineralisation (Wojdyła et al, 2008, Stefaniuk et al, 2011). In most cases, the basis for geological interpretation were resistivity cross-sections calculated by means of 2D inversion. For older continuous profiles, magnetotelluric data interpretation was performed also according to the EMAP standard (Torres-Verdin, Bostick, 1992a, b). Three examples of detailed studies were presented, with the application of continuous profiling within this set of issues: in the area of Cieplice Śląskie – Zdrój in Jelenia Góra Valley (Fig. 5.7.7), near Polanica – Zdrój in Kłodzko Valley (Fig. 5.7.8) and in the area of Nysa (Fig. 5.7.9). In the area of Cieplice Śląskie-Zdrój and Polanica-Zdrój, measurement works were performed in the version of AMT/MT continuous profiling, by means of MT-1 measuring system (Wojdyła et al., 2008, Stefaniuk et al., 2011).

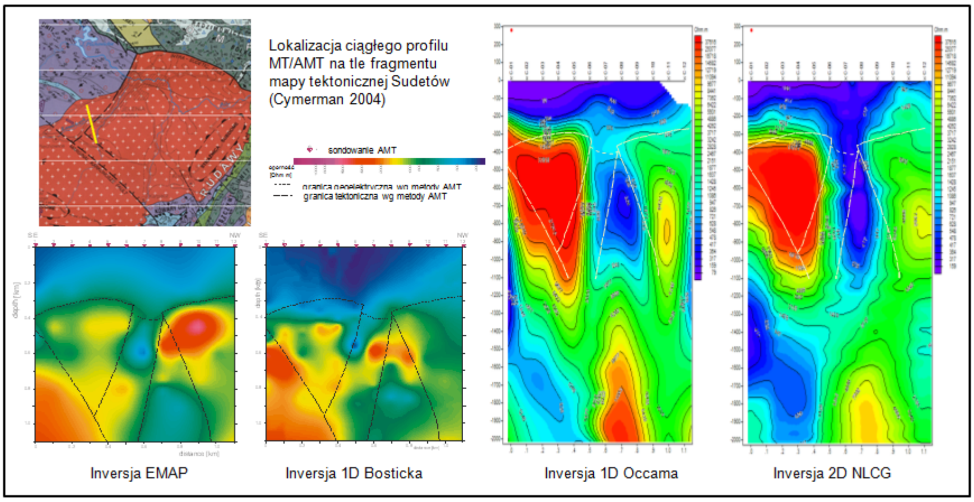


Fig. 5.7.7. Magnetotelluric cross-section of Cieplice Śląskie-Zdrój area
(frequency range: 1 – 100 Hz, tectonic map acc. to Cymerman, 2004, Stefaniuk et al., 2017)

The first presented profile is located within granite massif outcrop in the area of Cieplice – Zdrój (Fig. 5.7.7). A short continuous profile runs here in the zone of crossing faults which cut the Karkonosze massif. For this profile, resistivity cross-sections were designated, with the use of the EMAP procedure and on the basis of 1D and 2D inversion. Geothermal water filtration relates in this area with the fault zone. The structure of this zone is marked with clear resistivity differentiation at all studied resistivity cross-sections (Fig. 5.7.7). Water presence in fractures of the fault zone causes clear medium resistivity decline. This effect is reinforced by high water mineralisation and elevated temperature. As a result, in the fault zone medium resistivity decreases down to 100 Ωm, whereas normal resistivity of crystalline rocks is as high as several thousand Ωm. The roof of high-resistivity crystalline rocks is covered, in this area, by a complex with relatively reduced resistivity, comparable to tectonic zone resistivity. Locally, the thickness of this complex is 300-400 m.

Resistivity cross-section was constructed by means of Bostick transformation (Torres-Verdin, Bostick, 1992a, b). Bostick algorithm converts amplitude and phase curves for XY polarisation into 1D resistivity distribution with depth. EMAPK program, being a part of MT-1 system, combines the results of 1D interpretation and creates a 2D representation of resistivity data. The study area is located at the border between the Intrasudetic Basin and Upper Nysa Kłodzka graben. A substrate of relatively thin sedimentary stratum is made of metamorphic rocks in this region (Don, Don, 1960). A sedimentary complex is represented by Upper Cretaceous sandstones, although one cannot exclude the presence of older sediments, i.e. Permian or Carboniferous. Its thickness is estimated at several hundred metres. In the fault zone, mineral waters filtration is reported, probably causing significant medium resistivity decline. Locally, medium resistivity drops below 10 Ωm. Such low resistivity may relate to the presence of geothermal waters or sulphide mineralisation (Farbisz et al., 2001).

Magnetotelluric works performed in the area of Nysa were of research nature and they aimed at exploring geological medium resistivity in the area of the Town of Nysa in the aspect of evaluating geothermal conditions, particularly tectonic zone interpretation in the crystalline substrate built of metamorphic shales and gneisses.

Studies were designed with the use of audio-magnetotelluric method with an artificial source (CSAMT). After the initial analysis of recorded measurement curves, dramatic reduction of effective depth probing range was reported, relating to strong resistivity contrast at the border between the roof of the metamorphic substrate and clay Cenozoic cover, making it impossible to achieve the set goal. In consequence, a decision was made to change the study method and, additionally, measurements were made with the use of a natural magnetotelluric field in the version of AMT probings, thus increasing the scope of recorded frequency from 10 kHz up to 1 Hz, which guarantees the achievement of a suitable depth range of interpretation.

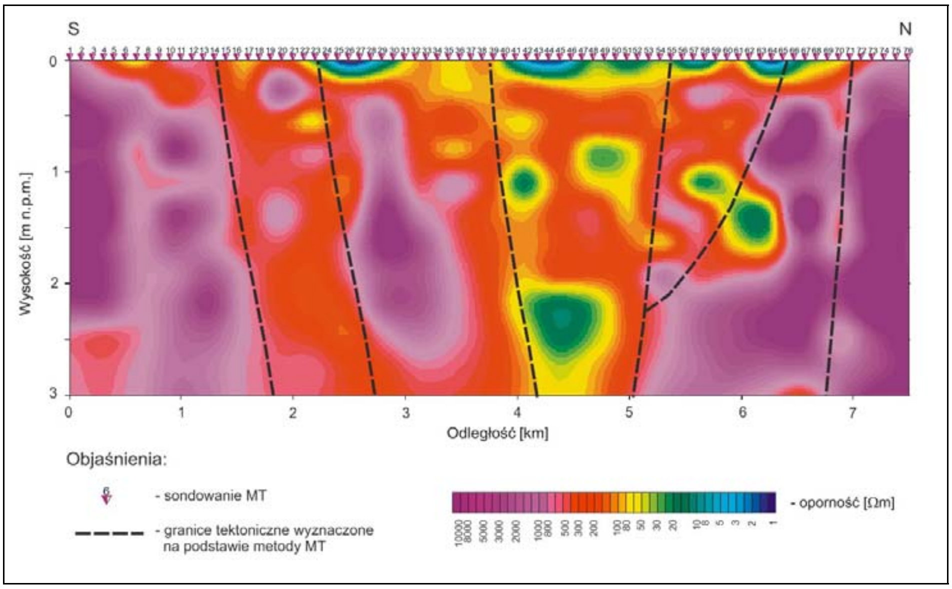


Fig. 5.7.8. Magnetotelluric cross-section of Polanica-Zdrój area, EMAP inversion (frequency range: 1 – 100 Hz)

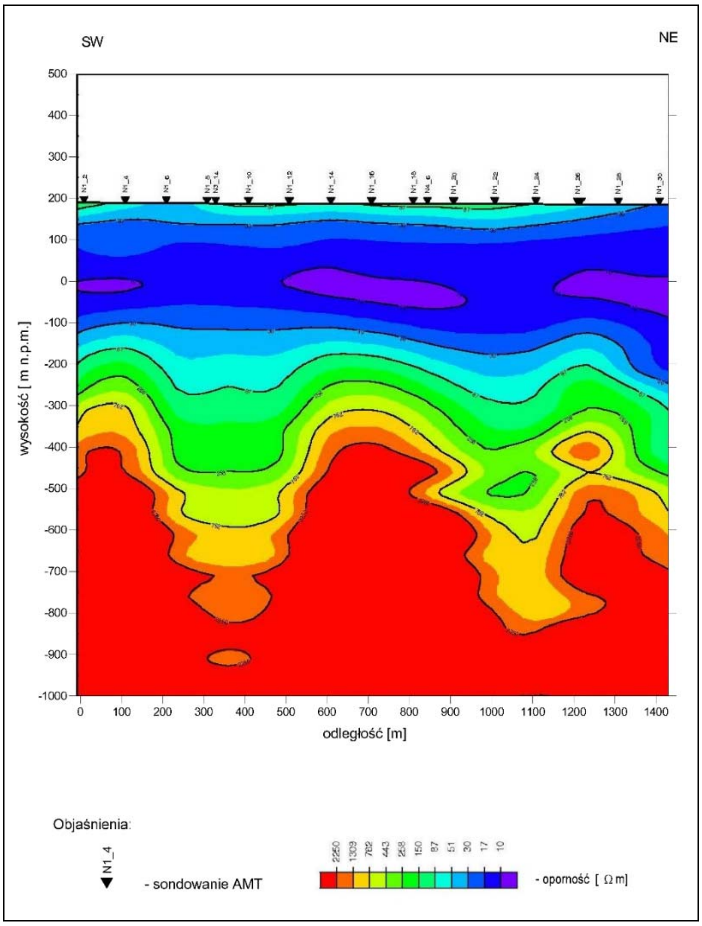


Fig. 5.7.9. Magnetotelluric cross-section in the area of Nysa, 1D inverssion accoring to the “Occama” algorithm

Quantitative interpretation was made by means of 1D inversion according to the Occama algorithm, both for CSAMT and AMT data (Canstable et al, 1987). The results of the studies are resistivity cross-sections developed along measurement profiles and a resistivity map in depth cuts. An example of a resulting cross-section is presented in Fig. 5.7.9. The results show a coherent picture of resistivity distribution with depth. The bottom of the low-resistivity (Cenozoic) complex is deposited with slight denivelations at the average depth of 120 m under sea level. Below that complex, there are low-resistivity formations with resistivity of several hundred and more ohm metres. However, in a high-resistivity complex, there are zones of anomalous resistivity decline, which should be interpreted as probably fault zones, related with metamorphic rock fracturing and water accumulation.

The examples presented above indicate various possibilities of effective use of different variants of magnetotellurics in the hydrogeothermal area and, more generally, in structural and lithological studies. This method is especially useful as a supplement and support for the seismic method in complex geological conditions. Continuous profiling ensures the densiest magnetotelluric field sampling, along the profile and, as a result, they enable using all currently available procedures of measurement data processing and interpretation. They also provide good statistical representation in the presence of strong artificial interference. The above-mentioned examples illustrate potential possibilities of using magnetotellurics in complex conditions of the Sudetic region. They also confirm the usefulness of this method in studies of crystalline massif tectonics.

5.7.2.6 Review of geophysical tests performed in the area of Lądek-Zdrój.

The area of Lądek-Zdrój has been known for several hundred years, due to the occurrence and utilisation of geothermal water springs. Gradual development of the Resort caused a growing interest in the geothermal reservoir, and particularly in increasing intake output. Within the frameworks of a wide scope of geological, hydrogeological, geochemical, isotope, radiometric and other tests, also geophysical tests were performed. In the area of geothermal water reservoir in Lądek-Zdrój, a set of geophysical works was carried out, which was oriented to the exploration of general geological conditions of the reservoir and its proximity, beginning with magnetic and geothermal studies, through radar emanations, VLF profiles, as well as sounding and electroprofiling, with three short magnetotelluric profiles each. The said studies enabled to interpret fault zones, detect temperature anomalies and spatial exploration, yet to a very limited extent, of fractured aquifers. Complex geological conditions and a limited amount of in-depth information did not allow building of a digital hydrogeothermal model of Lądek reservoir and its proximity, not simulating the impact of a new intake on the currently operating one, and hence, evaluating the hydraulic connection between hydrogeological levels.

The basic geophysical tests conducted here include tests with the use of potential fields, i.e. magnetometry and gravimetry. Disregarding the works of historic importance, the first ΔT magnetometric studies, which were semi-detailed and only partially detailed, were performed at the end of 1960's. They were presented, together with the summary of the earlier works, in collective documentation (Jagodzińska et al. 1969). The results of magnetic studies were used to explore area tectonics. They confirmed the occurrence and the course of already known faults and enabled mapping of earlier unknown dislocations. Those studies were supplemented and re-processed again in years 2005-2007 within the frameworks of semi-detailed magnetometric studies of the Sudetic region (Kosobudzka, Wrzeszcz, 2007; Fig. 5.7.10).

Magnetic tests enable exploration of the distribution of rock medium magnetic properties. In case of the area of Lądek-Zdrój, they will be useful for mapping outcrops of various kinds of rocks buried under the mantle, and to indicate the course of faults (in favourable conditions), which are usually related to fractured zones as well as zones of mineral and geothermal water migrations. An interesting issue, both in terms of extending basic knowledge and for utility applications (e.g. in geothermal systems), will be detailed exploration of magnetic anomalies in the area of basaltoid (basanite) outcrops known in at least three places located near Lądek-Zdrój. Distribution of those anomalies, related to elevated magnetite contents in basaltoids, could be linked to the geometry of intrusive bodies in the substrate, which will be used to solve the problem of the role of young intrusions and magma eruptions in shaping of the local geothermal field.

Grvavimetric studies conducted in the Sudetic region were of regional or semi-detailed nature. The first works of that kind, disregarding studies of historic importance, were performed in 1966 (Okulus 1968). Subsequent measurement works were performed in 1971 and 1973 (Cieśla, Margul 1972; Okulus et al., 1974). Small intensification of measurement works does not enable to use such data for detailed reservoir analyses.

When conducting this project, measurement data were reviewed and transformations allowing separation of fields into regional anomalies and a set of residual anomalies referred to the selected deep levels were calculated (Fig. 5.7.11). In a general sense, one can perceive convergence of the distribution of gravity field anomalies with maps of geological units outcrops, differing with lithological development, and those rock densities.

A special role in the geophysical area exploration, in the context of geothermal water occurrence, is played by surface geothermic studies. They were designed in two complementary methodological variants (Szarszewska, Madej 1974; Ciężkowski et al. 2016):

I. as shallow research probes in boreholes with the depth to 2.5 m,

II. as tests in drilling boreholes with the depth of about 25 m.

Location of research wells under variant II depended, according to the project, on results of tests under variant (stage) I.

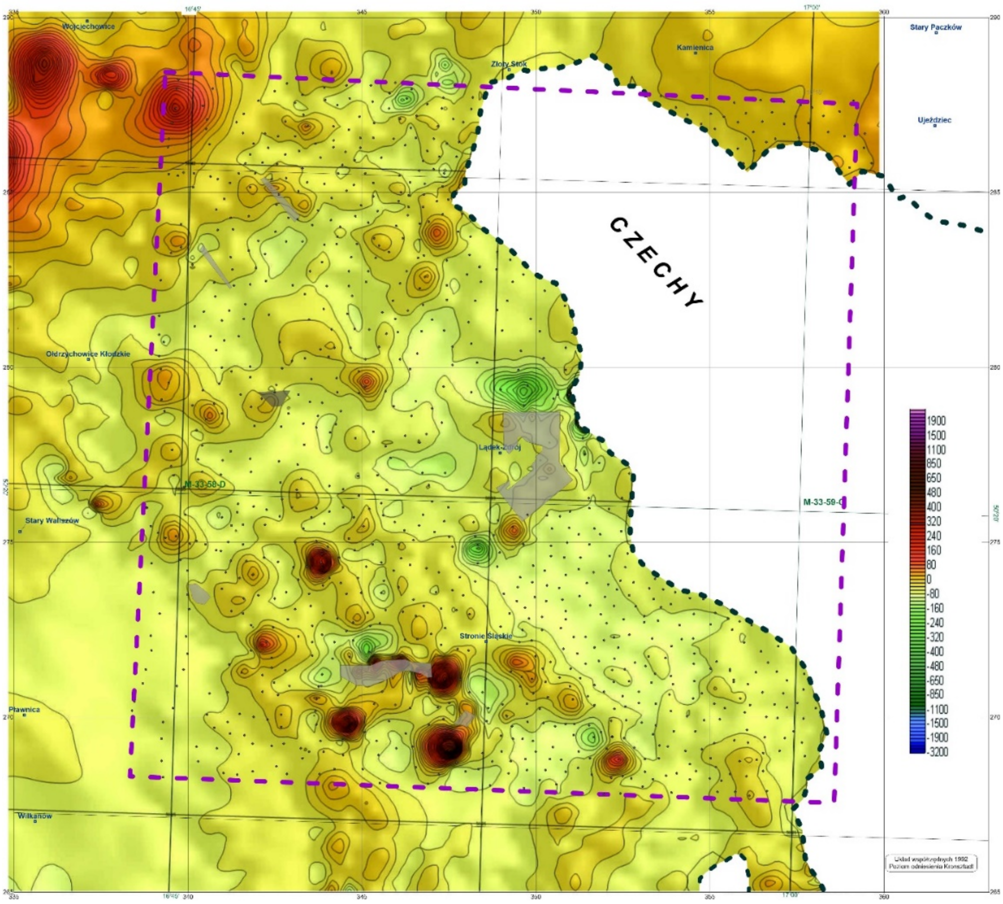


Fig. 5.7.10. Map of anomalies of the total magnetic field, T, for the area of Lądek-Zdrój (developed on the basis of data acc. to Kosobudzka, Wrzeszcz 2007)

Analysis of variant I was conducted in 853 wells made by vibratory hammers in two periods: November 1970 (about 150 probes) and May-August 1971 (about 700 probes). Different geological conditions did not enable to achieve the assumed depth of wells (it was achieved only in case of ca. 10% of probes). As a result, measurements were made in differentiated downhole conditions, within the scope of depths subject to obvious impacts of changes of daily temperatures and climatic fluctuations. As a result, the usefulness of test results for geothermal purposes was questioned (Szarszewska, Madej 1974). Despite control measurements in benchmarking wells no attempt was made to properly reduce the measurement results, due to a too high impact of daily changes on the measured temperatures.

Drilling works and tests in the drilled wells under variant II (stage II) were conducted in 1972 (February-September) (Szarszewska, Madej 1974). 53 wells were drilled with the depth of 25-30 m (some wells were deepened in relation to the designed assumptions). Thermal tests were performed in the complex of radon content measurements and hydrogeological, and they consisted in determining a geothermal gradient (a temperature gradient) (Szarszewska, Madej 1974; Ciężkowski et al. 2016). The result of those tests was to develop a map of thermal anomalies enabling to indicate zones with an elevated temperature, and thus, potential locations of geothermal wells.

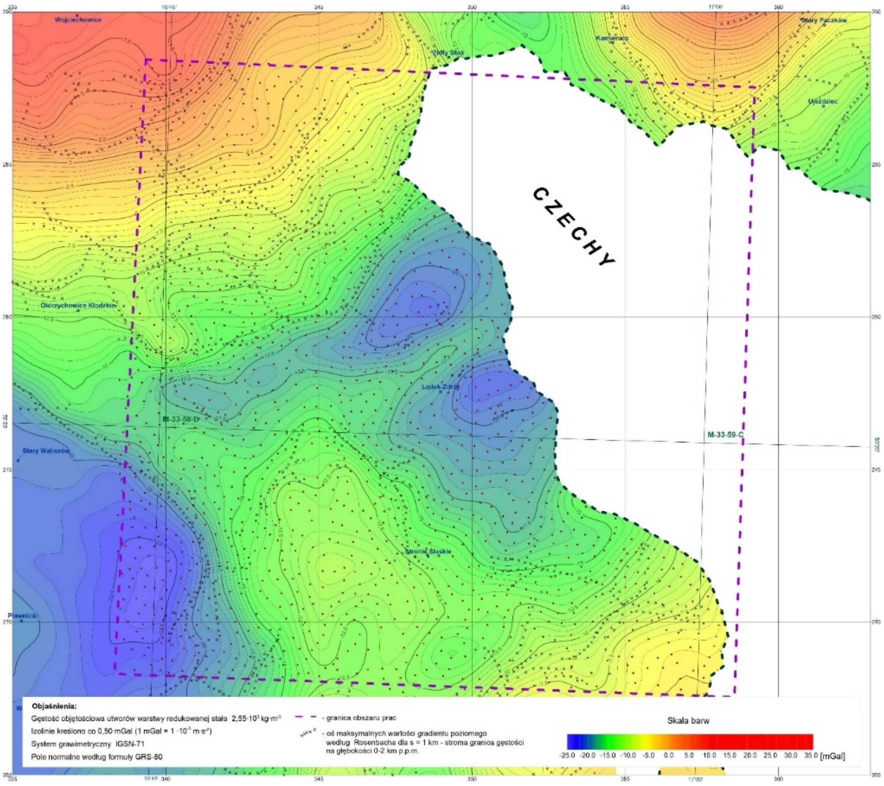


Fig. 5.7.11. Map of Bouguer gravity anomalies in the area of Lądek-Zdrój (developed on the basis of data included in measurements documentations presented in the text below)

Geothermal anomalies were linked to fault zones, which confirms earlier assumptions about geothermal water migrations through fault fractures zones. Distribution of geothermal parameters acquired as a result of tests under stage II, based on 53 measurements performed in relatively regularly distributed measurement points, seems to be fully reliable. The measurements were performed with the preservation of a suitable thermal conditions stability regime in the well surrounding. Nonetheless, the photo covers only a part of the area under consideration, and its density may turn out to be insufficient in the context of assuming a link between temperature anomalies and an ascension migration of heated waters with fault zones. It seems important from both the scientific and utility point of view to extend the territorial scope of the surface geothermal photo and its density. The performance of this undertaking by means of 25-30 metre drillings will be relatively costly, so it is advisable to use the combination of control measurements in benchmarking deeper wells and high-density measurements in shallow wells (3-4 m), with the application of state-of-the-art techniques and measuring methodologies, taking into account the reduction of the impact of daily, weather and seasonal temperature fluctuations. The results of such a photo will enable to determine more precisely the distribution of anomalies in the area of Lądek-Zdrój and to evaluate their extent in Lądek-Zdrój neighbourhood. It will be also possible, with a high dose of probability, to link or exclude a link between thermal anomalies with Neogene vulcanite outcrops occurring in the neighbourhood. New geothermal studies will be of crucial importance for planning further development of the Resort and a wider application of geothermal energy. Another important aspect of such works will be implementation of modern surface geothermal tests, which have been practically absent in Poland for three decades. A special attention in this study is paid to geoelectrical tests performed in the area of Lądek-Zdrój. The first geoelectric tests, in the form of series of geoelectrical sounding (SGE), being a supplement of semi-detailed magnetic tests, were carried out at the end of 1960's and they aimed at exploring tectonics elements (Jagodzińska et al. 1969; Fistek et al. 1975). Another series of geoelectrical soundings, supplemented with VLF (Very Low Frequency) electromagnetic profiling, was performed only in 2005, i.e. after about 30 years (Farbisz 2005) (Fig. 5.7.12). A supplement and a consequence of earlier geoelectrical tests were tests with the use of the continuous magnetotelluric profiling method, made in 2008 (Farbisz, Wojdyła 2008). Profiling by means of the VLF method (radio waves) was used to verify the course and to determine the nature of tectonic zones regarded as potential ways for geothermal waters. On the basis of those works, the courses were verified and the nature of main faults presented on tectonic sketches from this region was determined (Gierwielaniec 1968). It was found out that all studied faults with NW – SE directions, were confirmed in the measurement results, due to an increased intensity of anomalies being recorded (Farbisz 2005). In addition, an anomaly, which can be related to the earlier unknown fault, was mapped. From the point of view of searching for geothermal waters, the faults in Lądek – Gierałtów and Rasztowiec – Karpno (Lądek – Bielice, acc. to. Cymerman 2010) were regarded as the most promising; they present as tectonic zones made up of parallel, branching faults. Tests with the application of the geoelectrical sounding method (SGE) were used to explore the way in which prospective fault zones subside to the depth of about 250-300 m under ground level. Tests by means of the continuous magnetotelluric profiling method in 2008 supplemented earlier geoelectrical works with geophysical tests with a higher depth range (to the depth of 2-3 km) (Farbisz, Wojdyła 2008). Works were performed along three profiles with the total length of 1.9 km, located laterally to the selected sections of tectonic zones, in places with good measurement conditions. Performed profiles were marked: MT-I, with the length of 0.7 km, in the fault zone of Rasztowiec – Karpno, MT-II, with the length of 0.5 km, in the fault zone of Lądek – Gieratów and MT-III, with the length of 0.7 km, in the fault (overlap) zone fo Lądek-Zdrój. The test results were presented in the form of pseudo 2D resistivity deep cross-sections developed on the basis of 1D inversion, acc. to Occam algorithm (Constable et al. 1987). Resistivity contrasts in geological conditions of the Lądek-Zdrój area were linked to lithological differentiation of rock series, high-resistivity gneisses and less resistive metamorphic shales and tectonic phenomena. A typical symptom of tectonic phenomena is a decrease of the electric resistivity value related to rock fracturing and weathering processes, groundwater (including geothermal waters) circulation and frequent occurrence of ore mineralisations. The cross-sections present the most important elements of geological interpretation: determined axes of tectonic zones with vertical subsiding, lateral faults and a possible plane of an overlap relating to the fault (overlap?) of Lądek-Zdrój (Farbisz, Wojdyła 2008). Sections with intense fault zones fracturing, related to abnormally lowered resistivity values with high probability of geothermal water occurrence, particularly at higher depths, were exposed. The results of those tests were used to indicate two deep drilling locations for the purposes of geothermal water intakes (Farbisz, Wojdyła 2008, Ciężkowski et al. 2016).

5.7.2.7 Re-interpretation of magnetotelluric tests

Under the international project titled “Geothermal energy – a basis for low-emission heating, improving living conditions and sustainable development – preliminary studies for selected areas in Poland” detailed reinterpretation of magnetotelluric data was performed, including interpretation of gravimetric data. Within the scope of re-interpretation works, the measurements works were reviewed, procedures and results of measurement data processing were verified as well as sounding curves interpretation was checked and extended. An earlier 1D inversion of sounding curves, selected with regard to measurement system orientation, was extended with the analysis of dependence between the inversion results of 1D magnetotelluric data and the measurement system orientation in relation to the extent of geological structures. In addition, multiple option inversion 2D modelling was performed. Those analyses were to extend the expertise about in-depth geological structure of the Lądek – Zdrój area and to verify the earlier test results and tectonic concepts.

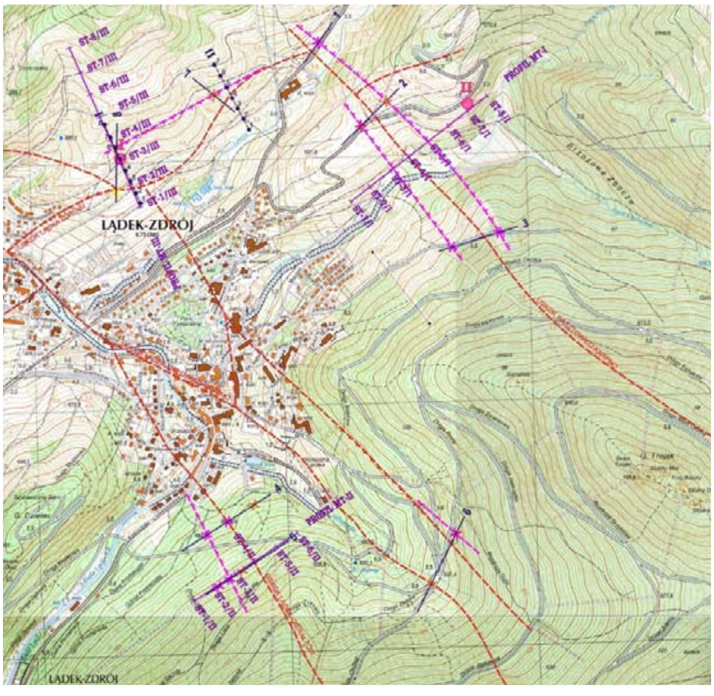


Fig. 5.7.12. Location of geoelectric tests on the topographic map, scale: 1:50 000
(acc. to Farbisz, Wojdyła 2008, amended)

Field magnetotelluric tests

Magnetotelluric data were acquired along three continuous profiles (Figs. 5.7.12, 5.7.13, 5.7.14, 5.7.15), with the application of the 2000.net system made by a Canadian company called Phoenix Geophysics Limited, in a high frequency variant called the audio magnetotellurics method (AMT) from the range of a recorded natural field. Measurement insutrments on the profile consisted of three V8-6R receivers, two RXU-3ER receivers and a set of AMTC-30 magnetic coils, as well as electric measurement dipoles grounded by means of non-polarizable electrodes (Fig. 5.7.16.). Measurements consisted in recording timelines of natural electromagnetic field components in the band from 0.1 - 10 000 Hz. Electromagnetic field oscilations within this range are generated by distant atmospheric discharges. The basic AMT measurement system at particular profile positions consisted of a V8-6R receiver and/or a RXU-3ER receiver, which enabled concurrent recording of an audio-magnetotelluric field by means of two pairs of mutually perpendicular electric dipoles Ex, Ey, which were 100 m long, and three AMTC-30 magnetic sensors to measure Hx, Hy, Hz components, respectively, located near the centre of the electric dipoles line (Fig. 5.7.16.). Electric dipoles were made of a shielded cabel and a pair of grounding in the form of PE4 non-polarizable electrodes (Pb/PbCl2). Two electric lines and magnetic sensors were connected to the V8-6R receiver, whereas two additional electric lines were connected to the RXU-3ER receiver. In order to eliminate the impact of electromagnetic intereference the measurements were performed in two points with the so-called remote reference point (a reference point), where electric and magnetic components were recorded. A reference point was located in Chyrowa Village near Przemyśl. As a result of applying the above-described measurement system, two pairs of electric components were recorded on the profile point: Ex, Ey; two horizontal and one vertical magnetic component on the profile point: Hx, Hy, Hz; two electric components on the reference point: Ex–r, Ey–r and two magnetic components on the reference point: Hx–r, Hy–r (Fig. 5.7.16.). Standard recording time in a single measurement point was about 8 hours.

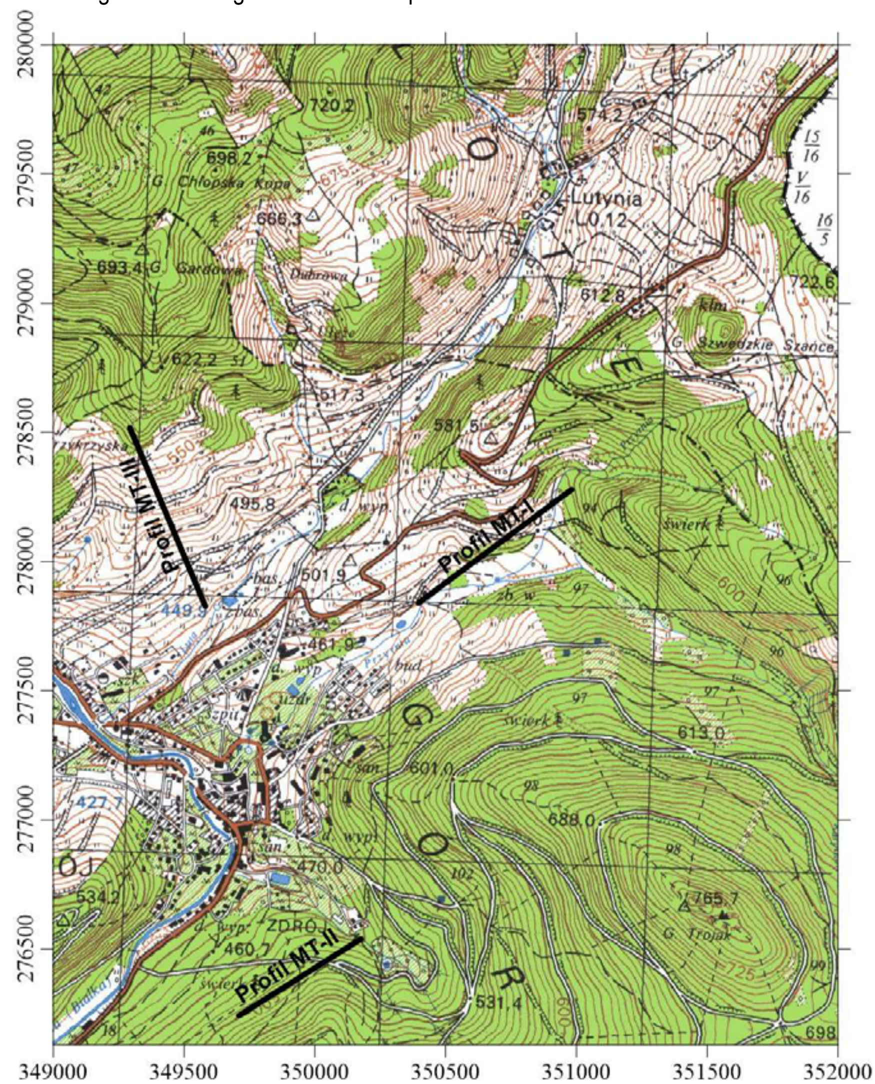


Fig. 5.7.13. Location of magnetotelluric profiles in the area of Lądek-Zdrój on the topographic map, scale: 1:25 000

Recordings of timelines were conducted independently in three frequency ranges with sounding frequencies of 24000 Hz, 2400 Hz and 150 Hz, respectively. Timelines in the first two bands were recorded in 0.1 second long records, whereas timelines from the third band were recorded continuously, which enabled obtaining the impedance value in the lower frequency range of the audiomagnetotelluric band. Synchronous recordings on field points and on the reference point provided input data for processing. Surveying works as well as calibration of the measurement instruments and magnetic field sensors were of standard nature.

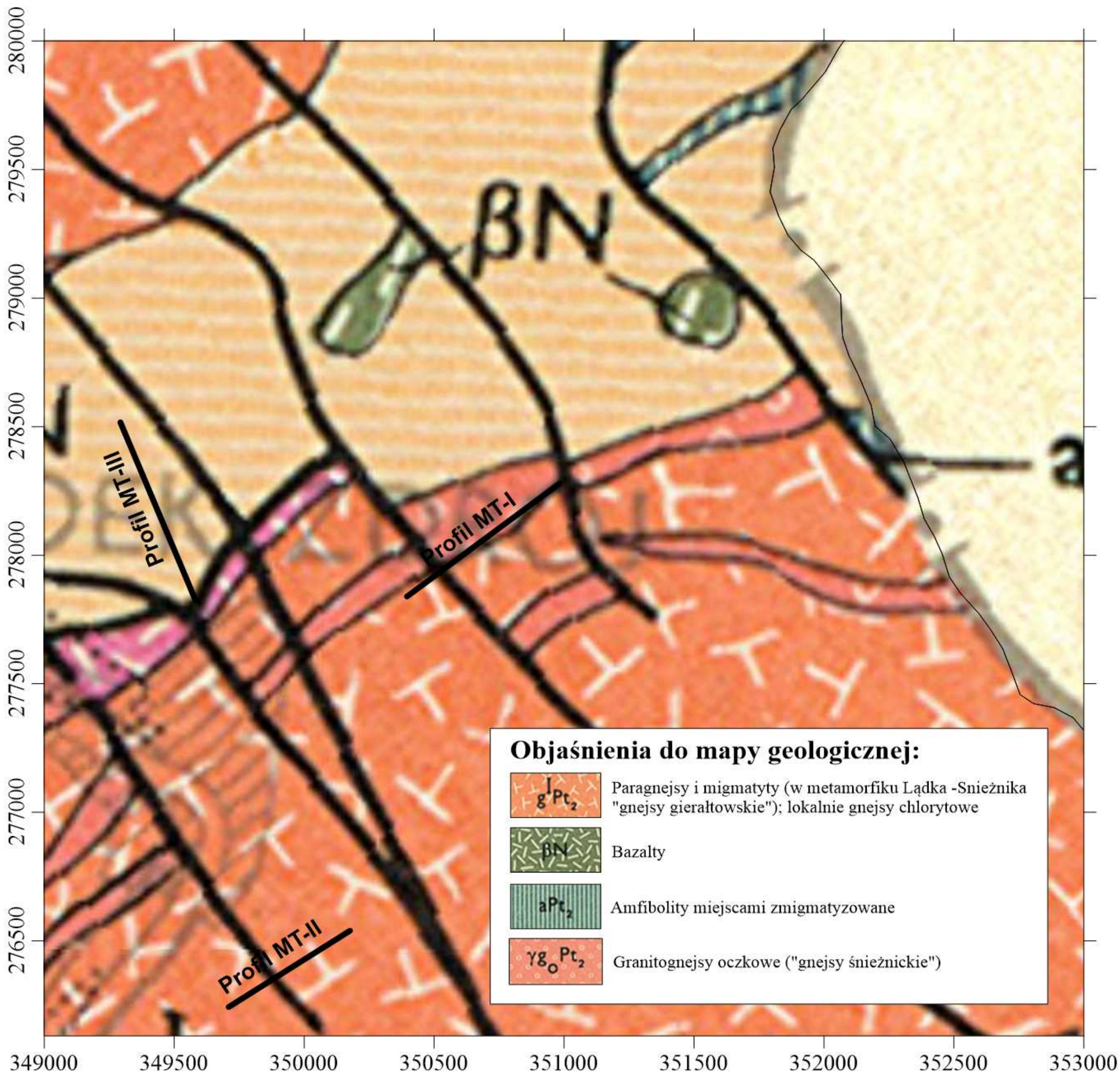


Fig. 5.7.14. Location of magnetotelluric profiles in the area of Lądek-Zdrój on the geological map of Poland (scale: 1:200 000, Kłodzko sheet)

Magnetotelluric data processing

Recorded timelines were the subject of numerical processing. Both in case of the primary processing (in 2008) and processing performed under this reprocessing project, robust reference procedures were used and implemented to SSMT2000 software made by Phoenix Geophysics Ltd. Robust processing is a statistical, iterative procedure to calculate impedance tensor components and other magnetotelluric parameters based on the smallest squares method. During data processing with the application of robust estimators, data related to noises, the distribution of which is different from ordinary distribution and a small amount of which may burden considerably the parameter being estimated, are identified and removed.

In data processing we can distinguish the following stages:

- grouping of measurements files in synchronised time groups,
- visual verification of data – selection in the time domain,
- calculation of Fourier transform for parts of field and reference timelines with the application of Fast Fourier Transform (FFT),
- construction of a parametric set for data processing by means of the robust method,
- data processing – estimation of impedance tensor components.

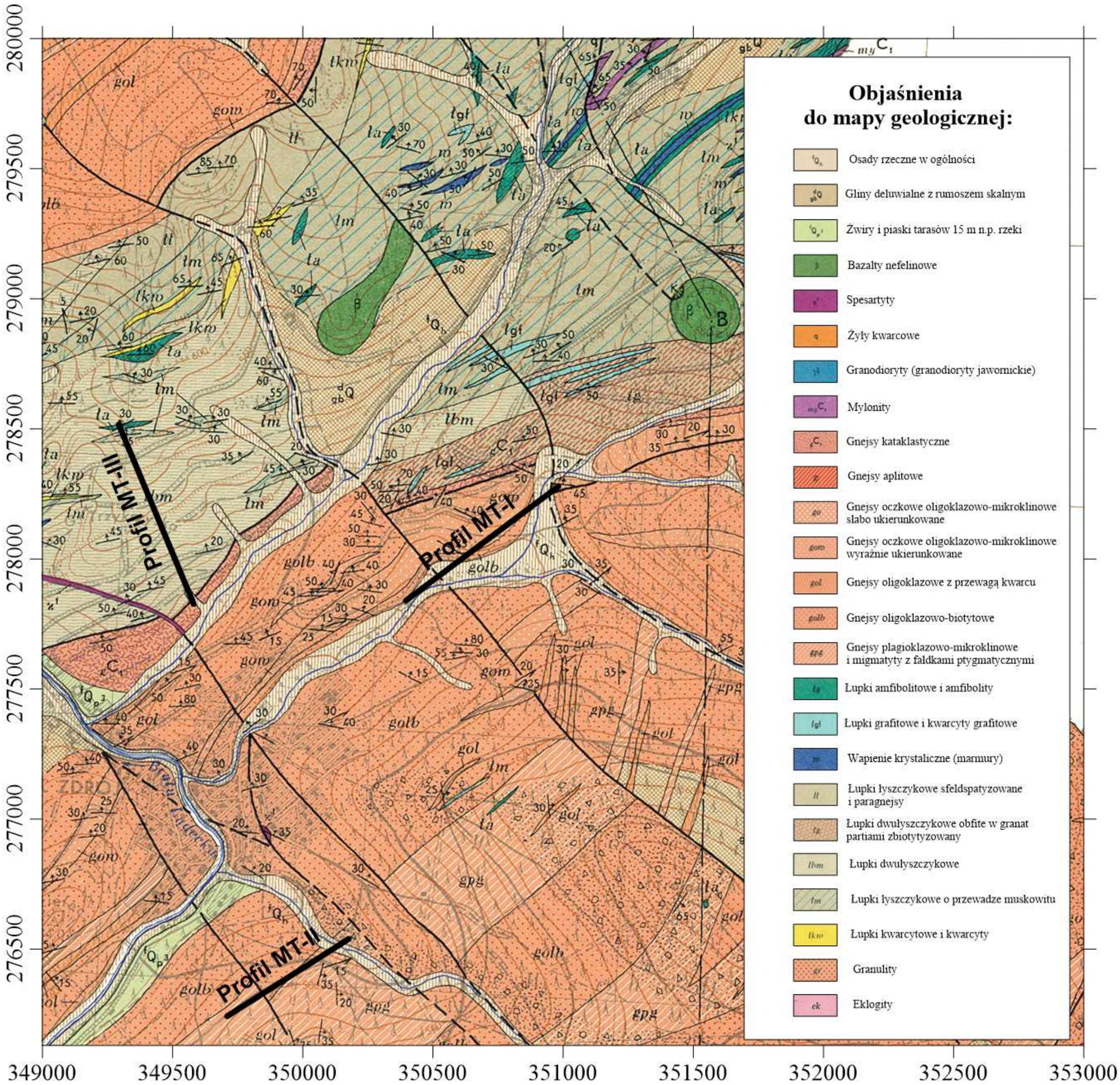


Fig. 5.7.15. Location of magnetotelluric profiles in the area of Lądek-Zdrój on the geological map of Poland (scale: 1: 25 000, Lądek-Zdrój sheet)

.

Estimated impedance tensor components were used to calculate sounding curves (amplitude and phase ones) and to edit their particular spectral components with the use of MT-Editor computer program (Phoenix Geophysics software), as well as to draw impedance directional diagrams and parameters of tensor impedance skew (Fig. 5.7.17, 5.7.17a). The initial set is magnetotelluric data recorded in the international SEG-Edi format, which are the subject of interpretation processing (geophysical interpretation).

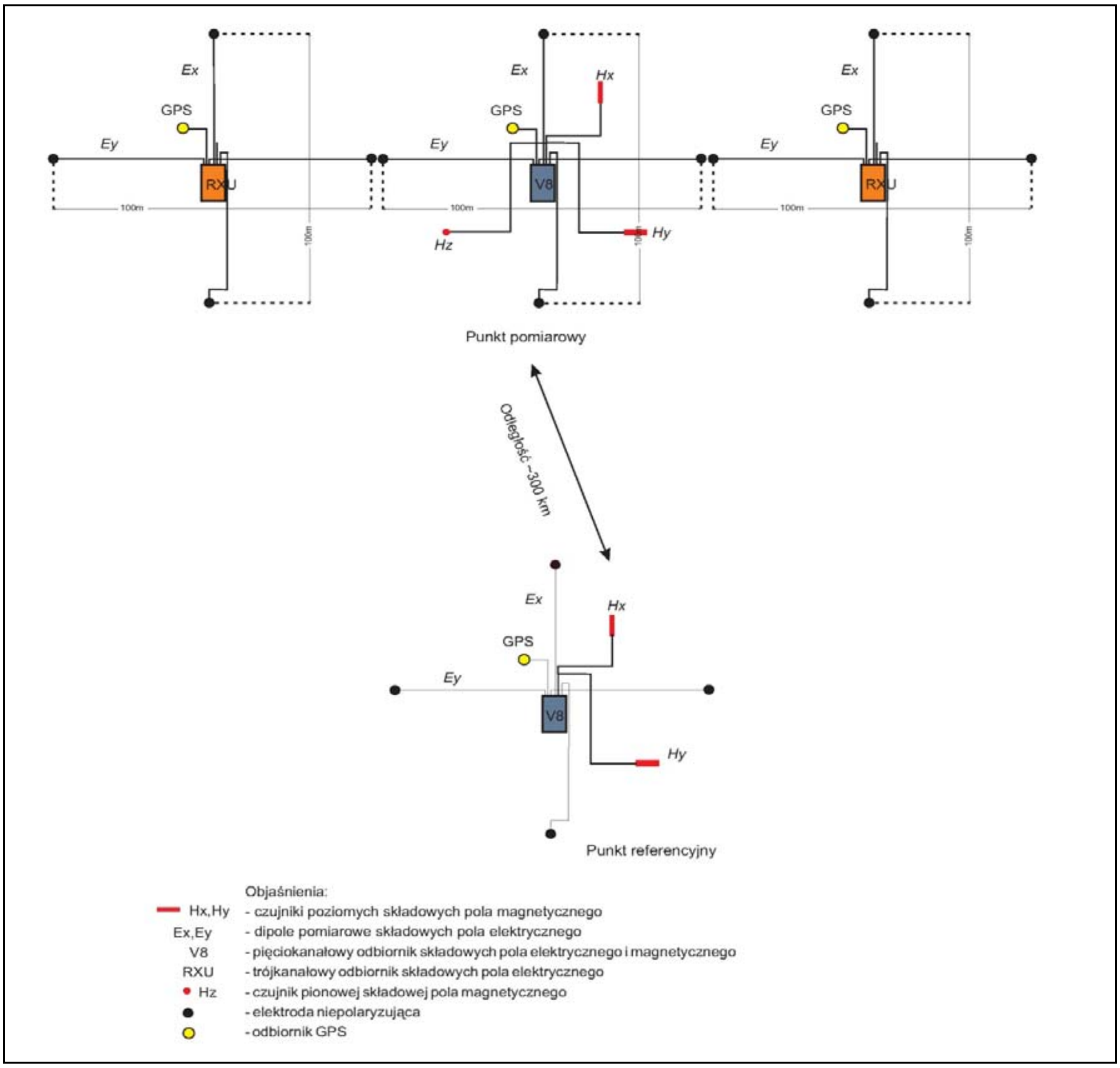


Fig. 5.7.16. Diagram of the AMT/MT measurement system in the continuous profiling version

Geophysical re-interpretation of magnetotelluric soundings

Sounding curves and impedance directional diagrams were the subject of re-interpretation with the application of interpretation procedures included in WinGLink software made by Geosystem srl. Introduction to the quantitative interpretation was qualitative analysis of the results of measurement data processing. It aimed at tracing variability of the curve shape along profiles, determining zones with a high level of interference, meaning areas of lower interpretation reliability, specifying the depth range for the AMT method, and defining the nature (1D, 2D, 3D) of the geoelectric medium. Figs. 5.7.17 and 5.7.17a present examples of magnetotelluric curves from different profiles and for different measurement system orientation. Fig. 5.7.17 presents sounding curves for the measuring orientation, i.e. “x” components are parallel to the measuring profile, whereas „y” components are perpendicular to it. The analysis of the mutual curve arrangement for “xy” and “yx” orientations enables stating methodologically improper LZ1 i LZ2 profiles location in relation to geological structures, making it difficult to apply effectively the 2D inversion procedures and introducing additional errors to the results. On the other hand, the LZ3 profile is oriented properly; in this case, “xy” orientation curves are located above “yx” curves and they meet, in general, the conditions of TM magnetic polarisation (“yx” curves correspond to TE polarisation).

Reprocessing - examples of magnetotelluric sounding curves

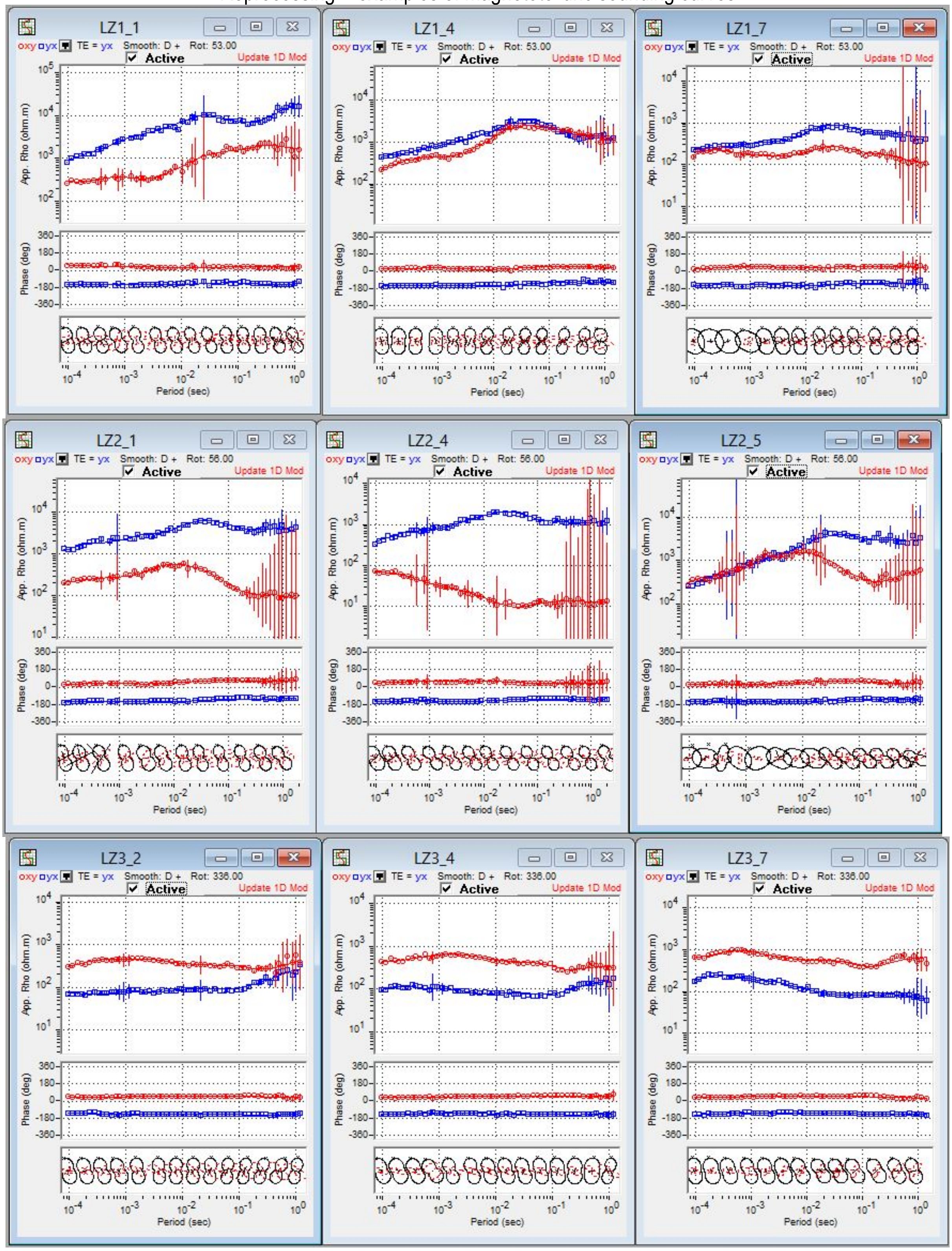


Fig. 5.7.17. Examples of magnetotelluric sounding curves for the rotation of the measurement system for the azimuth of the measurement profile

Reprocessing - examples of magnetotelluric sounding curves

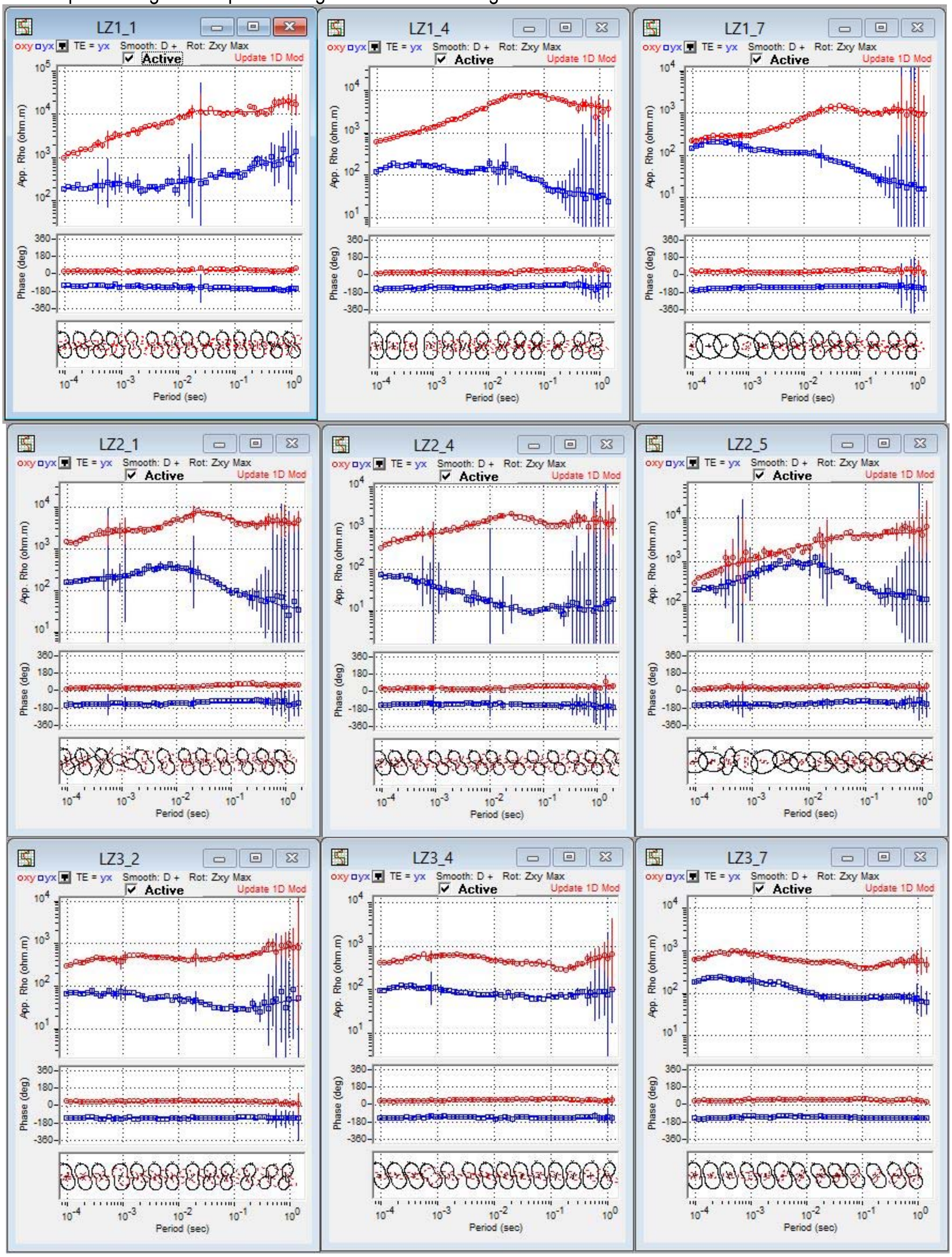


Fig. 5.7.17.a. Examples of magnetotelluric sounding curves for the rotation of the measurement system to the Zxy Max direction

This remarks is confirmed by mutual location of curves rotated to the direction of maximum impedance (Fig. 5.7.17a), which are only slightly corrected towards curves in the measuring orientation (Fig. 5.7.17). For LZ – 1 and LZ – 2 profiles, the shapes of sounding curves and mutual location of „xy" and „yx" curves after rotation to the direction of the maximum impedance change drastically, which proves three dimensionality of the geoelectric medium (Fig. 5.7.17a). Visible discrepancies in the shape of measurement curves for different measurement system rotations, and a different curve course with the “xy” orientation towards “yx” orientation proves high complexity of the geological structure in the study area. From the geoelectrical point of view, it is a 2D and 3D medium. Such a conclusion is confirmed by the arrangement of directional impedance diagrams visible in lower parts of the figures. On the other hand, from the data quality point of view, one can state that in the recorded frequency ranges they are mainly of good and very good quality.

Quantitative 1D interpretation of sounding curves

1D interpretation was performed by means of the Occam algorithm, which consists in computer approximation of 1D resistivity distribution in the geological medium on the basis of amplitude and phase sounding curves (Constable et al. 1987). The basic assumption of this method is to try to obtain as liquid solution as possible. As a result, resistivity distribution in the geological medium is generalised and deprived of clear contrasts. In practice, starter model is assumed in the form of a horizontally stratified medium with strata thicknesses growing regularly with depth, in accordance with the logarythmic scale. The error function minimisation procedure, describing discrepancy of measurement data, calculated for the assumed model, was constructed in such a way that resistivity gradients are minimum. As a result, for the a priori assumed number of strata in the starter model, their resistivities are subject to changes. An undeniable advantage of this method is its full automation. Interpretator’s interference boils down to data preparation, introduction of the number of strata and determination of the interpretation depth interval. Figs. 5.7.18 - 20 and 5.7.18a - 20a present geoelectrical 1D sections according to the Occam algorithm for different orientations of the measurement system (different polarisations). An electromagnetic picture obtained in this way, along the same section for the TE electric polarisation and TM magnetic polarisation (curves rotated to Zmin and Zmax directions, respectively) is clearly different, which obviously relates, as already mentioned above, to high complexity of the geological structure of the study area. That is why, models based on 1D inversion should be rather treated as initial or starter models, for 2D inversion. The conclusion can be drawn from the analysis of 1D geoelectrical sections for TM magnetic polarisation (Fig. 5.7.18, 5.7.19, 5.7.20.) that relatively low resistivity values occur along profile 3. In the prevailing part, those resistivities range from 200 to about 1000 Ωm. On the other hand, 1 and 2 sections are generally characterised by high and very high resistivity values, of about several thousand Ωm. Lower resistivity values along profiles 1 and 2 occur only in the near-surface part of sections. Geoelectrical sections made on the basis of 1D inversion, according to the Occam algorithm, in case of TE electrical polarisation (Fig. 5.7.18a, 5.7.19a, 5.7.20a.) are characterised by resistivity ranging from several up to several hundred Ωm. It should be also emphasised that those values are much lower (from one order up to even two orders of magnitude) than the resistivity values observed at sections obtained on the basis of 1D inversion, according to the Occam algorithm, in case of TM magnetic polarisation.

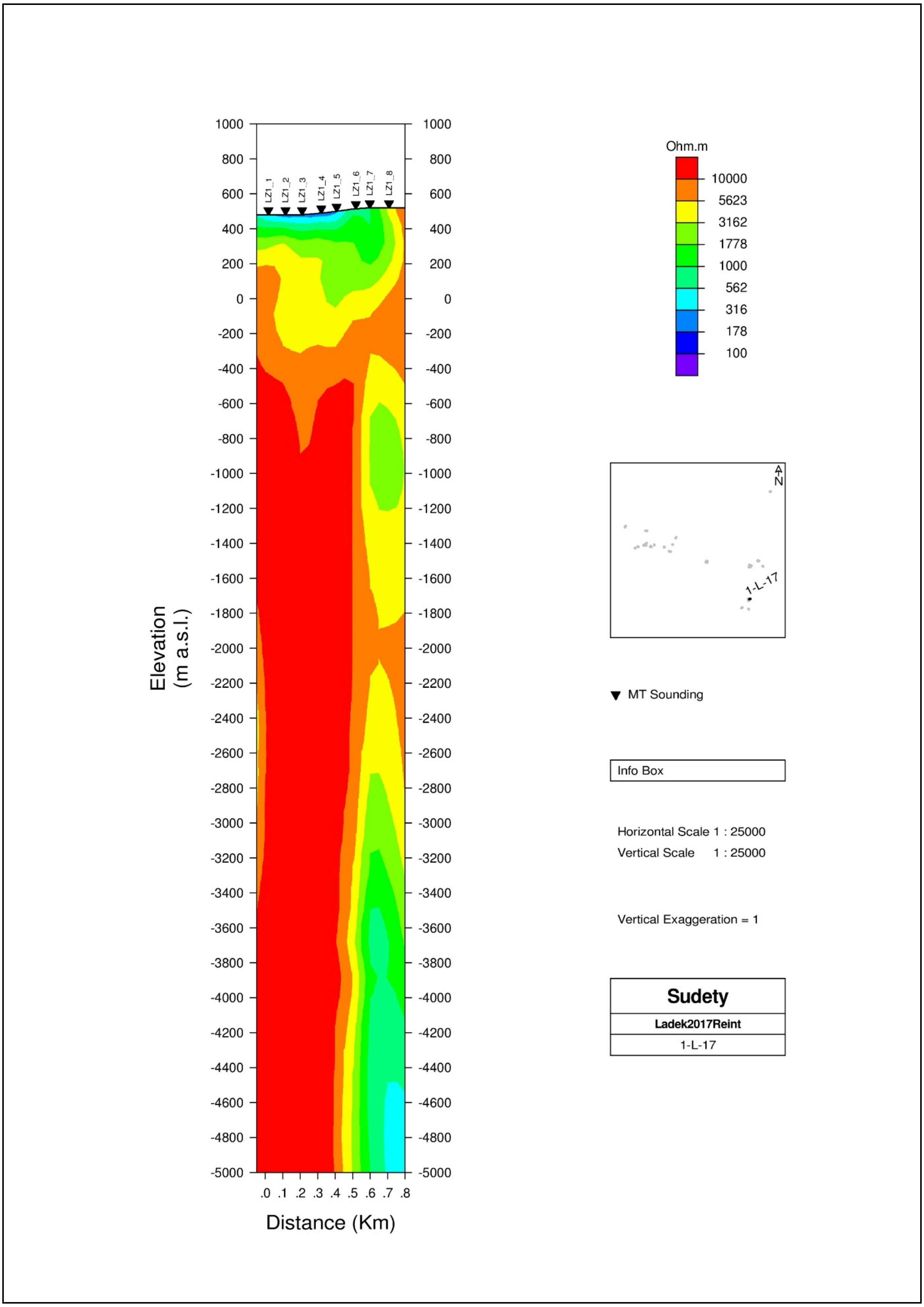


Fig. 5.7.18. Resistivity distribution along profile 1 based on 1D inversion, according to Occam algorithm for TM magnetic polarisation

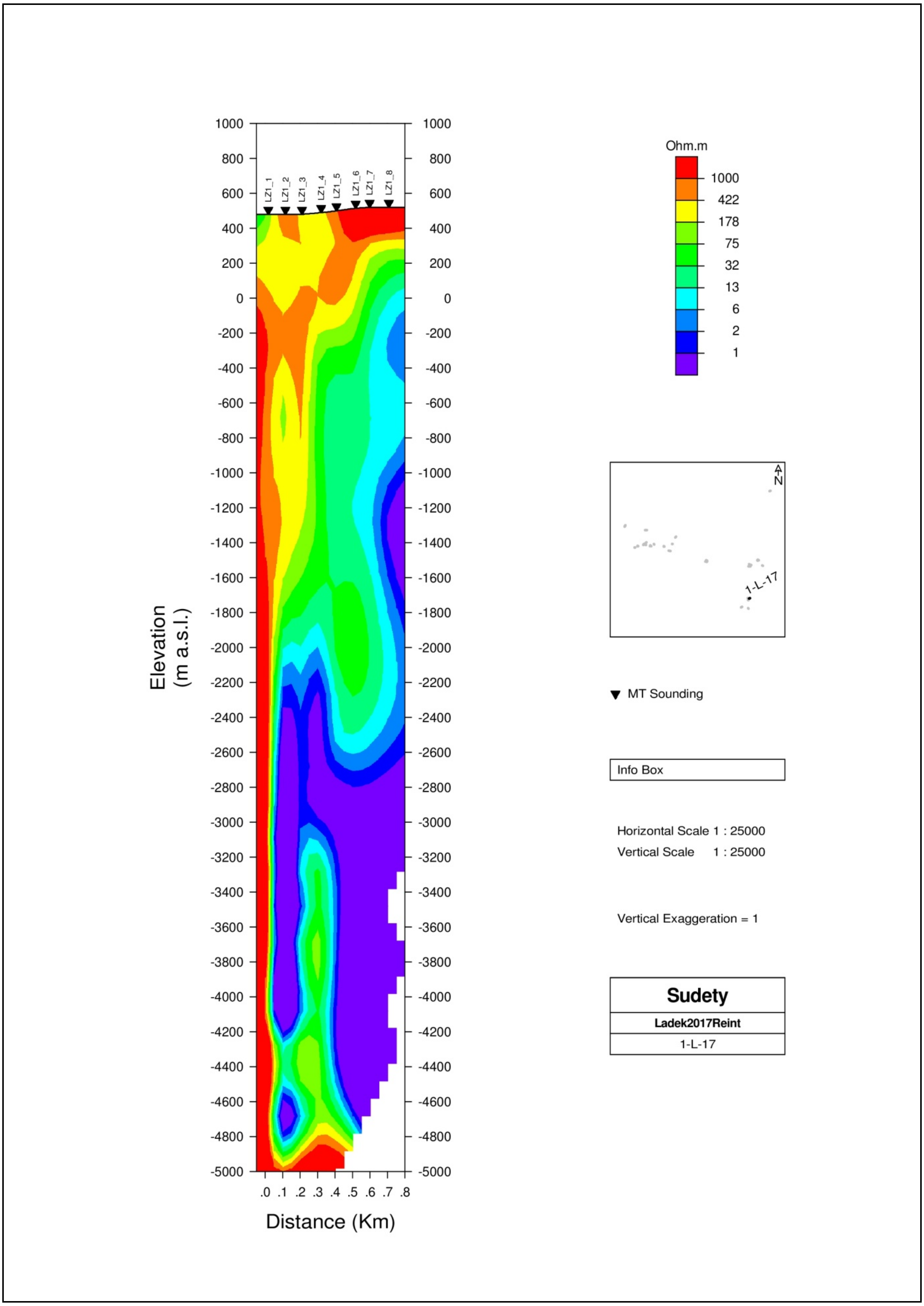


Fig. 5.7.18.a. Resistivity distribution along profile 1 based on 1D inversion, according to the Occam algorithm for TE electrical polarisation

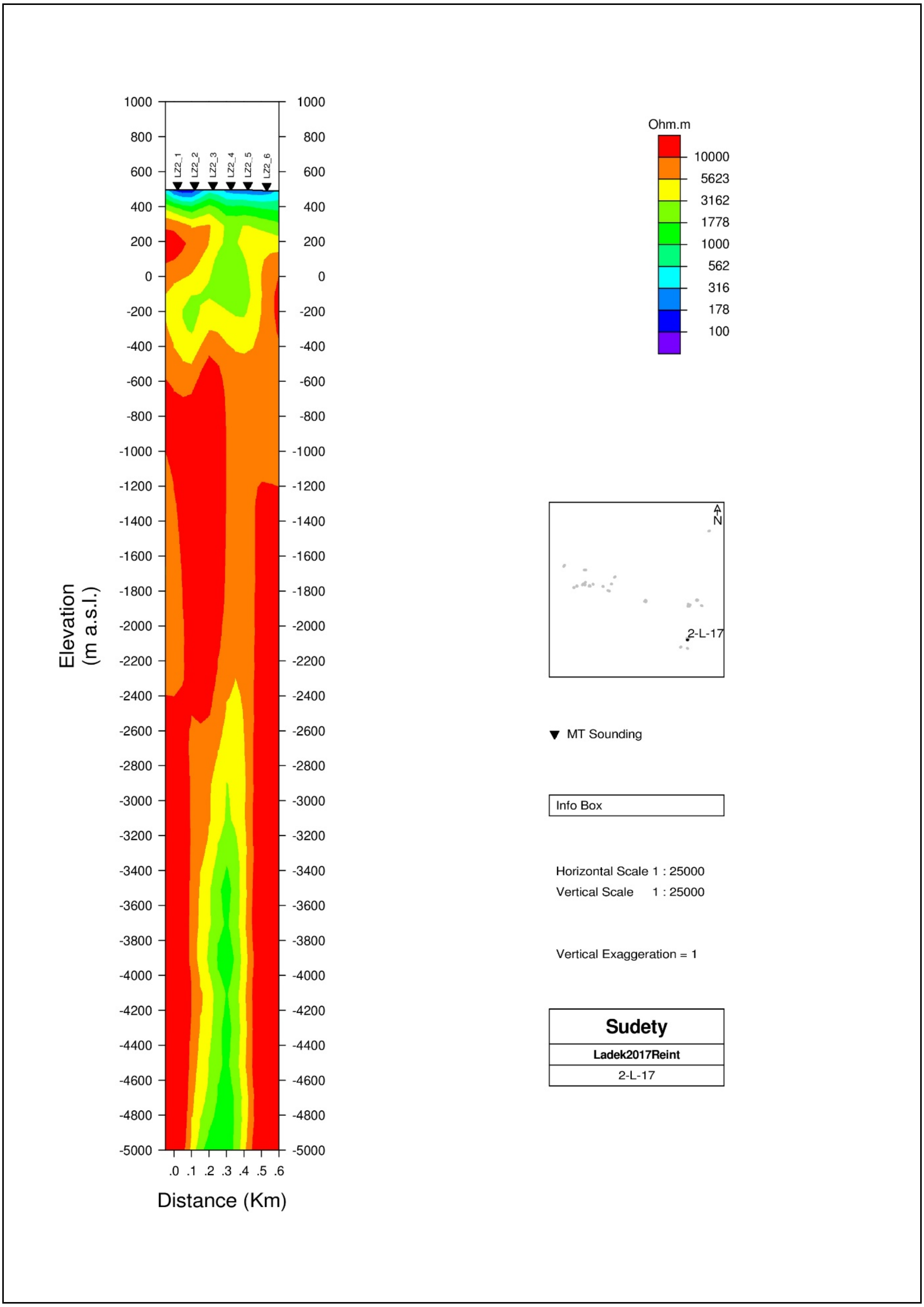


Fig. 5.7.19. Resistivity distribution along profile 2 based on 1D inversion according to the Occam algorithm for TM magnetic polarisation

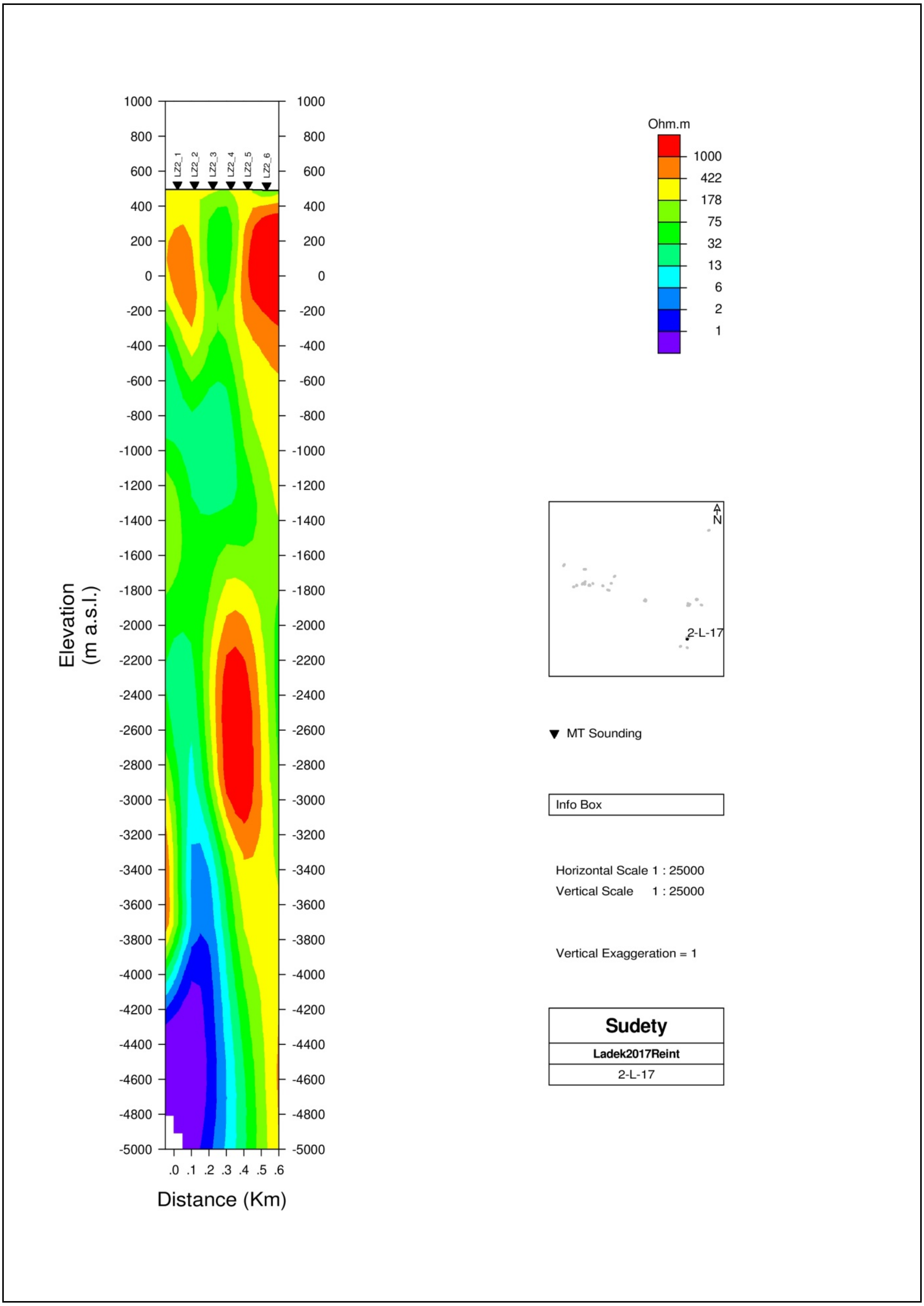


Fig. 5.7.19.a. Resistivity distribution along profile 2 based on 1D inversion, according to the Occam algorithm for TE electrical polarisation

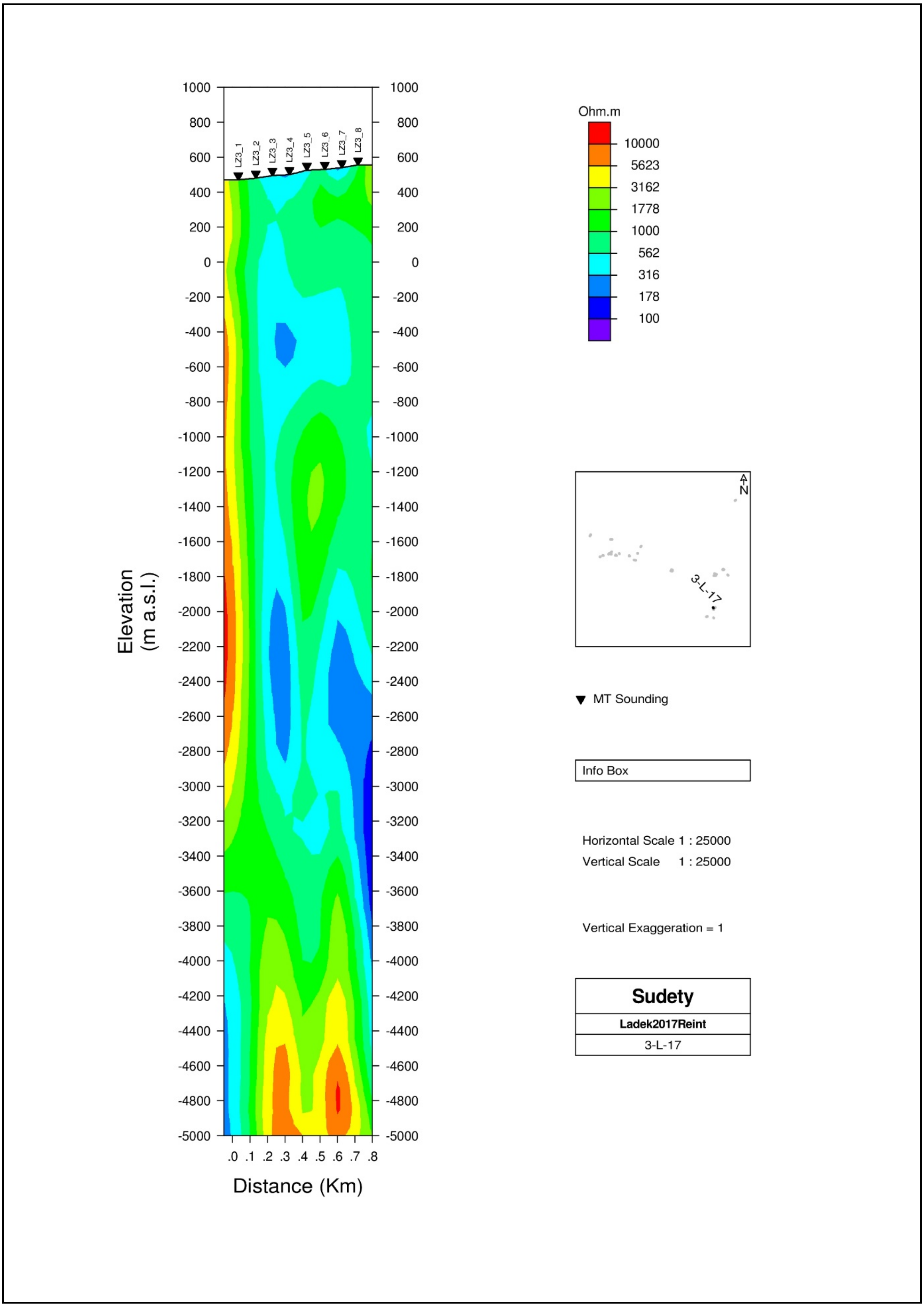


Fig. 5.7.20. Resistivity distribution along profile 3 based on 1D inversion, according to the Occam algorithm for TM magnetic polarisation

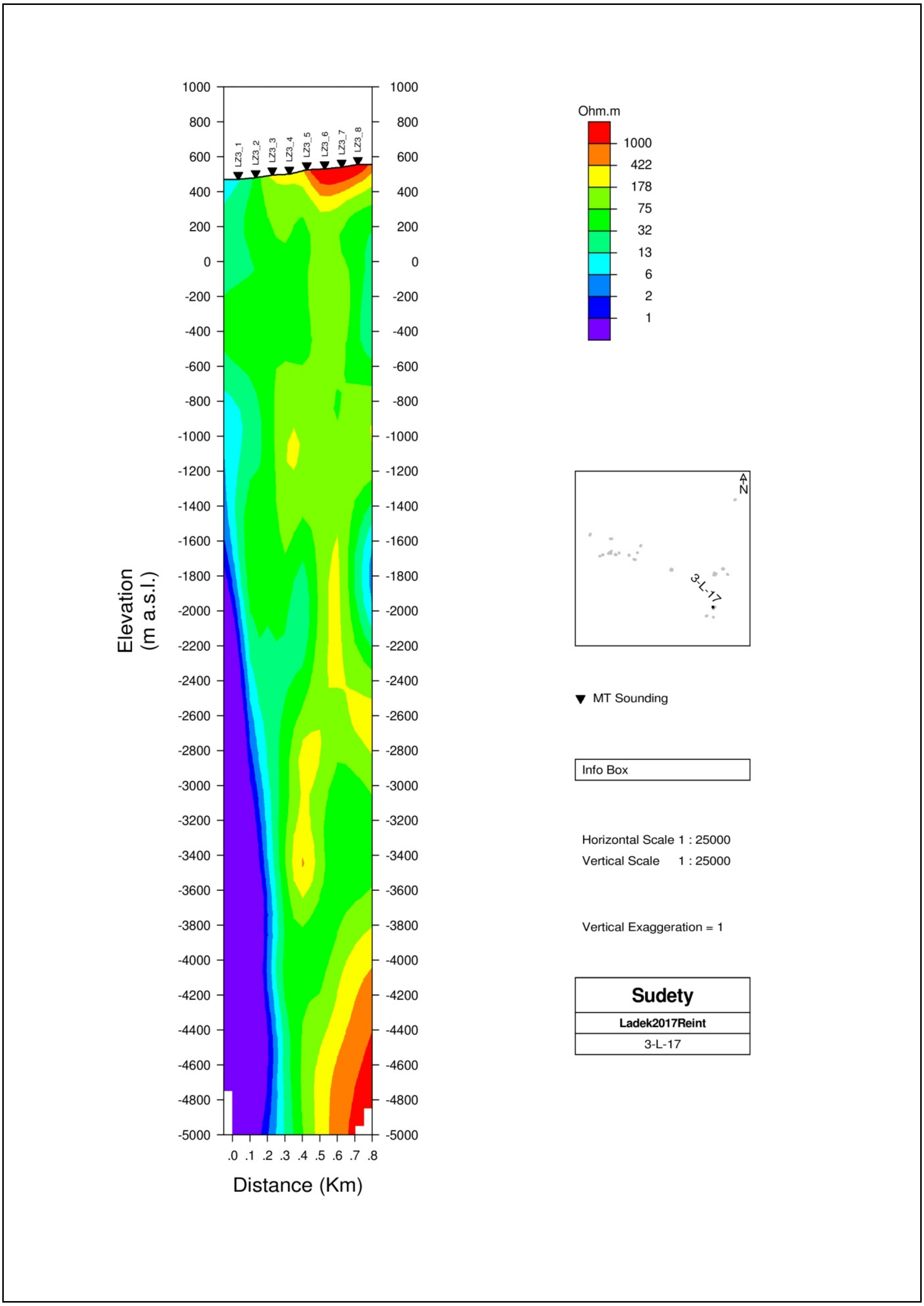


Fig. 5.7.20.a. Resistivity distribution along profile 3 based on 1D inversion, according to the Occam algorithm for TE electrical polarisation

Quantitative 2D interpretation

2D interpretation was performed with the application of the NLCG algorithm, consisting in iterative adjustment of a 2D geoelectric medium to amplitude and phase measurement curves, by means of the nonlinear conjugate gradient method (Rodi & Mackie 2001). The error function describing summaric discrepancy between empirical data and data calculated theoretically for the model, is minimised in subsequent iterative steps, leading to gradual modification of the starter model. In its assumption, the NLCG method aims to reach a smoothened model. The degree of smoothing is specified before the beginning of the inversion process by the attenuation parameter τ. Higher τ gives as a result a more smoothened model at the expense of poorer adjustment of measured curves in relation to the model ones. In order to obtain the optimum solution, a 2D inversion was performed for a series of starter models with variable attenuation parameters. The solution to the inversion issue is ambiguous, i.e. there are a number of different models, which can be adapted to empirical data with satisfactory precision. In this situation, what is essential for proper program utilisation is suitable imposition of ties making the obtained solution more realistic, and suitable initial conditions in the form of a starter model. Such a model can be a homogenous half-space (the simplest model) or a more or less complex 2D geoelectrical model. Introduction of a model close to the reality limits the scope of changeability of its parameters in the minimisation process and it usually leads to good solutions. An additional factor improving the quality of the resultant model is ties in the form of constant values of the selected parameters or limitation of the scope of their variability. A good solution, particularly in case of relatively flat geoelectrical models is to limit variability of geoelectrical layers parameters for meshes covering drilling wells. Layer thicknesses and resistivity stipulated on the basis of the interpretation of drilling electrometry profiling usually show well a real geoelectrical model and impose a proper solution to the inversion issue.

In the study area there are no drilling wells near magnetotelluric profiles based on which it would be possible to construct a starter model, so sections from 1D inversion were used to build it. Calculations for all sections were performed at the same time, namely, TE electrical polarisation, TM magnetic polarisation and the tipper parameter (Fig. 5.7.21, 5.7.22, 5.7.23.). Measurement curves were used after impedance tensor rotation to the Zxy max direction, with the range of frequencies from 10400 Hz to 1 Hz (AMT band). The algorithm to remove a disturbing impact of near-surface heterogeneities was also used, which was available in the interpretation system being used. The root mean square, R.M.S., calculated for resultant models was: for section 1: 2.73, for section 2: 3.47, for section 3: 2.12. In case of profiles nos. 1 and 2, the rotation of sounding curves for the Zmax and Zmin orientations generates a fictitious quasi – 2D medium, locally compliant with the geological structure, yet introducing uncontrollable errors to the results of 2D inversion. It illustrates a comparison with 2D inversion results for curves with the measuring orientation (Figs. 5.7.24, 5.7.25.), for which 2D conditions of the medium model are not met at all. It is difficult to evaluate which method generates inversion results closer to geological reality.

It stems from 2D geoelectrical sections (Figs. 5.7.21, 5.7.22, 5.7.23.) that along profile 3 there are completely different rocks than along profiles 1 and 2. Sections 1 and 2 are high resistivity values within which less resistive anomalies occur. Along profile 1 there are three such anomalies: the first one in the central part of the cross-section at the level from 100 to -200 m above sea level, the second and the third one in the final part of the cross-section at the level from -500 to -1200 m above sea level and form 3 to 5 km under seal level. (Fig. 5.7.21). The zone with lowered resistivity values occurs also in the central part of cross-section 2 at the level from 200 to -200 m above sea level (Fig. 5.7.22). From the point of view of geothermal studies, anomalies on profiles 1 and 2, as well as the area of profile 3 seem to be interesting, where rocks with lowered resistivity prevail (Fig. 5.7.22). However, we cannot exclude that the anomalies described on profiles 1 and 2 are the effect of lateral reflections of rocks, which are relatively less resistive and which occur north of profiles 1 and 2, marked on profile 3. Explanation of those doubts would be possible after making additional magnetotelluric profiles (or a profile) with the azimuth close to profile 3, but much longer – covering with tis range both the area of rocks with lower resistivity, located north of Lądek and the area of rocks with high resistivity, occurring south of that town. A still better solution would be to make a 3D magnetotelluric photo.

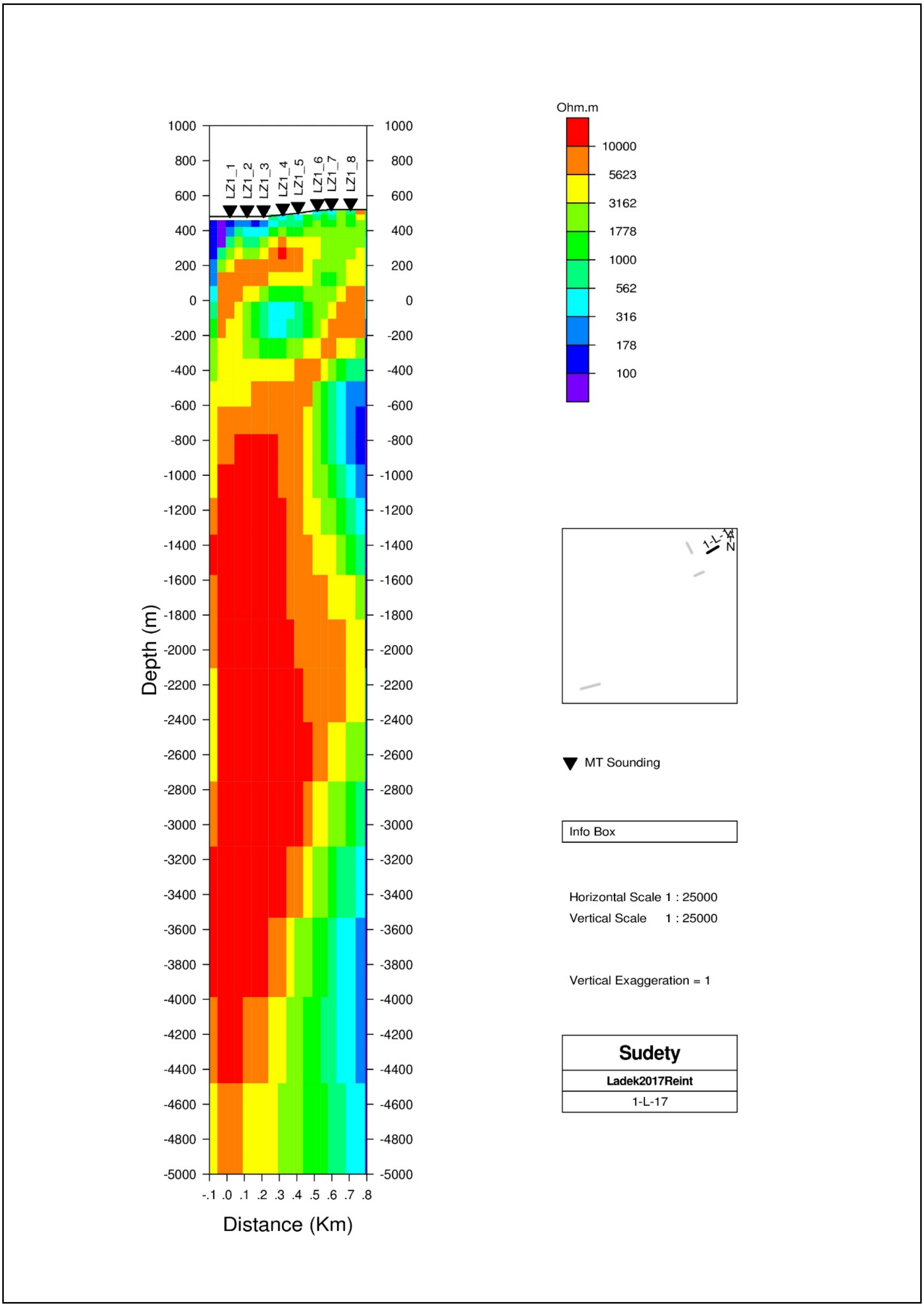


Fig. 5.7.21. Resistivity distribution along profile 1 based on 2D inversion NLCG, curves rotated to Zmax. and Zmin. orientations

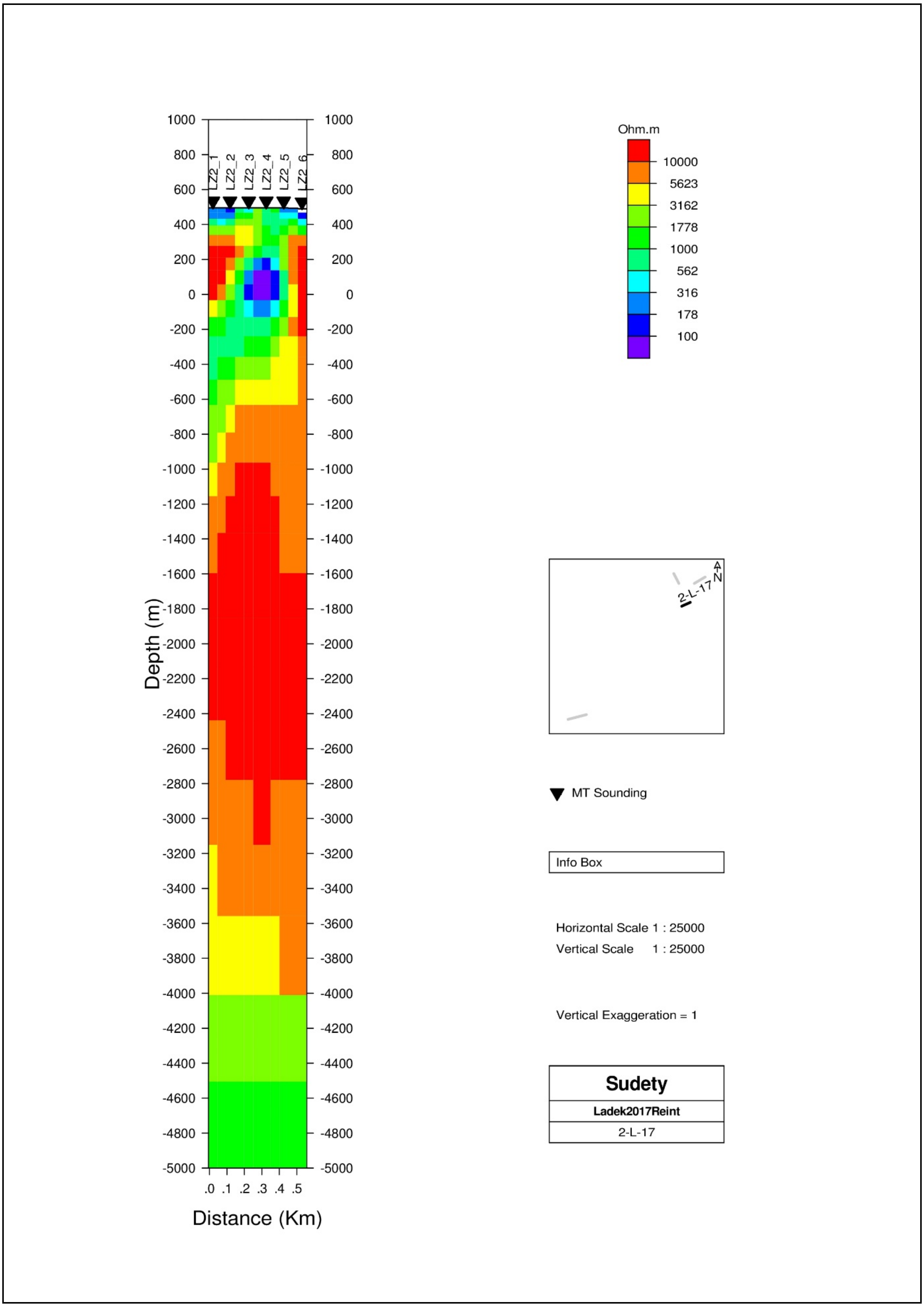


Fig. 5.7.22. Resistivity distribution along profile 2 based on 2D inversion, NLCG, curves rotated to Zmax and Zmin orientations

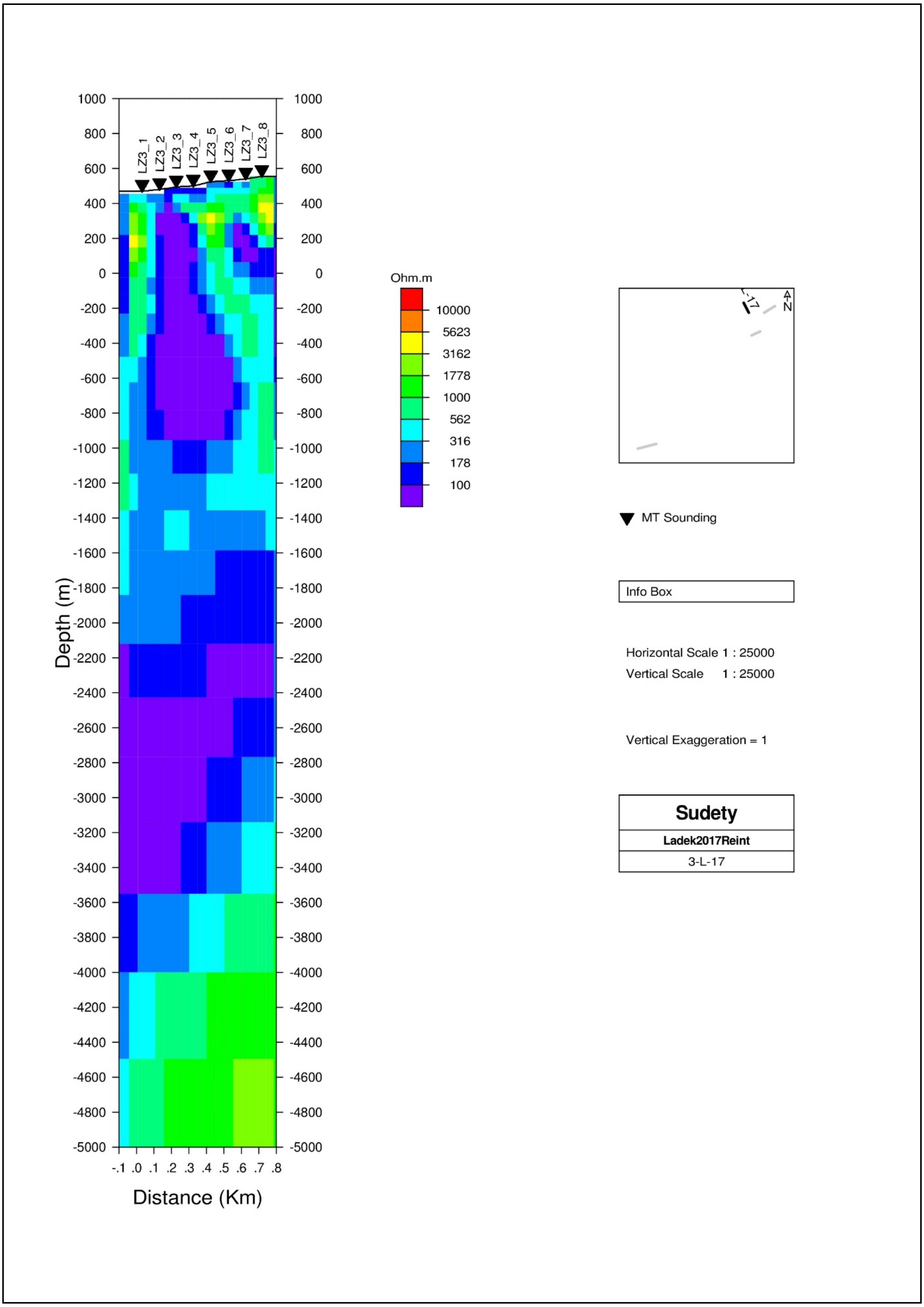


Fig. 5.7.23. Resistivity distribution along profile 3 based on 2D inversion, NLCG, curves rotated to Zmax and Zmin orientations

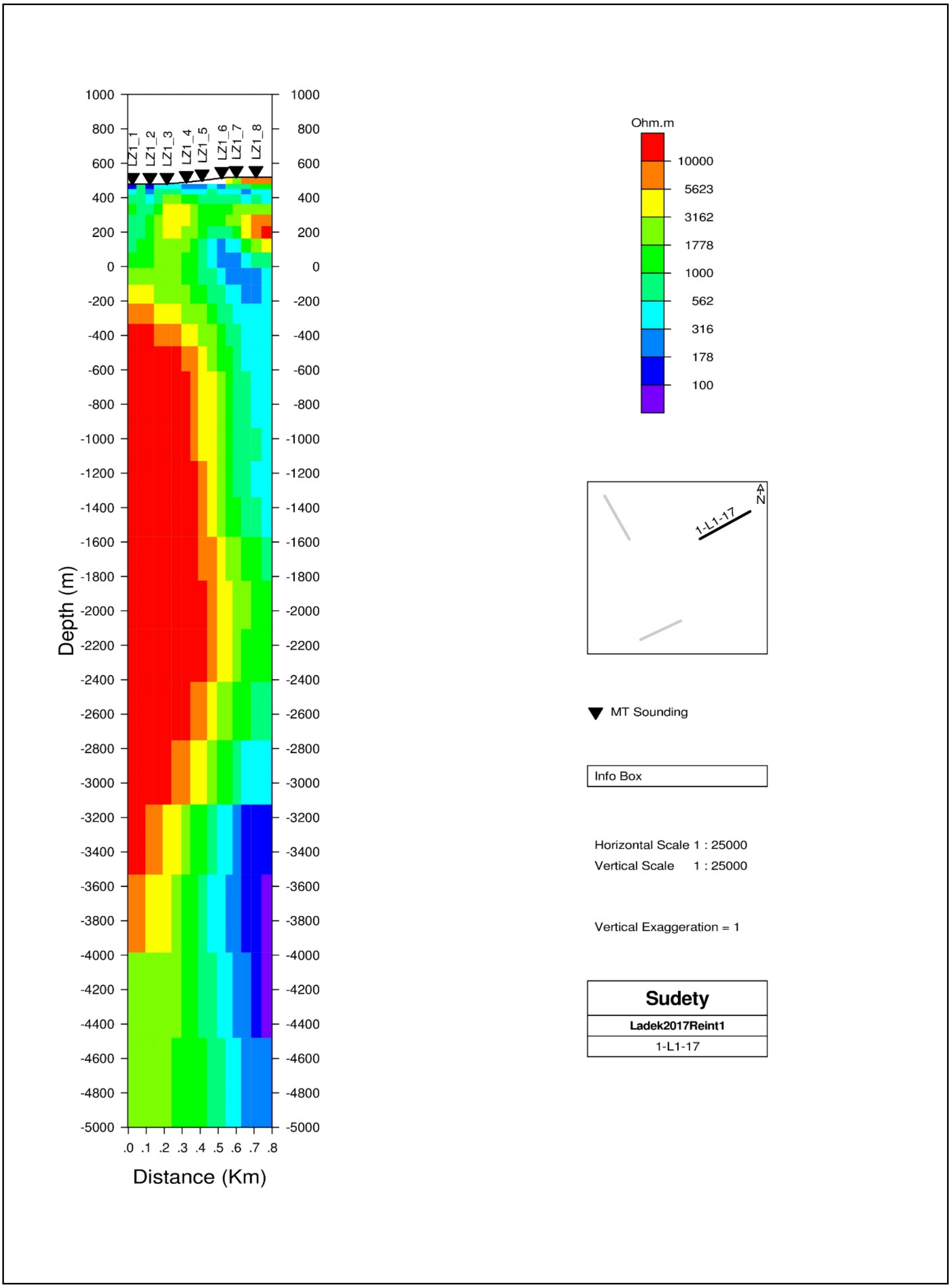


Fig. 5.7.24. Resistivity distribution along profile 1 based on 2D inversion, NLCG
for measuring orientation of the coordinate system

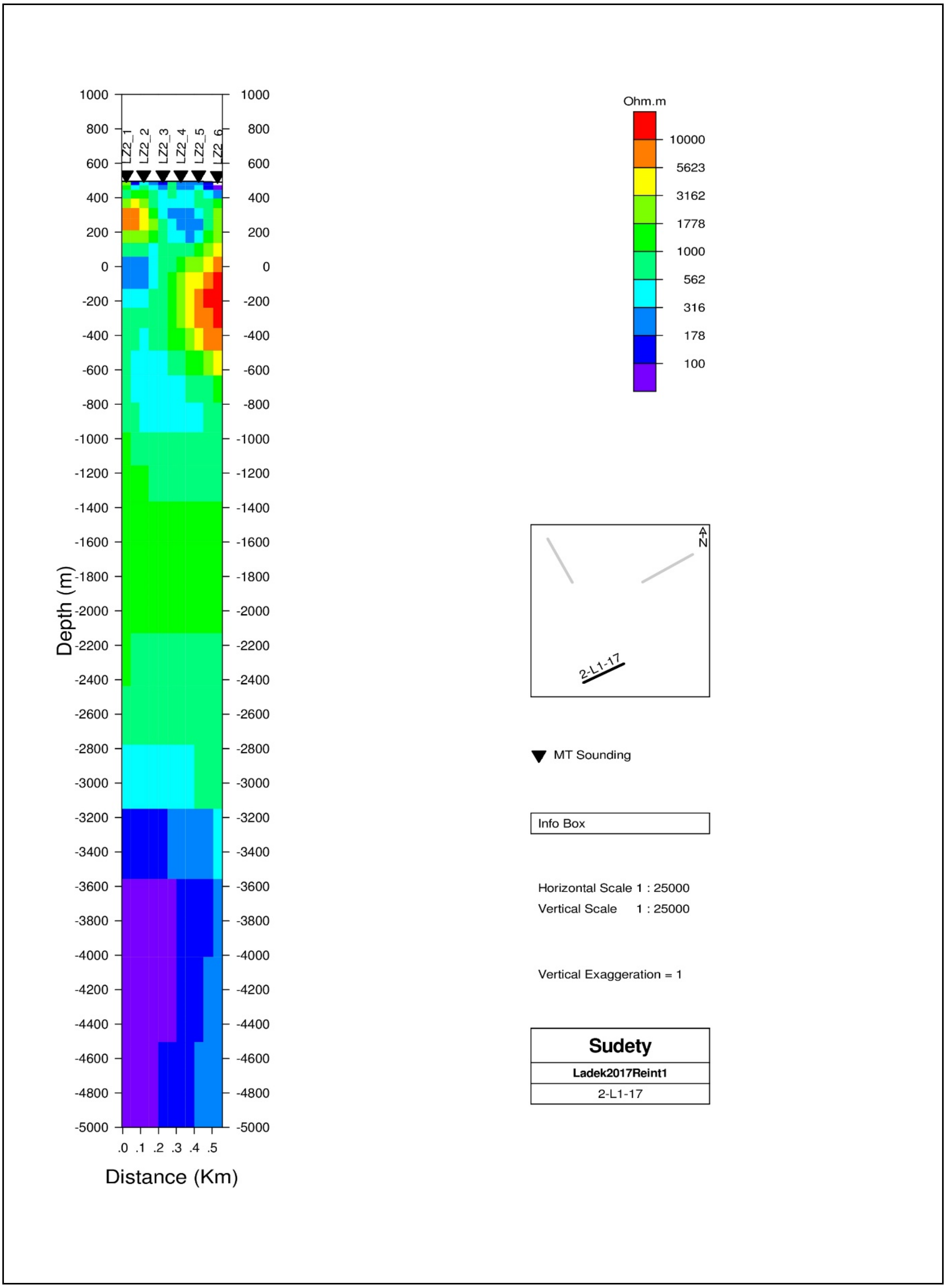


Fig. 5.7.25. Resistivity distribution along profile 2 based on 2D inversion, NLCG, for measuring orientation of the coordinate system

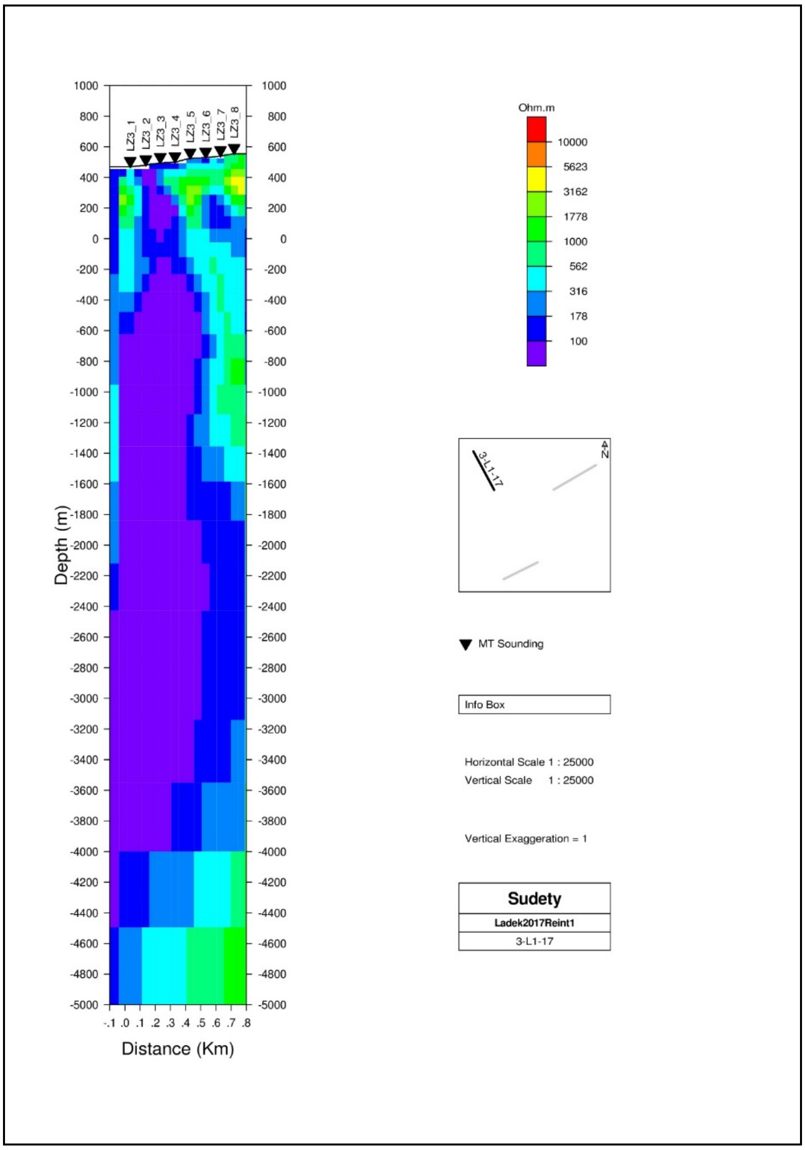


Fig. 5.7.26. Resistivity distribution along profile 3 based on 2D inversion, NLCG for measuring orientation of the coordinate system

5.7.2.8. Re-interpretation of geophysical tests with the application of potential field methods in the area of Lądek-Zdrój

Introduction

Studies of geophysical potential fields were performed on the area and in the surrounding of Lądek-Zdrój, with the application of the gravimetric and magnetometric method. Those works constituted a fragment of complex geophysical tests, aimed at extending knowledge about near-surface section of the rock medium (to the depth of 1 km), mainly in terms of structure and the course of tectonic lines, as well as conditions of minerals and geothermal water occurrence. The tests of potential fields boiled down to re-interpretation of archival data acquired in the following topics:

1. *Sudetic region*, Kosobudzka I., Wrzeszcz M., 2007;
2. *Lądek-Zdrój,* Jodłowski S., Cieśla E., Jagodzińska B., 1969;
3. *Fore-Sudetic Block, the area of Strzelin,* Cieśla E., Margul B., 1972;
4. *Sudetic region and Fore-Sudetic Block – eastern part*, Okulus H., 1968;
5. *Sudetic region, the area of Kłodzk and Węgliniec-Zgorzelec,* Okulus H., Margul B., Kleszcz T.,1974.

From among the above-mentioned studies, the first regarded magnetometric data, the third one is the work in the area of magnetometry and gravimetry, whereas the last two studies were the source of gravimetric data. The measurement results included in the documentation under Item 1 contain both data from years 2005-2007 and those taken from "magnetic data bank." The remaining topics mentioned above under Items. 2 - 5 come from 1960's and 1970's, so the precision of field measurements and processing works was at a lower level in relation to the ones made presently. The area of re-interpretation works was located within a quadrilateral, the vertices of which have the following coordinates of the 1992 system:

1. NW vertex: x = 339,348 km, y = 288,444 km;
2. NE vertex: x = 359,225 km, y = 287,529 km;
3. SE vertex: x = 358,564 km, y = 267,549 km;
4. SW vertex: x = 338,331 km, y = 268,312 km.

Due to the requirements of programs for data processing and interpretation, the course of x axis was assumed from the west to the east, and y axis from the south to the north – the opposite of the traditional cartography. The area described by corner coordinates has a shape close to a square with the surface of about 410 sq.km. In its eastern part, there is the country border with the Czech Republic, on the territory of which no field works were conducted, so this area could not be covered by the interpretation. For this reason, the surface of re-interpretation works was about 295 sq.km. 1603 gravimetric measurement points were located there, together with 943 magnetometric points in a distributed system, as well as several hundred positions from a detailed photo made in 1969. The methodology and the number of measurements, as well as the scope of processing works within each archival topic were described in particular documentations, from which the following data concerning measurement points were used for re-interpretation:

1. values of gravity acceleration for the IGSN-71 international system expressed in [mGal],
2. height of measurement positions and additional pickets for the Kronsztadt reference level in [m],
3. value of the total magnetic field, T, expressed in [nT].

Within the frameworks of re-interpretation works, values of gravity anomalies were calculated in Bouguer reduction, together with the anomalies of the total magnetic field, and next, basic maps were developed, namely, gravimetric and magnetic. At the next stage of tests, a gravitation field was transformed, which enabled development of the surface distribution of residual anomalies and a horizontal gravity gradient.

Picture of geophysical potential fields

Distribution of gravity anomalies in the Bouguer reduction for the study area (Fig.5.7.11.) is characterised by high variability: from -22.5 mGal to +7.5 mGal. The latter, highest values occur at the NW area corner, and the lowest ones in the SW part. On the study area, an interesting form, relatively negative, occurs near Lądek-Zdrój. It consists of two parts: a smaller one which is more oblong and covers with its range Lądek-Zdrój, and a larger one, with the centre located ca. 2 km NW of Lądek, which is clearly prolonged in the WSW direction. In both cases, amplitudes are similar and they are ca. 10 mGal (Fig. 5.7.11.), and the source of those negative forms can be lighter Upper Carboniferous formations. The picture of the total magnetic field, T (Fig. 5.7.10.) in general is calmer than the one described previously. Anomalies are less differentiated, except for numerous anomalous forms, which are small in terms of the area occupy, but with high amplitude, which are "chimney" in nature, and probably they were caused by the uplift of older magma formations. They are less differentiated, except for numerous, perhaps basalt forms, with very high magnetic susceptibility (Fig. 5.7.10.). It is confirmed by the gravitation field distribution – less visible on the map of Bouguer anomalies (Fig. 5.7.11.), very clear in the picture of residual anomalies for the penetration depth to 1 km under sea level (Fig. 5.7.27.) and probably continuing deeper, which could not be confirmed with interpretation results, due to the lack of measurements of gravity field background in the surrounding, which has been mentioned already earlier.
Another similarity (convergence) of magnetic and gravitation field interferences was recorded in north-western study area corner. Here, very clearly high magnetic susceptibility is accompanied by high increase of rock volume density (Figs. 5.7.10, 5.7.11.). The earlier mentioned minimum values of Bouguer anomalies (Fig. 5.7.11.) in the SW study area corner were not confirmed in the distribution of magnetic anomalies (Fig. 5.7.10.) and they were not clearly reflected on the map of gravimetric residual anomalies (Fig. 5.7.27.). It enables characterising the source of field distortions as a rock complex with slightly lowered volume density, minimum magnetic susceptibility and deposited at the depth of only several kilometers. On the other hand, in the SE study area corner, a relatively positive Bouguer anomaly was recorded (Fig. 5.7.11.) in the

surrounding of a closed isoline, with the value of 10 mGal. It is confirmed by a relatively positive residual anomaly with the amplitude of 10 mGal (Fig. 5.7.27), prolonged towards WNW, and having a branch towards SSW, through the boundary of the study range, and continuing further in the given direction. The signalled anomalous form is also reflected on the magnetic map as a positive, low-amplitude anomalous form (Fig. 5.7.10). On the above-described maps of basic potential fields (Figs. 5.7.10, 5.7.11) and on the map acquired after gravitational field transformation (Fig. 5.7.28), one can also see other anomalous forms, usually with smaller amplitudes and a smaller surface range in relation to the above-mentioned ones, but proving undoubtedly about differentiation of physical parameters of formations making up the rock medium.

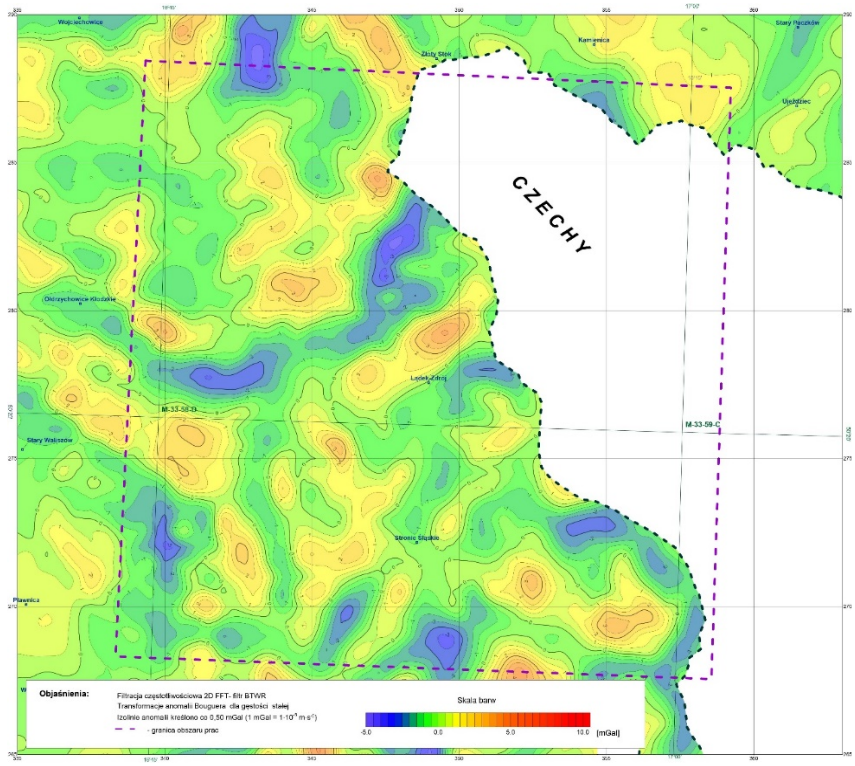


Fig. 5.7.27. Map of residual anomalies of the gravity field in the area of Lądek-Zdrój
(referred to the scope of depth: 0 – 1 km under ground level)

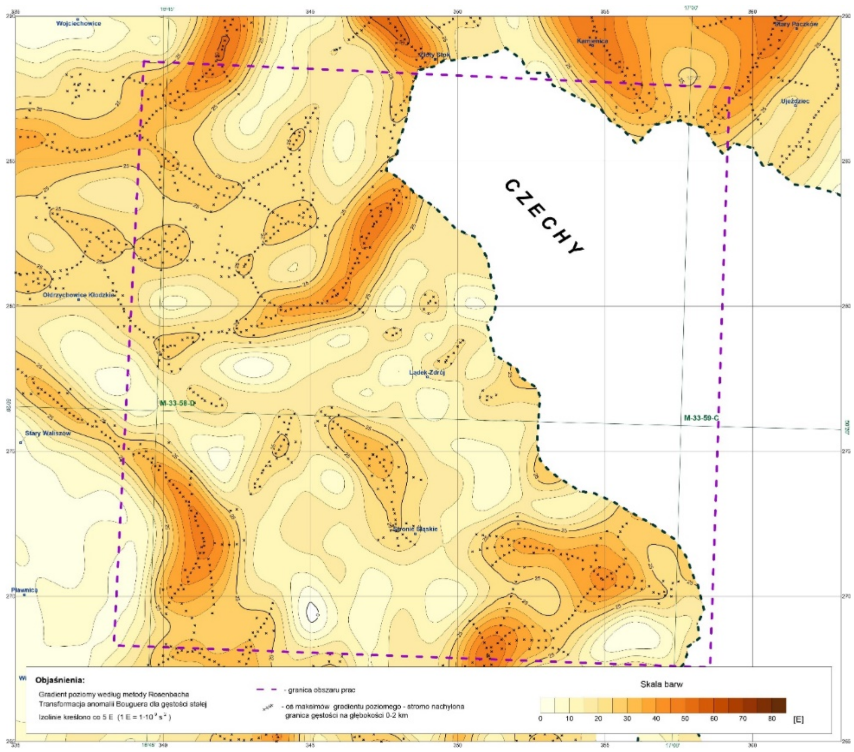


Fig. 5.7.28. Map of distribution of horizontal gradients of the gravity field in the area of Lądek-Zdrój

Another stage of re-interpretation works was the analysis of changes of horizontal (a horizontal gradient) Bouguer anomalies, calculated by the Rosenbach method (Fig. 5.7.28.). The results of those works have been presented in the form of axes of extremely positive values of that gradient. Gradient axes reflect courses of boundaries, located vertically or at a high angle towards the horizontal level, between adjacent formations, differing in terms of volume density. A difference in density of formations building the adjacent complexes can be of lithological origin, but much more frequently it is the result of tectonics impact (except for detachment tectonics). In the study area, several zones with an elevated horizontal gradient were interpreted. Most probably these can be fault zones with depths to 2 km under sea level. Such exploration depth was possible to be achieved, due to a very limited scope of measurement data from the study area surrounding. Among gradient zones (as mentioned above) reflecting tectonic lines, two directions of their course prevail. The first and the most frequently encountered direction from SW to NE was recorded:

- in north-western corner of the study area,
- 4.5 km away to the north west of Lądek-Zdrój,
- in south-eastern corner of the photographed area, with a branch towards Stronie Śląskie,
- from the area of the north-eastern corner towards Stary Paczków outside the study area.

The second direction of gradient lines, slightly more rarely from the previous one, and, at the same time, almost perpendicular to it, runs more or less from SE to NW, and it was found:

- in the south-western corner of the study area,
- from Stronie Śląskie at the section of 5 km towards NW,
- from the Czech border to the vicinity of Kamienica, outside the range of this study and further in the same direction,
- from Złoty Stok at the Czech border towards NW (in whole outside the study area).

In addition, rarely, there are other directions of gradient zones; they are visible clearly on the gravimetric map (Fig. 5.7.28).

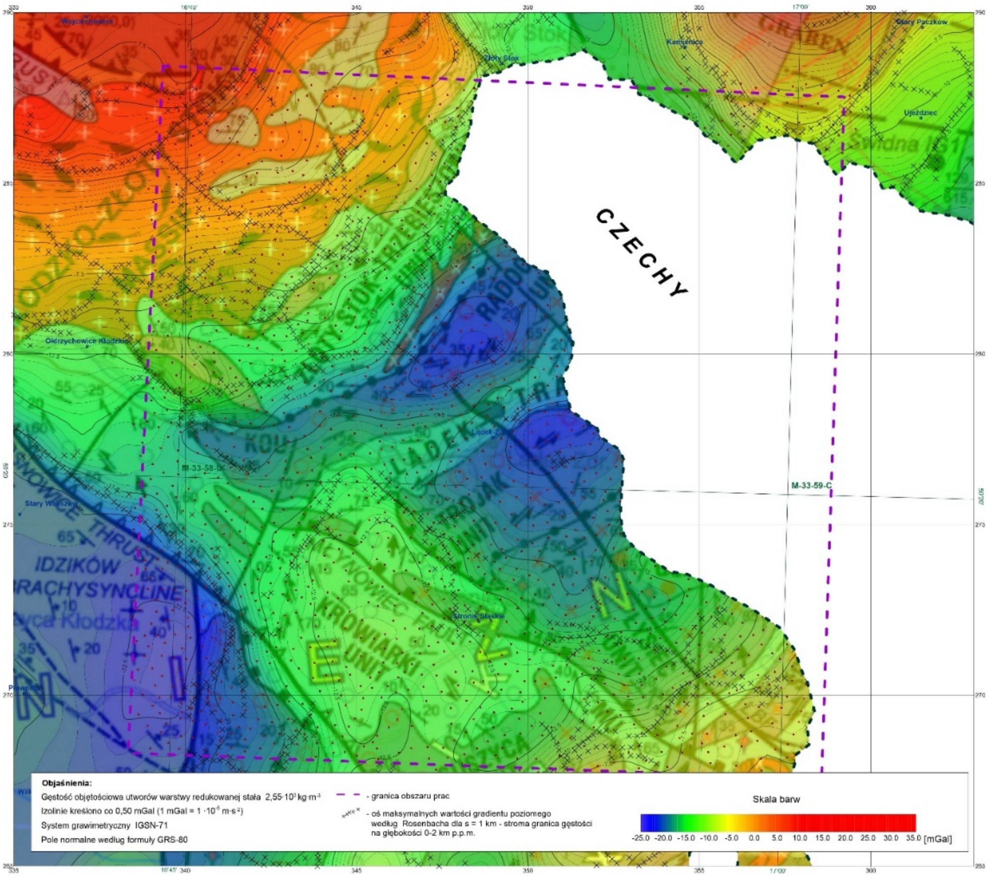


Fig. 5.7.29. Map of gravity field anomalies in Bouguer reduction in the area of Lądek-Zdrój at the background of main geological structures

Final remarks

The effect of the analysis of geophysical potential fields is the results of qualitative interpretation presented on gravimetric and magnetic maps. Anomalous geophysical forms are presented on them. Their surface spreading results mainly from horizontal ranges and physical parameters of bodies generating a given anomalous form. Distributions of anomalies and a horizontal gradient of gravity anomalies indicate tectonic zone courses (Fig. 5.7.28). Therefore, the performed tests confirmed the usefulness of the applied prospective methods for detailed exploration of the structure and tracing of the tectonic zones course. Potential fields tests were performed only to the depth of 1 km under sea level It was caused by an insufficient amount of archival data from the study area surrounding, particularly from the territory of the closely located Czech Republic. Disposal and use of data from the surrounding of the area of structure exploration is required when using the most recent program packages for interpretation and analysis of potential fields. When planning the next stage of structural geophysical and geological tests it is justified to:

- acquire geophysical and drilling data from the border zone on the side of the Czech Republic,
- perform a new detailed gravimetric photo in order to update data coming from before ca. 50 years,
- supplement the results of laboratory tests of physical parameters of rocks in the study area.

5.7.2.9. Summary and conclusions

A set of geophysical works was carried out in the area of Lądek Zdrój enabled to interpret fault zones, detect temperature anomalies and, to a very limited extent, spatially explore fractured aquifers. The justification of concerns that drilling of a new well and its potential exploitation will disturb the operation of the existing intakes used by the Resort is difficult to evaluate on the basis of currently available data. The results of magnetotelluric sounding interpretations indicate the presence of at least two levels (or zones) fractured and filled with mineral (geothermal) waters. The existing intakes, both surface (springs, wells) and borehole ones, reach down to the maximum level of ca. 700 m under ground level, so they exploit the first and the shallowest level, whereas the goal of the borehole being designed is at the depth of about 2500 m under ground level.

Unfortunately, it is impossible to say whether the layer separating those levels with an elevated resistivity is not cut with fractures providing hydraulic connection between them, nor it is possible to make a quantitative evaluation of such connection. A small scope of magnetotelluric data does not allow evaluation of a spatial distribution of aquifers and a potential isolation stratum.

Complex geological conditions and a limited amount of in-depth information did not allow building of a digital hydrogeothermal model of Lądek reservoir and its proximity, not simulating the impact of a new intake on the currently operating one, and hence, evaluating the hydraulic connection between hydrogeological levels.

The information obtained during the study visit and re-interpretation works enable (in our opinion) to formulate the below conclusions and propose further activities (for a wide discussion among specialists).

1. The near-surface zone of Lądek hydrogeothermal reservoir is well explored, whereas information about its in-depth part is fragmentary and uncertain.

2. No numerical model of the reservoir and its surrounding does not allow conducting simulations to explain the mutual impacts of the exploitation in its particular parts, and thus, determining the nature of hydraulic links, activity of the supply zones, the role of thermal convection (ascension and descending) etc.

From the analysis of geological conditions and the current status of reservoir exploration and management stem the proposals of further activities presented below, aimed at supplementing exploration of the reservoir and the geological structure of its surrounding, creating conditions for its rational and safe management.

3. In order to explore geological conditions of the hydrogeothermal reservoir in a greater detail, a critical analysis and the evaluation of the presently existing geophysical tests is necessary, together with their supplement and re-interpretation. Supplementing of geophysical tests should concern:

- making another shallow geothermal photo, in accordance with contemporary methodological and technical requirements in order to explore, in a reliable way, of geothermal field anomalies in the near-surface zone,

- performing a wider scope of electromagnetic tests (MT and optionally TEM) in order to determine a 3D distribution of aquifers and potential isolation complexes,

- performing a semi-detailed or detailed gravimetric photo and supplementing a detailed magnetic photo, as well as their complex interpretation, mainly tectonic one.

4. It will be advisable, or even necessary, to develop a numerical model of the reservoir and its geological surrounding on the basis of the results of earlier and proposed tests, as well as to make suitable hydrodynamic and geothermal simulations, particularly those referring to a mutual impact of particular parts of the reservoir.

Under the proposed tests it will be advisable to pay special attention to the manifestations of Miocene-Pliocene volcanism in this area and analysing its role in shaping contemporary geothermal phenomena. The reservoir model, a more perfect and more modern one, as more information becomes available, will be the basis not only for hydrogeothermal tests, but it will also be used to verify in-depth geophysical interpretations, with the application of simple modelling. The proposed research works go much beyond the frameworks of the current project and they can be treated rather as topics of future activities. Due to the similarity of geological structure and hydrogeothermal conditions, studies in the area of Lądek-Zdrój can be treated as pilot ones for the Sudetic region.

Literature

Berdichevsky M.N.: Elektriceskaja razvedka metodom magnetotelluriceskogo profilirovania. Moskwa, Nedra, 1968, 1-253.

Bujakowski W., Tomaszewska B., (eds.) et al..: Atlas of the possible use of geothermal waters for combined production of electricity and heat using binary system in Poland, MEERI PAS, Kraków, 2014, 305.

Cagniard L.: Basic theory of the magnetotelluric method of geophysical prospecting. Geophysics, 18, 3, 1953, 605-645.

Cieśla E., Margul B., 1972: Dokumentacja półszczegółowych badań grawimetryczno-magnetycznych, temat Blok przedsudecki, rejon Strzelin, 1971, BZG Warszawa.

Ciężkowski W., Marszałek H., Wąsik M., 2016: Projekt robót geologicznych poszukiwania wód termalnych otworem LZT-1 w Ladku-Zdroju.

Ciężkowski W.: Kierunki rozwoju i możliwości wykorzystania geotermii głębokiej na Dolnym Śląsku Instytut Górnictwa, Politechnika Wrocławska, Wrocław, 2011.
Constable, S.C., Parker, R.L., Constable, C.G.: Occam's inversion: A practical algorithm for generating smooth models from electromagnetic sounding data. Geophysics, 52, 1987, 289-300.
Cymerman Z., 2004. Tectonic map of the Sudetes and the fore–sudetic block, 1:200 000. PIG.
Don B., Don J.: Geneza rowu Nysy na tle badań wykonanych w okolicach Idzikowa. Acta Geologica Polonica, 10, 1960, 71-106.
Dowgiałło, J.: The Sudetic geothermal region of Poland. Geothermics 31, 2002, 343–359.
Farbisz J., 2005: Sprawozdanie z badań geofizycznych wykonanych dla potrzeb rozpoznania warunków występowania wód geotermalnych w rejonia Lądka-Zdroju.
Farbisz J., Farbisz E., Stefaniuk M.: Sprawozdanie z badań geofizycznych: poszukiwania wód termalnych w obszarze Polanicy Zdroju (niepublikowane) Archiwum PBG, Warszawa, 2001, 1-12.
Farbisz J., Wodyła M., 2008; Dokumentacja badań geofizycznych metodą Ciągłego profilowania Magnetotellurycznego (CPMT) wykonanych w rejonie Lądka-Zdroju w celu głębokiego rozpoznania stref tektonicznych dla potrzeb określenia perspektyw występowania wód geotermalnych.
Fistek J., Iwanowski S., Iciek., A., Jagodziński A., 1975; Badania geologiczne, geofizyczne i hydrogeologiczne jako przykład kompleksowego rozwiązania problemu poszukiwań wód leczniczych w uzdrowiskach sudeckich. Biul. Inf. Geofizyka, nr 1.
Gamble T.D., Goubau W.M., Clarke J.: Magnetotellurics with a remote reference. Geophysics, 44, 1979, 53-68.
Gierwielaniec J. 1968a; Objaśnienia do Szczegółowej mapy geolicznej Sudetów 1:25000, arkusz Lądek-Zdrój. PIG Warszawa.
Gierwielaniec J. 1968b; Lądek-Zdrój i jego wody mineralne. Kwart. Geol., t.12, nr 3.
Gierwielaniec J. 1970a; Lądek-Zdrój i jego wody mineralne w świetle dotychczasowych badań. Pr. Nauk. Inst. Geotech. PWr. nr 5, Studia I materiały nr 5.
Gierwielaniec J. 1970b; Z geologii Lądka-Zdroju. Pr Nauk. Inst. Geotech PWr nr 5, Studia i Materiały nr 5.
Goldstein M.A., Strangway D.W.: Audio-frequency magnetotellurics with a grounded electric dipole source. Geophysics, 40, 1975, 669-683.
Goubau W.M., Gamble T.D., Clarke J.: Magnetotelluric data analysis: removal of bias. Geophysics, 43, 1978, 1157-1166.
Jagodzińska B., Jodłowski S., Cieśla E., 1969; Dokumentacja badań geofizycznych, temat Lądek-Zdrój. Przedsiębiorstwo Poszukiwań Geofizycznych, Warszawa (niepublilowane)
Kosobudzka I., Wrzeszcz M.:, 2007 Dokumentacja, temat: Półszczegółowe badania magnetyczne T na obszarze Sudetów, 2005-2007, BZG Warszawa.
Levenburg K.: A method for the solution of certain non-linear problems in least-squares. The Quarterly of Applied Math. 2, 1994, 164-168.
Marks L., Ber A., Gogołek W., Piotrowska K.: Mapa geologiczna Polski w skali 1:500 000. Państwowy Instytut Geologiczny, Warszawa, 2006.
Marquardt D.W.: An algorithm for least-squares estimation of nonlinear parameters. Journal of the Society for Industrial and Applied Mathematics, 11(2), 1963, 431-441.
MT – 1 Magnetotelluric System Operation Manual, version 3.2, 1996. EMI Inc., Richmond, California, USA, 1-235.
Okulus H. 1968: Dokumentacja półszczegółowych badań grawimetrycznych, temat: Sudety i blok przedsudecki – część wschodnia, 1966, BZG Warszawa.
Okulus H., Margul B., Kleszcz T., 1974: Dokumentacja półszczegółowych badań grawimetrycznych, temat: Sudety, rejony: Kłodzka i Węglińca-Zgorzelca, 1973, BZG Warszawa.
Rodi W., Mackie R.L.: Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion. Geophysics, 66, 1, 2001, 174-187.
Simpson F., Bahr K.: Practical Magnetotellurics. Cambrigde University Press., 2005, 1-254.
Sims W.E, Bostick F.X. Jr., Smith H.W.: The estimation of magnetotelluric impedance tensor elements from measured data. Geophysics, 36, 1971, 938-942.
Smith J.T., Hoversten G.M., Gasperikova E., Morrison H.F.: Sharp Boundary Inversion of 2-D Magnetotelluric Data, Geophysical Prospecting, 47, 1999, 469-486.
Stefaniuk M., Czerwiński T., Klityński W., Wojdyła M.: Zastosowanie metody magnetotellurycznych profilowań ciągłych w badaniach strukturalnych. Kwartalnik AGH Geologia, t. 34, z. 1, 2008, 43-69.

Stefaniuk M., Klityński W., Wojdyła M.: Szczegółowe badania magnetotelluryczne metodą profilowań ciągłych w rejonie Raciechowice – Stadniki (polskie Karpaty zachodnie). Geologia, Kwartalnik AGH, 26, 3-4, 2003, 253-279.

Stefaniuk M., Maćkowski T., Sowiżdżał A.: Geophisical methods In the recognition of geothermal resources – selected problems (w druku) 2017.

Stefaniuk M., Wojdyła M.: Badania magnetotelluryczne z zastosowaniem sztucznego źródła pola pierwotnego. Biuletyn PBG Geofizyka 2/2007.

Stefaniuk M., Farbisz J., Wojdyła M. & Sito Ł.: Badania magnetotelluryczne na Dolnym Śląsku – nowe możliwości wykorzystania metody magnetotellurycznej w geologii strukturalnej, złożowej, poszukiwaniach wód mineralnych i termalnych. W: Mezozoik i kenozoik Dolnego Śląska : LXXXI zjazd Polskiego Towarzystwa Geologicznego; ed. A. Żelaźniewicz, J. Wojewoda & W. Ciężkowski; Polskie Towarzystwo Geologiczne. — Wrocław: WIND, 2011, 169–193.

Strangway D.W., Swift C.M.Jr., Holmer R.C.: The application of audio-frequency magnetotellurics (AMT) to mineral exploration. Geophysics, 38, 1973, 1159-1175.

Swift C.M.: A magnetotelluric investigation of an electrical conductivity anomaly in the South-Western United States, Unpubl. Ph.D. thesis, Dept. Geology Geophys., Mass. Inst. Technol., Princeton, 1962, 1-223.

Szarszewka Z., Madej E., 1974b; sprawozdanie z badań związanych z poszukiwaniem wód termalnych w Lądku-Zdroju. BPIUTBU Balneoprojekt, Warszawa (maszynopis).

Tichonov A.N.: Ob opredelenii električeskich charakteristik glubokich sloev zemnoj kory. Doklady AN SSSR, 73, 2, 190, 295-297.

Torres-Verdin C., Bostick F.X.Jr.. Implications of the Born approximation for the magnetotelluric problem in three dimensional environments. Geophysics, 57, 1992a, 587-602.

Torres-Verdin C., Bostick F.X.Jr.: Principles of spatial surface electric field filtering in magnetotellurics: Electromagnetic array profiling (EMAP). Geophysics, 57, 1992b, 603-622.

Torres-Verdin C.: Continuous profiling of magnetotelluric fields. Ph.D. Thesis, University of California, Berkeley, 1991, 1-97;

Wait J.R.: Theory of magnetotelluric fields. Journal of Research Radio Propagation, 66D, 1962, 509-541.

Wójcicki, A., Sowiżdżał, A. & Bujakowski ,W., (Eds.): Evaluation of potential, thermal balance and prospective geological structures for needs of closed geothermal systems (Hot Dry Rocks) in Poland. Warszawa/Kraków (in Polish) 2013.

Wojdyla M., Farbisz J., Klitynski W., Stefaniuk M.: Experimental exploration of geothermal and ore mineralized zones in Sudetes Mts in Poland with the use of AMT method, 70th EAGE conference & exhibition incorporating SPE EUROPEC, Rome 2008, Extended abstracts & exhibitors' catalogue. EAGE European Association of Geoscientists & Engineers, 2008, S. [1–5], P214.

Wojdyła M., Stefaniuk M.: Interpretacja złożonych struktur geologicznych z wykorzystaniem prostych i inwersyjnych modelowań pola magnetotellurycznego. Geologia, Kwartalnik AGH nr 1, 2011.

Yamashita M.: Controlled Source Audio-Frequency Magnetotellurics (CSAMT). Phoenix Geophysics Limited. Materiały niepublikowane, 2006.

Zonge K.L., Hughes L.J.: Controlled source audio-frequency magnetotellurics, in Electromagnetic Methods in Applied Geophysics, ed. Nabighian, M.N., Vol. 2, Society of Exploration Geophysicists, 1991, 713-809.

5.7.3. Plans for geothermal energy uses for space heating and other purposes in Lądek-Zdrój

Plans for the use of geothermal energy in heating and for other purposes in Lądek-Zdrój involve the expected geothermal water with appropriate parameters from planned LZ-1 well. For drilling this geothermal research borehole, September 2017 the Municipality was granted a subsidy from the Ministry of the Environment paid from the National Fund for Environment Protection and Water Management.1

The goal of the planned well is to recognise the possibilities of production of geothermal water from the deep formations of the metamorphous rock series in Lądek and Śnieżnik. The site selection for the planned exploration borehole in Lądek-Zdrój was based on the results of geophysical studies conducted in 2008. It is estimated that when the borehole depth reaches ca. 2,500 m, it will be possible to obtain water with the temperature of ca. 70°C and the water low rate of ca. 50 m^3/h. There is a high probability that the geothermal water reservoir will represent higher parameters.

By analogy to other operating geothermal water sources, one expects to obtain Na-HCO_3 water, with the mineralisation of ca. 0.2 g/dm^3, containing increased F^- ion concentrations, and (probably) H_2S. Obtaining the projected parameters will allow to manage the reservoir for the purposes of heat generation and agricultural, industrial and recreational facilities, as well as to strengthen and further development the spa activities in Lądek-Zdrój. Those aspects are especially essential considering the fact that the town is the oldest Polish spa, conducting its wellness and treatment activities based on geothermal waters. At the same time, however, still heating the buildings in the spa area, and especially the city is based on obsolete ovens and coal boilers. There is no district heating network. In addition, the quality of the air is deteriorated by the emissions from the nearby town of Stronie Śląskie, hence the urgent need is to change the heating method not only in Lądek itself, but also in its surroundings (this was one of the reasons to establish the local Energy Cluster which brings together several municipalities).

Lądek-Zdrój is one of the leaders of this Cluster. Cluster agreement was concluded with other health municipality of Kłodzko area in February 2017. At the same time, the County has secured cooperation on the use of heat from the neighboring Commune – Stronie Śląskie, as well as key customers in Lądek, not related to it legally and personally.

The general plan for the use of water and geothermal energy from the new planned well in Lądek Zdrój includes the following activities:

The general plan for the use of water and geothermal energy from the new planned well in Lądek Zdrój includes the following activities:

I. Liquidation of "low emission" air pollutants.

This objective shall be achieved thanks to the geothermal heating network that will supply historic buildings in the city center and the spa district (space heating and warm tap water) .o. and c.w.u.). Owing to the health spa character of the commune, it is of utmost importance to improve the air quality (particularly in the winter). Today, communal flats are heated by 272 tiled stoves and 101 coal stoves, which do not meet any emission standards.

II. Geothermal heat application in the II circulation for spa and recreation.

The spa and tourist nature of Lądek-Zdrój will gain new economic potential. At present, geothermal water is available only in the spa company. The intention is to provide geothermal water for medical and recreational purposes to a broader audience.

III. The use of geothermal heat in the III cycle to supply the greenhouse for organic cultivation.

Thanks to cooperation with the University of Natural Sciences in Wroclaw, the Lądek-Zdrój Commune is an important element of the regional strategy "Lower Silesia. Green Valley of Food and Health " which assumes the intensification of agricultural crops and the reconstruction of food processing in Lower Silesia.

IV. The use of heat in the IV cycle for the winter maintenance of roads and communal sidewalks.

Due to the mountainous location of Lądek-Zdrój, and consequently specific urban development (narrow streets with large slopes) and long snow cover, the winter maintenance of streets and sidewalks is more cost-effective than on the plains. Application of geothermal heat in this IV cycle for de-icing sidewalks and streets will significantly reduce the costs incurred by the municipality and limit the pedestrian accidents.

The sketch of the planned geothermal energy use in Lądek-Zdrój after successful drilling LZ-1 well is given in Fig. 5.7.3.1.

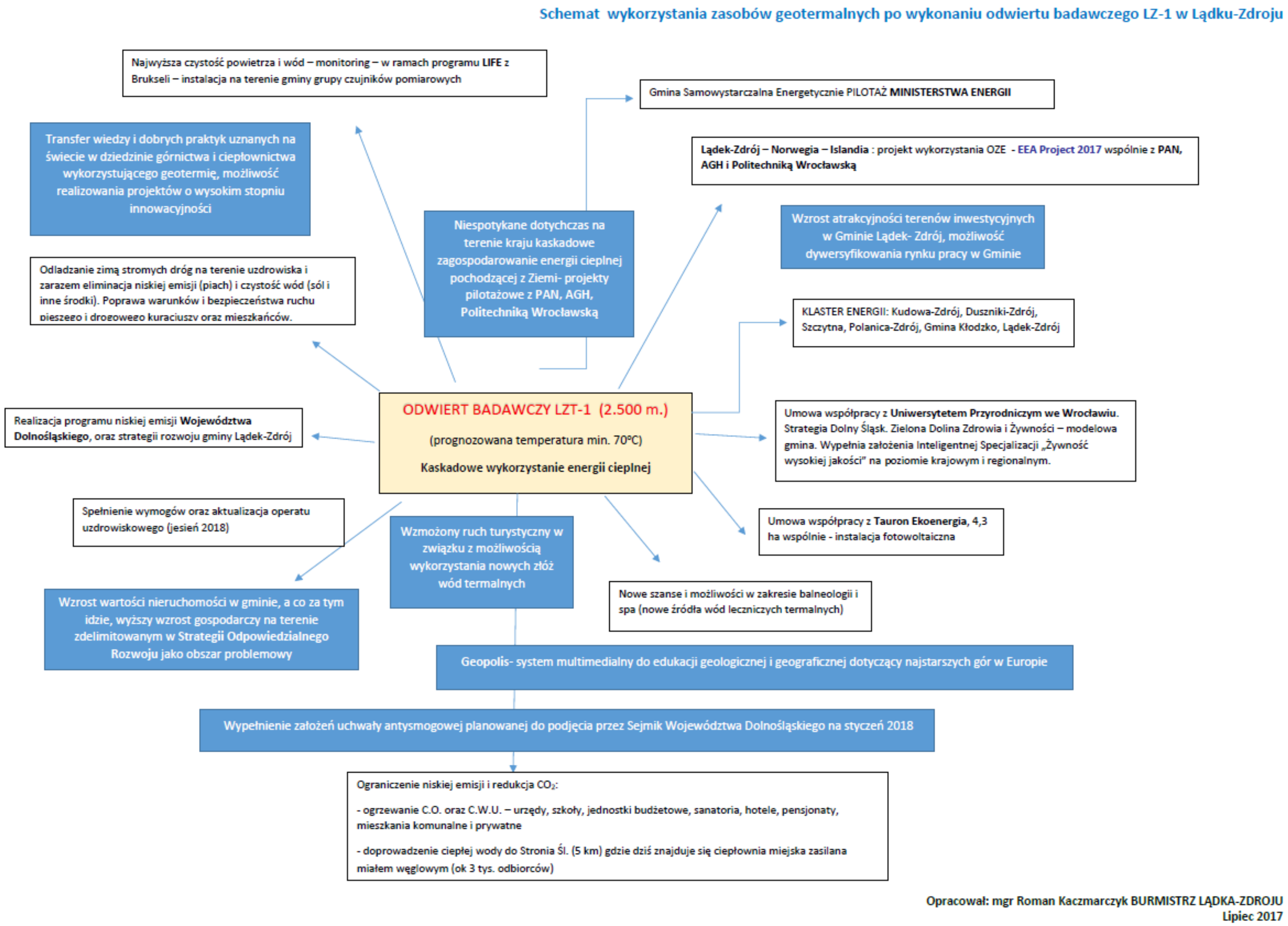


Fig. 5.7.3.1. The sketch of the planned use of geothermal energy in Lądek-Zdrój after drilling LZ-1 well (English version of text given in bars – given below)

The sketch of the planned use of geothermal energy in Lądek-Zdrój after successful drilling LZ-1 well
(English version of text given in bars – given below)

Exploration Borehole LZ-1 in Lądek-Zdrój
(2,500 m deep)
(prognosed temperature: min. 70°C)
Cascaded use of geothermal energy

Increasing air and water cleanliness, a monitoring system provided under the LIFE Programme from Brussels: installation of measurement detectors in the municipality

Energy Self-Sufficient Municipality, a Pilot Project of the Polish Ministry of Energy;

Lądek-Zdrój – Norway – Iceland: renewable energy source use project EEA Project 2017 conducted with MEERI PAS, AGH UST, WUST, CMR, OS, EGEC

Transfer of knowledge and good practice recognised globally in the areas of mining and heat generation, using geothermal resources, with a possibility of implementing highly innovative projects

Unique use of a cascaded geothermal heat energy management on Poland; Pilot projects conducted with PAS, AGH UST WUST, other

Increasing attractiveness of capital investment land in the Lądek-Zdrój Municipality, with possible diversification of labour markets in the Municipality

De-icing of steep roads in the spa in winter time, with low-emission of gas reduction (using sand) and increasing water cleanliness (reduction of using salt and other chemicals). Improvement of pedestrian an vehicle traffic for spa patients and residents.

ENERGY CLUSTER: Kudowa-Zdrój, Duszniki-Zdrój, Szczytna, Polanica-Zdrój, Kłodzko Municipality, and Lądek-Zdrój

Implementation of a low-emission of gas programme, under the Lower Silesian Region and Lądek-Zdrój Municipality Strategies

Co-operation Agreement with the Wrocław University of Environmental and Life Sciences.

Regional Strategy: "Lower Silesia, A Valley of Food and Health". A Model Municipality.

Fulfilment of the assumptions for Smart Specialisation in "High Quality Food" category on the national and regional scale. Fulfilment of the requirements and updating of the Spa Study (autumn 2018)

Co-operation Agreement with the Tauron Ekoenergia Corporation, a joint photovoltaic installation project on the surface area of 4.3 hectares

Increasing the real-estate value in the Municipality, contributing to a higher economic growth on the area identified as problem area in the Responsible Development Strategy

Increased tourist visits, associated with the possibility of enjoying new geothermal waters

New chances and opportunities in balneology, wellness and spa treatment (new sources of geothermal medicinal waters)

Geopolis, a multimedia system for geological and geographic education on the oldest mountains in Europe

Fulfilment of the assumptions of the anti-smog resolution, which is planned to be adopted by the Lower Silesian Assembly in January 2018

Low emission of gas limitation and CO_2 reduction:

- Central heating and hot utility water installations in offices, schools, government buildings, spas, hotels, pensions, and municipal and privately-owned flats
- Delivery of hot water to Stronie Śląskie (5 km away), currently operating a district heating station burning fine coal (supplying heat to ca. 3,000 customers)

5.7.4. Analysis and proposal for heat pump in space district heating systems in Lądek-Zdrój

Available geothermal energy resources

The newly designed LZT-1 borehole is located between two rock faults. That site is located close to a geothermal anomaly, in the zone where geothermal temperature reaches20-25 m/°C. The estimated parameters are the following: water output 50 m^3/handtemperature 70°C. Owing to favourable water properties (low water mineralisation), it is assumed that a single well can be used for the operation.

Existing infrastructure

The infrastructure existing in the Lądek-Zdrój town and spa was described in a study on the "Geothermal Waters in Lądek-Zdrój"(2016). Presently, there is no district heating network in the town.The main facilities located in the Lądek-Zdrój town and spa are presented in Table 5.7.4.1.

Table 5.7.4.1. Demand of energy, power and energy carriers for major objects located in the SPA area Lądek-Zdrój

No	Name of the object	Group in tariff	Ordered power(gas)		Natural gas used in 2016 [m^3/yr]	Amount of gas calculated in energy [kWh]	Heated area. [m^2]	Heat production for central heating and hot tap water preparation [GJ/yr]
			[m^3/h]	[kWh/h]				
1.	Heating plant JUBILAT	W5	59	647	149732	1658192	6381	5290
2.	Heating plant JAN	W5	20	219	45346	502939	1750,8	1669
3.	Heating plant JERZY	W5	48	527	125798	1392999	2924	4523
4.	Heating plant URSZULA	W4	No data	No data	20206	224340	766,06	736
5.	Heating plant DYREKCJA	W4	No data	No data	23451	260191	1275	853
6.	Heating plant WOJCIECH	W5	56	614	156709	1736975	4289,8	5638
7.	Heating plant ADAM	W5	60	658	149251	1653905	4619,1	5214
8.	Total			2665	670493	7429541	21906.36	23923

The heating demand of Lądek-Zdrój, the town located away from the planned LZT-1 borehole, is estimated at 10.68 MW or 23,501 MWh/y (i.e. 84, 604 GJ/y) ("Geothermal Waters in Lądek-Zdrój", 2016). 30% of that quantity of energy comes from coal burning, ca. 40% from gas burning, 5% from heating installations, and 25% from electricity.

Method of use

Hot watercollected from borehole LZT-1, is planned to be used for district heating and hot water preparation. In addition, the water from which thermal energy has been extracted, with the temperature of about 30°C or a bit more, is planned to be used for snow melting along the main transportation and walking routes (roads and sidewalks). Fig. 5.7.4.1 presents the CITY and SPA zones, defined for the needs of the present considerations. The Figure shows proposed pipelines connecting the identified zones with the planned geothermal well LZT-1. The length of the pipeline was estimated, taking into account the problemswithstraight-line run,at the section of ca. 1.5 km in the case of the LZT-1 CITY and ca. 2 km in the case of the LZT-1 SPA. Based on the main energy parameters characterising the customersand using the meteorological data relating to typical meteorological years and statistical climatic data, applied in the our energy calculations for buildings, the replacement customer descriptions were prepared for both CITY and SPA. The data available from the closest Kłodzko meteorological station, 20 km away to north-west of Lądek-Zdrój were used (Fig. 5.7.4.2). Customer characteristics related to capacity demand, working-medium temperatureand water output were presented in Figs. 5.7.4.3 to 5.7.4.6.

Considering the available geothermal energy resources and the method of extraction, as well as the customers, the following Options were analysed:

ngC – (**n**-atural **g**-as, **C**-ity) Reference Option, assuming the construction of a gas boiler facility to meet the needs of the customers located in the CITY zone,

ahpC – (**a**-bsorption **h**-eat **p**-ump, **C**-ity) Option, assuming that geothermal energy will be obtained with the use of absorption heat pumps in the CITY zone,

chpC – (**c**-ompressor **h**-eat **p**-ump, **C**-ity) Option, assuming that geothermal energy will be obtained with the use of compressor heat pumps in the CITY zone,

ngS – (**n**-atural **g**-as, **S**-PA) Reference Option assuming the construction of a gas boiler facility to meet the needs of the customers located in the SPA zone,

ahpS – (**a**-bsorption **h**-eat **p**-ump, **S**-PA) Option, assuming that geothermal energy will be obtained with the use of absorption heat pumps in the SPA zone,

chpS – (**c**-ompressor **h**-eat **p**-ump, **S**-PA) Option, assuming that geothermal energy will be obtained with the use of compressor heat pumps in the SPA zone.

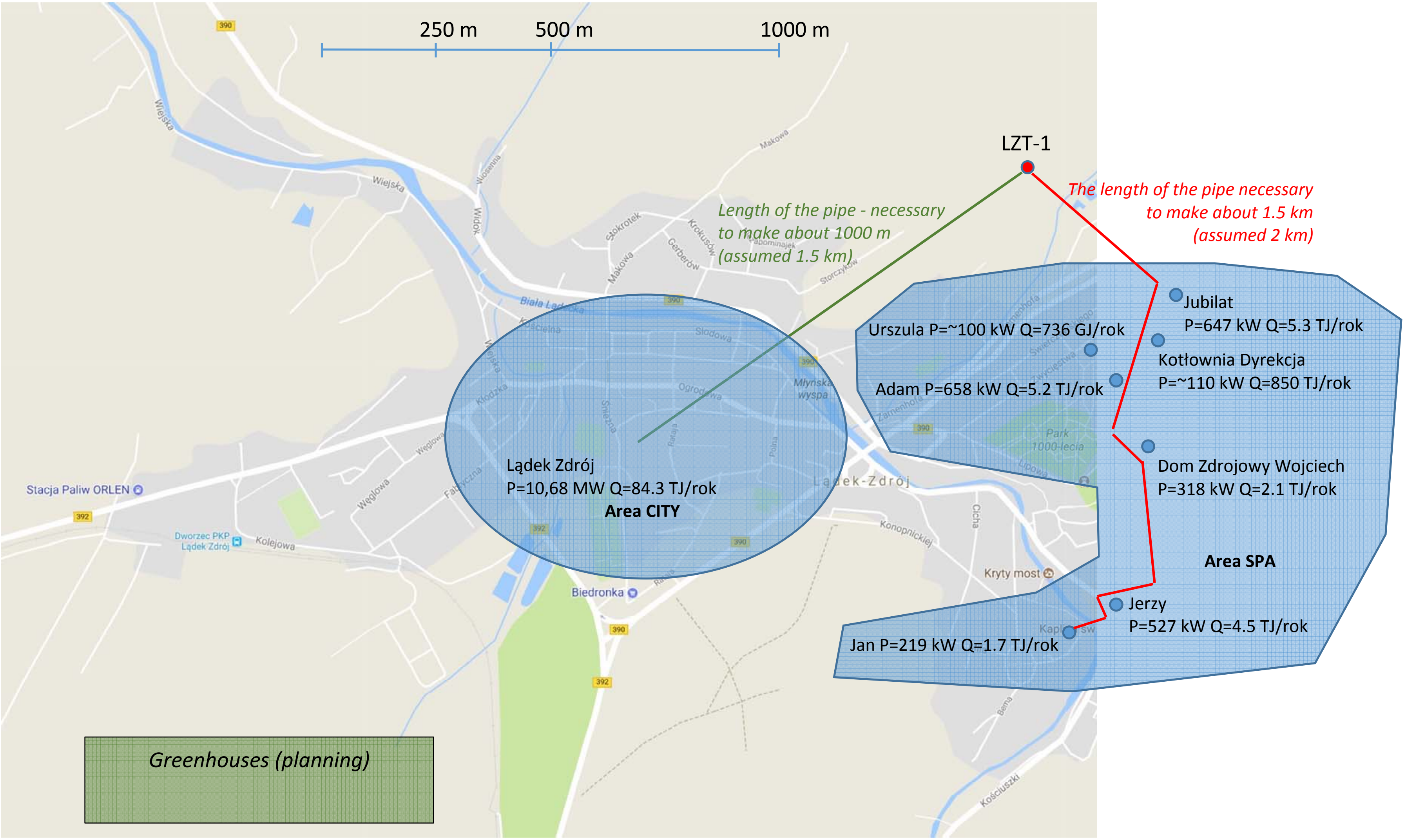


Fig. 5.7.4.1. Location of the objects considered by the analysis of the effects of geothermal energy use in Lądek-Zdrój

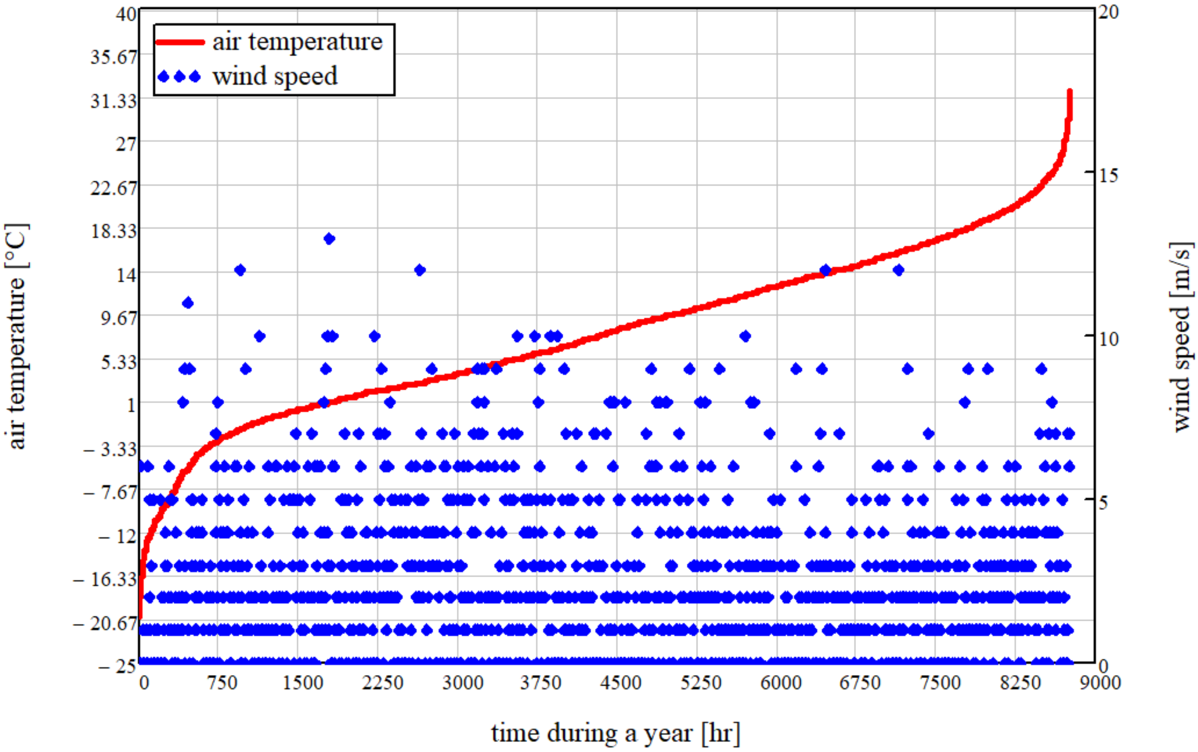


Fig. 5.7.4.2. Distribution of air temperature and wind speed for the nearest meteorological station for Lądek-Zdrój, Kłodzko station located about 20 km northwest

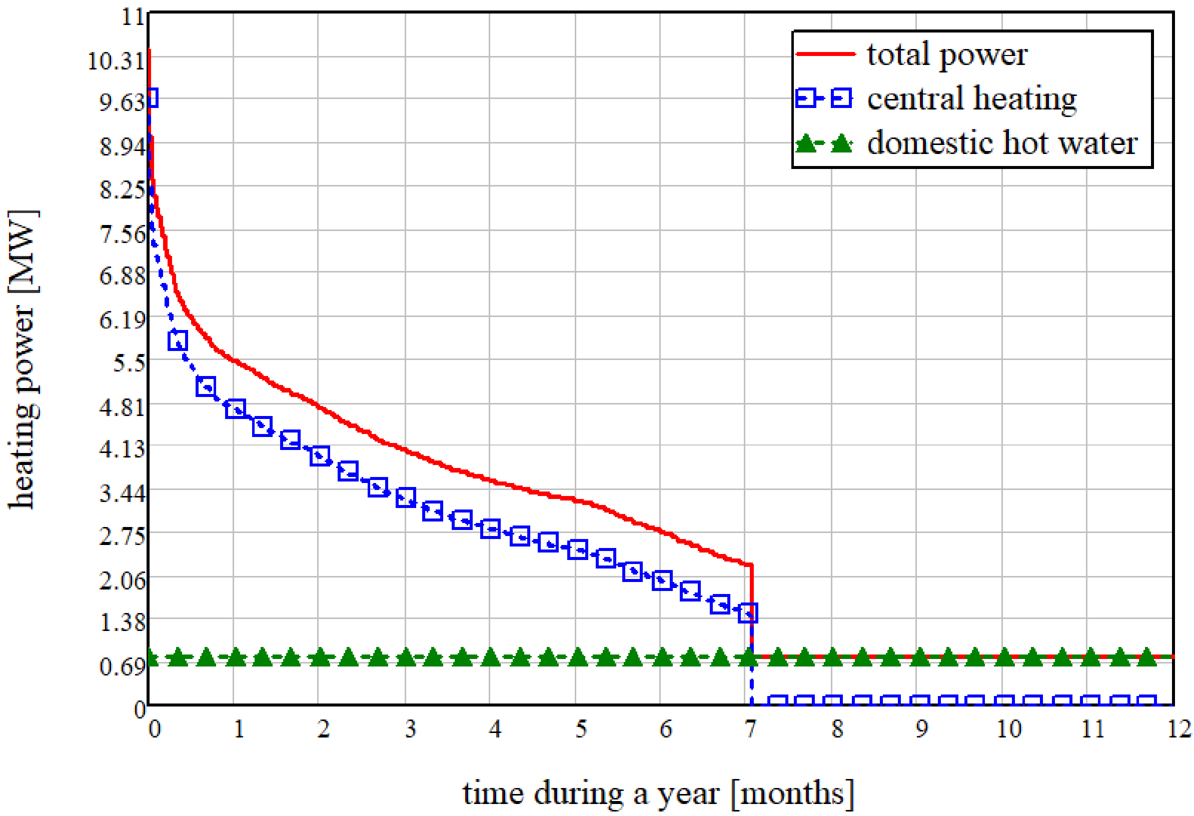


Fig. 5.7.4.3. Distribution of heat demand in the area CITY vs time

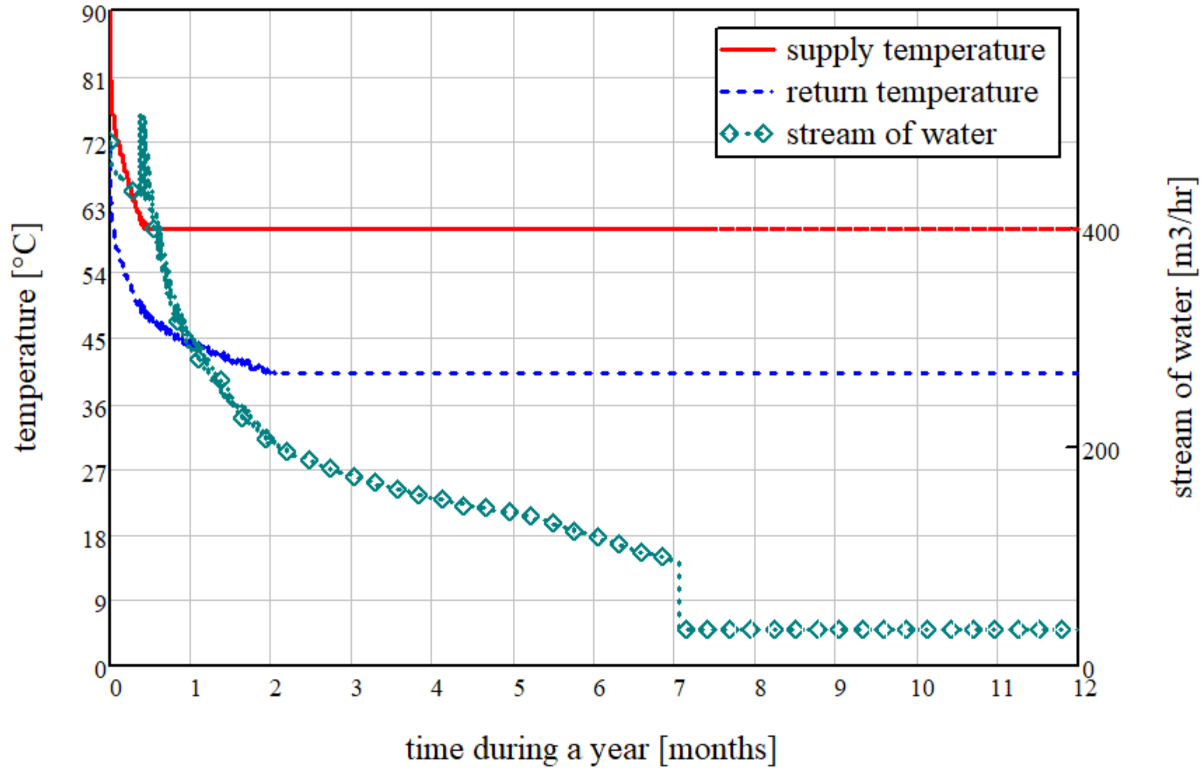


Fig. 5.7.4.4. Characteristics of the area CITY in terms of required temperature and flow of water vs time

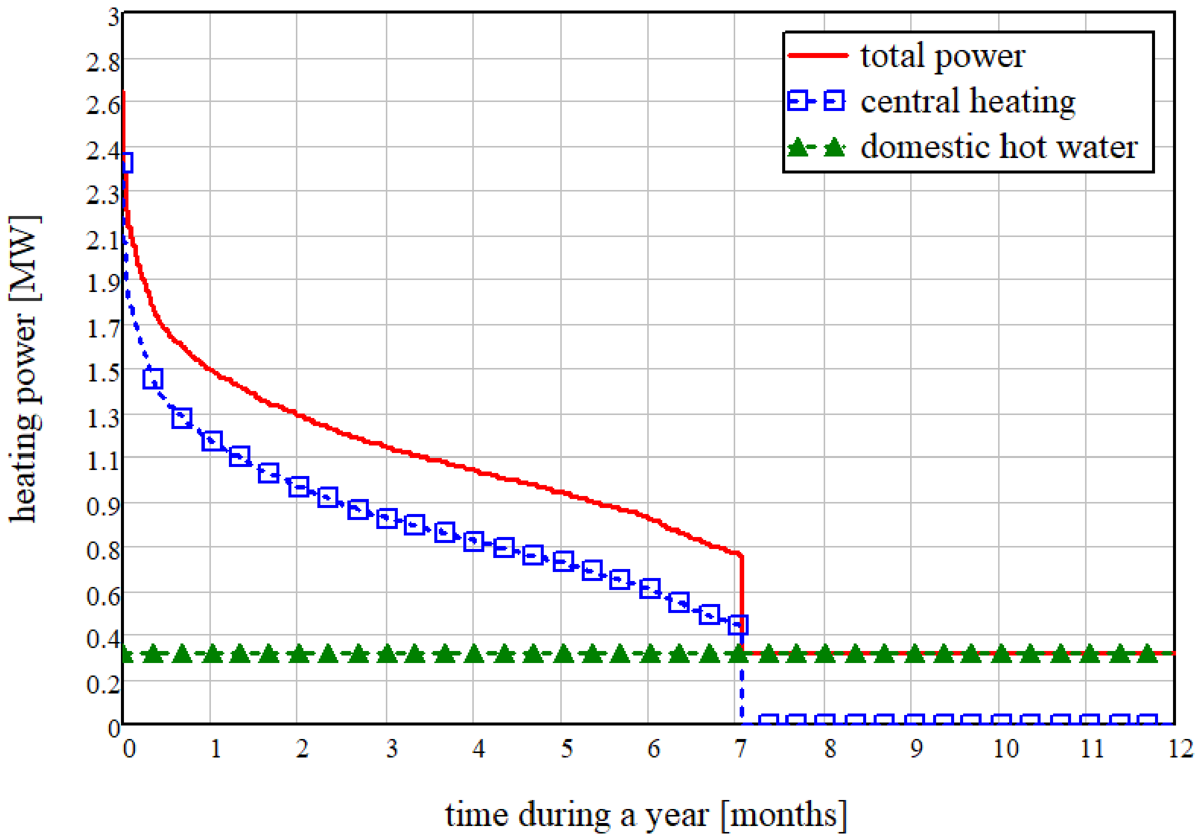


Fig. 5.7.4.5. Distribution of heat demand in the area SPA vs time

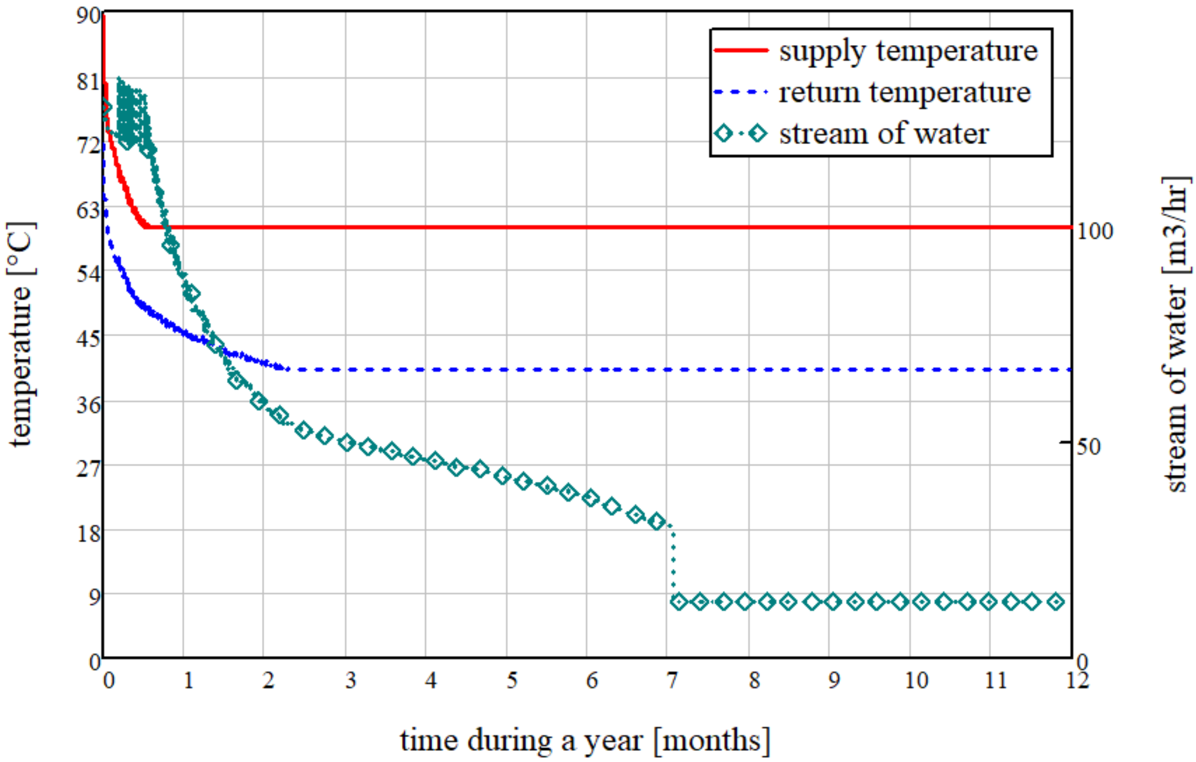


Fig. 5.7.4.6. Characteristics of the area SPA in terms of required temperature and flow of water vs time

Energy source model

Energy and economic calculations, as well as the estimations relating to the determination of the ecological effects were made with the use of a mathematical model of the energy source, adjusted to the predefined customer parameters. The energy source allowed for a possibility to analyse the results of the work of many sources, co-operating jointly under a hybrid system. A general design of the source is presented in Fig. 5.7.4.7. The design has been adapted to the related requirements. The model contained the following elements: direct geothermal heat exchanger, absorption or compressor heat pumps (alternatively, depending on the assumed calculation Option),and peak-demand boilers burning high-methane content natural gas. The following was excluded from our analyses: sun collectors, heat and current modules, and alternative fuel boilers. In the case of the compressor heat pumps, it was assumed that pumps would allow to achieve the temperaturesat the condenser outlet that are higher than those in standard solutions (small power). That will require to apply high condensation pressures in the working medium, together with other special solutions available on the market.

The prices of conventional energy media were assumed, taking into account the market prices. The net purchase price of network natural gas was assumed at 1,463 PLN/m^3. The net purchase price of electricity was assumed at 350 PLN/MWhr.

The issue to be discussed, and that can be clearly resolved, is the level of initial capital investment. The proposed equipment, mainly the heat pumps, are not available in series production or sold from stock. The purchase prices depend on the results of price negotiations. The proposed prices are based on the experience of the authors of this study, and the prices can be recognised as realistic. Regarding the absorption heat pumps, they also include expenditures borne for the purchase of a high-temperature driving boiler and an economiser.

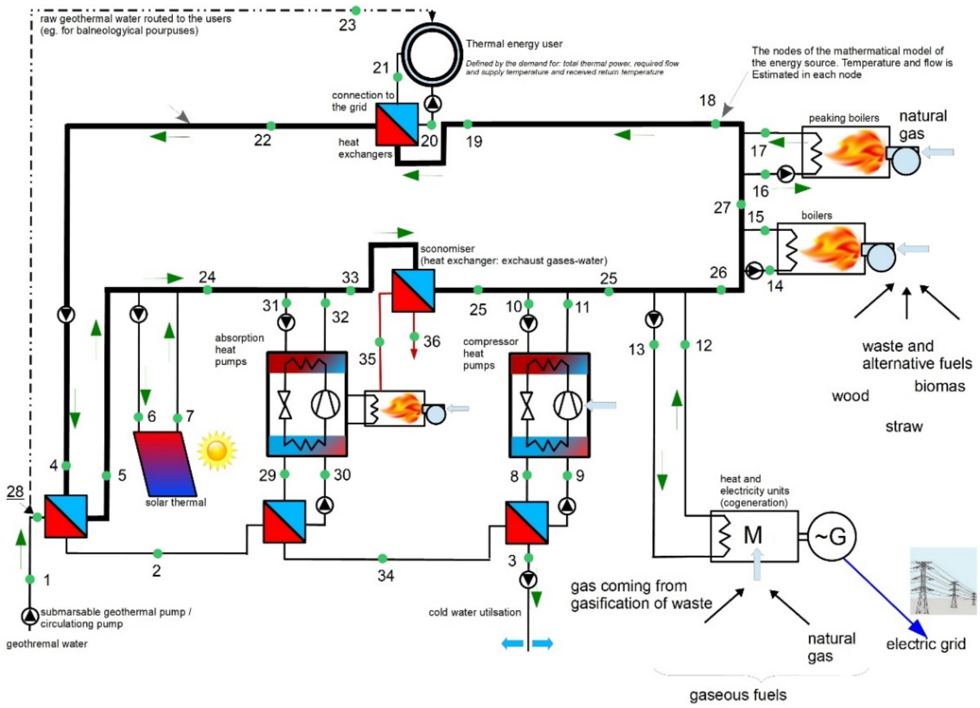


Fig. 5.7.4.7. The scheme of the energy source which utilise renewable energy sources –including geothermal energy

Results of using geothermal energy

The results of using geothermal energy in Lądek-Zdrój, depending on the assumed Options, are presented graphically in Figs. 5.7.4.8 to 5.7.4.13. The graphs indicate that, assuming the current customer characteristics, it will be necessary to use heat pumps and other equipment to cover the peak demand (natural gas burning boilers were analysed here).

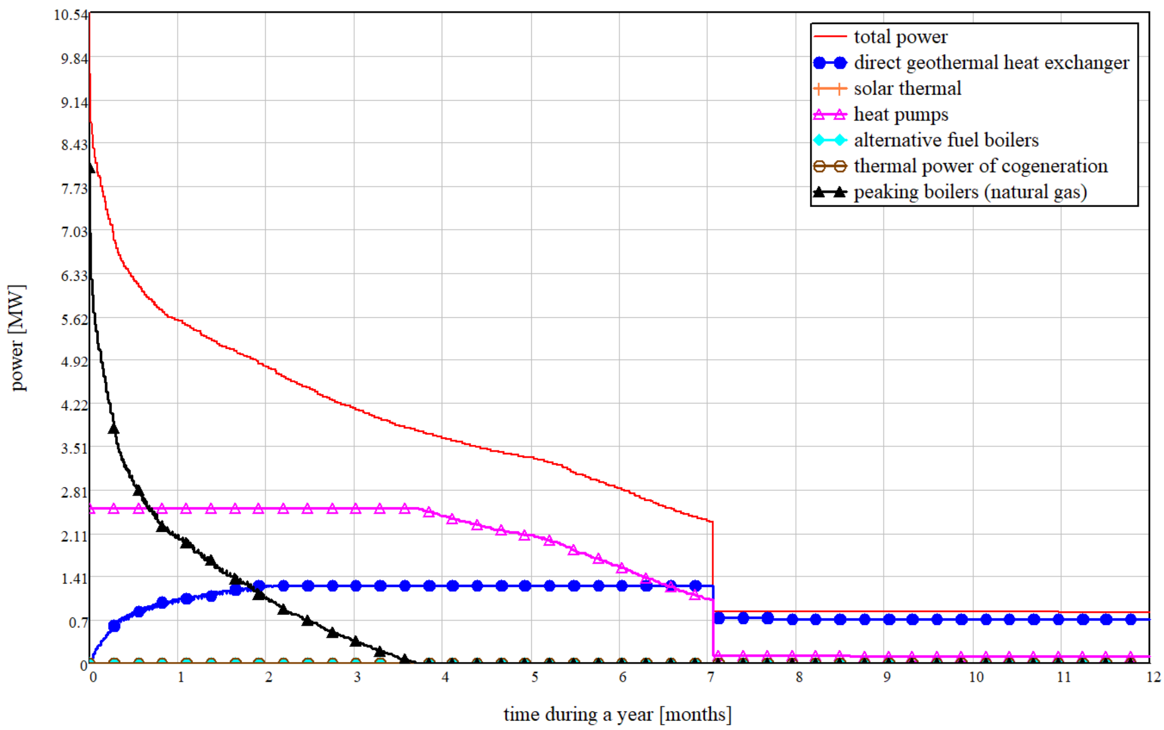


Fig. 5.7.4.8. The scheme of energy demands covering based on heat pumps, compression (chpC) and absorption (ahpC) in the area of CITY

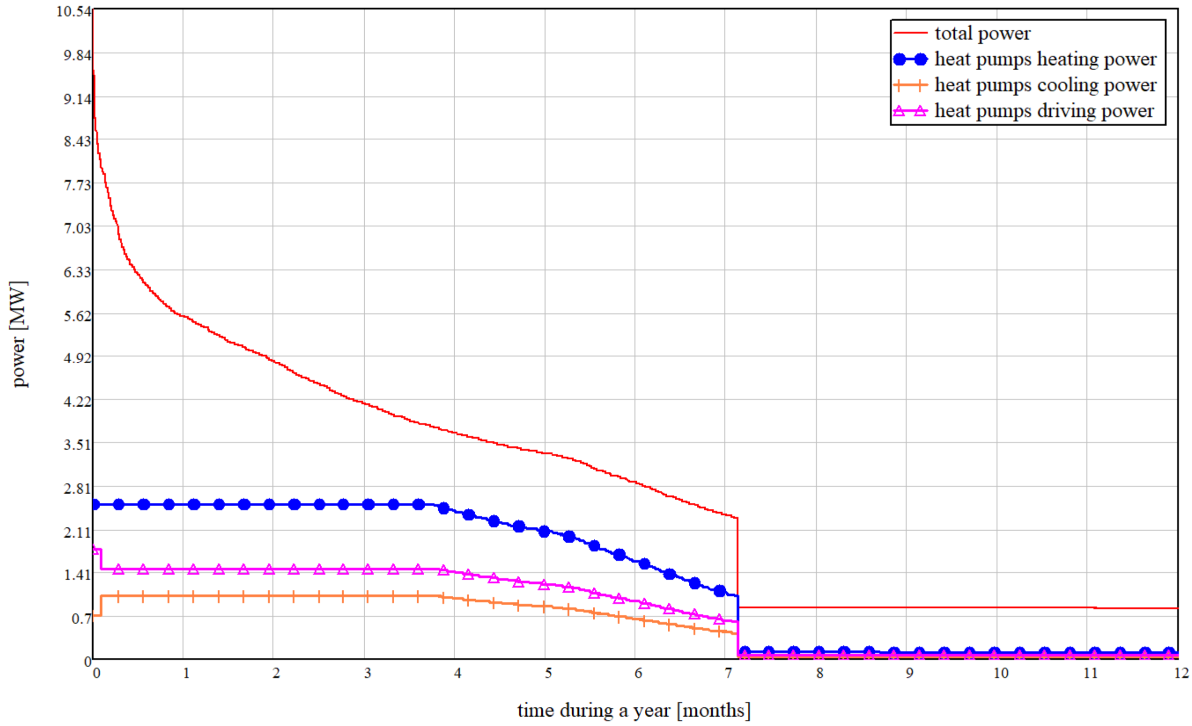


Fig. 5.7.4.9. Share of driving and cooling power in the heating power of compressor heat pumps in the option of chpC

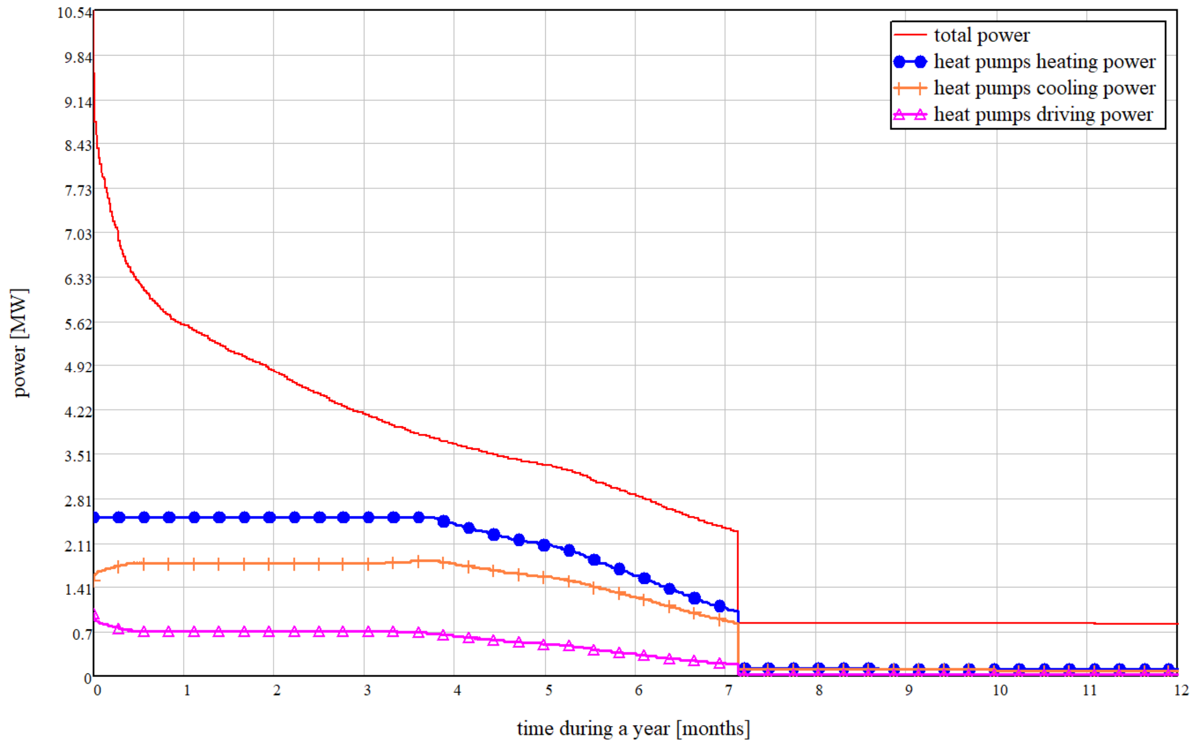


Fig. 5.7.4.10 Share of driving and cooling power in the heating power of compressor heat pumps in the option of chpC

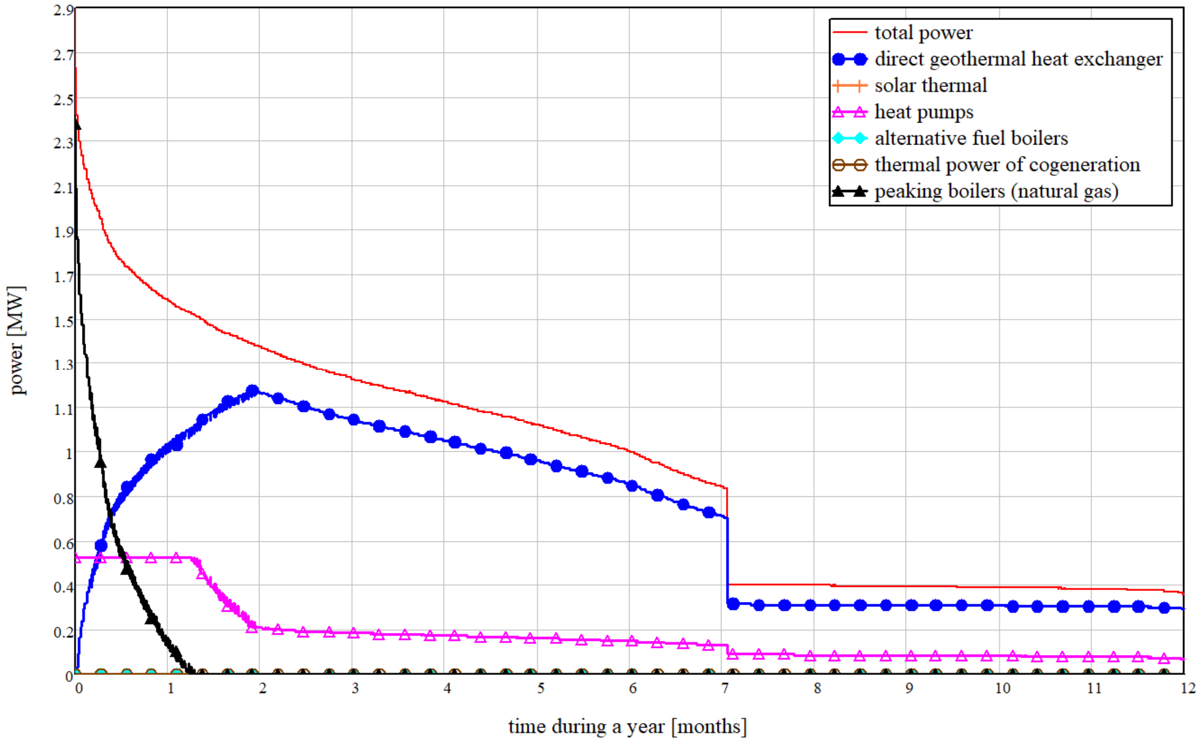


Fig. 5.7.4.11. The scheme of energy demands covering based on heat pumps, compression (chpS) and absorption (ahpS) in the area of SPA

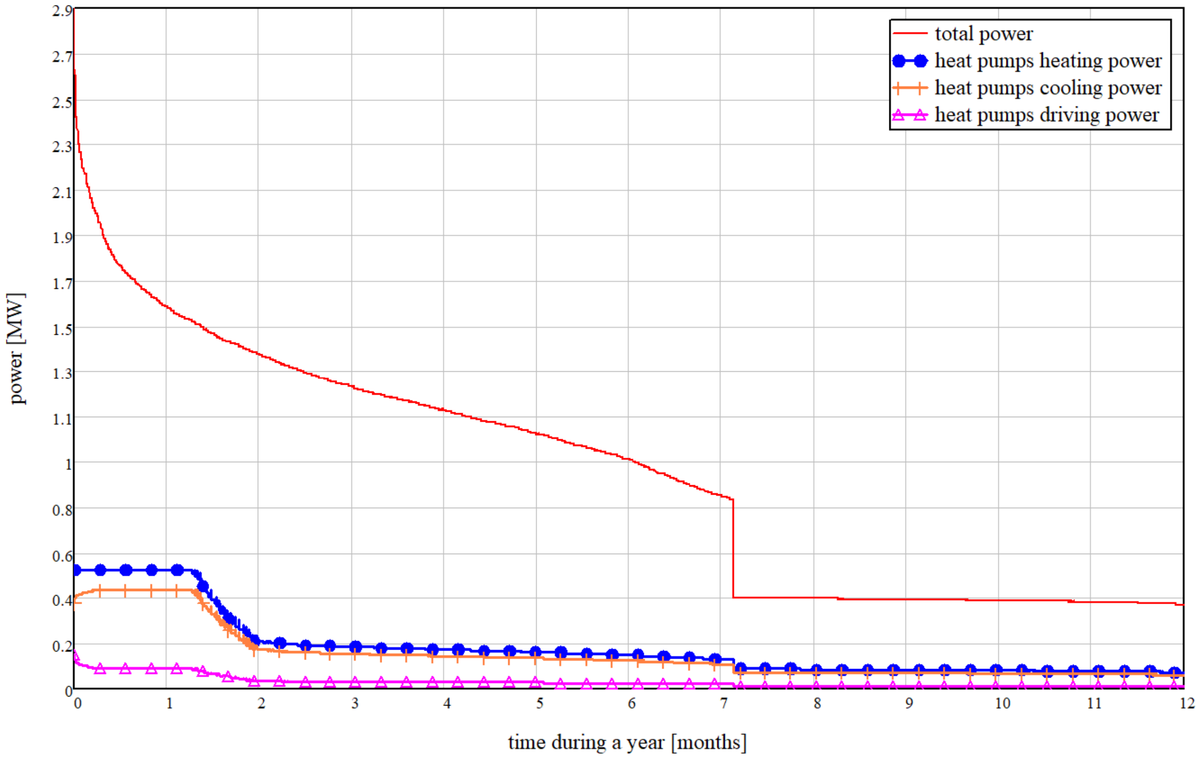


Fig. 5.7.4.12. Share of driving and cooling power in the heating power of compressor heat pumps in the option of chpS

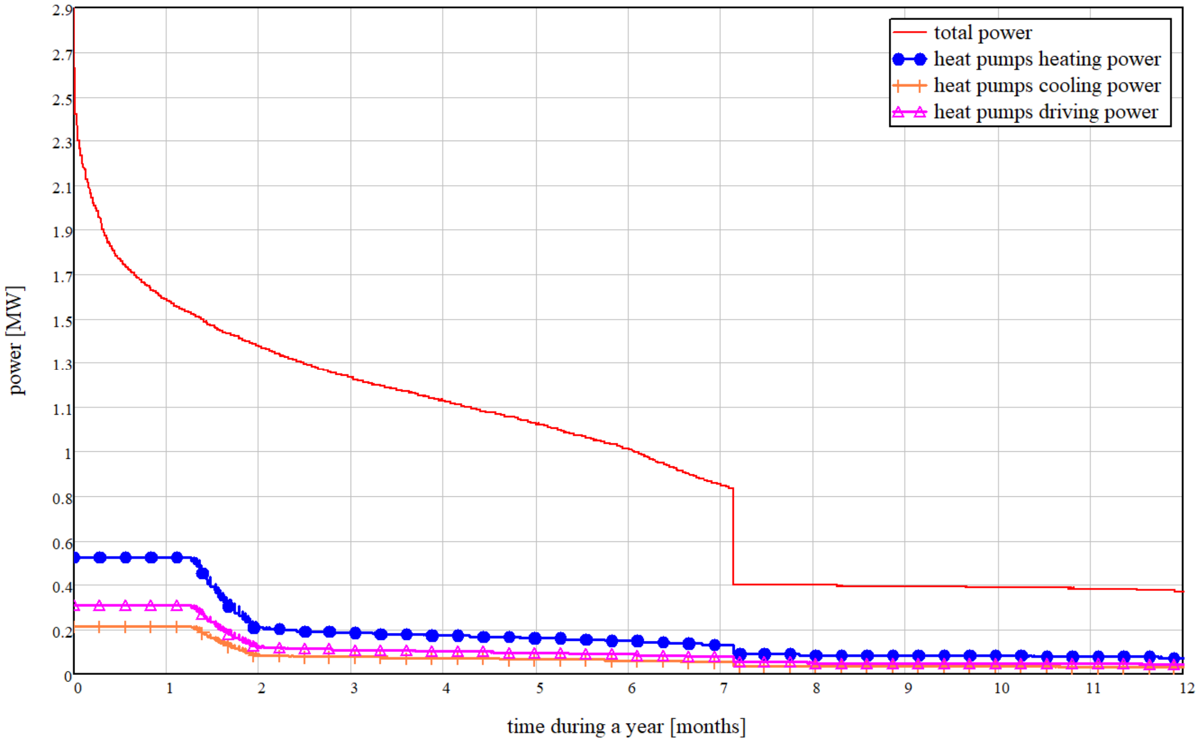


Fig. 5.7.4.13. Share of driving and cooling power in the heating power of absorption heat pumps in the option of ahpS

Table 5.7.4.2 contains the list of main technical, economic, and power parameters of the analysed options.

Table 5.7.4.2. Summary of the main technical and economic parameters characterizing the analysed variants for the town of Lądek-Zdrój

Parameter	Value	Value	Value	Value	Value	Value ć
Description of the variant	ngC	ahpC	chpC	ngS	ahpS	chpS
Maximal thermal power consumption [kW]	10388	10388	10388	2664	2664	2664
Consumption of thermal energy consumed by the user [GJ/year]	85474	85474	85474	25513	25513	25513
Annual value of the load factor [-]	0,261	0,261	0,261	0,303	0,303	0,303
Supply temperature (maximum = nominal) [°C]	89,8	89,8	89,8	89,4	89,4	89,4
Return temperature (maximum = nominal) [°C]	71,1	71,1	71,1	71,5	71,5	71,5
Nominal flow of working medium [m3/hr]	504,9	504,9	504,9	134,7	134,7	134,7
Nominal geothermal water outflow [m3/hr]	0	0	0	0	0	0
Estimated length of main pipelines [m]	0	3000	3000	0	4000	4000
Calculated maximum power losses on transmission [kW]	0	155	155	0	200	200
Calculated energy loss during distribution [GJ/year]	0	2128	2128	0	2799	2799
Net purchase price of natural gas [PLN/m3]	1,463	1,463	1,463	1,463	1,463	1,463
Net purchase price of electricity network [PLN/MWhr]	350	350	350	350	350	350
Selling price of electricity produced in thermal and current modules [PLN/MWhr]	250	250	250	250	250	250
----------- Description of energy sources ----------						
1. ----- Geothermal (direct use) -----						
1.1. Depth of geothermal horizon [m below ground level]	0	2500	2500	0	2500	2500
1.2. Water temperature driven to evaporator of heat pumps [°C]	8	70	70	8	70	70
1.3. Water stream [m3/hr]	0	50	50	0	50	50
1.4. Assumed static water level [m bgl]	0	10	10	0	10	10
1.5. Assumed unitary depression [m / m3/hr]	1	1	1	1	1	1
1.6. Production borehole status ('new', 'existing', 'reconstruction', 'no well')	no well	new	new	new	new	new
1.7. Injection borehole status ('new', 'existing', 'reconstruction', 'no well')	no well	no well	no well	no well	no well	no well
1.8. Assembled borehole diameter [m]	0,244475	0,244475	0,244475	0,244475	0,244475	0,244475
1.9. Maximal temperature reached on the production wellhead [°C]	7,8	65,5	65,5	7,8	65,5	65,5
1.10. Maximal power achieved on direct heat exchanger (without heat pumps) [kW]	0	1263	1263	0	1216	1216
1.11. The amount of energy obtained from the direct heat exchanger [GJ/year]	0	30972	30972	0	21113	21113
1.12. Nominal driving power estimatet for goethermal water pumps (exploitation and reinjection) [kW]	0	23	23	0	23	23
1.13. Electricity consumption by geothermal pumps [MWhr/year]	0	201	157	0	201	185
2 .----- Solar collectors -----						
2.1. Surface area of ??solar collectors [m2]	0	0	0	0	0	0
2.2. Thermal efficiency of collectors [-]	0,55	0,55	0,55	0,55	0,55	0,55
2.3. Solar radiation absorption coefficient [-]	0,9	0,9	0,9	0,9	0,9	0,9

2.4. Emission factor [-]	0,8	0,8	0,8	0,8	0,8	0,8
2.5. Maximum operating medium temperature [°C]	104,29	104,29	104,29	104,29	104,29	104,29
2.6. The amount of heat input to the customer's installation [GJ/year]	0	0	0	0	0	0
3. ----- Heat pumps (low energz source: geothermal) -----						
3.1. Heating capacity installed (maximal used) [kW]	0	2500	2500	0	500	500
3.2. Maximal working medium temperature at evaporator outlet [°C]	73,13	77,49	77,49	73,51	76,26	76,26
3.3. Maximal allowable water temperature at evaporator outlet [°C]	100	100	100	100	100	100
3.4. Minimum temperature of water at evaporator outlet [°C]	20	26,15	12,48	20	41,34	40,25
3.5. Maximum value of COP (on heating side) [-]	1,4	1,7	6	1,4	1,7	6
3.6. The amount of heat generated by heat pumps [GJ/year]	0	41830	41830	0	5390	5390
3.7. Amount of used drive energy consumed to drive the heat pump [MWhr/year]	0	6854	3059	0	881	252
3.8. Amount of used electric power used to drive geothermal pumps [MWhr/year]	0	201	157	0	201	185
4. ----- Thermoelectric units -----						
4.1. Thermal power of modules [kW]	0	0	0	0	0	0
4.2. Electrical power generated by modules [kW]	0	0	0	0	0	0
4.3. The amount of thermal energy generated by the thermoelectric modules [GJ/year]	0	0	0	0	0	0
4.4. The amount of electricity generated by the thermoelectric modules [MWhr/year]	0	0	0	0	0	0
4.5. Costs of obtaining biogas derived from gasification of waste [PLN/m3]	0,9	0,9	0,9	0,9	0,9	0,9
5. ----- Boilers for alternative fuels and biomass -----						
5.1. Maximum installed power (used) in alternative fuels and biomass boilers [kW]	0	0	0	0	0	0
5.2. The amount of heat generated in boilers for alternative fuels and biomass [GJ/year]	0	0	0	0	0	0
5.3. Cost of acquisition / purchase price of fuels and biomass (average) [PLN/Mg]	400	400	400	400	400	400
6. ----- Peak boilers for natural gas -----						
6.1. Maximum installed power (used) in gas boilers [kW]	10388	8043	8043	2664	2364	2364
6.2. The amount of thermal energy produced in gas boilers [GJ/year]	85474	14801	14801	25513	1809	1809
Estimated investment outlays for heat source [thousands PLN]	8407	34999	35649	2156	27542	27672
- production well [thousands PLN]	0	18327	18327	0	18327	18327
- well for reinjection [thousands PLN]	0	0	0	0	0	0
- direct heat exchanger [thousands PLN]	0	63	63	0	61	61
- installation of solar collectors [thousands PLN]	0	0	0	0	0	0
- heat pumps [thousands PLN]	0	3750	4250	0	750	850
- installation of gasification of waste together with thermal and current modules [thousands PLN]	0	0	0	0	0	0
- alternative fuels and biomass [thousands PLN]	0	0	0	0	0	0
- peak boilers for natural gas [thousands PLN]	6233	4826	4826	1599	1419	1419
- connection pipelines and transmission lines [thousands PLN]	0	3000	3000	0	4000	4000
- energy source building [thousands PLN]	277	281	281	71	76	76

- cost of assembly, reserve for unexpected expenses [thousands PLN]	1898	4752	4902	487	2909	2939
Total annual operating costs [thousands PLN/year]	4517	4179	4130	1325	2092	2036
- constant costs [thousands PLN/year]	546	2275	2317	140	1790	1799
- flexible costs [thousands PLN/year]	3971	1904	1813	1185	302	237
- depreciation of fixed assets [thousands PLN/year]	420	1750	1782	108	1377	1384
- costs of maintenance and repairs [thousands PLN/year]	126	525	535	32	413	415
- costs of buying conventional energy carriers [thousands PLN/year]	3971	1904	1813	1185	302	237
- incomes from the sale of electricity produced in combination by thermal current modules [thousands PLN/year]	0	0	0	0	0	0
Unitary costs of energy generation (excluding transmission losses) [PLN/GJ]	53	48	47	52	74	72
The price of energy for final customer (including transimission losses) [PLN/GJ]	53	49	48	52	82	80
Emission of pollutants emission related to the unit of generated heat [kg/GJ]						
- benzo (a) pyrene locally	0	0	0	0	0	0
- soot locally	0	0	0	0	0	0
- total dust locally	0	0	0	0	0	0
- CO2 locally	60,48	27,933	10,473	60,48	11,806	4,289
- CO locally	0,011	0,005	0,002	0,011	0,002	0,001
- NOx (recalculated to the NO2) locally	0,039	0,018	0,007	0,039	0,008	0,003
- SO2 locally	0	0	0	0	0	0
- aliphatic hydrocarbons locally	0,033	0,015	0,006	0,033	0,006	0,002
- aromatic hydrocarbons locally	0,001	0	0	0,001	0	0
- benzo (a) pyrene in global scale	0	0	0	0	0	0
- soot in global scale	0	0	0,001	0	0	0
- total dust in global scale	0	0,001	0,014	0	0,003	0,007
- CO2 in global scale	60,48	30,399	49,864	60,48	20,068	22,234
- CO in global scale	0,011	0,011	0,091	0,011	0,021	0,042
- NOx (recalculated to the NO2) in global scale	0,039	0,022	0,078	0,039	0,023	0,035
- SO2 in global scale	0	0,015	0,244	0	0,051	0,111
- aliphatic hydrocarbons in global scale	0,033	0,015	0,006	0,033	0,006	0,002
- aromatic hydrocarbons in global scale	0,001	0,001	0,005	0,001	0,001	0,002

Summary and conclusions

Owing to the lack of temperature coherence between the presently used heating installations and the available temperatureof the geothermal energy source in Lądek-Zdrój, it will be necessary to apply heat pumps, while the use of peak-demand boilers burning high-methane content natural gas seems to be economically justified. The heat pump and boiler operating time will depend on the type of customer, or the required thermal capacity. Together with the increase of capacity, the operating time of the equipment supporting the direct use of thermal energy will increase. In the case of meeting the district heating needs in the town section (CITY zone, Fig. 5.7.4.1), the peak-demand boiler operating period can be estimated at ca. 3-4 months a year. In the case of the spa area (SPA zone, Fig. 5.7.4.1),the period will be ca. 1.5 months a year. In the spa case, some capacity will be lost in distribution and that will be accompanied by temperature drop. It may be thus necessary to operate the heat pumps all the year around. At the execution stage, that effect can be reduced by using a summer heat pipeline with a smaller diameter (three-pipe system) or allowing for a lower supply temperaturefor heating. That will require increase of the surface areas of heat exchangers in the installation for the hot utility water preparation.

Assuming the final price for energy paid by the customer, as the criterion of the economic feasibility of the project relating to the use of geothermal energy for heating purposes, we can conclude that the use of geothermal energy can be economically profitable in the town area (CITY zone, Fig. 5.7.4.1). The final thermal energy price can be lower than that paid for the energy originatingfrom local gas facilities, despite significant investment expenditures (estimated at ca. 35 million PLN, Table 5.7.4.2). Our estimations do not include the expenditures for the execution of a distribution network. Such expenditures can be quite high in the present project. However, considering the safety of using the energy source and the environmental conditions on this special spa area, bearing such expenditures can be fully justified. Unfortunately, considering only the economic criterion, the use of geothermal energy in the Spa area (SPA zone,Fig. 5.7.4.1) is not profitable. Again, we need to mention here the specific significance of the analysed zone and the quality of the environment required there. The use of geothermal energy is associated with the reduction of local pollution in each of the analysed cases (Table 5.7.4.2). Pollution reduction can also be expected on a global scale.

Recommendations for Lądek-Zdrój

1. Low temperature heating systems

The heating system in buildings is designed for relatively high supply/return temperatures. Future district heating networks are moving towards lower design temperatures, such that these can be successfully integrated to renewable energy supplies. This would require that the heating system in buildings are planned accordingly.

Choice of low temperature heating system require higher investment costs and offer lower return investments. However, this choice enable easy integration and increased utilization of geothermal heat in the district heating networks.

Lądek-Zdrój is an old town. Several anticipated customers for the future district heating network will be old buildings where renovation of heating system is coming in near future. It is recommended that district heating network should base its design on choice of supply temperatures closer to 60°C. This choice will open possibilities for integration of renewable energy in longer future. A district heating network can then of practical reasons be operated at higher supply temperatures to enable the transitions of older high temperature heating systems to low temperature heating systems.

The district heating network should then define requirements for the customers such that they are obliged to or prefer to choose lower temperature heating system in their buildings. One solution could be that the district heating company collaborate with the building owners and find common investment solutions alongside governmental support programs and subsidies. The investment solutions must look into total cost of both the heating system in houses alongside geothermal heat supplies to make offers to the building owners who are interested in choosing lower temperature heating systems along with connection the district heating network.

2. Implementation of district heating network

One of the key parameters for success of a district heating network lies in reaching higher density of heat sales per unit pipe length. Sparsely distributed areas often lead to slow penetration of district heating and offers low return on investments. Improvement in energy efficiency of building envelops should be important consideration in this regard. Although, it might look attractive to sell large amount of heat to few buildings, refurbishment of these buildings might change the scenario. District heating network are investments for at least next 60 yerars. It is therefore important to evaluate if the district heating network could reach such sales density in Lądek-Zdrój. Alternative solution can be to evaluate application of local energy supply solutions that is limited to heat supply to building in close vicinity to limit the investments scale.

3. Successful implementation of geothermal heating

Thermal waters have remained large attraction and resource for Lądek-Zdrój. It of therefore important to ensure that deep geothermal extraction of waters does not interfere with curative water resources. In case of positive results, the borehole will be supply around 2-4 MW of heat at 70°C. As the system will be connected to existing buildings with design temperatures (most probably) 90/70°C or 80/60°C, a certain amount of heat will still be supplied by peak load boilers. The system typology in such case might be such that heating from a district heating network (DHN) covers only base load, while the existing boilers cover the peak loads. Alternatively, the peak loads may be covered by centrally located boiler based on either gas or biomass. To avoid excessive use of peak boilers, it is strongly recommended to choose design temperatures for DHN closer to, or above, the design temperature in buildings.

Another alternative for the town of less risk of affecting existing sources and well, will be to utilize shallow geothermal boreholes with close loop heat exchangers. In this case, the heat will be taken from shallow geothermal boreholes at temperature between 10 -20°C and upgraded to required temperatures using heat pump technology. Shallow borehole with close loop heat exchangers are already installed in at least one kindergarden in Lądek-Zdrój with success and therefore greatly reduce the risk involved in the project. Such solution can be implemented with great success at individual or cluster of buildings. Moreover, a large amount of waste water from treatment facilities that is rejected at moderate temperatures of about 30°C can be combined with heat pump technology to upgrade available waste heat to required temperatures.

A heat source temperature of approx. 20°C is adequate for using a vapor compression heat pump (VCCHP) to raise the available temperature to 80-95°C. A total COP in the range of 3.0-4.0 can be expected from commercially available solutions. A three stage VCCHP installation may be needed, depending on design. Should the design temperature be closer to a low-temperature solution, around 60-70°C, commercial solutions should produce COPs in a range closer to 3.5-4.5. These figures are very sensitive to the choice of components in the heat pump, such as refrigerant, compressor and system design.

Snow melting of pavements is highly energy intensive. Heating load for snow melting varies as function of outdoor temperature, air velocity and amount and temperature of precipitation. Typical design load for de-icing lies at around 200-300 W/m^2. It is therefore recommended to limit the application of snow melting to only streets with high utilization factor. Snow melting should be limited to only pavement on one side of the street/road and identified with color coding or similar solution. The energy can be supplied to the deicing system using return side of the district heating network. Waste heat from curative thermal waters might also be used for the purpose depending on distances, amount and quality of required heat. Experience in Norway shows that need for snow melting often occurs in temperature zones near 0 to -6 °C and probability of precipitation at very lower temperatures is seldom. Typical energy use with optimal control strategies lies near between 100 – 150 kWh/m^2 but might soon go up to 400 kWh/m^2 with badly design and controlled system. It is therefore, recommended that these considerations are made in the design phase so that snow melting in the town does not become contrast to the original ambition of finding climate friendly energy solutions.

References:

Wody Geotermalne w Lądku Zdroju. Załącznik do wniosku o dofinansowanie w Programie Geologia i Górnictwo, 2016.02.11.

5.7.5. Energetic–economic analysis of optimal geothermal water and energy use for heating/district heating system and other multipurposed uses in Lądek-Zdrój

The optimisation of the use of geothermal water and energy consists in the application of certain general principles:

- We should try to use energy directly, without heat pumps if possible. Heat pumps can appear if there is still energy demand, while the geothermal water temperature is too low to be used directly,
- After using the energy contained in geothermal water, we should try to continue to manage water, e.g. as potable water or for other purposes (balneology, medicinal treatment, cosmetology, industry, etc.).

To attain the aim of the maximum use of geothermal energy, without applying heat pumps, the conception of a cascade system will be useful. In a cascade system, energy recipients are arranged in a sequence of decreasing heating-medium temperature demand. Water used by one customers is transported to subsequent ones who can still use water with lower temperature. The operation of a cascade system requires building proper heating installations, characterised by expanded heat-exchange surface areas (large heaters in space heating).This Section is dedicated to the optimisation of the use of geothermal energyin Lądek-Zdrój,with the presentation of the results of the operating philosophy under discussion. Optimisation will concern the quantitative energy, economy, and ecology effects. It will be based on the assumption of changing customer characteristics in the town, and, to be precise, on the reduction of the required supply and return water temperaturesin the heating installations as low as possible, without the necessity to apply large-area heating systems, e.g. floor heating.It was assumed that the recipients (customers) will be equipped with the heating installations designed for 60/40/20/-20°C, while the utility water preparation installation will be adjusted to 60/30°C. The effects to be obtained will be comparable to those described in Section 5.7.4, presenting the calculations of the results obtained, without correcting any customers' heating installation characteristics. The Option symbols are those described in the previous Section, although letter "o" has been added to stand for o-ptimised.The customers' capacity demand characteristics is not changing in time. What is changing is the parameters of supplied capacity control. A new characteristics is presented in Figs. 5.7.5.1 and 5.7.5.2.

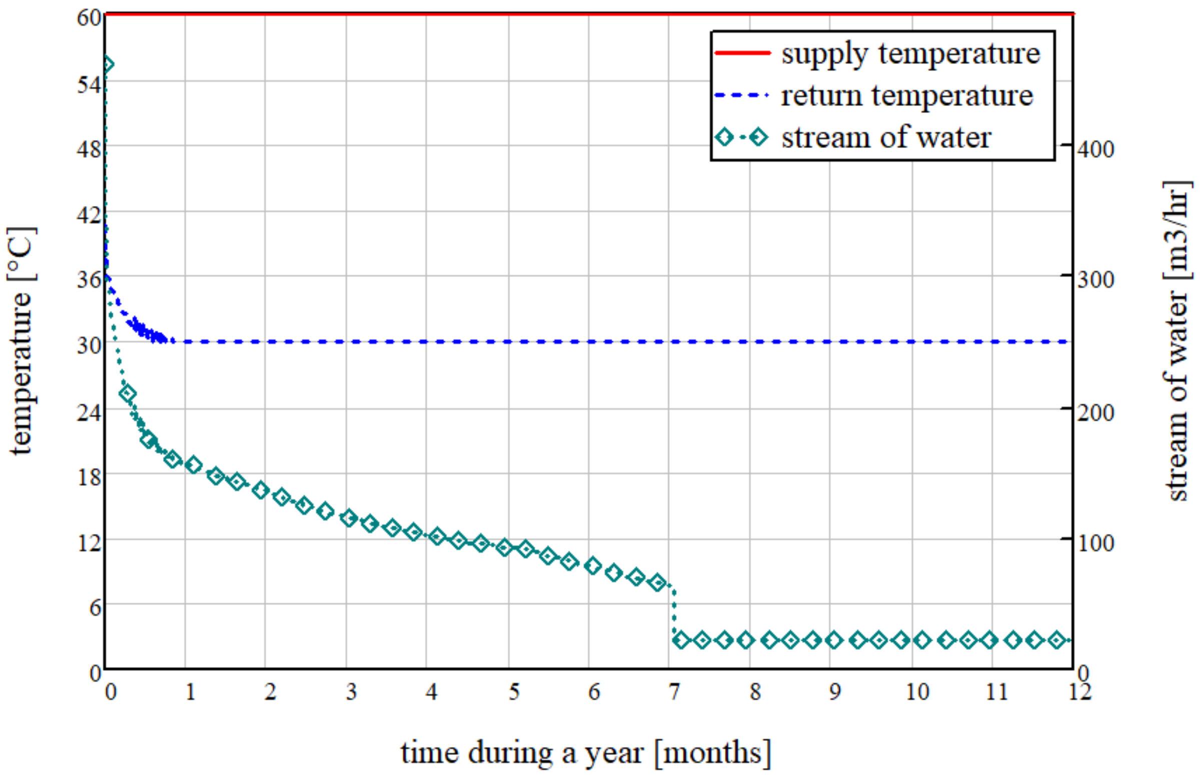


Fig. 5.7.5.1. Characteristics of the area CITY in terms of required temperature and flow of water vs time after retrofitting of the heating systems

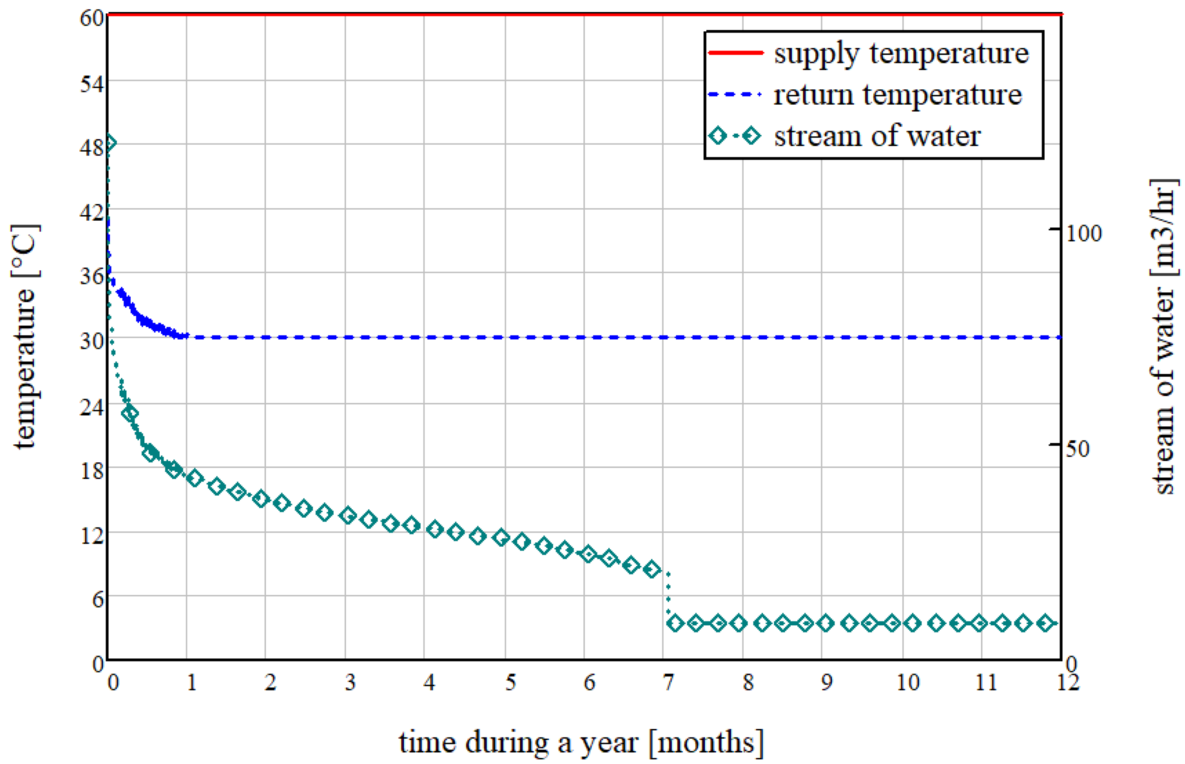


Fig. 5.7.5.2. Characteristics of the area SPA in terms of required temperature and flow of water vs time after retrofitting of the users heating systems

Results of using geothermal energy after modernisation of customers' installations

The results of energy source operation were modelled in analogy to the present operating results. However, we took into account a new customer characteristics. Selected calculation results, showing the schedule of covering the heating needs, are presented in Figs. 5.7.5.3 to 5.7.5.7. By comparing them with analogous graphs presented in the previous Section, one can notice that the maximum capacity and the heat pump operating periods have changed. Also, the peak-demand boiler operation has been reduced.

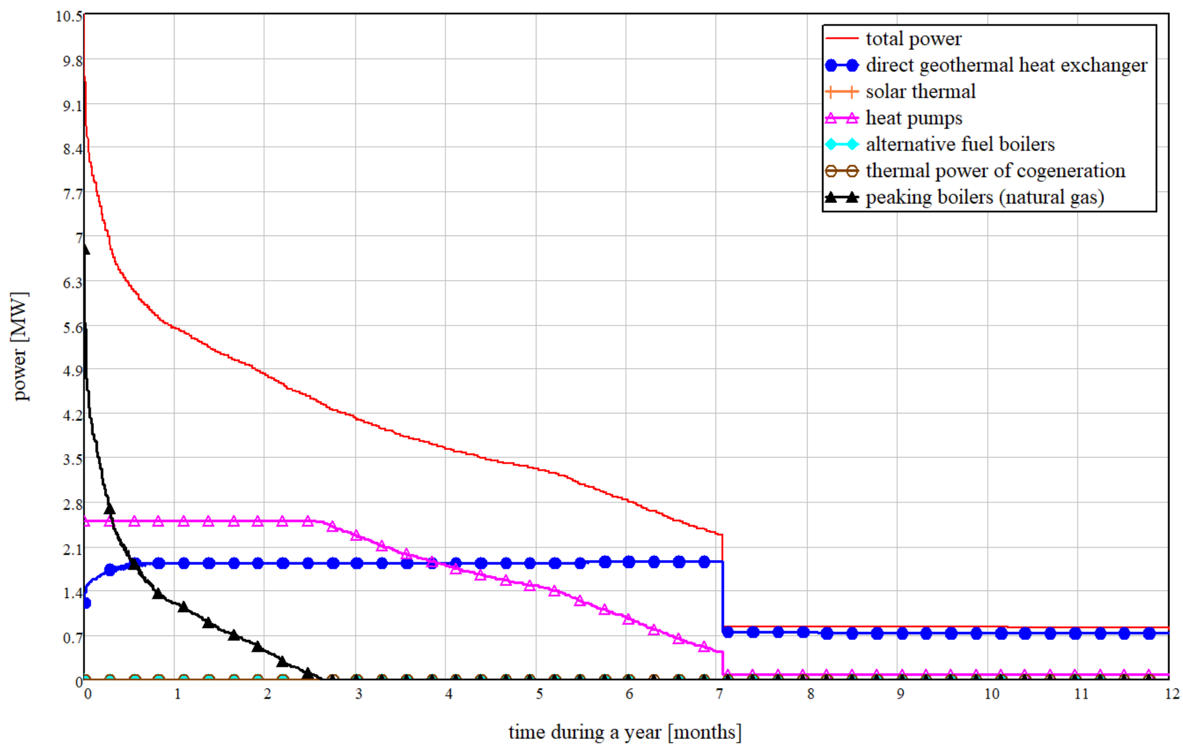


Fig. 5.7.5.3. The scheme of energy demands covering based on absorption heat pumps (ahpCo) in the area of CITY after retrofitting the users heating systems

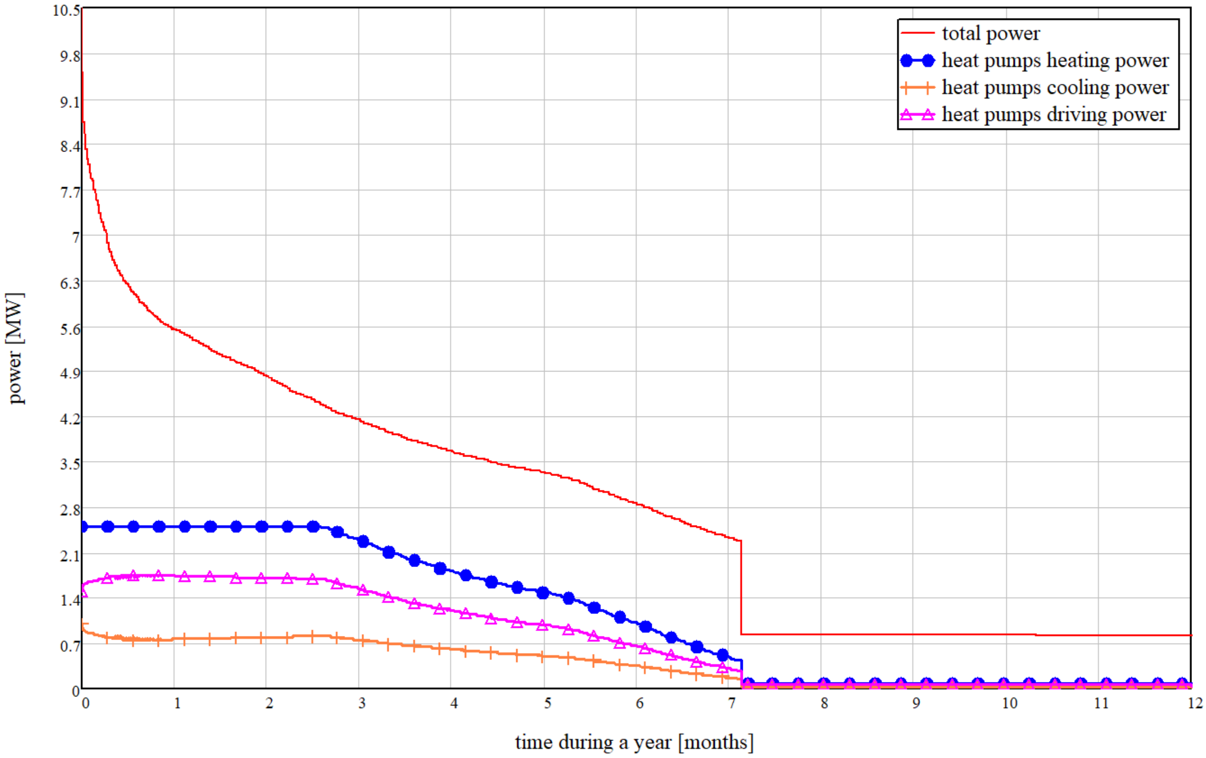


Fig. 5.7.5.4. Share of driving and cooling power in the heating power of absorption heat pumps in the option of ahpCo

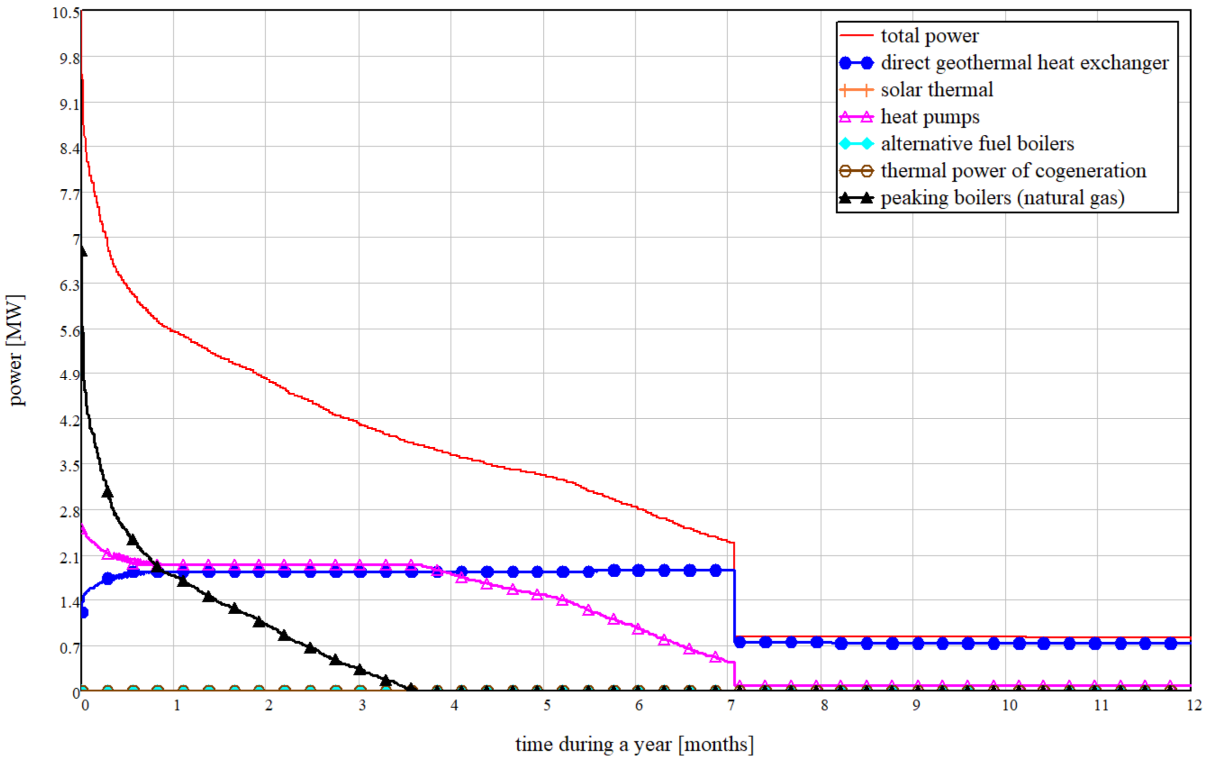


Fig. 5.7.5.5. The scheme of energy demands covering based on compression heat pumps (chpCo) in the area of CITY after retrofitting the users heating systems

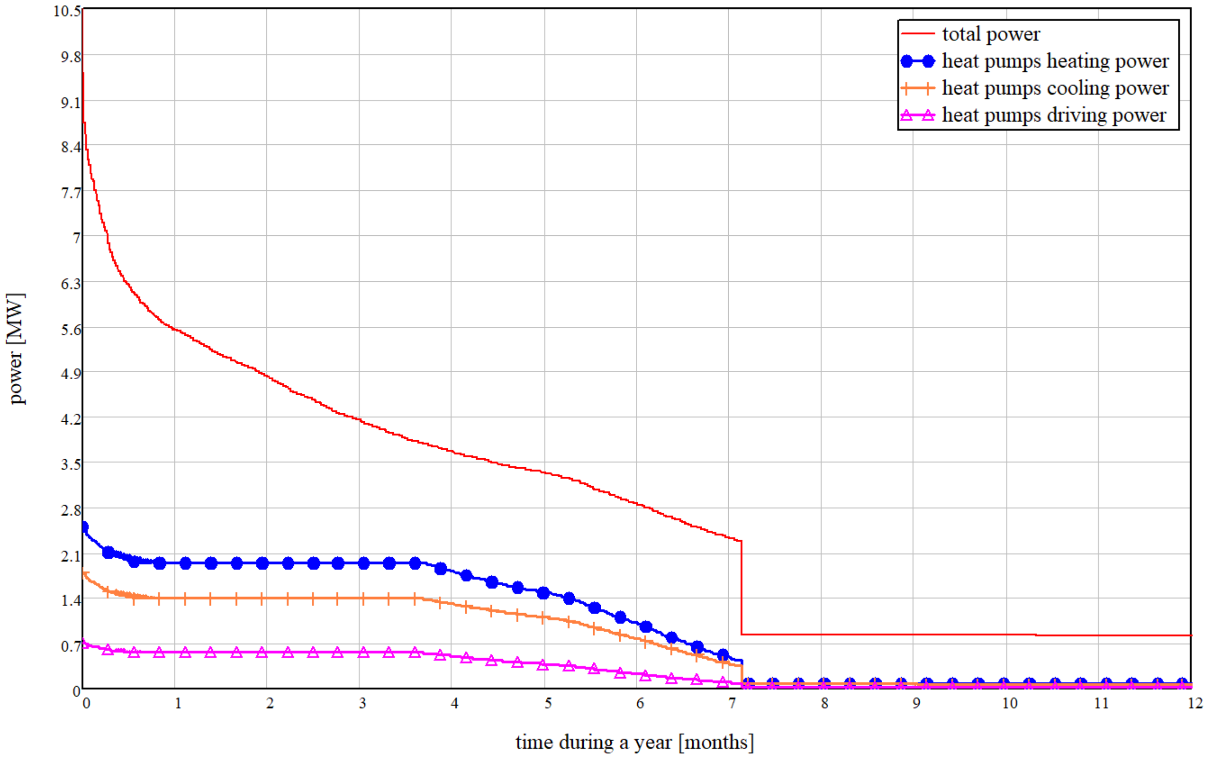


Fig. 5.7.5.6. Share of driving and cooling power in the heating power of compressor heat pumps in the option of chpCo

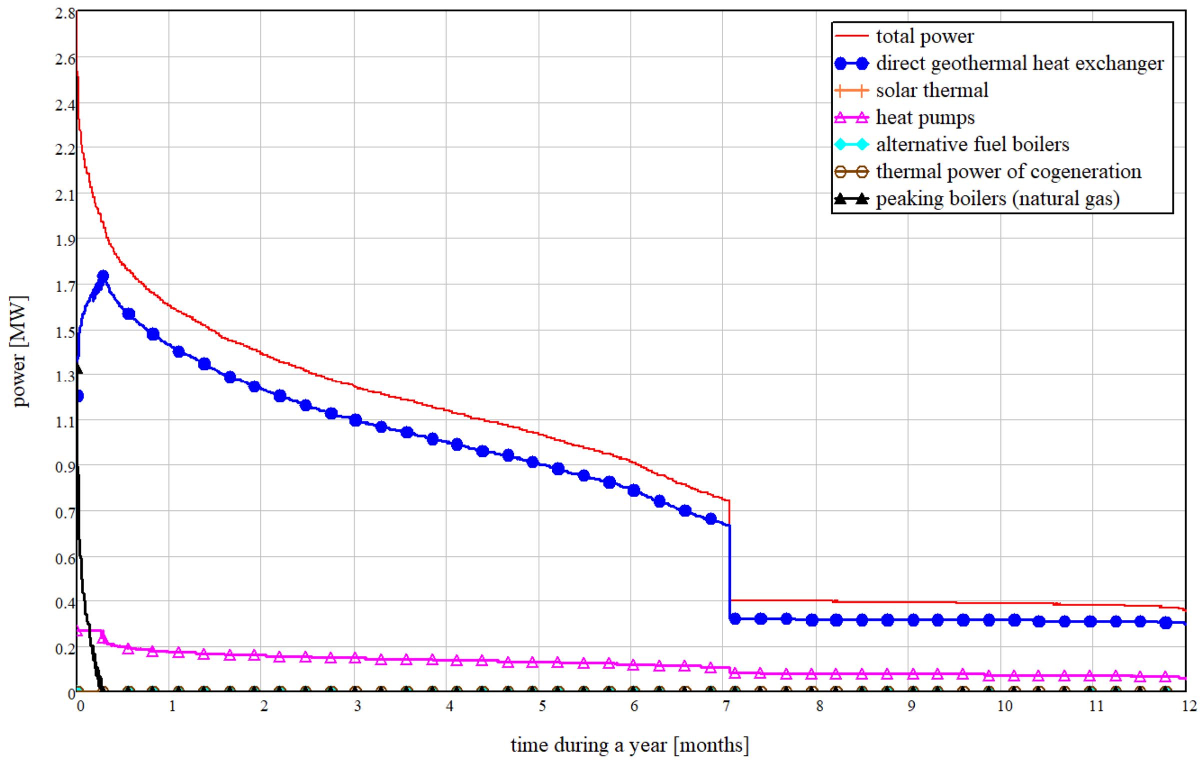


Fig. 5.7.5.7. The scheme of energy demands covering based on absorption and compressor heat pumps in the area of SPA (ahpSo and chpSo) after retrofitting of heating systems at users

Table 5.7.5.1 contains the list of main technical, economic, and ecological parameters of the energy source with modernised energy recipients.

Table 5.7.4.2. Summary of the main technical and economic parameters characterizing the analysed variants for the town of Lądek Zdrój after retroffiting of users heating systems

Parameter	Value	Value	Value	Value	Value	Value
Description of the variant	ngCo	ahpCo	chpCo	ngSo	ahpSo	chpSo
Maximal thermal power consumption [kW]	10388	10388	10388	2664	2664	2664
Consumption of thermal energy consumed by the user [GJ/year]	85474	85474	85474	25513	25513	25513
Annual value of the load factor [-]	0.261	0.261	0.261	0.303	0.303	0.303
Supply temperature (maximum = nominal) [°C]	89.8	60	60	89.4	60	60
Return temperature (maximum = nominal) [°C]	71.1	40.7	40.7	71.5	40.9	40.9
Nominal flow of working medium [m3/hr]	504.9	461.7	461.7	134.7	120.1	120.1
Nominal geothermal water outflow [m3/hr]	0	0	0	0	0	0
Estimated length of main pipelines [m]	0	3000	3000	0	4000	4000
Calculated maximum power losses on transmission [kW]	0	108	108	0	140	140
Calculated energy loss during distribution [GJ/year]	0	1867	1867	0	2481	2481
Net purchase price of natural gas [PLN/m3]	1.463	1.463	1.463	1.463	1.463	1.463
Net purchase price of electricity network [PLN/MWhr]	350	350	350	350	350	350
Selling price of electricity produced in thermal and current modules [PLN/MWhr]	250	250	250	250	250	250
----------- Description of energy sources ----------						
1. ----- Geothermal (direct use) -----						
1.1. Depth of geothermal horizon [m below ground level]	0	2500	2500	0	2500	2500
1.2. Water temperature driven to evaporator of heat pumps [°C]	8	70	70	8	70	70
1.3. Water stream [m3/hr]	0	50	50	0	50	50
1.4. Assumed static water level [m bgl]	0	10	10	0	10	10
1.5. Assumed unitary depression [m / m3/hr]	1	1	1	1	1	1
1.6. Production borehole status ('new', 'existing', 'reconstruction', 'no well')	no well	new	new	new	new	new
1.7. Injection borehole status ('new', 'existing', 'reconstruction', 'no well')	no well	no well	no well	no well	no well	no well
1.8. Assembled borehole diameter [m]	0.244475	0.244475	0.244475	0.244475	0.244475	0.244475
1.9. Maximal temperature reached on the production wellhead [°C]	7.8	65.5	65.5	7.8	65.5	65.5
1.10. Maximal power achieved on direct heat exchanger (without heat pumps) [kW]	0	1845	1845	0	1718	1718
1.11. The amount of energy obtained from the direct heat exchanger [GJ/year]	0	43501	43501	0	24307	24307
1.12. Nominal driving power estimatet for goethermal water pumps (exploitation and reinjection) [kW]	0	23	23	0	23	23
1.13. Electricity consumption by geothermal pumps [MWhr/year]	0	201	201	0	201	186
2 .----- Solar collectors -----						
2.1. Surface area of ??solar collectors [m2]	0	0	0	0	0	0
2.2. Thermal efficiency of collectors [-]	0.55	0.55	0.55	0.55	0.55	0.55
2.3. Solar radiation absorption coefficient [-]	0.9	0.9	0.9	0.9	0.9	0.9

2.4. Emission factor [-]	0.8	0.8	0.8	0.8	0.8	0.8
2.5. Maximum operating medium temperature [°C]	104.29	104.29	104.29	104.29	104.29	104.29
2.6. The amount of heat input to the customer's installation [GJ/year]	0	0	0	0	0	0
3. ----- Heat pumps (low energz source: geothermal) -----						
3.1. Heating capacity installed (maximal used) [kW]	0	2500	2500	0	250	250
3.2. Maximal working medium temperature at evaporator outlet [°C]	73.13	63.55	63.55	73.51	67.64	67.64
3.3. Maximal allowable water temperature at evaporator outlet [°C]	100	100	100	100	100	100
3.4. Minimum temperature of water at evaporator outlet [°C]	20	20	10	20	31.51	30.41
3.5. Maximum value of COP (on heating side) [-]	1.4	1.67	5.71	1.4	1.7	5.81
3.6. The amount of heat generated by heat pumps [GJ/year]	0	35391	31175	0	3486	3486
3.7. Amount of used drive energy consumed to drive the heat pump [MWhr/year]	0	6623	2339	0	651	183
3.8. Amount of used electric power used to drive geothermal pumps [MWhr/year]	0	201	201	0	201	186
4. ----- Thermoelectric units -----						
4.1. Thermal power of modules [kW]	0	0	0	0	0	0
4.2. Electrical power generated by modules [kW]	0	0	0	0	0	0
4.3. The amount of thermal energy generated by the thermoelectric modules [GJ/year]	0	0	0	0	0	0
4.4. The amount of electricity generated by the thermoelectric modules [MWhr/year]	0	0	0	0	0	0
4.5. Costs of obtaining biogas derived from gasification of waste [PLN/m3]	0.9	0.9	0.9	0.9	0.9	0.9
5. ----- Boilers for alternative fuels and biomass -----						
5.1. Maximum installed power (used) in alternative fuels and biomass boilers [kW]	0	0	0	0	0	0
5.2. The amount of heat generated in boilers for alternative fuels and biomass [GJ/year]	0	0	0	0	0	0
5.3. Cost of acquisition / purchase price of fuels and biomass (average) [PLN/Mg]	400	400	400	400	400	400
6. ----- Peak boilers for natural gas -----						
6.1. Maximum installed power (used) in gas boilers [kW]	10388	6779	6779	2664	1333	1333
6.2. The amount of thermal energy produced in gas boilers [GJ/year]	85474	8450	12666	25513	200	200
Estimated investment outlays for heat source [thousands PLN]	8407	34051	34701	2156	26281	26346
- production well [thousands PLN]	0	18327	18327	0	18327	18327
- well for reinjection [thousands PLN]	0	0	0	0	0	0
- direct heat exchanger [thousands PLN]	0	92	92	0	86	86
- installation of solar collectors [thousands PLN]	0	0	0	0	0	0
- heat pumps [thousands PLN]	0	3750	4250	0	375	425
- installation of gasification of waste together with thermal and current modules [thousands PLN]	0	0	0	0	0	0
- alternative fuels and biomass [thousands PLN]	0	0	0	0	0	0
- peak boilers for natural gas [thousands PLN]	6233	4068	4068	1599	800	800
- connection pipelines and transmission lines [thousands PLN]	0	3000	3000	0	4000	4000
- energy source building [thousands PLN]	277	280	280	71	75	75

- cost of assembly, reserve for unexpected expenses [thousands PLN]	1898	4534	4684	487	2618	2633
Total annual operating costs [thousands PLN/year]	4517	3784	3733	1325	1897	1851
- constant costs [thousands PLN/year]	546	2213	2256	140	1708	1712
- flexible costs [thousands PLN/year]	3971	1571	1478	1185	189	139
- depreciation of fixed assets [thousands PLN/year]	420	1703	1735	108	1314	1317
- costs of maintenance and repairs [thousands PLN/year]	126	511	521	32	394	395
- costs of buying conventional energy carriers [thousands PLN/year]	3971	1571	1478	1185	189	139
- incomes from the sale of electricity produced in combination by thermal current modules [thousands PLN/year]	0	0	0	0	0	0
Unitary costs of energy generation (excluding transmission losses) [PLN/GJ]	53	43	43	52	68	66
The price of energy for final customer (including transimission losses) [PLN/GJ]	53	44	44	52	74	73
Emission of pollutants emission related to the unit of generated heat [kg/GJ]						
- benzo (a) pyrene locally	0	0	0	0	0	0
- soot locally	0	0	0	0	0	0
- total dust locally	0	0	0	0	0	0
- CO2 locally	60.48	22.851	8.962	60.48	6.032	0.475
- CO locally	0.011	0.004	0.002	0.011	0.001	0
- NOx (recalculated to the NO2) locally	0.039	0.015	0.006	0.039	0.004	0
- SO2 locally	0	0	0	0	0	0
- aliphatic hydrocarbons locally	0.033	0.012	0.005	0.033	0.003	0
- aromatic hydrocarbons locally	0.001	0	0	0.001	0	0
- benzo (a) pyrene in global scale	0	0	0	0	0	0
- soot in global scale	0	0	0.001	0	0	0
- total dust in global scale	0	0.001	0.011	0	0.003	0.006
- CO2 in global scale	60.48	25.317	40.082	60.48	14.294	15.644
- CO in global scale	0.011	0.01	0.072	0.011	0.02	0.035
- NOx (recalculated to the NO2) in global scale	0.039	0.019	0.062	0.039	0.019	0.028
- SO2 in global scale	0	0.015	0.192	0	0.051	0.094
- aliphatic hydrocarbons in global scale	0.033	0.012	0.005	0.033	0.003	0
- aromatic hydrocarbons in global scale	0.001	0.001	0.004	0.001	0.001	0.002

Summary and conclusions

The reduction of the required working temperatures by heating system modernisation and adjustment to the requirements of low-temperature heating has brought measurable economic, ecological, and energy effects, as expected. The final net price of thermal energy applicable to the final customer has been reduced by ca. 10% on average. In the case of the town area (CITY zone, Fig. 5.7.4.1), the price is attractive in comparison to that of natural gas. However, it is still higher than the price of energy generated by coal burning (which can be estimated at net ca. 35 PLN/GJ). Also, initial capital investment costs of energy source construction have been reduced. That is associated mainly with the reduction of the capacity installed in heat pumps. An important remark has to made here: it is much better to design an energy source for the customer with a modernised heating installation than to construct a source matching the current parameters, with subsequent modernisation of the heating installations on the customers' side. In the latter case, the project will require re-sizing of such expensive pieces of equipment as heat pumps.

5.8. A review and lessons learnt from the-so-far experiences in applying geothermal drilling technologies, well equipment, borehole research and logging – conclusions for selected areas in Poland

Regions with favourable geothermal conditions in Poland overlap with areas with high density of urban conurbations and areas of intense agricultural activity. Mazowieckie, Łódzkie, Kujawsko-Pomorskie, Zachodnio-Pomorskie, Wielkopolskie, Małopolskie and Dolnośląskie provinces have the biggest possibilities of using geothermal waters in Poland.

The tests performed so far show exploitation possibilities of geothermal water reservoirs, but technical production possibilities can be established only during industrial operation and they depend on numerous technical factors, including:

- method of exploitation (size of collection and continuity of geothermal water injection),
- treatment of geothermal water being injected,
- permanence of geothermal water cooling,
- anti-corrosive protection of the whole geothermal system, and
- precipitation and settlement of secondary minerals in the borehole zone in injection boreholes.

The existing geothermal heating plants differ in terms of technical solutions used. Those differences relate, first of all, with different parameters of geothermal waters, the size of acquired thermal power as borehole as the size and kind of heat recipients.

The basic way of geothermal energy acquisition is to perform drilling boreholes, which enable exploitation or injection of geothermal waters. Due to deep occurrence of geothermal water aquifers and different geological areas of their occurrence, boreholes may also play a prospecting role. That is why, as a rule, the structure of the first geothermal borehole has to take into account performance of detailed specialist tests in it, including geophysical and hydrogeological ones. They lead to studying an aquifer containing geothermal waters. Therefore, it should be assumed that a borehole made as the first one also plays the role of a test borehole, enabling learning of fundamental features of a geothermal water reservoir, i.e.:

- reservoir pressure,
- depth of geothermal waters occurrence,
- water temperature,
- water flow rate from a borehole,
- geothermal water mineralisation,
- kind of a reservoir (porous, fractured, porous-fractured),
- stratigraphy and physical properties of reservoir rocks,
- filtration parameters of rock medium.

As a rule, test boreholes are designed in such a way that, in the future, they can play the function of exploitation boreholes. When performing geothermal boreholes, one can distinguish two drilling stages:

a) drilling through an overburden over a geothermal layer,
b) drilling through a reservoir layer.

Drilling of exploratory geothermal boreholes should be planned thoroughly, in accordance with the requirements concerning application of drilling technologies, completion and providing for exploitation, as borehole as the budget. The anticipated budget should include *inter alia*:

- preparatory works, including preparation of proper documentation and permits,
- application of suitable drilling techniques and tools,
- work performance by the main contractor and subcontractors,
- borehole equipment and
- performance of an installation on the surface.

Work performance should take place in accordance with a prepared schedule, according to applicable regulations, when performing geological works relating geothermal reservoir prospecting and explorations, while minimising negative impacts upon the natural environment and surrounding. Planning of each work stage and proper project management will ensure high probability of the whole project performance with technological success, within the planned budget. However, in case of works in an area not recognised geologically, where geothermal boreholes have not been drilled before or tested in order to exploit geothermal waters, a risk of project performance in accordance with the assumed schedule and a budget becomes higher.

Geothermal project management should be divided into three main stages: preparation of documents and obtaining respective permits, technical performance of a borehole and testing, as borehole as commissioning.

5.8.1. Preparation of documentation and obtaining of permits

The most important documentation includes *Geological Works Design* and *Operations Plan* of a company carrying out geological works not consisting in geophysical studies requiring to use explosive materials. Drilling boreholes with the depth higher than 30 m in order to utilise Earth's heat are performed in accordance with the Act of 9 June 2011: Geological and Mining Law, as later amended. Geothermal water is mineral if its temperature at the intake outflow is not lower than 20°C.

In order to begin drilling, it is necessary to obtain environmental permits, relating to production of hazardous waste (on a drilling device), generation and management of drilling waste, including muds and cuttings. Development of a drilling rig site management plan requires obtaining a permit for disposing of land property. Access to the property requires permits for heavy transport, in some cases, exceeding allowed load. The location of the drilling rig site may require a building investment or reconstruction of an access road.

During this stage of works, it is necessary to plan the following costs:

- documentation preparation (Geological Works Design, Operations Plan, Drilling Technical Design, detailed technical designs of particular drilling project performance stages, test design, trial exploitation),
- preparation of access roads and hardened drilling yard, as per the environmental protection requirements for a selected drilling device, including foundations,
- mounting of a drilling device, together with technical and social/living infrastructure.

Drilling project management

The key cost of drilling is hiring of the main contractor and purchasing of the borehole completion. The main contractor is a drilling contractor providing drilling equipment, together with a crew as borehole as technical and social infrastructure. In the drilling industry, the following kinds of contracts are usually entered into.

5.8.1.1. Turnkey contact

A turnkey contract is characterised with commissioning drilling works to the main contractor, beginning with yard preparation, through drilling, casing and cementation, ending with testing and installation of the production borehole head. A turnkey contract for drilling of a geothermal borehole begins with entry of a device into service by the investor, and ends with installing of a production borehole head or borehole removal. An advantage of this kind of contract is transfer of a big portion of a risk during drilling operations to the main contractor. If such a contract is concluded, the contractor presents the works schedule and the cost. The main contractor, having its own tools and technology, will try to perform a geological task as soon as possible. However, in case of exploratory boreholes, there is a risk of some non-compliance between actual geological conditions with the designed ones, and thus, delays might occur (e.g. poorer drilling progress than expected) and drilling complications (e.g. loss of fluid, borehole instability – borehole reconstruction, complications or breakdowns). In such situation, the risk of any additional costs occurrence is usually on the contractor, unless the contract states otherwise, taking into account other geological conditions than planned. The main contractor is responsible for the kind of drilling tools and equipment used. At this stage, the role of the investor's representative on the site is important, as he takes care of the compliance of the applied technologies and equipment with those assumed in particular designs. A drawback of this kind of contract is usually the lack of direct influence on the way in which works are conducted or the technology being used. In order to perform the project within the budget and with the assumed margin, the main contractor will use techniques and tools enabling works completion as soon as possible, with minimum own expenditures, which will not always be translated into top quality. That is why, it is important for the investor's representative to control particular work stages, technologies used and borehole equipment.

Advantages:

- cost of drilling on the part of the main contractor, unless changeable geological conditions cause changes in the settlement method,
- a smaller amount of necessary technical and engineering staff on the investor's part,
- in case of a breakdown, the main contractor removes it at its own cost.

Disadvantages:

- smaller investor's involvement in detailed works schedules,
- small influence upon the technology and drilling tools used,
- no quality control over drilling tools used,
- as a result of a drilling breakdown, the date of works completion may change,

– as a result of serious breakdowns or changing geological conditions, the main contractor may be unable to complete a given geological task.

5.8.1.2. Contract based on a rate per day

In case of a contract based on a rate per day, the investor fully controls planning of particular stages of drilling, casing and cementing. It influences the selection of drilling tools and proposes a bottom drilling set by providing its components. It ensures using top quality equipment, compliant with industry-specific standards. Taking care of detailed drilling technologies, including muds composition and parameters ensures full control over each stage of drilling works, and thus minimising negative impacts on drilling through reservoir strata. A drawback of this kind of contract is that it is the investor who takes the risk of changeable geological conditions and hence time of drilling, longer than assumed, as borehole as drilling complications and their removal. In such case, the investor may incur additional costs relating to drilling performance and continuity. However, full control over planning and performance of the drilling process, use of drilling tools and borehole equipment increases the probability of successful technological completion of the whole project.

Advantages:

– daily control of the quality of drilling device works,
– daily control of the quality of works carried out by the crew, influence upon crew composition,
– preparation of detailed works schedules in accordance with the requirements and expectations,
– control of drilling tools and a decision regarding selection of drilling sets,
– a possibility to insure the borehole against likely drilling failures (e.g. tearing off the set and leaving it in the borehole),
– in case of broken drilling device or unsatisfactory crew work, the provision regarding service payment reduction or no payment for the service,
– applying different rates depending on the work stage (drilling, technological downtime with a crew, technological downtime without a crew, weather conditions, waiting for the investor's decision,
– breakdown during drilling at the contractor's fault is removed at the contractor's cost.

Disadvantages:

– risk of increasing the costs of works as a result of actual geological conditions,
– necessity to employ a group of specialists planning and supervising the drilling process.

5.8.1.3. Contract based on a daily rate of drilling device rental

Such contract combines the features of a turnkey contract with a daily rate contract. In case of most frequently used initial stages of borehole drilling, where the risk of changeability of geological conditions, and thus, drilling complications, is low, turnkey contracts are used. At a further stage of drilling works in geological formations, requiring planning and continuous control of the drilling process, where there is a risk of complications, a daily rate is used, which enables the investor to manage the risk.

5.8.1.4. Investor's supervision - drilling

When pareparing technical documentation and a detailed works schedule, it is worth using experienced engineers, having experience and expertise in the drilling industry. During works performance, it is a good practice to run continuous supervision of the works being conducted by the drilling contractor, i.e. the main contractor. It forms an additional cost for the investor, which should be accounted for when planning the project budget. Continuous drilling supervision by experienced specialists can be the key to success of the whole investment.

Tasks within drilling supervision are as follows:

– control of site preparation for a drilling device, including construction of a borehole cellar,
– acceptance and approval of a drilling device, together with infrastructure for task performance, including compliance of the delivered equipment with Terns of Reference,
– during works performance, quality control of particular works at each work stage,
– control of materials used for preparing muds, slurries and casings,
– agreeing and planning with the contractor of detailed work programs and technical designs,
– taking care of work effectiveness, following safety standards and environmental protection,
– monitoring of drilling parameters on a daily basis,
– reacting to drilling complications, making decisions together with the investor,
– detailed documenting and reporting of works.

5.8.1.5. Specification of a drilling device to perform a geothermal borehole

In order to identify the requirements of drilling device to make a geothermal borehole to a required depth, with specific geological reservoir conditions, it is necessary to take the following into account:

a) kind of a drilling device, year of manufacture and the date of the most recent certification,
b) load capacity of a drilling device,
c) height of mast and substructure,
d) lifting capacity of a drilling table and lifting capacity on the setback,
e) kind of a drilling table, clearance and bushing characteristics,
f) ability to house a suitable amount of a drill pipe,
g) power of drawworks and driving unit characteristics,
h) drawworks brake, together with the date of the most recent certification,
i) block system, together with specification of a drilling line,
j) characteristics of high-pressure mud fittings,
k) kind of drilling drive: Top Drive (spindle lifting capacity, max. torque, rotary speed, unit drive) or a kelly,
l) number and kind of mud pumps, together with technical data, power and hydraulic characteristics, method of power supply, requirements regarding materials used in the hydraulic part, resistant to high temperatures of drilling fluid,
m) power devices, methods of electricity supply for a drilling rig: kind and parameters of power generators, air compressors, electrical switchboard.
n) diesel fuel tank,
o) capacity of processed water tanks,
p) required drill pipe and a set of drill collar, together with their characteristics and certificates, a set of connectors for connecting drilling logs,
q) drilling tools: wedges and elevators,
r) wrenches for drill pipes,
s) equipment for running and wrenching up casings,
t) characteristics of a mud system: diagram, capacities, possibilities of mud preparation, capacity of mud preparing unit, mud treatment system (in case of expected high temperature of mud, additional equipment to cool mud may be required),
u) auxiliary equipment: shaft winches, winches for preventer installation,
v) social infrastructure and method of power supply,
w) a set of preventers and a control unit.

5.8.2. Drilling techniques in geothermal systems

Boreholes for the geothermal needs in Poland are made in two categories:

- geothermal wells,
- borehole heat exchangers.

The most typical geothermal boreholes are used for exploitation and injection of geothermal waters. Typical geothermal water exploitation systems are one-borehole systems (Fig. 5.8.2.1) and doublet systems (Fig. 5.8.2.2).

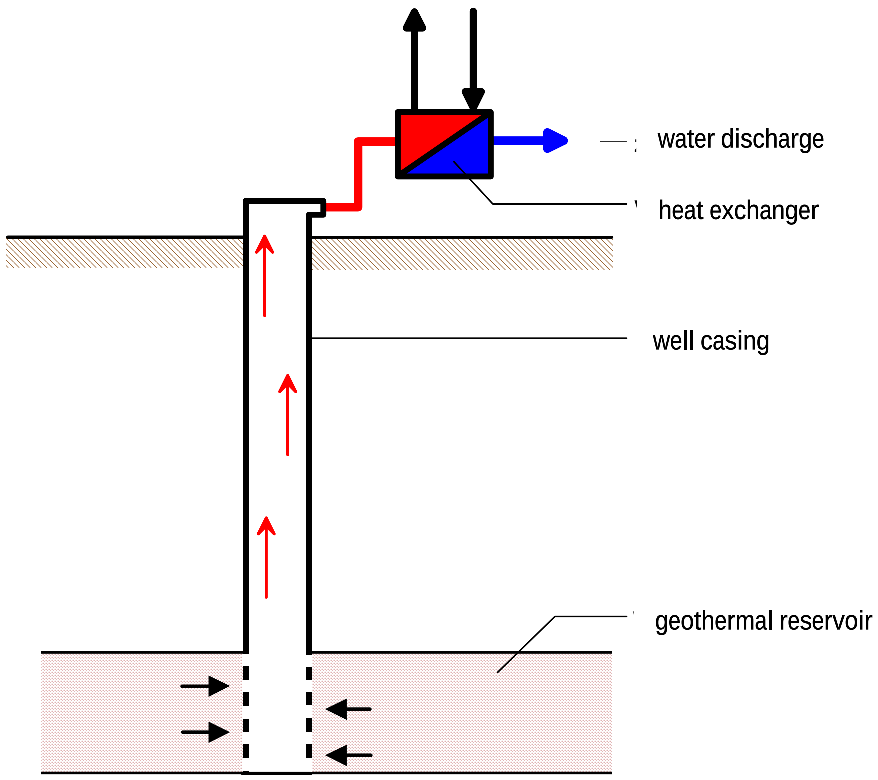


Fig. 5.8.2.1. One-borehole geothermal water exploitation system (Gonet et al, 2011)

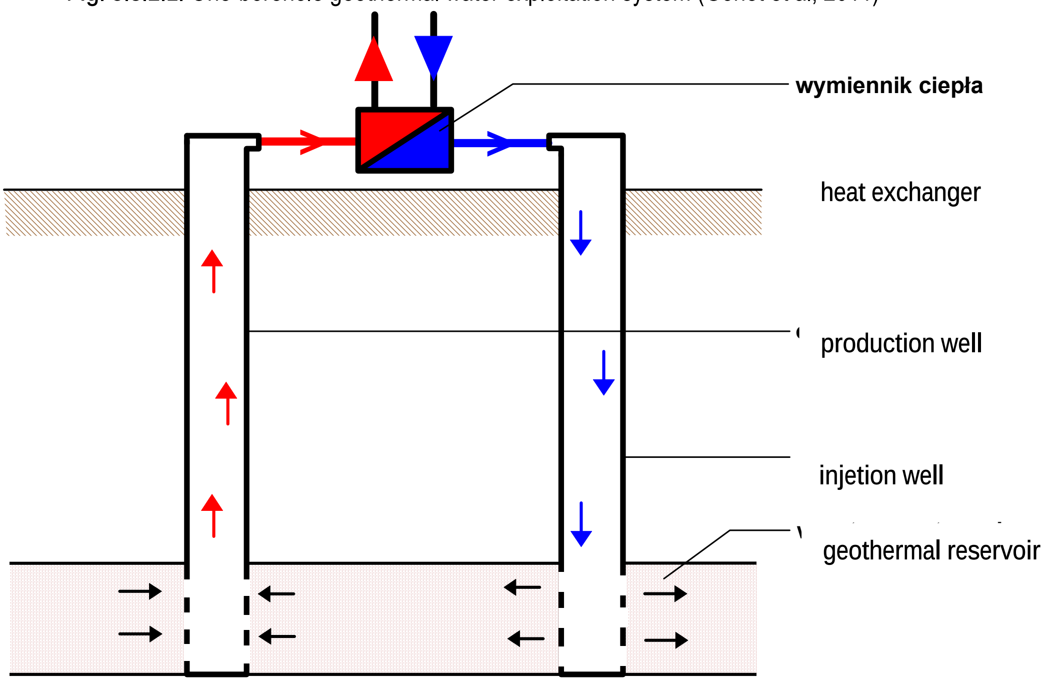


Fig. 5.8.2.2. Two-borehole exploitation-injection system - geothermal doublet (Gonet et al, 2011)

Borehole heat exchangers are used for acquiring Earth's heat, owing to heat carrier circulation, which is not in hydraulic contact with rock mass. There are many kinds of structural borehole heat exchangers. The most typical one is a borehole exchanger with a single or double U-tube, creating a closed circulatory system in a borehole (Fig. 5.8.2.3).

Vertical heat exchangers are the best way to acquire heat from the Earth. Owing to borehole exchangers, one can not only collect heat from rock mass, but also introduce it and store it there (Śliwa et al, 2007). Borehole heat exchangers can be drilled by means of different methods (Wiśniowski 2006) and made based on the existing boreholes (Śliwa and Nycz 2010), liquidated (Dudla et al, 2007) or partially liquidated.

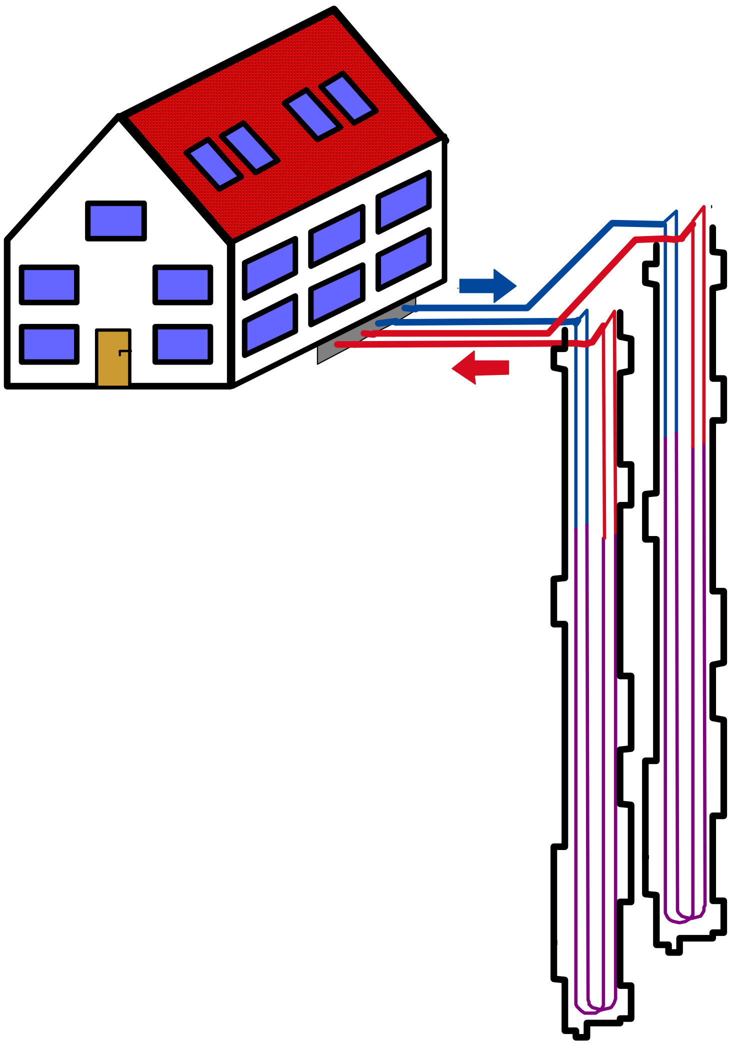


Fig. 5.8.2.3. Diagram of two borehole heat exchangers with a double U-tube

Effective prospecting and opening of geothermal waters is possible owing to cutting edge drilling techniques and technologies. Presently, most frequently used method for drilling geothermal boreholes is rotary method with rightward mud circulation. A diagram of the borehole drilling device has been presented in Fig. 5.8.2.4, and Fig. 5.8.2.5 shows a view of a Drillmec drilling device during drilling of Bańska PGP3 borehole; Fig. 5.8.2.6 shows drilling tower substructure.

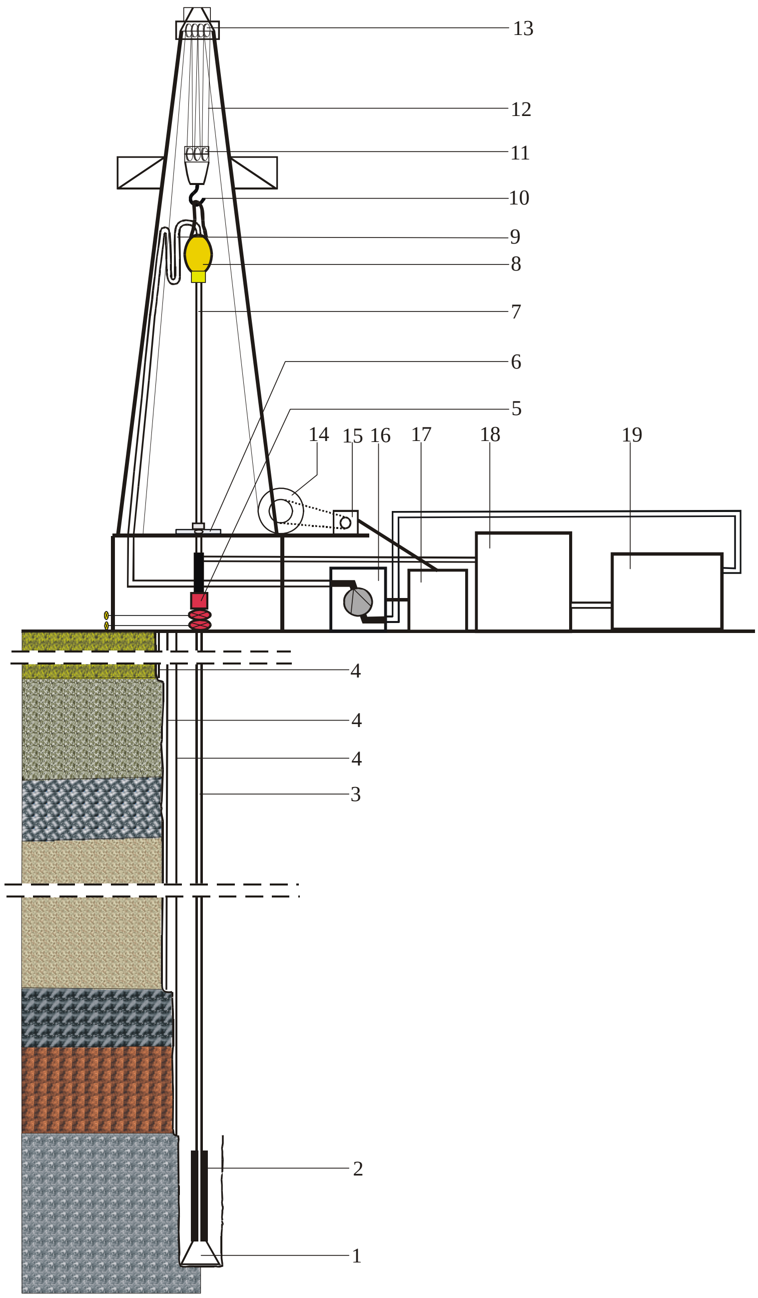


Fig. 5.8.2.4. Diagram of a drilling device and borehole, 1 – bit, 2 – drill collars, 3 – drill pipes, 4 – casing columns, 5 – preventer, 6 – drilling table, 7 – kelly, 8 – swivel, 9 – drilling hose, 10 – hook, 11 – travelling block, 12 – rope, 13 – fixed block, 14 – drawworks, 15 – transmissions, 16 – mud pump, 17 – propulsion engines, 18 – mud treatment system, 19 – mud tanks

Fig. 5.8.2.5. Drillmec device on Bańska PGP3 borehole

Fig. 5.8.2.6. Substructure of Drillmec tower during drilling in Bańska Niżna

5.8.2.1. Rotary drilling

A number of activities are necessary to make a borehole and their proper performance guarantees achievement of the assumed target. Boreholes are most frequently drilled with a rotary method with rightward mud circulation. In many cases, tricone bits are used for rock drilling, whereas clay mud, sometimes native mud, is used for taking cuttings out from the borehole bottom to the surface. When drilling to geothermal waters reservoirs, more sophisticated muds are used, without a solid phase, in order not to damage skin permeability. Below, the most important elements, occurring when performing boreholes by means of the rotary method, have been described.

Particular stages of borehole drilling consist of drilling device installation, mud preparation, building of an initial casing column, rock drilling and lifting operations relating to a drill pipe.

Installation and positioning of a drilling device

Every borehole drilling project (with few exceptions) requires preparation of geological works design, which include all important information concerning works to be performed. One of guidelines is coordinates of the planned boreholes. That is why (in case of deep boreholes and in case of large investments, where many boreholes are made), it is important for a certified surveyor to draw points, where boreholes are to be drilled. Obviously, after drilling works completion, all boreholes should be levelled with regard to the state cartographic system and it is necessary to identify geographic location in the state coordinate system.

The second factor relating to proper setting of a drilling device is its precise vertical alignment. It is aimed at obtaining as vertical borehole as possible. After a drilling rig is set in the desired place, the device mast has to be levelled horizontally. Levels installed on the mast should be used for that purpose. In small drilling devices, levels equipped with torus tubular vials are used (Fig. 5.8.2.7).

Since the mast may deviate in different planes, at least two levels should be used. When bubbles in both levels can been seen in the line scale, it means that the device is set properly.

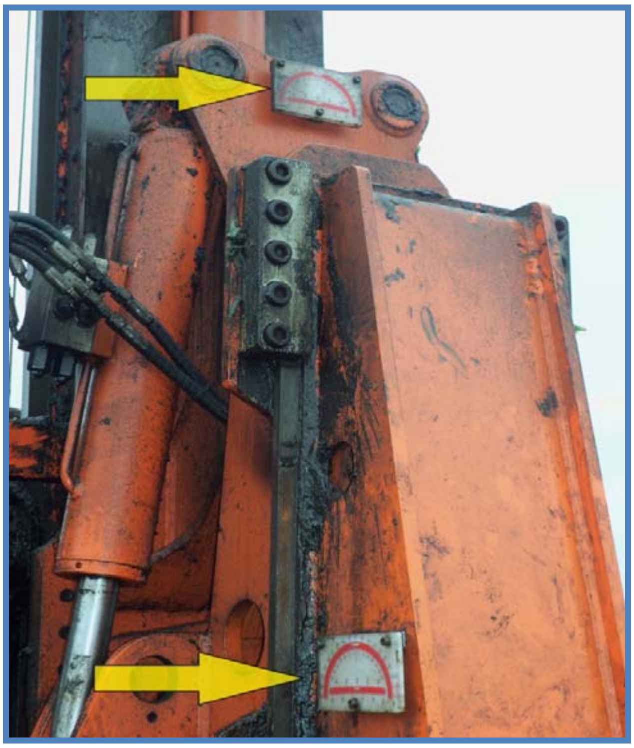


Fig. 5.8.2.7. Levels used for proper setting of a drilling rig

Preparation of a mud system and mud

Once the device is set, one can proceed to mud circulation preparation. A very simple mud system is sufficient for shallow drilling, used for making boreholes to install heat exchanger pipes. Usually, no device known from deep geothermal drilling is used, but at least a jet or mechanical mixer should be used.

Mud preparation begins with filling a tank with water, from which it is collected by a pump and injected to the borehole. In shallow boreholes, native or bentonite mud is used most frequently. It is advisable to direct water being collected towards the mixer set on the tank, where water with bentonite creates homogenous suspension.

Depending on a kind of device, a mud tank or a mud pit is used (Fig. 5.8.2.8). Each method has its advantages and disadvantages. A pit is characterised with a possibility of using it for drilling two or more boreholes, since mud flowing out of the borehole may flow, at a certain distance, in an isolated ditch made in soil. A group of two pits can be also created: to one of them mud would flow from the borehole, and next, after cuttings drop down, it would go to the other pit, from which it would be injected to the borehole. It has a significant impact on treating mud going to the borehole. A basic disadvantage of mud pits is the necessity to make them and bring the site back to the condition from before drilling. Gravitational seperation of cuttings from mud is not very effective using this method.

Fig. 5.8.2.8. A mud pit and a mud tank

An advantage of using mud tanks is the lack of significant interference in the site, where works are performed. After the tank is removed, only a cuttings layer remains, which can be collected and removed. There are many more drawbacks, firs of all, economic one. Once it is used in a given place, it cannot be usually used in the next borehole. Therefore, the device has to be equipped with two tanks. In order to be able to use the mud used with the first borehole again, it is necessary to set a new tank and pump mud there. Each time, it is necessary to use new foil, used as tank walls.

Mud circulation begins in the tank, where it is sucked in by the pump, and next injected to the swivel. From the swivel it goes to drill pipes and drill collars, as well as to bit nozzles, where it begins to play its crucial role. At the bottom, it washes out cuttings occurring as a result of bit rotations. Mud, together with cuttings, flows out by annular space to the soil surface. It goes to a mud tank, where, as a result of sedimentation, cuttings are separated. Mud treated in this way goes back to the drill pipe.

Isolation of the top soil layer

Area surface is usually a soil layer, which is often light. That is why, it is important to make it impossible for it to be in contact with mud flowing out of the borehole under pressure. To this end, a pipe with a larger diameter than the planned borehole is used. By means of a bit with a larger diameter or an auger bit a several metre long borehole is drilled, to which a casing is run (Fig. 5.8.2.9), being the initial casing column. Rarely, in case of an unfavourable geological structure, it is necessary to apply the second casing column. In case of drilling through an aquifer, it is recommended to isolate it tightly from a borehole drilled further down. In many cases, this goal is not achieved when performing borehole heat exchangers.

Fig. 5.8.2.9. Drilling borehole and casing running to the borehole

In the event of using a mud pit, a pipe is run in such a way that it does not protrude over the area surface in order to enable mud outflow. On the other hand, during works with the use of a tank, casing has to protrude over the area surface ca. 1.5 metres, since in this way mud is transported gravitationally from the borehole to the tank.

It should be emphasised that companies drilling boreholes for heat exchangers usually do not use the most recent devices for preparing and treating mud of cuttings. Bearing econological aspects in mind, it is necessary to ensure tightness of the whole mud circulation, and particularly of mud pits.

Borehole drilling

After preparing the works site and equipment, one may proceed to proper drilling of a borehole. In order to introduce borehole heat exchanger pipes (most frequently: 2x40 mm), a borehole with a stabile diameter of ca. 120 – 130 mm is needed, most often a bit with the diameter of 143 or 149 mm is used. (Fig. 5.8.2.10). In case of such boreholes, bits equipped with nozzles are not necessary. Tools with central mud outflow are sufficient. Drill pipes should have the largest allowed diameter in order to maintain turbulent flow in the annular space (when using a 143 mm bit for drilling, pipes may have a diameter of 4 ½ - 5" (114.3 – 127 mm). Most frequently, pipes with welded couplings, upset to the inside, with the length of 2–6 m, are used. The length of drill pipe pieces depends on a kind of drilling device, and first of all, the height of its mast.

Fig. 5.8.2.10. Rock bit and drill pipes

To drill a borehole, a drill pipe ended with a drilling tool is used. After setting appropriate technological parameters, i.e. pressure on a bit, speed of rotation and mud volume stream (Table 5.8.2.1), rock mass mining begins. When a swivel lowers down to the level of hydraulic pliers, another piece of pipe is added. Particular stages of this operation can be the following:

a) capturing of pliers of the pipe located in the borehole,
b) unscrewing and moving the head upwards,
c) transporting of a drill pipe by means of a boom ended with a magnet and placing it on a pipe coupling in the borehole,
d) setting of the added pipe section in the vertical position,
e) head lowering and wrenching of drill pipes,
f) releasing of hydraulic pliers.

Drilling can be continued after finishing to add a new pipe section.

Table 5.8.2.1. Drilling parameters used when performing borehole exchangers

Technological parameter	Dimension	Value	
		from	to
Bit totary speed	s^{-1}	1,5	3,0
Weight on bit	kN	10	50
Volume stream mud	dm^3/min	80	200
Pressure mud	bar	30	50

Drilling ends when borehole depth assumed in the geological works design has been achieved. Before works are commenced, it is necessary to prepare drill pipes with the total length corresponding to the planned borehole depth. Some drilling contractors do not use drill collars, which is conducive to pipe bucling at higher weights on bit, and hence, it causes curving of a borehole axis. In deep geothermal boreholes, after drilling casing of the working is done.

Drill pipe pullout

After a borehole has been made, it is necessary to pull out the drill pipe. Pulling up the pipe is done by means of a rotary head on a mast, until coupling of the pipe being pulled out passes hydraulic pliers. Then pliers close and pipes are unscrewed by means of head rotation. Mounting on a pipe of a boom arm ended with an electromagnet makes it easier to move an unscrewed item to a desired place.

Pulling out of a drill pipe is a rather trouble-free but time-consuming operation. Yet, it has to be remembered that when a pipe is pulled out, and also during sinking of a borehole mud can be lost rapidly. It may cause lack of stability of a borehole wall and caving of light rocks inside the borehole, which will cause difficulties with running of casings, heat exchanger pipes and/or reduction of borehole depth.

5.8.2.2. Impact-rotary drilling

Recently, it has become more and more common to use drilling with down the hole hammer (impact-rotary drilling), particularly in harder rocks. Boreholes, where vertical heat exchanger are installed, can be drilled by the rotary drilling method (Gonet et al, 2012) or the impact-rotary method. The most frequently used technique of impact-rotary drilling is referred to as “down the hole” (DTH).

The purpose of drilling boreholes for heating and heating/cooling installations with heat pumps is to introduce heat exchanger pipes, with a specific diameter, into required depth. In such systems it is the only purpose of drilling. The issue of permeability of reservoir strata zone near the borehole is not significant, which is important, e.g. in case of drilled boreholes. The issues of how structural elements behave in case of temperature changes are important, e.g. hardened of sealing slurry and its contact with a borehole wall and exchanger pipes, which is decisive about thermal resistance of rock mass-heat carrier heat exchange.

Characteristics of the down-the-hole drilling method

When using the down-the-hole method, a driving factor is compressed air, which, directed to the hammer by the mechanism of rotating a drill pipe, additionally cleans a borehole being performed of cuttings as aerated mud. Exhaust of compressed air generated in a compressor (Fig. 5.8.2.11) from the hammer takes place through boreholes in a bit. It has been presented in Fig. 5.8.2.12.

Fig. 5.8.2.11. Compressor


Fig. 5.8.2.12. Drilling bit

Rotations given by the head installed on a drilling rig mast are transferred to the hammer by drill pipes. Drill pipes are connected by means of a thread, so a drill pipe can be extended as a borehole is deepened. Weight force is also transferred by the rotation mechanism and drill pipes.

Down-the-hole hammers are very productive devices and they are applied, among other things, in quarries, underground mining, engineering works and well-drilling industry. Detailed structure of a 3" down-the-hole hammer is presented in Fig. 5.8.2.13. Table 5.8.2.2 specified basic technical and technological parameters of Puma down-the-hole hammers, and in Tables 5.8.2.3 – 5.8.2.7 basic data of Puma down-the-hole hammers are shown.

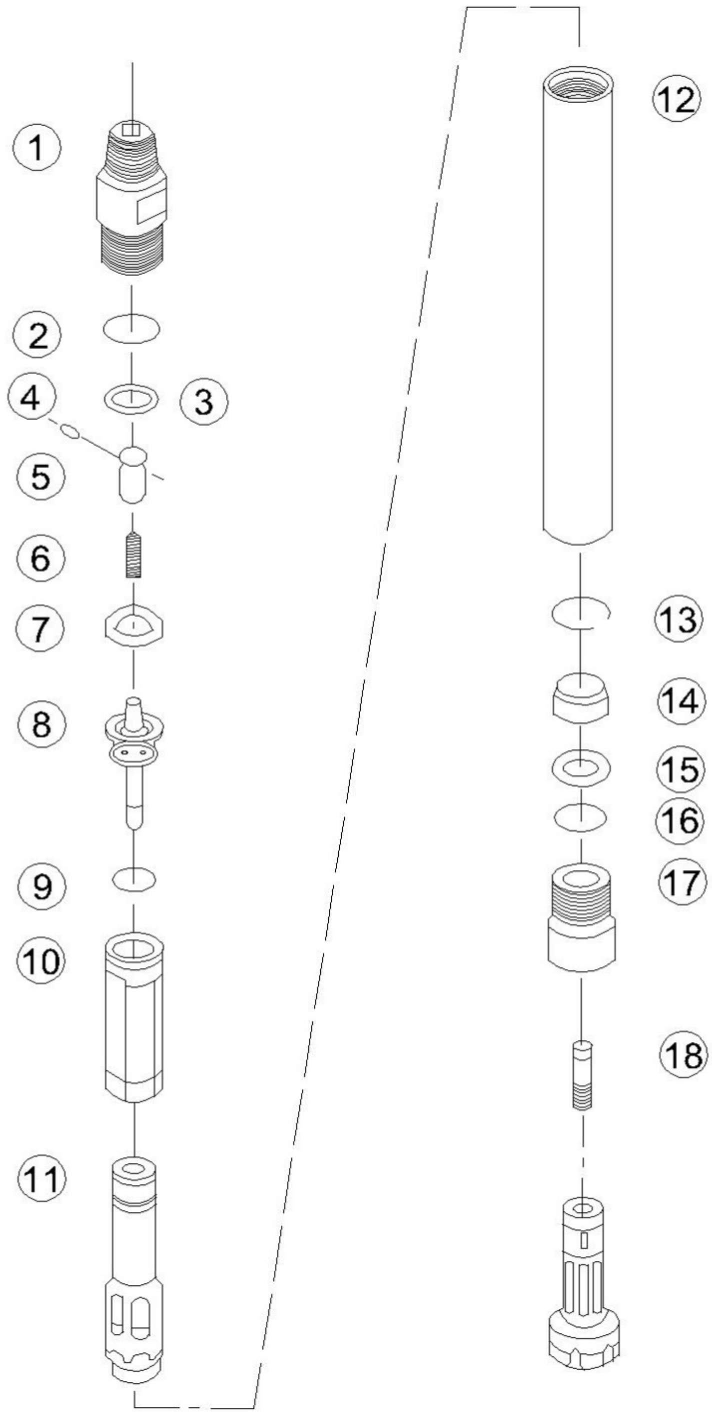


Fig. 5.8.2.13. Structure of down the hole with the diameter of 3''; 1 – thread connection 2 $^{3}/_{8}$" API reg., 2 – gasket for thread connection, 3 – washer, 4 – chock, 5 – check valve, 6 – spring, 7 – ring, 8 – air separator, 9 – separator ring, 10 – cylinder, 11 – piston, 12 – body, 13 – retaining ring, 14 – guide bit, 15 – spacer ring, 16 – ring retaining a bit, 17 – bit handle, 18 – foot valve

Table 5.8.2.2. Basic technical technological data of Puma down the hole hammers (Gonet et al, 2012)

		Puma 3	Puma 4	Puma 5	Puma 6	Puma 7	Puma 8	Puma 9
Length (mm)		836	1002	1093	1098	1373	1305	1694
External diameter (mm)		79	96	115	142	168	180	215
Weight (kg)		22	40	62	90	162	168	317
Kind of thread		2 3/8"	2 3/8"	3 1/2"	3 1/2"	4 1/2"	4 1/2"	5 1/4"
Air compression (m³/min) at pressure	10,3 bar	4,4	5,1	8,8	8,2	13,9	13,5	19,5
	13,8 bar	6,5	7,4	12,0	12,7	19,8	19,0	27,8
	17,2 bar	8,8	9,8	15,4	17,3	25,8	25,9	36,3
	20,4 bar	11,2	12,3	18,7	21,5	31,7	34,0	45,3
	23,8 bar	13,7	15,0	22,0	25,3	37,7	43,6	54,8
Rotary speed (rotations/min)		25-85	25-85	20-70	15-60	13-40	13-40	13-40
Impact weight (kg)		200-800	300-900	500-1400	900-2000	1000-2300	1200-2800	2300-5000

Table 5.8.2.3. Basic technical data of 3''down-the-hole hammer (Gonet et al, 2012)

General description	Weight		External dimension		Hammer length		Hammer length with a bit			
							Hidden bit		Reamed bit	
	kg	lb	mm	in	mm	in	mm	in	mm	in
	22	49	79	3,11	829	32,6	829	32.6	930	36.6

Air demand	Pressure	bar	10,3	13,8	17,2	20,4	23,8
	Volume stream	m³/min	4,4	6,5	8,8	11,2	13,7

Table 5.8.2.4. Basic technical data of 4'' down-the-hole hammer (Gonet et al, 2012)

General description	Net weight		External dimension		Hammer length		Hammer length with a bit			
							Hidden bit		Hidden bit	
	kg	lb	mm	in	mm	in	mm	in	mm	in
	44	98	100	3,93	980	38,6	1073	42,3	1104	43.5

Air demand	Pressure	bar	10,3	13,8	17,2	20,4	23,8
	Volume stream	m³/min	5,1	7,4	9,8	12,3	15

Table 5.8.2.5. Basic technical data of 5'' down-the-hole hammer (Gonet et al 2012)

General description	Net weight		External dimension		Hammer length		Hammer length ze bit			
							Hidden bit		Hidden bit	
	kg	lb	mm	in	mm	in	mm	in	mm	in
	66	146	118	4,64	1093	43	1188	46,7	1225	48,2

Air demand							
Air demand	Pressure	bar	10,3	13,8	17,2	20,4	23,8
	Volume stream	m³/min	8,8	12	15,4	18,7	22

Table 5.8.2.6. Basic technical data of 6'' down-the-hole hammer (Gonet et al, 2012)

General description	Net weight		External dimension		Hammer length		Hammer length with a bit			
							Hidden bit		Hidden bit	
	kg	lb	mm	in	mm	in	mm	in	mm	in
	95	209	141,5	5,57	1151	45,3	1256	49,4	1296	51

Air demand	Pressure	bar	10,3	13,8	17,2	20,4	23,8
	Volume stream	m³/min	8,2	12,7	17,3	21,5	25,3

Table 5.8.2.7. basic technical data of 8'' down-the-hole hammer (Gonet et al, 2012)

General description	Net weight		External dimension		Hammer length		Hammer length with a bit			
							Hidden bit		Hidden bit	
	kg	lb	mm	in	mm	in	mm	in	mm	in
	179	395	180	7,08	1305	51,4	1434	56,5	1485	58,5

Air demand	Pressure	bar	10,3	13,8	17,2	20,4	23,8
	Volume stream	m³/min	15	20,8	26,9	33,1	39,3

Practical example of using the down-the-hole hammer drilling method

In Gola Dzierżoniowska, DemaxDrill company made boreholes for heat exchangers by means of the down-the-hole drilling method. That company was to make one hundred boreholes, which would be used as heat exchangers in the castle in Gola Dzierżoniowska. In accordance with the design, distribution of boreholes with the depth of 120 m was planned at the castle yard. Boreholes were made by the impact-rotary method, using a drilling device made by KLEMM Bohrtechnik KR805-2W. Fig. 5.8.2.14. shows basic parts of the down-the-hole hammer.

Fig. 5.8.2.14. Fundamental parts of a down-the-hole hammer

Compared with other down-the-hole drilling techniques, it is highly efficient and can be used in almost all rock formations. Apart from that, this method is characterised with high drilling speed, and borehole axis is vertical and straight line. Performance of a ready borehole to 120 m, together with running exchanger pipes (U-tubes) and sealing with "Hekoterm" cement-bentonite-silica mix with higher thermal conductivity took about 12 hours. The lithological profile (to 150 m) of a borehole can be seen in Table 5.8.2.8.

Table 5.8.2.8. Lithology of a borehole with the depth of 150 m

No.	Lithology	Roof, m under ground level	Bottom, m under ground level	Thickness, m
1	made ground	0.0	2.0	2.0
2	clay with stones	2.0	12.0	10.0
3	granite-gneiss saprolite	12.0	54.0	42.0
4	gneisses interbedded with basalts	54.0	150.0	96.0

Different drilling muds are used to make boreholes by means of the down-the-hole method. One of them is foam. To fulfil its function, foam has to be heavy, which allows cuttings maintenance and removal from a borehole. Foam can also transport water from formations being drilled, in case of intense inflow, reducing back pressure exerted on a hammer.

In some situations, it can be advisable to use foam to increase efficiency of borehole bottom cleaning. Foam use in DTH required additional caution to maximise efficiency and hammer life cycle. It should be remembered that foam, consisting mainly of soap, decomposes lubricating oil of the hammer, which may cause problems with lubrication, so oil doses should be enlarged during drilling. Apart from that, after drilling completion, oil coating is removed, leaving internal parts of the hammer without anti-corrosive protection. When foam is used, when it goes through the hammer, air bubbles are created and disappear, which polish steel parts, making them less sensitive to corrosion and it is a big advantage. After drilling completion with the use of foam, all foam residues should be removed from inside the hammer and cover it with oil. In the event that the hammer remains idle for a longer period of time, it is necessary to:

- blow the hammer for several minutes with air and a large quantity of water,
- cut off water inflow and further blow the hammer with air and oil, until oil appears on the core drill.

In order to obtain the best results, the hammer should be cleaned every day, at the end of the day. If the hammer is not to be used for a longer period of time, before storage it is recommended to disassemble it, clean, lubricate and assemble again.

Borehole heat exchangers can be drilled successfully by means of the impact-rotary method. In a set of such a drilling rig, it is necessary to use an air compressor, which triggers bit hitting against rock. Additionally, injected air plays the mud function. Impact force of a bit against borehole bottom depends on its diameter, weight and pressure of the unit operation.

5.8.2.3. Drilling with concurrent borehole casing

Drilling with a double drill pipe, also referred to as drilling with a “double head” (Fig. 5.8.2.15), is used when drilling through loose and light layers. This system enables borehole stability throughout its depth in a fast and efficient way, at the same time, separating aquifers and preventing communication of water from varying depth strata.

Fig. 5.8.2.15. Double head

The pipe consists of a lower rotating head (usually counterclockwise), external drill pipe (casings) and an upper internal pipe rotating clockwise, together with a tool. A core drill is installed on casing pipes, whereas a drill pipe can use a hammer or rock bits, depending on the method used.

Nordmayer manufactures a DSB drilling device equipped with a head with a double rotor. The head with a double rotation enables drilling with successive borehole casing to the anticipated depth, which guarantees optimum drilling progress, without significant mud loss. The head with a rotor enables concurrent rotation of drilling poles and protective pipes in the same direction. Furthermore, it is possible to move an internal column (pole) and an external column (protective pipes) towards each other. Cuttings are transported in the annular space between those columns upwards and discharged from the rotor by means of a hose to the tank.

After overburden drilling, the rotor is dismantled from the head and by means of a boom mounted on a rotary crown of the mast is deposited next to a drilling rig. Further drilling can be performed by means of a down-the-hole hammer, wing bits or rock bits.

A similar way of performing boreholes for heat exchanger piping installations is ODEX- PUMEX system, which also consists in concurrent borehole casing during borehole drilling, preventing caving of a borehole wall behind the bit. Pipe running in the overburden by means of eccentric hole opener, prevents caving of a borehole wall in all geological conditions. By means of the ODEX system, casings can be run through an overburden stratum to the required depth in solid rock deposited underneath. After pulling out ODEX from the borehole, drilling can be continued below a cased section using a traditional method. The ODEX system can be pulled out from the borehole at any moment during drilling in overburden. Fig. 5.8.2.16 shows general system structure and basic dimensions, whereas Table 5.8.2.9 presents basic dimensions of the down-the-hole hammer from the ODEX system.

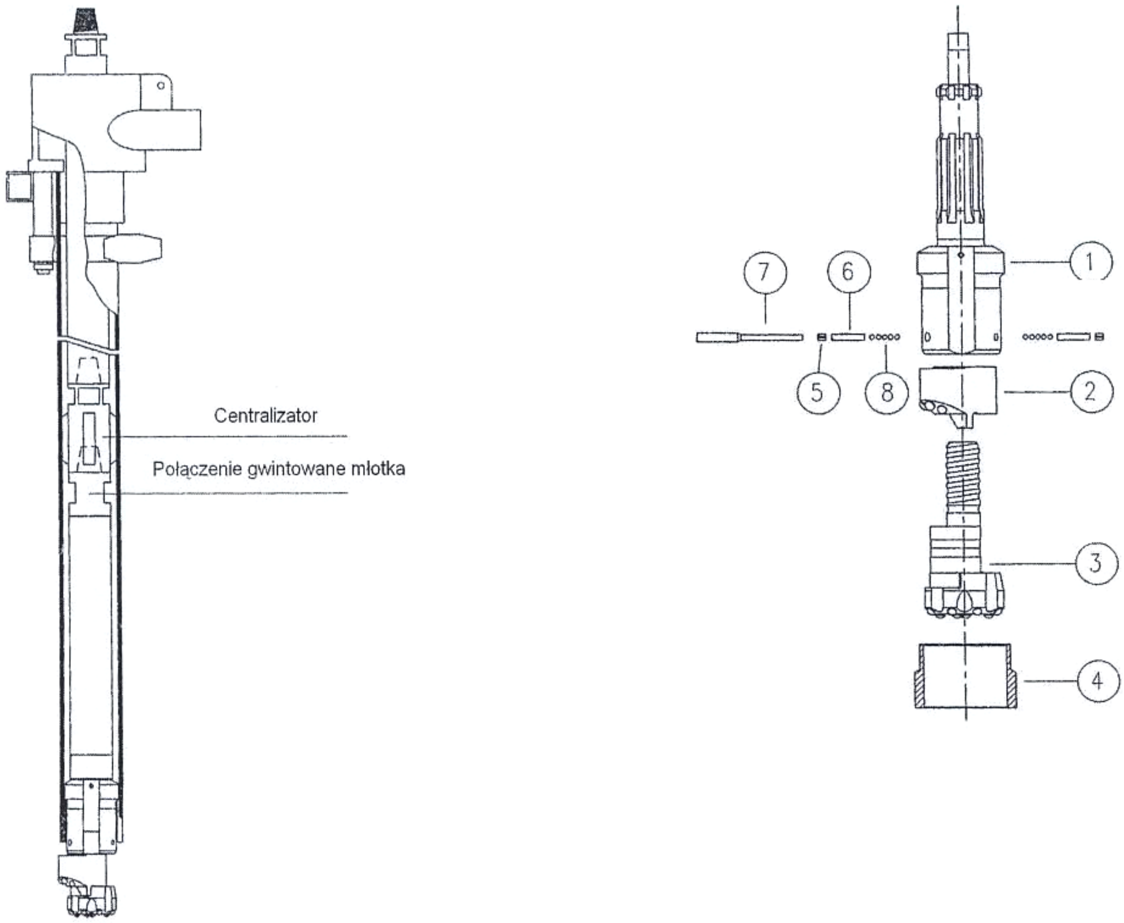


Fig. 5.8.2.16. Down the hole- system ODEX: 1- guide, 2 - hole opener, 3 - core drill-pilot, 4 - shoe of a protective pipe, 5 - flexible bolt, 6 - bolt, 7 - punch, 8 - blocking balls (Gonet et al, 2012)

Table 5.8.2.9. Basic dimensions of a down-the-hole hammer - ODEX system (Gonet et al, 2012)

Pumex	Internal pipe diameter	Diameter of hole opener	Protective pipe			Shoe diameter of protective pipe
			Maximum external dimension	Minimum internal dimension	Minimum wall thickness	
DT-90	73 mm	123 mm	115 mm	102 mm	5 mm	93.5 mm
DT-115	89 mm	152 mm	142 mm	128 mm	5 mm	118.3mm
DT-140	114.3 mm	181 mm	171 mm	157 mm	5 mm	143.4mm

Using the down-the-hole drilling method, one can drill with a single or double drill pipe. A single drill pipe is used in solid rock strata. This drilling technology is based on using a down-the-hole hammer, operated by a remotely controlled air compressor, which provide compressed air necessary to supply hammer and concurrent cleaning of a borehole being drilled from cuttings. In some cases, a solid stratum can be preceded with loose strata, so initial drilling is usually performed by means of casings with a core drill (Fig. 5.8.2.17) in order to stabilise a borehole wall.

Fig. 5.8.2.17. Drill pipe with a core drill

Methods with the application of a head with double rotation enable drilling with successive borehole casing, which guarantees better drilling progress, without significant mud loss in fractured rocks. During borehole casing, a casing with a core drill can be both impact-rotary drilling and rotary drilling with mud.

5.8.2.4. Coiled tubing drilling

One of the methods of borehole drilling to perform borehole heat exchangers is the method with coiled tubing using a downhole drilling motor as a drilling device drive. Owing to it, it is possible to make slant boreholes, which becomes more and more often necessary, due to the lack of an available surface to perform vertical boreholes.
Borehole drilling in order to install heat exchanger pipes can be done in a rotatable way with liquid mud (Gonet et al, 2012), in an impact-rotating way with air mud (Śliwa et al, 2011) and by means of a downhole drilling motor and coiled tubing or drill pipes.
Slant borehole heat exchangers (Fig. 5.8.2.18) enable opening heat reservoirs in rock mass located under infrastructural objects. Owing to slant borehole heat exchangers, it is possible to make boreholes from one position and open large areas of rock mass (Gonet et al, 2011).

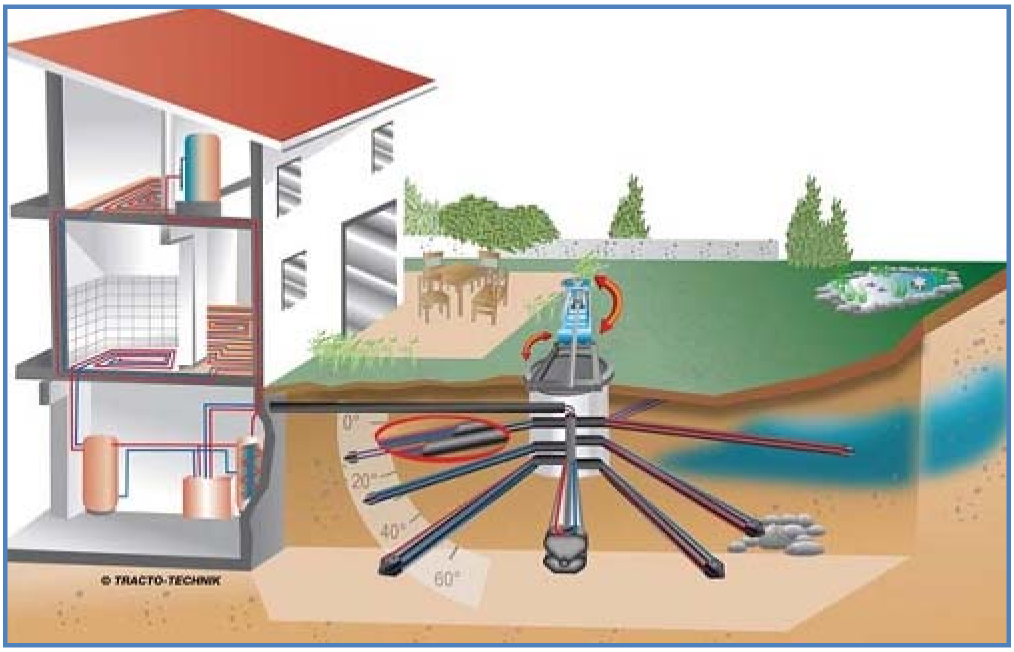


Fig. 5.8.2.18. Radiant borehole exchanger [Informational materials, Geothermische Energie (http://www.geothermie.de) no. 54, 2007]

Drilling technique

Drilling by means of coiled tubing devices is possible owing to the application of coiled tubing wound on a working drum of the device. A downhole drilling motor is fixed to coiled tubing by means of a special connector, through which a bit starts moving. An example of such a device is a AMKIN DCT 150V drilling rig, shown in Fig. 5.8.2.19 and 5.8.2.20. When drilling with a downhole drilling motor, one of the most important parameters is the degree of mud cleaning. It is very important and it translates significantly to its durability. Fig. 5.8.2.21 shows a set for mud cleaning, Mud Puppy 170-2sc, together with an APLEX 115 L QUINTUPLEX mud pump mounted on it. A downhole drilling motor is a kind of a hydraulic motor. It consists of a stator, which constitutes its external immovable part (motor housing), and of a rotor. In such a system, mud, apart from basic functions, i.e. borehole wall stability, taking cuttings out, and cooling of a drilling tool, is also an agent driving the rotor of a downhole drilling motor. Use of a downhole drilling motor requires mud provision with specific pressure. Manufacturers specify minimum pressure, at which the motor works smoothly, with a specific torque and maximum pressure, going beyond of which may damage it. A downhole drilling motor should be selected with a view to a kind of rocks drilled. Motors range from low-speed ones with high torque to high-speed ones with low torque. On the other hand, a downhole drilling motor conditions the selection of a suitable mud pump. Its operating characteristics should be as linear as possible, since any vibrations coming from the pump are transferred directly to the pipe and the device. Meeting of this condition enables to use a five-piston pump and/or a pressure compensator at the outlet from a mud pump. Before drilling commencement, it is also necessary to select a bit, with which rock mass strata will be drilled through. It is worth pointing out that such a bit should enable to make the whole borehole – to the planned depth, without any need to change it. Application of coiled tubing allows saving time during drilling as well as running and pulling out of tubing (operation of screwing, unscrewing, supplying, and putting back drill pipe sections). However, each use of tubing shortens its life cycle. Manufacturers of tubing for use in coiled tubing specify an approximate number of its windings/unwindings. That is why, coiled tubing devices are usually applied when drilling through homogenous strate with similar drilling parameters. It is also possible to drill in diversified rocks, yet, it requires the contractor to be well familiar with geology in order to select a downhole drilling motor (its parameters) and a bit in an optimal way. Fig. 5.8.2.22 shows a readymade drilling unit, i.e. a downhole drilling motor combined with coiled tubing, AMKIN DCT 150V, before drilling.

Fig. 5.8.2.19. Self-propelled drilling rig with coiled tubing as a drill pipe (Photo by W. Teper)

Fig. 5.8.2.20. Self-propelled drilling rig with coiled tubing as a drill pipe (photo by W. Teper)

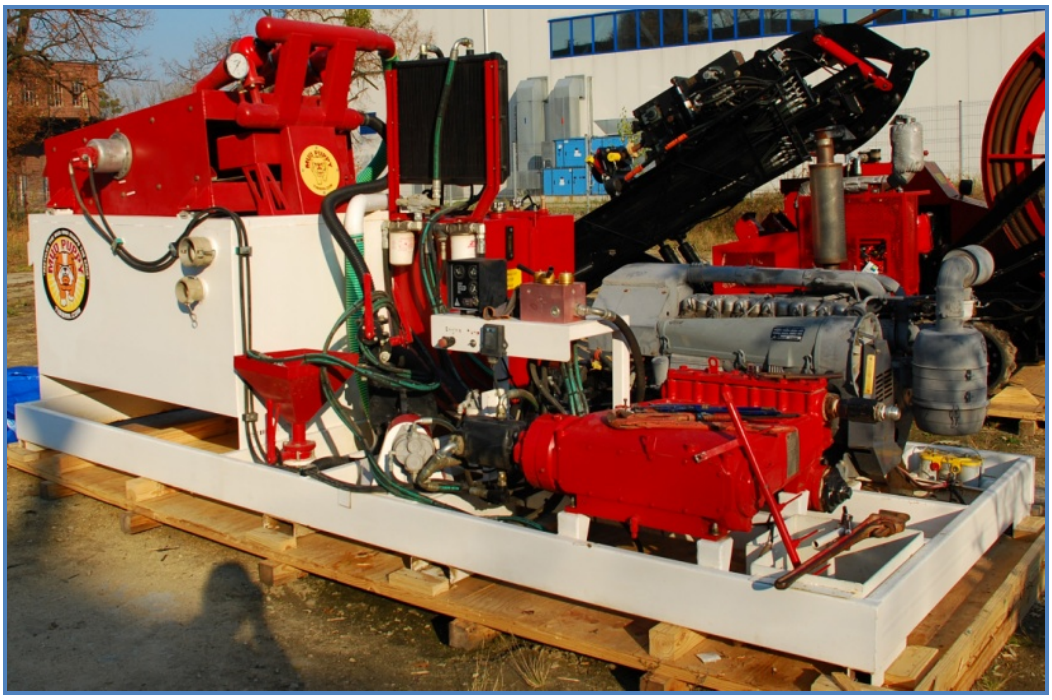


Fig. 5.8.2.21. Mud circulation system unit (photo by W. Teper)

Fig. 5.8.2.22. Self-propelled AMKIN DCT 150V drilling rig with coiled tubing as a drill pipe ready to work with a downhole motor (Photo by M. Pacewicz)

An example of making borehole heat exchangers by means of drilling with a downhole motor, included in a AMKIN DCT 150V unit, is to apply it when drilling through sandy clays in the area of Wrocław. It is mainly a suitable selection of a downhole drilling motor, a bit and its nozzles that influences drilling progress. Time of making a borehole with the depth of 100 m is 4–5 hours. When making boreholes specially selected swelltonite-based mud is used, together with polymers modifying its parameters. To run heat exchanger pipes a hydraulic winch made especially for this purposes and pipe pushing poles are used. The application of the aforementioned set enables performance of 2 complete borehole exchangers per day. The way of exchanger sealing is up to the investor.

Drilling technology

A drilling technology depends, to a high extent, on a kind of rocks being drilled. It conditions the selection of a downhole drilling motor – its rotations, torque and the required pressure in bit nozzles. Working parameters of the device shown in Fig. 5.8.2.22 have been collected in Table 5.8.2.10. Table 5.8.2.11. presents working parameters of a downhole drilling motor working with a AMKIN DCT 150V unit.

Table 5.8.2.10. Parameters of device operation when making a borehole in the area of Wrocław

Weight	1,4 – 1,7 T
Rotations	320 – 360 rotations/min
Differential mud pressure	3,6 – 3,9 MPa
Volume stream mud	7-8 dm^3/s

Table 5.8.2.11. Working parameters of a 2 $^{7}/_{8}$`` downhole drilling motor working with a AMKIN DCT 150V unit

Volume stream mud	60 – 130 GPM	4 – 8 L/S
Rotary speed	188 – 366 rotations/min	
Min. pressure difference	406 psi	2.8 MPa
Max pressure difference	570 psi	3.92 MPa
Torque	388 lb·ft	526 N·m
Max torque	545 lb·ft	736 N·m
Recommended weight on bit	2640 lb	12 kN
Max weight on bit	5500 lb	25 kN

During drilling, parameters of a downhole drilling motor are adjusted by suitable setting of the mud pump. Weight on bit is made by means of a pipe through an "injector" on a head with pliers moving coiled tubing. Maximum head weight is 4.5 tonnes. Motor maintenance is very important, i.e. putting oil or cup grease if they are not used for a longer period of time. In case of short downtimes it is enough to rinse a motor with water.

When making the first borehole, bit selection was made for specific geological conditions. Better drilling progress was achieved with a 5 $^{5}/_{8}$" three-wing bit, compared with a tricone bit with the same diameter. Yet, it is characterised with a tendency to go to strata with lower hardness, which causes that a motor leans against a borehole wall and reduces the actual borehole diameter. It may, in turn, complicate running of borehole heat exchanger pipes. A good solution is to apply a bit sub stabiliser, which helps to maintain the required borehole diameter.

Device use in winter conditions makes it necessary to perform additional operations and apply a compressor with high air spending, used in order to blow mud out from coiled tubing. After drilling and in case of any complications in negative temperatures, it is necessary to clean coiled tubing completely of mud.

Drilling of slant boreholes for heat exchanger pipes is possible. Yet, it is difficult to control the trajectory of borehole axis. Some downhole motors have an integrated curved connector in the housing, which enables to set a curving angle. Also, some coiled tubing devices are equipped with an orienter used for motor rotation and trajectory control, owing to non-magnetic instruments for measuring azimuth and inclination, placed in a drill collar. Information about bit location is sent by means of geophysical cable placed inside coiled tubing. Such solutions, however, are now relatively expensive, and thus, not competitive for shallow boreholes.

Slant borehole heat exchangers enable opening of heat reservoirs in rock mass, which are located under infrastructural objects. Owing to slant borehole heat exchangers, one can make boreholes making large rock mass areas available from one position.

Drilling borehole to the depth of 100 m for a borehole heat exchanger installation lasted 5 hours in the Polish conditions. It is possible to make two borehole heat exchangers, fully equipped with pipes and sealed, during one day. Due to noise, works can be conducted only during the day in urbanised areas.

The application of downhole motors and coiled tubing devices in the process of making slant heat exchangers gives a lot of possibilities and can be competitive for traditional drilling, yet, it requires considerable initial financial expenditures.

5.8.2.5. Geothermal Radial Drilling (GRD)

The basis for good designing of heating and cooling systems, based on heat borehole exchangers is their effective thermal conductivity. This value depends on geological structure of a given region, and more precisely, on the value of thermal conductivity of particular strata. For initial recognition and establishing average thermal conductivity λ_{ef}, the method based on data from literature is sufficient, where effective conductivity is determined as weighted average referred to particular strata of a given profile.

In order to be able to optimise an average value of thermal conductivity and use those strata in a given geological profile which have the best properties from the point of view of thermal output, the Geothermal Radial Drilling (GRD) technology proves to be very good.

Owing to making borehole heat exchangers by means of GRD, i.e. from one place radially under different angles of inclination, one can make large rock mass areas, located even under building objects, available, and also, concentrate boreholes outlets in one place, which is conducive to good control of heat carrier distribution. A GeoDrill 4R drilling rig, especially designed for the GRD technology, enables drilling boreholes under the angle from 35 to 65 degrees, owing to this, together with the knowledge of the geological profile, one can design exchangers distribution in such a way that the longest part of the exchanger is in the most energy-producing strata. In addition, GRD exchangers, depending on the length and angle of inclination (as a standard, the length of particular exchangers is 40-50 metres), may apart from geothermal energy, acquire also solar energy collected in the upper zone of rock mass.

Construction of borehole heat exchangers (GRD)

The number of borehole exchangers is decisive about thermal power exchanged with rock mass in specific temperature conditions, but also their construction influences exchanger operation. The GRD technology uses a construction solution based on a centric scheme, coaxial with right liquid circulation. An external pipe (casing) has the diameter of Ø 63 mm, whereas the internal pipe (centric) has the diameter of Ø 32 mm. Through the internal pipe, cold working medium flows downward, whereas, on the bottom of the exchanger, it goes to an external duct and, flowing upwards, it collects heat from rock mass. A direct contact between the external pipe edge and rock mass is conducive to more intense heat exchange. A change in duct diameters may also change the nature of flow from turbulent into laminar, which enables reduction of hydraulic resistance and significant energy savings of pump operation compared with a U-tube.

In centric exchangers, it is best to use a pipe as a whole, without any connections, ended with a round shoe, since it makes it much easier to run pipes. A special uncoiler is very helpful in running of such kind of pipes, which makes it possible to run pipes directly from coils. It is not necessary to straighten the whole section, but only several first metres in order to make it easier to introduce pipes. If an uncoiler for running pipes is used in this technology, it is not necessary for pipe shoes to play also the function of drill collars.

When selecting the share of particular strata, it is necessary to select drilling rig inclination in such a way as to bear in mind the most prospective strata, i.e. those with the highest thermal output, and try to place them in such a way that they have the highest possible share in apparent thickness. In case when standard working time of T_{SP} compressor of a heat pump will exceed 2000 h/year, due to thermal soil regeneration, it is necessary to increase exchanger length proportionately with the $\Delta l_{w.}$ value.

In one starting borehole, as a standard, up to 18 exchangers can be performed and installed. In case of larger installations, in which exchangers will be placed in two or more starting boreholes, boreholes should be distributed perpendicularly to the direction of groundwater flow, as well as it is necessary to distribute exchangers in such a way as to eliminate the likelihood of collision of exchangers from different boreholes.

Process of constructing slant BHEs

The process of constructing slant BHEs already begins with the designing stage. Every project should be studied individually, including the recognition of the geological structure of a given region, the design of boreholes and optimization of the construction of boreholes in reference to energy efficiency. However, the drilling process itself and construction of slant exchangers consists of the following stages:

1. Installation of a drilling chamber DN 1000 in the area of planned boreholes (Fig. 5.8.2.23).

Fig. 5.8.2.23. A drilling chamber with a ring mounted onto it. Two connecting tubes are visible inside (Sliwa and Kucper 2017)

2. Preparation (Fig. 5.8.2.24) and setting the drill rig on the chamber (Fig. 5.8.2.25), disconnection of the drill rig carrier from the driving unit (Fig. 5.8.2.26) and setting the proper drilling angle (Fig. 5.8.2.27).

Fig. 5.8.2.24. Preparation prior to the integration of the drill rig carrier and the drilling chamber (Sliwa and Kucper 2017)

Fig. 5.8.2.25. Setting the drill rig onto the chamber (Barthel P., 2005)

Fig. 5.8.2.26. The driving unit and the drill rig (Sliwa and Kucper 2017)

Fig. 5.8.2.27. An angle gauge set to the transporting position (Sliwa and Kucper 2017)

3. Depending on the geological structure and hydrogeological conditions, while the equipment is being prepared for works (Fig. 5.8.2.28), drilling is made with casing (Fig. 5.8.2.29) or done with the drilling string alone (Fig. 5.8.2.30). It is also possible to apply a down-the-hole hammer in very difficult working conditions.

Fig. 5.8.2.28. Equipment ready for drilling (Sliwa and Kucper 2017)

Fig. 5.8.2.29. Casing pipes with a drilling crown (Sliwa and Kucper 2017)

Fig. 5.8.2.30. Drilling without casing pipes with a preventer (Sliwa and Kucper 2017)

4. If drilling was done without casing, having reached the assumed depth MD and made sure that walls of the borehole are stable, the drill string is pulled out and exchanger tubes are inserted with the use of an uncoiler (Fig. 5.8.2.31).

Fig. 5.8.2.31. Inserting the exchanger with an injection pipe (Sliwa and Kucper 2017)

5. Next the annulus is sealed with filling slurry of increased thermal conductivity using the underwater concreting, generally known as the Contractor method. Once the annulus is filled, casing pipes are pulled out of the borehole.
6. Further BHEs are drilled according to the scheme given above.
7. The last stage is another leakage test of exchangers, closing the boreholes with boreholeheads, installation of distributors coupled with necessary fixtures (Fig. 32) and filling the whole installation with working fluid.

Fig. 5.8.2.32. A ready chamber with a complete installation (Sliwa and Kucper 2017)

A set of borehole exchangers in the GRD technology can be performed from inside of construction objects, which is shown in the example in Fig. 5.8.2.33. Another example: drilling in areas to which access is difficult, is shown in Fig. 5.8.2.34.

Fig. 5.8.2.33. Preparation prior to drilling in a garage (OPTIMA POLSKA 2015) (Sliwa and Kucper 2017)

Fig. 5.8.2.34. Transport of the drilling rig through a forest (left) and its operation (right) (Sliwa and Kucper 2017)

5.8.3. Review of the so-far experience in the area of borehole equipment, studies and borehole measurements

The issues regarding measurements and exploitation of geothermal boreholes include the following:

- testing of geothermal boreholes, within the scope of establishing allowed and recommended production, as well as determining potential exploitable resources of doublet systems,
- aspects of reservoir engineering within the scope of temperature changes in a reservoir in forecasted exploitation conditions in relation to the adopted aquifer opening solutions (also pressure and mineralisation changes),
- analysis of hydrodynamic performance of a geothermal water intake.

5.8.3.1. Principles of designing geothermal tests and recommendations for the exploitation process of low-enthalpy geothermal projects

The goal of the tests is to:

- clean well walls from mud remnants,
- determine hydrogeological parameters of strata made available (to define the storage abundance and hydraulic conductivity factors),
- determine well production characteristics (flow rate/pressure depression),
- determine shape, structural and hydrodynamic borders of the reservoir,
- determine well interference,
- determine supply conditions.

In hydrogeology one can distinguish the following kinds of pumping: initial, exploratory, exploratory-exploitation. From the point of view of the number of employed wells, one can also distinguish individual, hydrotechnical and group pumping.

The above-mentioned division results mainly from the need to determine regional resources of groundwaters, well depth and well distribution. The method of such pumping is described in the following studies: Z. Pazdro, B. Kozerski, (1990) and in the "Instruction manual for hydrogeological drilling" (1981).

In case of deep geothermal wells, it seems necessary to modify, or simplify, the above-mentioned diagram. This opinion is confirmed in publications concerning running of hydrodynamic tests (Grant et al., 1982, Chilingar, et al. 1982, Ramey, Jr., 1988, Ungemach, 1988, Bixley, 1988).

Physical phenomena taking place in geothermal wells (regardless of their composition) and depth of aquifers being made available make it difficult to carry out standard hydrogeological tests. Typical phenomena occurring in one-phase geothermal reservoirs are as follows:

a) change in water column temperature during exploitation, in relation to static temperature in established conditions; this phenomenon depends, to a high extent, on well flow rate, depth and heat exchange in a well.
b) separation of gases dissolved in geothermal water, particularly carbon dioxide, when pressure drops below system saturation pressure.

5.8.3.2. Kinds hydrodynamic tests in geothermal and oil engineering

Depending on a kind of test, as a result of interpretation, information is obtained about the following reservoir information, such as:

a) filtration parameters (conductivity),
b) initial or average reservoir pressure,
c) condition of zone near the well (well damage/perfection),
d) nature of inflow to the well (turbulence),
e) degree of its drilling,
f) reservoir limits (occurrence of barriers and faults),
g) potential flow rate of a reservoir,
h) hydraulic connection between wells.

Tests of individual wells with permanent flow rate and changeable flow rate

No observation piezometers are used in those tests. Pressure measurement is performed only in a well, at its bottom. For this reason, those tests are similar to classical oil tests. When interpreting a test, it is necessary to account to a storage factor regarding well volume. Those tests are combined with a reservoir pressure build-up test. Usually, pressure and temperature measurements are performed at the well bottom.

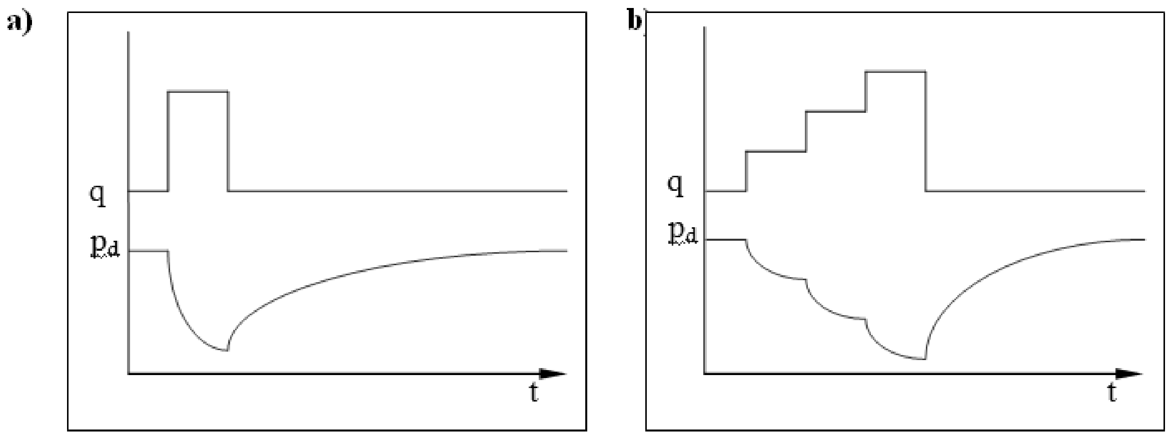


Fig. 5.8.3.1. Example of a reservoir pressure decline and build-up test – triggering of pressure distortions by changing well flow rate. *q - flow rate, p_d – dynamic pressure at the bottom, t -time, a) singe decline/ build-up pressure test, b) multi-cycle decline and build-up pressure test*

Hydrodynamic interference tests

Tests performed for several wells concern pressure measurements made in "active" wells (in which flow rate changes) and "observation" wells. Usually one of wells is active and interference measurements are made in neighbouring ones. In case of production from several wells interference interpretation is difficult, mainly due to "noise" relating to uneven production. Such tests are commonly used in hydrogeology, and that is why, they will be described only briefly.

Pulsation-interference tests

One of interference test variances is pulsation test, characterised with flow rate pulsation and shorter performance time. Interpretation of such test is more complex.

"Production Logging" tests

Those tests have been performed since 1990's in Poland (much earlier in the world). They consist in running of a suitable probe and measuring flow rate (anemometric measurement, the so-called spinner) as well as measuring of pressure, temperatures and fluid density. Measurements are made by moving a probe in a vertical profile during fluid inflow to the well or during water injection to the well. Combination and interpretation of pressure decline tests and production logging tests is extremely interesting.

Well outreach tests and well operation stability tests

The so-called long-term tests consisting in water abstraction from a well for a long period of time (e.g. two weeks or a month). They also enable detecting potential changes in reservoir parameters at a longer distance (e.g. a fault). They also allow precise estimation of reservoir temperature and the so-called established production parameters.

5.8.3.3. Test designing

In principle, a hydrodynamic test design should specify, in detail, the goal, test performance method, means used, water discharge method. Detailed conditions of works performance should specify the following:

a) level of static water table (for established temperature conditions) or measurement of pressure at the head,
b) well flow rate,
c) expected dynamic level of the water table (or pressure) during pumping (exploitation),
d) time of pumping (exploitation) commencement,
e) time when well flow rate changes,
f) time of pumping (exploitation) discontinuation,
g) measurements frequency: flow rate, pressure at the bottom and head pressure, water and air temperature, barometric pressure,
h) equipment used for measuring flow rate, pressure and temperature,
i) number and kind of water samples, as well as place and method of collection,
j) other necessary instruments and devices (compressors, pumps, discharge pipelines, cooling devices, filters etc.),
k) other tests and measurements made during the test.

The test programme should be flexible and enable earlier test completion or extension, caused by reservoir conditions and environmental protection limitations (water discharge).

A basic problem with running test pumping is to identify the method and place of geothermal water discharge. Each time test design and approval of the Supplement to the Mining Operations Plan requires obtaining of a water law permit issued by authorised environmental protection authorities. Such a permit for waters with low mineralisation can be obtained provided that discharged water has temperature below 35°C.

The requirement to cool down water down to temperature below 35° can be troublesome in case of test performance for a period of several days with high flow rate, despite building auxiliary retention reservoirs with capacity up to several thousand cubic metres. The issue of disposal and discharge of strongly salted geothermal waters should be solved by water storage and potential disposal or discharge of diluted water.

It should be emphasised that test pumping design should depend on discharge conditions of those waters.

5.8.3.4. Elements of hydrodynamic tests interpretation

Interpretation models of hydrodynamic tests

Building of a reservoir model and its review is a basic task before test performance. The model shows simplified structure of a gas reservoir under analysis and it is determined on the basis of data acquired from all geological and geophysical works, data from drilling, well sampling, data from tests, as well as data from exploitation.

From the point of view of reservoir engineering, taking into account the whole complexity of useful minerals reservoir characteristics, one can distinguish three basic models:

a) homogeneous reservoir model,
b) model of a reservoir with double porosity,
c) model of a reservoir with double permeability.

In a homogeneous reservoir there is only one porous medium and only that porous medium is responsible for reservoir fluid inflow to a well. This definition is of mathematical nature and it refers to the shape of an appropriate reservoir model in relation to well flow rate changes. In no way does it mean that the reservoir has actual homogeneous properties in a geophysical and geologic sense. Schematically, homogeneous impact of a reservoir can be illustrated as in Fig. 5.8.3.2.

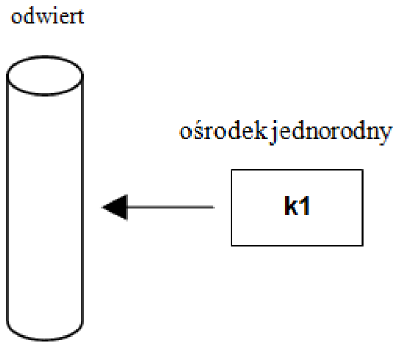


Fig. 5.8.3.2. Diagram of homogeneous reservoir impact on a well

Behaviour of a reservoir with double porosity can be explained by treating the reservoir as a double system of two homogeneous media with different porosity (matrix and fractured), which have an impact on each other. Those media can be freely distributed in relation to a borehole, however, inflow takes place only to one medium; the other one should be treated as a source of reservoir fluid. The model of such a reservoir is shown in Fig. 5.8.3.3.

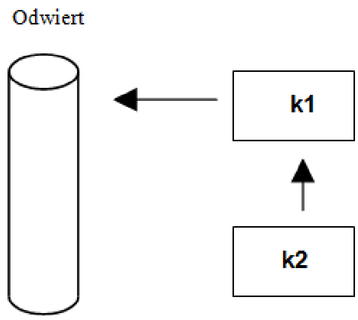


Fig. 5.8.3.3. Diagram of impact on a well of a reservoir with double porosity

Typical examples of reservoirs with double porosity are the following reservoirs:

a) naturally fractured and cracked,
b) multi-strata reservoirs with strongly varying permeability,
c) single-stratum reservoirs with very high changeability of permeability in a vertical direction.

The model of a reservoir with double permeability refers to two different media, where each of them can deliver reservoir fluid to a well. This model has been shown in Fig. 5.8.3.4.

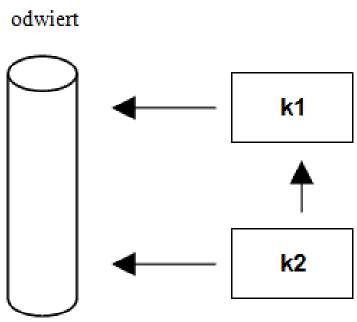


Fig. 5.8.3.4. Diagram of impact on a well of a reservoir with double permeability

Examples of reservoirs with double permeability can be:

a) multi-strata reservoirs with low permeability changeability,
b) unconventional reservoirs (natural gas in shale layers)
c) multi-strata reservoirs separated by impermeable formations.

5.8.3.5. Characteristics of fluid inflow to a borehole

Characteristics of fluid inflow to a borehole stems from hydrodynamic condition, adopted reservoir model, as well as from a kind of procedures performed in a well (stimulation), such as acidizing or hydraulic fracturing.
The following three basic kinds of fluid inflow to a borehole can be distinguished:

a) radial
b) linear
c) double linear

Regardless of the flow characteristics presented above, we can distinguish flat, spherical and semi-spherical inflow. Extent of opening a reservoir stratum through well exploitation is decisive about the occurrence of one of them. If the whole stratum thickness has been opened, we have to do with a flat inflow stream. The main flow direction is the horizontal direction.
In case of partial stratum opening, we can speak about spherical or semi-spherical inflow, depending on the location of the opened zone in relation to the stratum roof or bottom. Combining both inflow classifications, we can characterise inflow as: flatly radial, spherical-radial, spherical-linear, etc.

Characteristics of radial gas inflow to a borehole
A stratum is fully opened (intaken), current lines converge radially to the exploitation well (Fig. 5.8.3.5).

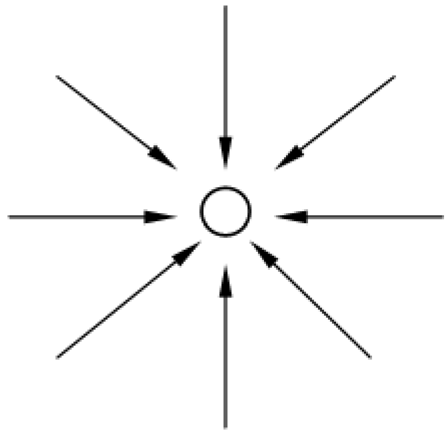


Fig. 5.8.3.5. Diagram of radial inflow

Characteristics of linear fluid inflow to a borehole

Geothermal reservoirs usually have good hydraulic properties (permeability). Sometimes, in case of problems with obtaining a suitable fluid inflow to a reservoir, procedures aimed at facilitating such inflow are performed. One of them can be fracturing. Such procedures are often performed, e.g. within the EGS (Enhanced Geothermal System) technology. Wells fractured hydraulically have characteristics of linear inflows from a reservoir matrix to a fracture and from a fracture to a borehole (Fig. 5.8.3.6). If a well cuts a fracture with high hydraulic conductivity, a factor decisive about inflow is flow rate from a matrix to a fracture, whereas in a fracture itself, pressure drop is minimum.

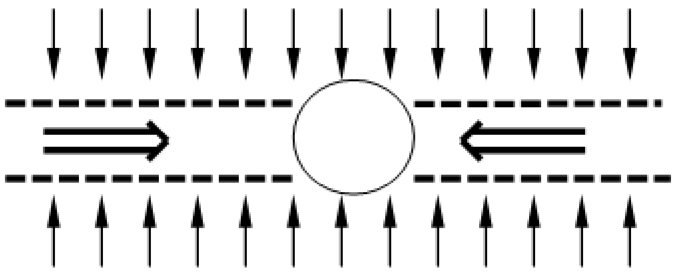


Fig. 5.8.3.6. Diagram of linear inflow

Characteristics of double linear fluid inflow to a borehole

Fluid inflow to a well from a fracture with limited conductivity is a function of linear flow from a medium matrix to a fracture and flow from the fracture to a borehole (Fig. 5.8.3.7). Such a kind of inflow is called double linear.

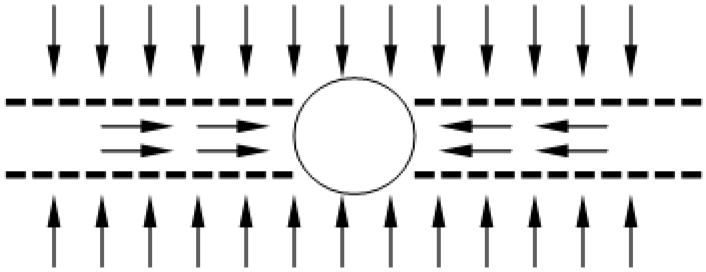


Fig. 5.8.3.6. Diagram of double linear inflow

5.8.3.6. Pumping method (or automatic exploitation)

Well stimulation (initial pumping)

There are the following methods of well stimulation (for systems with static water table below a well head):

a) nitrogen injection (lift),
b) use of borehole pumps,
c) air-lift (not recommended),
d) well swabbing (not recommended).

Nitrogen injection. This method was used for the first time in Italy (1970). It is commonly used in oil industry (in Poland used since 1990's). If water level is much below a head, it is sometimes beneficial to inject water (not aerated (!)) to a well in order to raise the level and enable water exploitation by means of nitrogen lift method. A nitrogen lift is made of drilling pipes or a coiled drill pipe (coil tubing). Nitrogen is pumped to a well, gas inlet is usually located at the depth twice as big as water table.

For instance, in case of water table estimation at the level of 150 m, estimated nitrogen inlet location is 300 m under ground level, and gas pressure should be at about 15 bars. Water density in a well is much reduced by nitrogen solution in water. When flow is triggered, warmer water flows to hte surface and in some cases, it is sufficient for well stimulation and initiation of the exploitation process. However, in case of wells with water table located below 20 m, water density change is not sufficient for do initiating of the exploitation process.

Use of a borehole pump. This method is recommended especially for making long-term production tests and conducting the exploitation process. Pump running should be done in such a way that the planned water table depression enabled pressure at least equal to water column pressure, 100 m above the point of water suction.

Air-lift. This method is known and used in hydrogeologic samplings. Oxygen reacting with some dissolved compounds (e.g. iron) causes their precipitation from water and falling to the well bottom. Furthermore, oxygen is always a corrosive agent. Products of corrosion pollute water, damage a casings column. This method is not recommended for testing of geothermal systems because of introducing a lot of oxygen into abstracted water).

Swabbing. A method with the use of a drill pipe as a piston. In case of well commissioning, it is necessary to remove a pipe, which is particularly dangerous for a well and difficult. This method is not recommended for testing geothermal systems, since a lot of oxygen is introduced into abstracted water.

In the authors opinion, only well stimulation and supporting production by means of a nitrogen lift or using borehole pumps is justified with a recommendation, to use them in practice.

5.8.3.7. Measurements performed during tests

Measurement of geothermal water flow rate

Change in well flow rate can result from a change in supply voltage in a pump, air temperature change, humidity, mix supplying a combustion engine, partial valve closure, change in temperature of water flowing from a well, etc. When using pumps, control through speed change is unsatisfactory, particularly, when a pump delivers water to the surface with low pressure.

Speed of flow rate change can be measured very precisely by means of an overflow box of suitable construction (triangle, square) - see respective industry-specific standards.
The application of turbine (ultrasound) flow meters solves the problem, yet, a drawback of this method is usually a delay in establishing the initial flow rate for a test.
The method with using a choke is commonly used in Western countries. However, it is particularly sensitive to disturbances caused by pulsation on the part of a pump.

Measurements of downhole pressure (for tests of pressure decline- build-up)

It is recommended to measure pressure by means of a special downhole manometer, due to change in water density in a deep well and related water table change (head pressure). For instance, change in geothermal water density by 2% causes, along the well length, a change in water table location by ca. 40 m. In addition, pressure measurement at the head or water table measurement is charged with an error caused by flow resistance in a well. In case of low flow rates, this error is small, yet, it grows with flow rate, particularly in case of using 7'' and 6 $^{5}/_{8}$'' casings; it is a dozen up to several dozen meters. In oil industry, high-class electronic manometers with memory (e.g. 0.05) have been used for many years. Those manometers are run through a lubricator and drawworks to the well bottom, where they are hanged for the duration of measurement. Another solution is the application of electronic manometers with continuous surface registration through a cable playing a transmission role and fixing a manometer in a well.

Pressure measurements at the head

Concurrently with measuring downhole pressure, usually pressure at the head is measured as a control measurement. Pressure at the head is also measured during interference tests in artesian reservoirs.

Measurement of atmospheric pressure

It is necessary to measure atmospheric pressure in order to determine (adjust) absolute pressure, as well as to determine barometric performance (necessary to adjust pressure measurement results in a well for interference measurements). Such measurement should be synchronised with the frequency of downhole pressure measurements, water table measurements and measurements of pressure at the head (in case of artesian waters) in case of an interference test.

Measurements of water table level (exclusively for interference tests)

In observation wells, water table level can be measured manually, electrically, mechanically or acoustically. These are instruments commonly used in hydrogeological tests.
Tables 5.8.3.1–3 specify recommended frequencies of measurements.

Table 5.8.3.1. Recommended frequencies of measurements, electronic measurements

Exploitation (or injection) well	
Time from test beginning	Frequency
0-5 min	5-10 s
5-60 min	20-30 s
60-120 min	30-60 s
>120 min	60-120 s

Table 5.8.3.2. Recommended frequencies of measurements, manual measurements (not recommended)

Exploitation (or injection) well	
Time from test beginning	Frequency
0-5 min	0.5 min
5-60 min	5.0 min
60-120 min	20.0 min
>120 min	60.0 min

Table 5.8.3.3. Recommended frequencies of measurements in case of observation measurements

Observation (piezometric) well	
Time from test beginning	Frequency
0-2 min	10 s
2-5 min	30 s
5-15 min	1 min
15-50 min	5 min
50-100 min	10 min
100 min-5 h	30 min
5-48 h	1 h
>48 h	8 h

5.8.3.8. Recommended hydrodynamic tests

Generally, two kinds of hydrodynamic tests (usually multi-cycle) are performed for geothermal reservoirs, together with "production logging" tests.

Multi-cycle pressure decline test

These are relatively short tests regarding flow rate as well as pressure decline and build-up (Fig. 5.8.3.7) for wells, where flow characteristics is measure at changeable pressure for a short period of time (hours-day). Those tests should be combined with production logging tests. A problem with those tests is always production stimulation and maintenance, in case of water table of geothermal waters located under area surface.

This test consists in making a trial well exploitation with several flow rates for a period of time ensuring pressure stability in a well. The moment of pressure stability at the end of each exploitation period means appearance, around the well, of pseudo-steady condition. Time of stability appearance is shorter if a reservoir has better filtration (petrophysical) properties. In poorly-permeable reservoirs, it is often difficult to obtain such stability in a suitably short period of time. This test precedes the period of well closure in order to stabilise reservoir pressure.

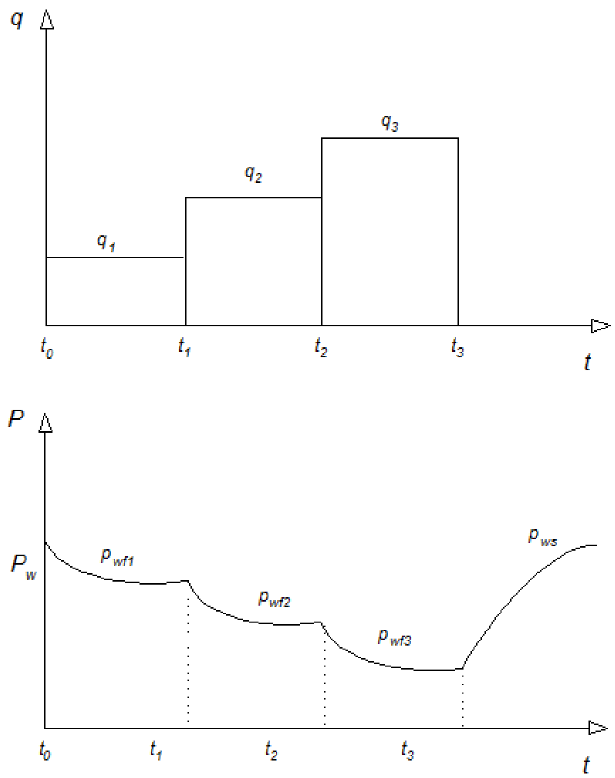


Fig. 5.8.3.7. Classical multi-cycle test

The result of a classical multi-cycle test is flow rate and pressure at the bottom measure at the end of each cycle of trial exploitation. Test interpretation is done by means of a Forhcheimer formula (due to turbulence near a well in case of well exploitation with high flow rate):

$$\Delta p = aq + bq^2 \qquad (1)$$

$$\frac{\Delta p}{q} = a + bq \qquad (2)$$

and next, put measurement points on a diagram in $\frac{\Delta p}{q}$ vs q (Fig. 5.8.3.8).

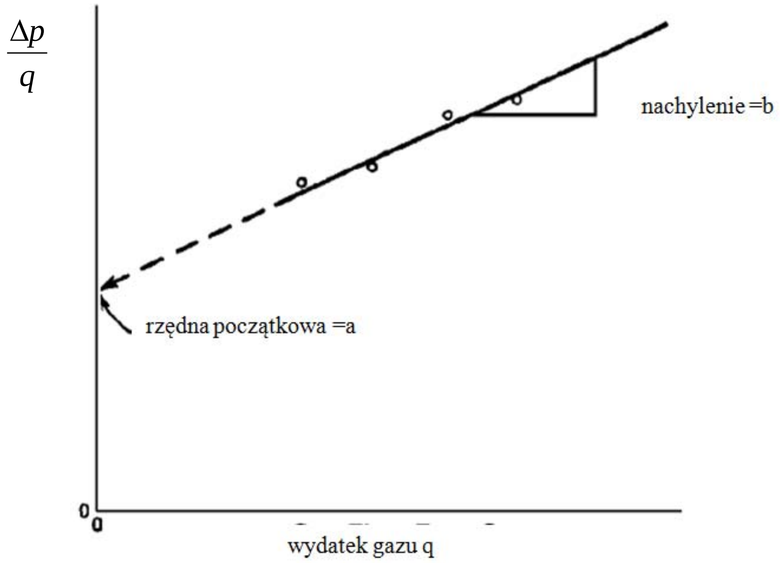


Fig. 5.8.3.8. Classical multi-cycle test (interpretation)

It means in practice that tests on geothermal wells are performed within several days (or even hours) rather than within weeks or months necessary to observe changes in a reservoir or well impact.
Pressure decline-buildup tests are most appropriate to identify reservoir properties near a well. As a result, it is possible to determine hydraulic conductivity or permeability, shape and condition of a zone near a well (Tab. 5.8.3.4).
New interpretation techniques enable, in addition, to specify properties of fracturing-porous medium. Flow rate tests performed for several degrees are particularly desired in case of very big well flow rates and in case of installing filtering systems. They make it possible to identify filter performance and flow nature very close to a well. Pressure buildup tests allow precise identification of skin-effect.

Table 5.8.3.4. Table of basic interpretation models used for interpretation of hydrodynamic tests in oil and geothermal (one-phase) reservoirs

Type of reservoir model	Dimensionless parameters characterising the curve	Calculated reservoir parameters	Remarks
Homogenous model, incomplete stratum extent, tight roof and bottom, uniform distribution of initial pressure	$p_D = \frac{k \cdot h}{1{,}866 \cdot 10^3 \cdot B_w \cdot Q \cdot \eta} \cdot \Delta p$ $t_D = \frac{3{,}557 \cdot 10^{-6} \cdot k}{\phi \cdot \eta \cdot c_t \cdot r_w^2} \cdot \Delta t$ $\mathrm{r_D} = \frac{\mathrm{r}}{\mathrm{r_w}}$	$k \cdot h = 1{,}866 \cdot 10^3 \cdot Q \cdot B_w \cdot \eta \cdot (\frac{p_D}{\Delta p})$ $\phi \cdot c_w \cdot h = \frac{3{,}557 \cdot 10^{-6} \cdot k \cdot h}{\eta \cdot r^2 \cdot (\frac{t_D / r_D^2}{\Delta t})}$	Classical This curve, used for interference test interpretation, with participation of piezometers

Type of reservoir model	Dimensionless parameters characterising the curve	Calculated reservoir parameters	Remarks
Homogenous model with a skin effect and with the storage volume effect	$p_D = \frac{k \cdot h}{1{,}866 \cdot 10^3 \cdot B_w \cdot Q \cdot \eta} \cdot \Delta p$ $t_D = \frac{3{,}557 \cdot 10^{-6} \cdot k}{\phi \cdot \eta \cdot c_t \cdot r_w^2} \cdot \Delta t$ $C_D = \frac{5{,}02 \cdot C}{\phi \cdot c_t \cdot h \cdot r_w^2}$ s	$k \cdot h = 1{,}866 \cdot 10^3 \cdot Q \cdot B_w \cdot \eta \cdot (\frac{p_D}{\Delta p})$ $C = \frac{8{,}98 \cdot 10^{-5} \cdot k \cdot h}{\eta \cdot (\frac{t_D / C_D}{\Delta t})}$ $s = 0{,}5 \cdot \ln\left[\frac{(C_D \cdot e^{2s})}{C_D}\right]$	
Homogenous model with the storage volume effect and with fracture of incomplete conductivity	$p_D = \frac{k \cdot h}{1{,}866 \cdot 10^3 \cdot B_w \cdot Q \cdot \eta} \cdot \Delta p$ $t_{Df} = \frac{3{,}557 \cdot 10^{-6} \cdot k}{\phi \cdot \eta \cdot c_t \cdot x_f^2} \cdot \Delta t$ $C_{Df} = \frac{5{,}02 \cdot C}{\phi \cdot c_t \cdot h \cdot x_f^2}$	$k \cdot h = 1{,}866 \cdot 10^3 \cdot Q \cdot B_w \cdot \eta \cdot (\frac{p_D}{\Delta p})$ $x_f = \sqrt{\frac{3{,}557 \cdot 10^{-6} \cdot k}{\eta \cdot c_t \cdot \phi \cdot (\frac{t_{Df}}{\Delta t})}}$ $C = \frac{\phi \cdot c_t \cdot h \cdot x_f^2 \cdot (C_{Df})}{5{,}02}$	
Model with double porosity, with the storage volume effect and skin effect	$p_D = \frac{k \cdot h}{1{,}866 \cdot 10^3 \cdot B_w \cdot Q \cdot \eta} \cdot \Delta p$ $t_D = \frac{3{,}557 \cdot 10^{-6} \cdot k}{\phi \cdot \eta \cdot c_t \cdot r_w^2} \cdot \Delta t$ $C_D = \frac{5{,}02 \cdot C}{\phi \cdot c_t \cdot h \cdot r_w^2}$ s $\lambda = \alpha \cdot r_w^2 \cdot \frac{k_m}{k_f}$	$k \cdot h = 1{,}866 \cdot 10^3 \cdot Q \cdot B \cdot \eta \cdot (\frac{p_D}{\Delta p})$ $C = \frac{8{,}98 \cdot 10^{-5} \cdot k \cdot h}{\eta \cdot (\frac{t_D / C_D}{\Delta t})}$ $s = 0{,}5 \cdot \ln\left[\frac{(C_D e^{2s})}{C_D}\right]$ $\omega = \frac{(C_D \cdot e^{2s})_{f+m}}{(C_D \cdot e^{2s})_f}$ $\lambda = (\lambda e^{-2s}) \cdot e^{2s}$	λ-parameter characterising ability of flow from matrix to fractures α-characterises structure geometry: $\alpha = \frac{12}{h_h^2}$ lub $\alpha = \frac{12}{r_h^2}$ h_m^2- thickness of matrix block (for rectangular blocks), r_k^2- matrix block radius (for spherical blocks) k_m, k_f -permeability of matrix and fractures
Model with double permeability with the storage volume effect	$p_D = \frac{(k_1 h_1 + k_2 h_2)}{1{,}866 \cdot 10^3 \cdot B_w \cdot Q \cdot \eta} \cdot \Delta p$ $C_D = \frac{5{,}02 \cdot C}{[(\phi \cdot c_t \cdot h)_1 + (\phi \cdot c_t \cdot h)_2] \cdot r_w^2}$ $t_D = \frac{3{,}557 \cdot 10^{-6} \cdot (k_1 h_1 + k_2 h_2)}{[(\phi \cdot \eta \cdot c_t \cdot h_1) + (\phi \cdot \eta \cdot c_t \cdot h_1)] \cdot r_w^2} \cdot \Delta t$ s $\lambda = \alpha \cdot r_w^2 \cdot \frac{k_1 \cdot h_1}{k_1 \cdot h_1 + k_2 \cdot h_2}$ $\kappa = \frac{k_1 \cdot h_1}{k_1 \cdot h_1 + k_2 \cdot h_2}$	$k_1 \cdot h_1 + k_2 \cdot h_2 = 1{,}866 \cdot 10^3 \cdot Q \cdot B_w \cdot \eta \cdot (\frac{p_D}{\Delta p})$ $C = \frac{8{,}98 \cdot 10^{-5} \cdot (k_1 \cdot h_1 + k_2 \cdot h_2)}{\mu \cdot (\frac{t_D / C_D}{\Delta t})}$ $s = 0{,}5 \cdot \ln\left[\frac{(C_D \cdot e^{2s})}{C_D}\right]$ $k_1 \cdot h_1 = \kappa \cdot (k_1 \cdot h_1 + k_2 \cdot h_2)$ $k_2 \cdot h_2 = (k_1 \cdot h_1 + k_2 \cdot h_2) - k_1 \cdot h_1$	κ-parameter interpreted from a curve for function minimum, i.e. in the point of derivative inflection

Advanced interpretation methodology of pressure buildup test

It stems from the analysis of hydrodynamic test interpretation that the curve of buildup pressure itself (in time function) is very similar for different kinds of reservoirs. In order to learn flow conditions in a reservoir, identify particular effects distinguishing a given kind of porous medium and identify their impact on pressure buildup, it is necessary to make diagnostic diagrams. The analysis of a derivative of dimensionless pressure P_D' expressed with the equation:

$$P_D'\left(t_D\right) = \frac{dP_D\left(t_D\right)}{d\ln t_D} \quad (3)$$

makes it easier to specify the nature of the impact of particular boundary effects and heterogeneity in reservoir structure. Since the course of pressure changes in time is not given with a continuous function, pressure derivative is calculated by means of the numerical method, according to the following algorithm. For numerical specification of a derivative obtained in time function, an algorithm using three measurement points is usually adopted: proper point B, point before and point after point B (Fig. 5.8.3.9).

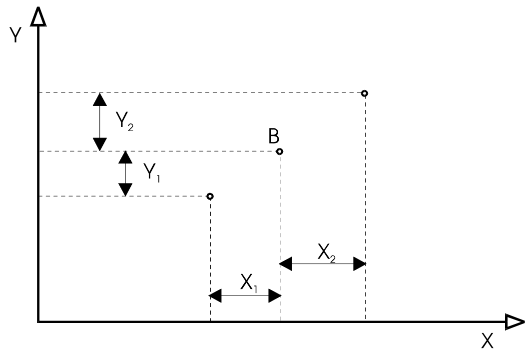


Fig. 5.8.3.9. Diagram for numerical determination of function derivative [own study]

Value of a function derivative in selected point B is calculated from the dependence:

$$\left(\frac{dy}{dx}\right)_B = \frac{\frac{Y_1}{X_1}X_2 + \frac{Y_2}{X_2}X_1}{X_1 + X_2} \quad (4)$$

In industrial practice, the analysis process of pressure buildup derivative is conducted by means of a computer and it consists in matching the curve, obtained as a result of the test, characterising the reservoir under analysis with suitable calibration curves called diagnostic curves.

The course of changes on a pressure buildup curve depends on internal boundary conditions, discontinuity in reservoir structure and external boundary conditions.

Example of interpretation of a classical hydrodynamic test regarding pressure decline and buildup

Fig. 5.8.3.10 presents a traditional diagram of a pressure buildup curve in a semi-logarithmic plot (Horner) for transient state in time function of superposition, defined as:

$(t_p+\Delta t)/\Delta t$ (5)

where:

t_p – working time of the well,

Δt- pressure buildup time.

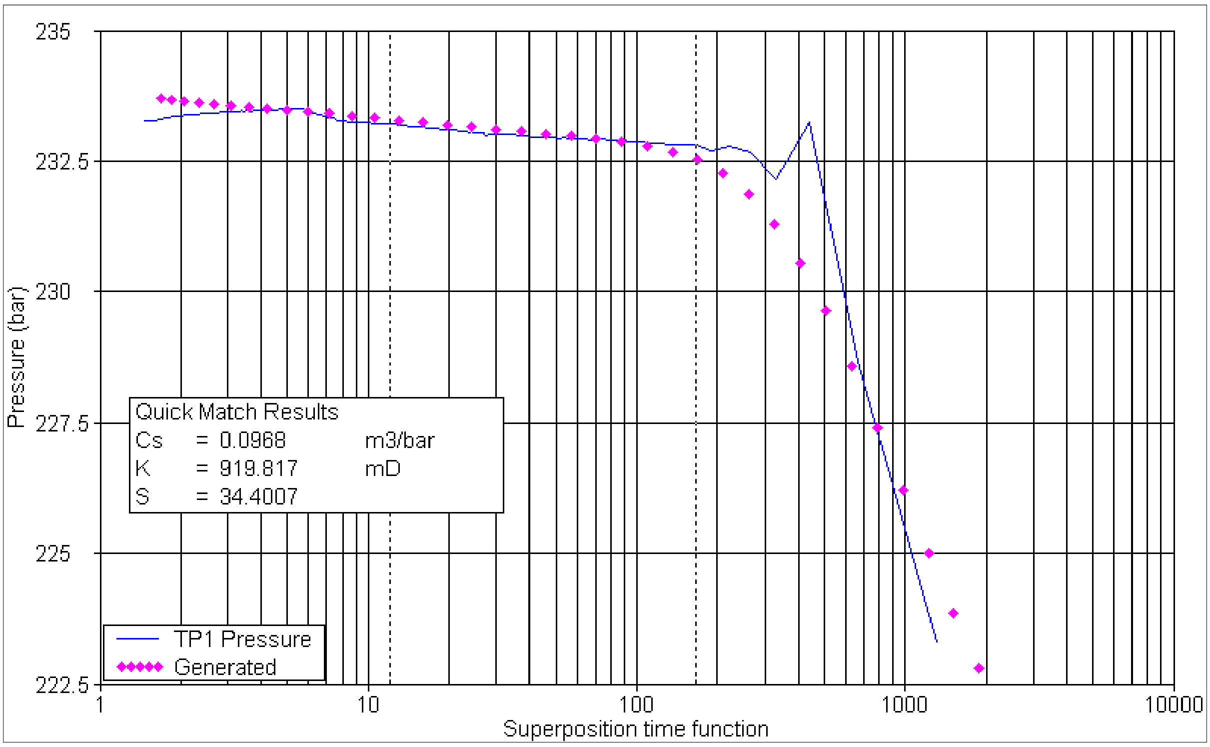


Fig. 5.8.3.10. Horner plot graph for a buildup test in Biały Dunajec PAN-1 well

Equation determining the product of permeability and effective thickness k h_e is as follows:

$$p_i - p_{wf} = m \cdot \log(\frac{t_p + \Delta t}{\Delta t}) \qquad (6)$$

where:

$$m = 2{,}149 \cdot 10^3 \cdot \frac{q \cdot B \cdot \mu}{k \cdot h} \qquad (7)$$

The skin effect is determined from the equation (Lee, 1982):

$$S = 1{,}151 \cdot \left(\frac{p_{1hr} - p_{wf}}{m} - \log(\frac{k}{\phi \cdot \mu \cdot c_t \cdot r_w^2}) \right) + 5{,}1 \qquad (8)$$

Production logging tests

Absorption tests using Production Logging technique are known in oil engineering and they are directly related to the hydrodynamic evaluation of injection wells, related to secondary oil exploitation methods and gas-condensate reservoirs.

Apart from traditional production testing of geothermal wells following the example of hydrogeological and oil wells, after drilling completion, also cold water injection tests are performed. Such tests require collection of a large quantity of water, which should be suitably prepared for injection procedure and with the use of suitable pumps enabling injection flow rate change. Pressure and temperature measurements made during that test enable identification of a place and i characteristics of the supplying zone. If a well has one such zone, interpretation of such a procedure is simple. Since geothermal wells are usually opened at a big length, there is rarely a single supplying zone. Having precise data and making cautious interpretation, it is possible to attribute suitable permeability characteristics to individual supplying zones and determine actual reservoir pressure for each zone.

Such test programme depends obviously on initial drilling results. In fractured formations, the programme of finding steady temperature and pressure is recommended, whereas in formation with low permeability, it is recommended to perform cold water absorption test.

Example of tests run in Poronin PAN-1 well

In Poronin PAN-1 well, a Production Logging test was conducted during a hydrogeological test programme conducted in Podhale in 1996. Measurements of flow rate for a downhole flow meter obtained from two logs (down/up) allowed identifying zones of inflow to the reservoir and percentage flow rate distribution falling on particular zones. On the basis of production logging profiling, 10 zones were separated, including 5 productive ones with considerable inflow differentiation. The below characteristics may be the result of incomplete perforation and the existence of a natural fracture grid around the well (Tab. 5.8.3.5, Fig. 5.8.3.11).

Table 5.8.3.5. Table of the results of production logging profiling in Poronin PAN-1 well

From	To	Effective thickness	% capacity
1768	1784	0	0
1785	1789	4	9
1790	1806	0	0
1807	1810	3	25
1811	1814	0	0
1815	1819	4	41
1820	1821	0	0
1822	1823	1	19
1824	1836	12	6
1836	1864	0	0
	Total	24	100

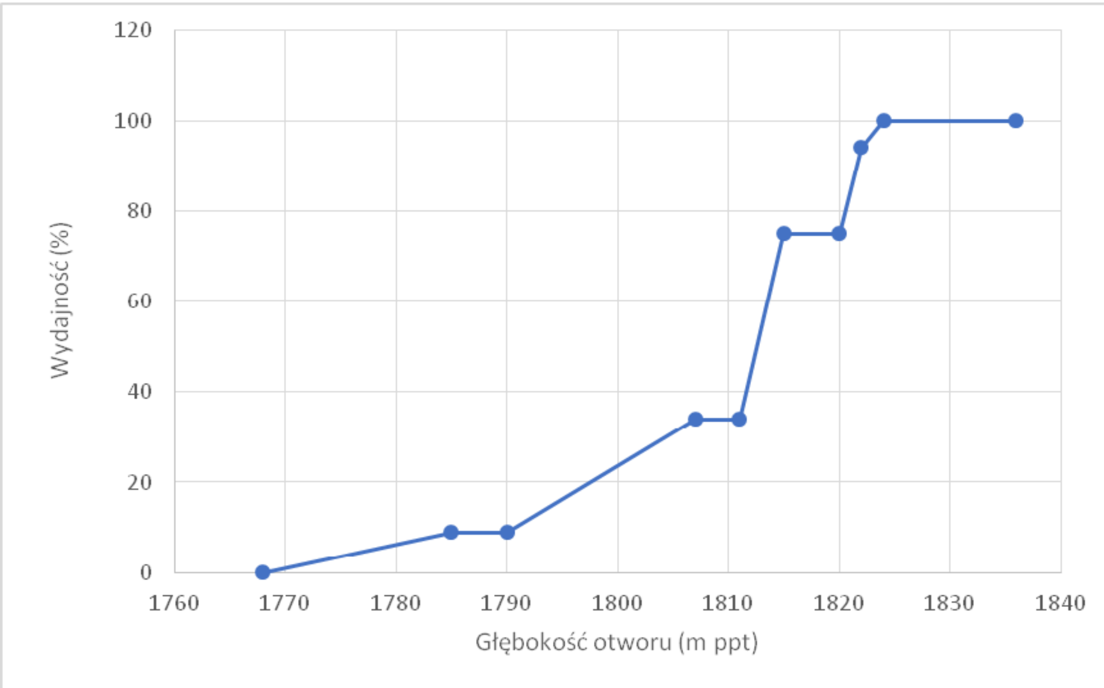


Fig. 5.8.3.11. Figure showing heterogeneous properties of inflow zone in Poronin PAN-1 well (on the basis of the Production Logging test)

Long-term test

Alternatively, a long-term production test is performed. Pressure or flow rate is constant and other flow parameters are measured (for a period of several months or years). A period necessary to obtain stable flow is variable at each degree. Wells with high permeability may stabilise pressure drop within several hours from the test beginning and a flow rate test can be performed within several days (2-3). Long-term production tests are performed almost only during geothermal station commissioning, after drilling process completion. It usually relates to environmental protection limitations, particularly mineralised water discharge to surface water courses.

Influence of well structure on pressure

Well structure has a big impact on water exploitation conditions. High flow rates, i.e. 100-200 m^3/h, require pipes with the diameter of ca. 7'' and higher to exploit water from the depth below 2000 m. For example, exploitation of 200 m^3/h by means of 6 5/8'' pipes causes pressure decline as a result of friction of about 5 bar, which corresponds to additional water table depression of 50 m (see Fig. 5.8.3.12).

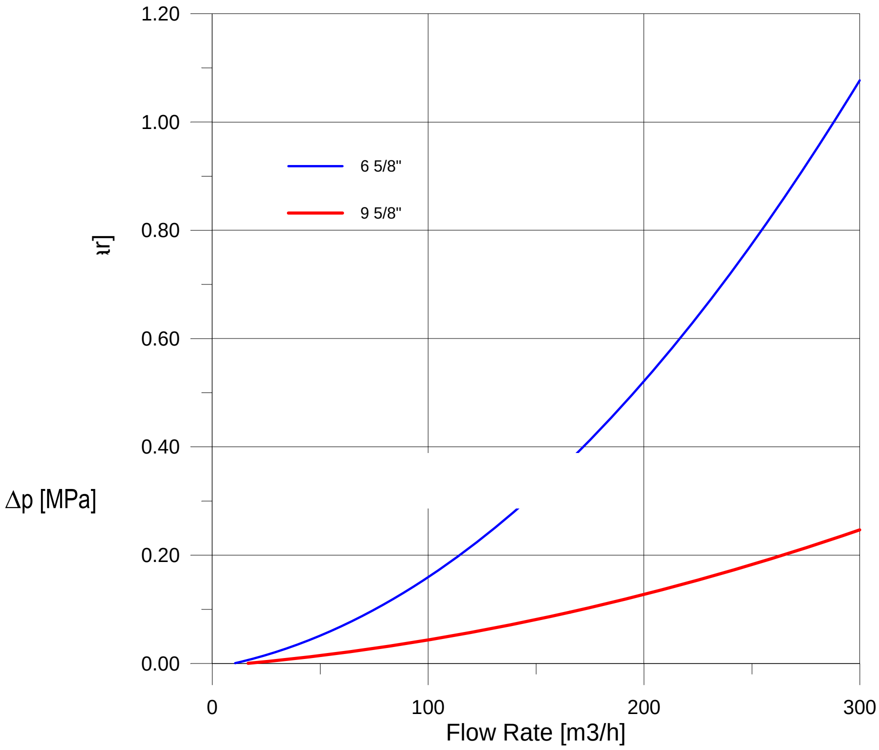


Fig. 5.8.3.12. Pressure losses in 6 5/8 and 9 5/8 pipes in production flow rate function for the depth of 2100m (example).

Influence of exploitation time on temperature stability on the well surface

Temperature during a test changes in time, that's why measurements are always distorted in the first period. In particular, if reservoir temperature is high, surface measurements present a high margin of uncertainty.

That is why, in case of geothermal reservoirs one should always use bottom measurements for interpretation (measured at the depth of making an aquifer available).

Fig. 5.8.3.13 shows examples of temperature changes at the head after test commencement. Temperature depends, in this case, e.g. on reservoir temperature, depth, water flow rate, diameters of production pipes.

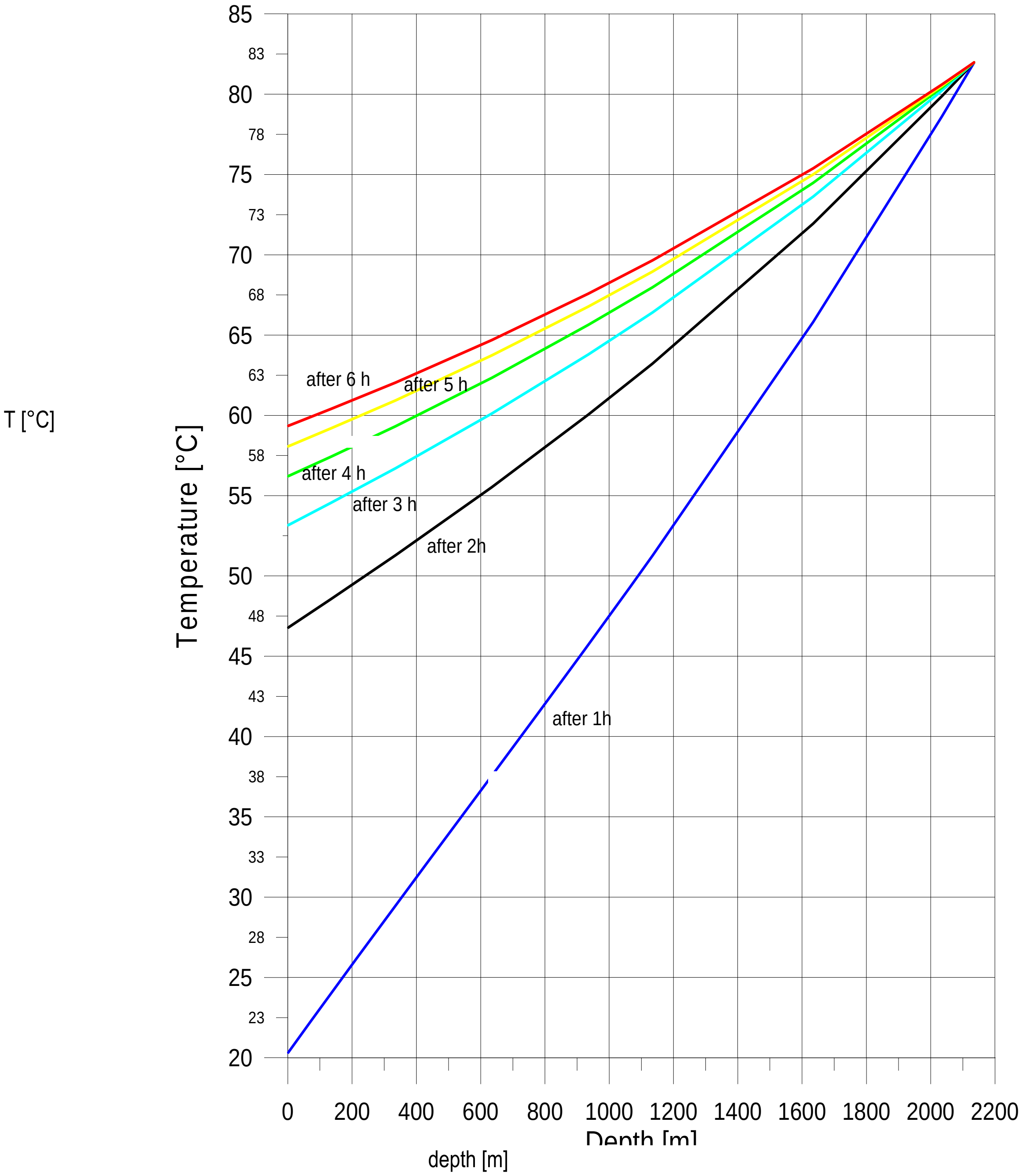


Fig. 5.8.3.13. Water temperature changes in time and depth function (an example)

5.8.3.9. Water injection to the reservoir – damaging of a zone near the well

Problems occurring at injection – loss of absorption

Growth of injection pressure may be caused by one or more reasons (Wright, Chilingarian; 1989, Collins, 1975):

a) reservoir filling up (closed trap),
b) clay swelling and hence permeability decrease,
c) movement of particles from the reservoir caused by dissolution of rock cementing binder; such particles close pore canals thus reducing permeability,
d) presence of "suspended" solid particles in water, which, by blocking pores, also reduce permeability, leading to total or partial loss of absorption,
e) bacteria occurrence in the zone being made available.

Problem of filling reservoirs is identified by long-term production tests and interference tests.

Clay swelling. Every clay mineral reacts with foreign water to a different degree. The degree of clay swelling is a function of e.g. ion force, water pH, and presence of organic polar compounds. Injection to clay zones should be avoided (a suitable filter construction is required).

Movement of particles from a porous reservoir. Pore canals in a reservoir are winding and have an irregular shape. Particles from a reservoir (parts of minerals, crystals, clays, etc.) may be loosely cemented with walls of pore canals. Every change, which distorts cementation of porous medium can also cause movement of particles in a canal (in a direction from the well to external boundaries of the reservoir) until they encounter some barrier (e.g. narrowing of a pore canal). Accumulated effect of such a process may cause a dramatic loss of reservoir absorption. Some reasons causing the largest destruction of reservoir particles cementation include: significant change in water salinity (either salinity growth or decline), pH factor change and a very high injection flow rate.

A solution to the problem of transporting loosely cemented particles is to reduce flow down to the level below that phenomenon occurrence. It can be achieved, e.g. by installing a filter with gravel (glass) pack, which causes significant decrease of reservoir particles transported to the reservoir. Another method is the reduction of water injection flow rate of water injection to the reservoir. Obviously, other "chemical" methods can be considered in order to integrate injection zones, but they present a high risk of this operation failure.

Issue of solid particles deposition. There are two mechanisms relating to the creation of insoluble material and its deposition:

a) reaction of injected water with reservoir water, which creates precipitation (Collins, 1975),
b) delayed reaction of injected water, which results also in the creation of solid particles after it is injected to the reservoir; the latter case is not very significant in case of a reservoir with high permeability, since deposition with created reaction products tales place far away from a borehole and it has a low impact upon borehole absorption.

Problem with the occurrence of suspended solid particles. Usually, "suspended" solid particles are understood as particles precipitated, in contrast with actual solution of water being injected. There are three kinds of "suspended" particles: dispersed crude oil, clay, mud, sand, algae, incrustation (scaling) products, corrosion products (iron sulphide, ferrous hydroxide), bacteria, bacteria impact products, non-compatible chemicals (e.g. improper inhibitors).

A solution to the phenomenon of deposition of solid particles and suspended particles is an injection of suitably clean water (see the item below). In addition, injected water may contain corrosion inhibitors, inhibitors of the occurrence of some mineral sediments and biocide solutions to prevent bacteria development on a well bottom.

Requirements regarding cleanliness of geothermal water being injected

A solution to the issue of solid particles deposition and damaging of the zone near a well is injection of clean (filtered water, preferably with a 1-2 um filter), without any oxygen content (below 5-10 ppb), without iron content (below 4 ppm), without hydrogen sulphide (below 11 ppm), without high content of suspended solid particles (TDS < 50 ppm). Water should have a pH factor between 6-7.

The conditions presented above usually limit the process of damaging a zone near a well, however, they do not give any guarantee of maintaining the same absorption during operation throughout the period of production/injection system functioning.

Cleaning of an injection borehole – sediments deposition and clogging

The most frequent cleaning operation of an injection geothermal well (in case of a two-borehole system) is the removal of mineral sediments from internal surfaces of casings and of the bottom filter. The most frequently encountered minerals, which precipitate, include calcite, silica and sulphides rich in silicon or iron compounds. There are a lot of references in literature regarding calcite and silica precipitation, there are also detailed chemical models, which are used for the evaluation of sediment deposition tendencies. However, modelling of deposition processes of other minerals is more difficult. In case of downhole completion of an „open hole," it is possible to remove scale by means of drilling. However, in case of a well with a filter, that method is impossible to be used. Another method is to extend zones of a "bare" well being made available.

When cleaning a well with a filter (Johnson type) by means of injection solutions dissolving sediments (e.g. respective acids), at the same time, corrosion inhibitors should be injected as well, which counteract reaction in a well.

In order to combat deposition of mineral compounds on filter walls or column walls, chemical compounds are used as an inhibitor. e.g. strongly diluted hydrochloric acid in combination with a corrosion inhibitor.

The most important method of securing the system against corrosion effects and deposition of mineral compounds is well protection against access of oxygen.

References:

1. Barkman, J.H. and Davidson, D.H., 'Measuring Water Quality and Predicting Well Impairment", J. Pet. Technol., 865-873, July 1972.
2. Barthel P., Grundsätliche Überlegungen zur regionalenhydrogeologischen B.eurteilung von Standorten für den Eisatz von Erdwärmepumpen, *Hydrogeologie und Umwelt*, Heft 33, Würzburg, 2005
3. BATTISTELLI A. & NAGY S. 2000 – Reservoir engineering assessment of low-temperature geothermal resources in the Skierniewice municipality (Poland). Geothermics, Vol. 29, 6.
4. Battistelli, A. S Nagy, R Rossi, P Teleki, 1998, GEOTHERMAL RESOURCES ASSESSMENT IN THE SKIERNIEWICE-ZYRARDOW AREA (POLAND), Energy Source.
5. Biernat H., Kulik S., Noga B., 2010r. – Problemy związane z eksploatacją ciepłowni geotermalnych wykorzystujących wody termalne z kolektorów porowych. Technika Poszukiwań Geologicznych. Geotermia, Zrównoważony Rozwój nr 1-2/2010.
6. Biernat H., Posyniak A., 2006r. – Sprawozdanie z wykonanych prac na otworach geotermalnych Pyrzyce GT-2, Pyrzyce GT-3, Pyrzyce GT-4. Arch. POLGEOL S.A., Warszawa.
7. Bixley P.F., 1988 - Downhole measurements in geochemical wells, E.Okandan (ed.) Geothermal Reservoir Engineering, 41-53.
8. Bodvarson G.S., Pruess K., O'Sullivan M.J., 1985 - Injection and energy recovery in fractured geothermal reservoirs, SPEJ, vol. 25, no.2, p. 303-312.
9. Bodvarson G.S., V. Stefansson, 1988 - Reinjection into geothermal reservoirs. (w: Geothermal Reservoir Enginnering, p. 103-120, Ed. E. Okandan), Kluwer Academic Publishers.
10. Bourdet D., Alagoa A., Ayoub J.A., Pirard Y.M., 1984 - New Type Curves Aid Analysis of Fissured Zone Well Tests, World Oil, Apr. 1984, p.111-124.
11. Bourdet D., Ayoub J.A., Pirard Y.H., 1989 - Use of Pressure Derivative in Well Test Interpretation, SPE Formation Evaluation, June.
12. Bourdet D., Whittle T.M., Douglas A.A., Pirard Y.M., 1983 - A New Set of Type Curves Simplifies Well Test Analysis, World Oil, May 1983 , p.95-106.
13. Cinco-Ley H., Samaniengo V.F., 1981 – Transient Presure Analysis for Fractured Wells, SPEJ, Sept. P. 1749-1766.
14. Coleman, J.R. and McLelland, W.G., "Produced Water Re-Injection; How Clean is Clean?," SPE 27394 presented at the SPE Intl. Symposium on Formation Damage Control, held in Lafayette, LA, Feb. 9-10, 1994.
15. Collins A.G., 1975 - Geochemistry of oilfield waters, Developments in Petroleum Science 1, Elsevier.
16. Długosz P., Nagy S., 1995 - Hydrodynamic Parameters of Podhale Geothermal Reservoir, Buletyn PAN (Geologia), z..4.
17. Domenico P.A., Schwartz F.W., 1990 - Physical and chemical hydrogeology, John Wiley and Sons.
18. Dowgiałło J., Karski A., Potocki I., 1969 - Geologia surowców balneologicznych - Wyd. Geol. Warszawa.
19. Dowgiałło J.,1987 -Problematyka hydrogeologiczna regionu sudeckiego, Prz.Geol. nr 6.
20. Economides M.J, Nolte K. G., 1987 - Reservoir Stimulation, Schlumberger Edu. Services.
21. Eylander, J.G.R., 'Suspended Solids Specification for Water Injection from Coreflood Tests", SPE Res. Eng. J., November, 1988.
22. Facca G., 1973 - The Structure and Behaviour of Geothermal Fields, 'Geothermal Energy Review of Review and Research and Development, H.C.H. Armstead (ed.), U.N.E.S.C.O. Doc. ISBN 92-3-101063-8.
23. Gonet A., Macuda J., Wiertnictwo hydrogeologiczne, Uczelniane Wydawnictwa Naukowo-Dydaktyczne AGH, Kraków 2004.
24. Gonet A., Mirosław Sowa, Tomasz Śliwa, *Wykonywanie otworowych wymienników ciepła – wiercenia obrotowe,* GLOBEnergia, nr 1 s. 24–262012
25. Gonet A., Sowa M., Śliwa T., Wykonywanie otworowych wymienników ciepła, Globenergia. 2012.
26. Gonet A., Śliwa T., *Konstrukcje otworowych wymienników ciepła,* Czysta energia, czyste środowisko 2008, red. Ireneusz Soliński; Małopolsko-Podkarpacki Klaster Czystej Energii, Wydawniczo-Poligraficzna "ART-TEKST", Kraków 2008, s. 125–133.
27. Gonet A., Śliwa T., Stryczek S., Sapińska-Śliwa A., Jaszczur M., Pająk L., Złotkowski A. *Metodyka identyfikacji* potencjału cieplnego górotworu wraz z technologią wykonywania i eksploatacji otworowych wymienników ciepła

(Methodology for the identification of potential heat of the rock mass along with technology implementation and operation of the borehole heat exchangers), ed. A. Gonet, Kraków, Wydawnictwa AGH, p. 439, 2011.

28. Gonet A., Tomasz Śliwa, Stanisław Stryczek, Aneta Sapińska-Śliwa, Marek Jaszczur, Leszek Pająk, Albert Złotkowski, Metodyka identyfikacji potencjału cieplnego górotworu wraz z technologią wykonywania i eksploatacji otworowych wymienników ciepła, praca zbiorowa pod red. Andrzeja Goneta, Kraków, Wydawnictwa AGH, 2011.
29. Gonet Andrzej, Mirosław Sowa, Tomasz Śliwa (2012), Wykonywanie otworowych wymienników ciepła – wiercenia obrotowe (Making borehole heat exchangers – rotary drilling), GLOBEnergia, nr 1 s. 24–26.
30. Górecki W., 1995 - red. Atlas zasobów energii geotermalnej na Niżu Polskim, Kraków.
31. Górecki W., 2007 - red. Atlas zasobów geotermalnych formacji mezozoicznej na Niżu Polskim, Kraków.
32. Górecki Wojciech, Andrzej Szczepański, Andrzej Sadurski, Marek Hajto, Bartosz Papiernik, Tomasz Kuźniak, Tomasz Kozdra, Jan Soboń, Jan Szewczyk, Andrzej Sokołowski, Wojciech Strzetelski, Andrzej Haładus, Jarosław Kania, Krzysztof Kurzydłowski, Andrzej Gonet, Marek Capik, Tomasz Śliwa, Roman Ney, Beata Kępińska, Wiesław Bujakowski, Lucyna Rajchel, Jacek Banaś, Wojciech Solarski, Bogusław Mazurkiewicz, Maciej Pawlikowski, Stanisław Nagy, Krzysztof Szamałek, Anna Feldman-Olszewska, Ryszard Wagner, Tomasz Kozłowski, Zdzisław Malenta, Aneta Sapińska-Śliwa, Anna Sowiżdżał, Jarosław Kotyza, Krzysztof P. Leszczyński, Marzena Gancarz (2006), Atlas zasobów geotermalnych formacji mezozoicznej na Niżu Polskim (Atlas of geothermal resources of Mesosoic formations in the Polish Lowlands), pod red. Wojciecha Góreckiego, Akademia Górniczo-Hutnicza im. S. Staszica w Krakowie. Wydział Geologii, Geofizyki i Ochrony Środowiska. Zakład Surowców Energetycznych AGH Kraków, p. 484.
33. Grant M.A., Donaldson I.G., Bixley P.E., 1982 - Geothermal Reservoir Engineering, Academic Press.
34. Hall H.N. 1953 - Compressibility of reservoir rocks transaction, AIMF vol 198, p.309-311.
35. Halliburton Logging services, 1993 - Production logging training notes.
36. Harrison R., Mortimer N.D., Smarason O.B., 1990 - Geothermal Heating a Handbook of Engineering Economics, Pergamon Press.
37. Horne R.N., 1994 - Advances in Computer-Aided Well Test Interpretation, JPT, July 1994.
38. Horner D.R., 1951 - Presure Built-Up in Wells, Proc. Third Word Pet. Cong. E.J.Brill, Leiden, II, 503.
39. http://www.archonspzoo.pl
40. Kapuściński J., S. Nagy i inni, 1996, Zasady i metodyka dokumentowania zasobów wód termalnych i energii geotermalnej oraz sposoby odprowadzania wód zużytych. Poradnik metodyczny, Warszawa.
41. Kjaran S.P., Eliasson J. 1983 - Geothermal Reservoir Enginnering Lecture Notes, UNU Geothermal Training Programme, Iceland.
42. Kruseman G.P., de Ridder N.A. 1989 - Analysis and Evaluation of Pumping Test Data, ILRI publ. 47, Sec. Ed.
43. Kucper M., Pozyskiwanie ciepła Ziemi z otworowych wymienników ciepła wykonanych w technologii GRD - Geothermal Radial Drilling, Master Thesis, Faculty of Drilling, Oil and Gas, AGH University od Science and Technology, Krakow, p.90, 2016.
44. Lane H.S., Lee W.J., Watson A.T., 1991 - An Algorithm for Determination Smooth, Continuous Pressure Deritivatives From Well Test Data, SPE Formation Evaluation, Dec.
45. Lee J. 1982 - Well Testing, SPE Textbook Series, Vol.1, SPE, Dallas.
46. Lippmann M.J., Tsang C.F., Whiterspoon P.A., 1977 - Analysis ofthe response of geothermal reservoirs under injection and production procedures, SPE 653.
47. Macioszczyk A., 1987 - Hydrogeochemia, Wyd. Geol. Warszawa.
48. Macuda J., Bujakowska K., 1997 - Zasady i metodyka dokumentowania zasobów wód termalnych i energii geotermalnej oraz sposoby odprowadzania wód zużytych. Ministerstwo Ochrony Środowiska Zasobów Naturalnych i Leśnictwa.
49. Nagy S., J. Soboń, Geothermal waters reinjection into sandstones and carbonate reservoir rocks, 2007, Wiertnictwo – Nafta Gaz, Tom 24, p. 347-354.
50. Nagy, S., P. Długosz, Identification of the low-enthalpy Podhale geothermal reservoir based upon long term interference and pulse hydrodynamic testing, WGC 2000 Japan.
51. Nasr-El-Din, H.A. A.A. Al-Taq,1996, Water Quality Requirements and Restoring the injectivity of Waste Water Disposal Wells, SPE 39487.
52. Nowak J.: Zawisza L., Gadek W., Nagy S., 1999, interpretacja testu production logging w połączeniu z testem hydrodynamicznym złoża wielowarstwowego (mlt), X Konf. NT, AGH.

53. Nowak W., Stachel A., - 2004r. – Ciepłownie geotermalne w Polsce – stan obecny i planowany. Czysta Energia lipiec/sierpień 2004.
54. Pazdro Z., Kozerski B. 1990- Hydrogeologia ogólna. Wyd. Geol. Warszawa.
55. Posyniak A., 2015r. - Sprawozdanie z wykonanych robót wiertniczych z otworze geotermalnym Pyrzyce GT-4. Arch. G-DRILLING S.A., Warszawa.
56. Posyniak A., 2016r. – Dokumentacja otworowa otworu geotermalnego Stargard GT-3. Arch. G-DRILLING S.A., Warszawa.
57. Posyniak A., Bentkowski A., Biernat H. Kapuściński J., - 2006r. – Dokumentacja hydrogeologiczna ustalająca zasoby eksploatacyjne ujęcia wód termalnych z utworów jury dolnej w Stargardzie Szczecińskim. Arch. POLGEOL S.A., Warszawa.
58. Przybyłowski Ł., Posyniak A., 2016r. – Projekt techniczny wiercenia otworu Stargard GT-3. Arch. G-DRILLING S.A., Warszawa.
59. Przybyłowski Ł., Posyniak A., 2017r. – Projekt geologiczno-techniczny wiercenia otworu Pyrzyce GT-1 Bis. Arch. G-DRILLING S.A., Warszawa.
60. Ramey H.J., Jr., 1992 - Advances in Practical Well Test Analysis, JPT, June 1992, p.650.
61. Reynolds A.C., Chen J.C., Raghaven R, 1984 - Pseudoskin Factor Caused by Partial Penatration, JPT, Dec., p. 2197.
62. Rochon J., Creusot, M.R., Rivet, P., Roque, C. and Renard, M., 'Water Quality for Water Injection Wells", SPE 31122 presented at the SPE Formation Damage Control Symposium, held in Lafayette, LA, Feb. 14-15, 1996.
63. Sabet M.A., 1991 - Well Test Analysis, Contributions in Petroleum Geology and Engineering, Gulf Publishing Company, Houston.
64. Samaniengo F. V., H. Cinco-Ley, Reservoir Engineering Concepts (in Handbook of Geothermal Energy, red. Fertl, 1982.
65. Sokołowski J., Sokołowska J., Plewa S., Nagy S., Krokoszyńska M., Krzysiek U., 1995 - Geothermal Provinces and Basins in Poland, Polish Geothermal Association and Polish Academy of Science, MEERC, Kraków.
66. Szczepański A. 1990 - Warunki hydrogeologiczne dolnojurajskiego i dolnokredowego zbiornika geotermalnego - Atlas wód geotermalnych Niżu Polskiego. Kraków.
67. Śliwa T., *Badania podziemnego magazynowania ciepła za pomocą kolektorów słonecznych i wymienników* otworowych (Research on underground thermal energy storage by use solar collectors and borehole heat exchangers), Wydawnictwa AGH, Kraków, p. 272, 2012.
68. Śliwa T., Gonet A., Analiza efektywności wymiany ciepła w wymiennikach otworowych o różnej konstrukcji, *Wiertnictwo Nafta Gaz*, vol. 28, no. 3, pp. 555-570, 2011.
69. Śliwa T., Gonet A., Złotkowski A., Górotwór jako rezerwuar ciepła, Nowoczesne Budownictwo Inżynieryjne, nr 6, 2007.
70. Śliwa T., Kucper M., Accessing Earth's heat using Geothermal Radial Drilling for borehole heat exchangers, AGH Drilling, Oil, Gas 2017 vol. 34 no. 2, s. 495–512. — Bibliogr. s. 512, Summ. — Toż na CD-ROMie.
71. Śliwa T., M. Mazur, A. Gonet, A. Sapińska-Śliwa (2011), Wiercenia udarowo-obrotowe w geoenergetyce (Hammers-rotary drilling for geoenergetics), *Wiertnictwo, Nafta, Gaz* t. 28 z. 4 s. 759–770.
72. Śliwa T., M. Mazur, A. Gonet, A. Sapińska-Śliwa (2011), Wiercenia udarowo-obrotowe w geoenergetyce (Hammers-rotary drilling for geoenergetics), Wiertnictwo, Nafta, Gaz t. 28 z. 4 s. 759–770.
73. Śliwa T., Maciej Mazur, Gonet A., Sapińska-Śliwa A., Knez D., Wiercenia udarowo-obrotowe dla geoenergetyki, Wiertnictwo Nafta Gaz, nr 4, 2011.
74. Śliwa T., Nycz., Analiza potencjalnych możliwości pozyskiwania ciepła z karpackich odwiertów naftowych, Technika Poszukiwań Geologicznych Geotermia Zrównoważony Rozwój, nr 49, zeszyt 1-2, 2010.
75. Śliwa T., Rosen M.A., Poniedziałek M., Use of heat from a snow melting installation in a parking lot surface as a heat regeneration source for underground heat storage via borehole heat exchangers, eSim 2016 Hamilton, Ontario, May 3rd to 6th Conference proceedings, McMaster University Engineering Canada 2016 p. 247–256 http://esim.mcmaster.ca/index.php/2016/index/pages/view/program.
76. Śliwa T., Stryczek S., Wysogląd T., Skakuj A., Wiśniowski R., Sapińska-Śliwa A., Bieda A., Kowalski T., Wpływ grafitu i diatomitu na parametry wytrzymałościowe stwardniałych zaczynów cementowych — Impact of graphite and diatomite on the strength parameters of hardened cement slurries, Przemysł Chemiczny 2017 t. 96 nr 5, s. 960–963. — Bibliogr. s. 963.

77. Śliwa T., Gonet A., Złotkowski A. (2007), Górotwór jako rezerwuar ciepła (Rockmass as heat reservoir), Nowoczesne Budownictwo Inżynieryjne, nr 6 2007, pp. 12-14.
78. Śliwa T., Mazur M., Gonet A., Sapińska-Śliwa A. (2015), Wykonywanie otworowych wymienników ciepła – wiercenia udarowo-obrotowe, GLOBEnergia+, Odnawialne Źródła Energii i Efektywność Energetyczna, nr 1.
79. Śliwa T., Pacewicz M. (2012), Wykonywanie otworowych wymienników ciepła z wykorzystaniem silnika wgłębnego – wiercenia urządzeniami ,,coiled tubing" (Borehole heat exchangers drilling using a downhole motor and coiled tubing equipment), AGH Drilling, Oil, Gas, vol. 29 no. 1, pp. 293–300.
80. Śliwa T., Nycz P. (2010), Analiza potencjalnych możliwości pozyskiwania ciepła skał z karpackich odwiertów naftowych (Analysis of potential possibility the heat extraction from rocks using oil wells in Carpathian Mountain), Technika Poszukiwań Geologicznych Geotermia Zrównoważony rozwój, R. 49, z. 1-2, pp. 119-131.
81. Thomas C.E.,. Mahoney C.F,. Winter G.W.,1988 - Water-Injection Pressure Maintanace and Waterflood Process, w: :Petroleum Engineering Handbook, Ed. Bradley, Ch. 44.
82. Ungemach P. 1987 - Reservoir Engineering Assessment of a Low Enthalpy Geothermal Field. Paris Basin.Ed. Ender Okandan, Geothermal Reservoir Engineering, NATO ASI, Series E:Appl.Sci.v.150, Kluwer Acad. Publ. p. 332.
83. van der Knaap W. 1959 - Nonlinear Behaviour of Elastic Porus Media, Petr. Trans. AIME, Vol. 216, 179-197.
84. Wilkie, DJ., Kennedy, W.L. and Tracy, K.F., "Produced Water Disposal - A Learning Curve in Yemen" SPE 35030 presented at the SPE Formation Damage Symposium held in Lafayette, LA, Feb. 14-15, 1996.
85. Wiśniowski R., Nowe technologie wiertnicze stosowane w wierceniach inżynieryjnych, Wiertnictwo Nafta Gaz, R. 23/1, 2006.
86. Wright C.C., G.V. Chillingarian, 1989 -Water quality for subsurface injection, w: "Surface operation for petroleum production", II, Eds. Chillingarian, Roberson, Kummar, Developments in Petroleum Science, Elsevier.

5.9. Best practices in geothermal drillings in Iceland suitable for Poland

5.9.1 Geothermal drilling technologies, wells' equipment, measurements and exploitation in Iceland – recommendations for Poland

5.9.1.1. Pre - while - and post drilling issues

Assuming all geo-related studies are over with, permits & environmental issues has been taken care off and the location of the well has been chosen. There are however some aspects to consider prior, while and after the drilling.

General items such as:

- Drill site preparation including electricity & water supply to site.
- Disposal of contaminated water and drill cuttings from the operation
- Sound attenuation in case of drilling near residential areas,
- Traffic considerations, haulage, loading & unloading of heavy machinery
- Risk assessment, health & safety considerations throughout the entire operation

Well design and other issues including:

- Depth and diameter of well sections
- Casing programs & cementing
- Straightness requirements, limitations of deviation from vertical
- Geo-related research during drilling incl. well logging, sampling of cuttings etc.
- Need for BOPs (Blow Out Preventers)

"What to do if" considerations:

- Unexpected aquifers are encountered
- Cross contamination, water lost from another well
- Unstable formations, caving of hole walls
- Stuck drill string or items lost in hole
- Hazard factors, such as occurrence of hydrocarbons, radioactivity etc.

Post drilling activities:

- Well logging and testing (Fig. 5.9.1.1 and 5.9.1.2)
- Well completion
- Drill site remediation

Fig 5.9.1.1. Logging gear

No fancy or expensive equipment are needed for most well logging purposes. A hydraulic winch coupled to an excavator or a conventional truck-crane plus some simple ancillaries will do.

Fig. 5.9.1.2. An example of a useful logging recorder from www.star-oddi.com.
This particular recorder is suitable for temperature, pressure and inclination

5.9.1.2 The tendering process and drilling supervision

The value of an unambiguous tender document can never be overemphasized. Not only is this valid for the client, but not less for the contractor and the project as a whole. The tender docs are the project recipe and the framework in which contractors base their time and cost calculations. Included in the tender documents shall be most of the items listed under above section - 5.9.1.1 - but furthermore such issues as:

- The time frame of the project
- Who is responsible for which task
- How to handle unexpected happenings, indicated by the "what if" issues above
- Payment terms, etc. etc.

The drilling procedure is a highly specialized field within the contracting industry. One careless moment or a wrong decision can result in catastrophic consequences. It is a standard practice with larger scale drilling projects in Iceland that the client hires an expert people to prepare the tender docs and to supervise the entire operation. The supervisor also has the role of qualifying or rejecting the contractor´s invoices for payment.

The authorities of Sochaczew, Konstantynów Łódzki and Ladek-Zdrój are strongly recommended to adhere to the above practice.

The cost of drilling in Iceland and elsewhere are dependent upon number of factors such as:

- Purpose of the drilling, fresh water, geothermal, high-temperature etc.
- Diameter and depth, casing program and grouting requirements
- Market situation, busy market, monopoly etc.
- Risk factors, drilling conditions, known or unknown fields etc.

An indication of drilling cost is as follows:

- A: 250 m fresh water / low-temp well, 60 to 100 €/m Small rig
- B: 1000 m geothermal well 350 to 550 €/m Medium rig
- C: 2500 m high-temp well 1.100 to 1.400 €/m Large rig.

5.9.1.3 Drilling procedures and different technologies involved

Introduction

The geology of Poland is characterized by:

1) Loose overburden and soft to medium-hard sedimentary formations and

2) Hard igneous and metamorphic rocks.

The drilling of above formations involves different equipment and approach, depending upon target depth and drilling conditions.

Drilling with tricone bits and water or mud

The drilling of soft to medium- hard formations are fairly well known and developed. The „tricone bit" - also referred to as - „roller bit" together with mud or water circulation are the prevailing methods used for those circumstances. The local drilling companies will normally know better than the outsiders which bit to choose and how to mix the mud for optimum results.

The drilling of a hard rocks with tricone bits are time consuming and expensive as a consequence. The ROP (Rate Of Penetration) can easily sink to < 1 m/h and the bit inserts will wear flat during some 50 to 150 m of drilling (Fig. 5.9.1.3). This in turn will inevitably cause substantial tripping time, ie the time required to pull the string out of the hole, change the bit and run in again.

For medium to hard formations PDC bit should be considered. This is a proven technology that ensures higher rates of penetrations Recent common practice in the drilling industry is to use PDC (Polycrystalline Diamond Compact) bits especially for medium and hard formations.

Fixed cutter bits are either diamond bits, synthetic diamonds bits, or PDC bits. Fixed cutter bit selection is influenced by the type of drilling fluid used. Water based mud does not clean PDC bits as effectively as oil based mud does. This becomes significant in hydrateable formations like shale or clay. In soft formations, PDC bits with less blades or larger cutters should be used. One of the disadvantages of the diamond bits in relatively soft formations is that the bit drills so fast that removal of the cuttings becomes a problem Sufficient hydraulic power must be available to achieve the best performance. The cuttings on the surface are finer than rock bit is used. This also cause that mud parameters are more difficult to control.

Recent industry common practice is drilling applying PDC bits with high speed mud motors or rotary steerable system as a more expensive option however ensuring control of well trajectory with no impact to weight on bit.

For bit selection the offset information is required, if available, with bit records, run reports, mud logs.

Fig. 5.9.1.3. A worn tricone bit

Recent drilling in Sweden. A high quality tricone bit after drilling 122 m in hard and abrasive rock. The inserts were worn out, butbearings still in perfect shape.

Drilling with percussive DTHs and compressed air

The absolutely fastest and most efficient way of drilling hard rocks are the air driven DTH.

(DTH = Down TheHole) Those percussion hammers are available from a vast number of manufacturers, they are relatively cheap and same applies for the bits which will cost only a fraction of a similar size tricone bit (fig. 5.9.1.4).

Fig.5.9.1.4. Air driven hammers and bits

An example of a DTH. Those vary in size from fairly small to really large ones.

The DTH and the compressors feeding them has limitations however. While the ROP can reach some 10 to 20 m/h in the uppermost 200 meters or so, the ROP will sink as the drilling advances deeper. A modern air compressor will have a discharge pressure of 35 bar, but the air pressure is in fact the limiting factor with respect to depth capacity.

While the air driven DTH is ideally suitable for drilling to say 500 m or perhaps somewhat further, the efficiency of drilling from there is subject to many factors. In some cases a booster compressor, boosting the air pressure further up can be used to reach greater depths. At a certain point however, the fuel consumption versus the ROP will reach the question mark where tricone drilling or other solutions may be a better alternative.

Drilling with DTHs and high pressure water.The Wassara technology

Yet another well known drilling technology is the Wassara concept. In this case the percussive effect is brought about by high pressure water.Those hammers will require a thorough filtration of the circulating water or best of all, a fresh water supply as they are sensitive against impurities in the water. Those DTHs will cost substantially more compared to the air driven DTHs and have a shorter lifespan. They will on the other hand keep a fairly good ROP even at considerable depth.

Further considerations and recommendations

While the proposed drillings in Konstantynów Łódzki and Sochaczew appears to be a „standard drilling procedure", the drilling in Lądek-Zdrój would provide an excellent opportunity to try and develop the best practises in deep & hard rock drilling. One angle that immediately springs to mind is to consider starting with a suitable "DTH rig" and pre-drill as far as it goes before moving in the larger equipment. Not only is this important for Lądek-Zdrój, but also for future drillings in Poland and elsewhere.

Starting with DHT rig and further drilling with standard drilling procedure would require contracting two different drilling rigs. That would increase the cost of entire project as a mobilization cost of two rigs need to be considered. Usually pre-drill with a standard drilling is conducted with satisfactory rate of penetration. Also it is practiced in the industry that smaller rig is contracted to pre-drill, enough to set 18 5/8" casing and then the heavier unit is rigged up.

5.9.1.4 Successful Drilling Projects in Low Temperature Fields in Iceland

The drilling of low temperature wells has rapidly gained attention in Iceland. A geothermal water of adequate temperature for house heating is sometimes hard to find. In cases, a better and cheaper solution is to drop the deep geothermal drilling and utilize a low-temp water for feeding a heat pump.

The Vík example is explained elsewhere in this document , but the drilling of a deep geothermal well was consideredtoo risky and expensive to proceed with. Some more examples are well known, such as at a certain location in W-Iceland where 30°C water was found at a shallow depth. The customer who runs a hotel and tourist resort installed a heat pump showing COP of around 5,5. That means in other words, an energy saving of 82%! No district heating company in Iceland can compete pricewise with that.

More examples are known, to many however to list and discuss. In some cases the objective with the drilling was to acquire cold drinking water for the relevant household or farm. Heat pump has been installed at some of those locations, resulting in the benefit of hot water and fresh drinking water at the same time.

Fig. 5.9.1.5. Small drilling package

Successful drilling of a 246 m low-temp geothermal hole in W-Iceland recently completed in just 5 days. The well yield is 1,5 l/sec of 30°C water. Note the size of the drilling package (Fig. 5.9.1.5).

5.9.1.5. Success of Geothermal Heat Pumps in Iceland – Real Data on Electricity Savings

Introduction

Although Icelandic house owners enjoy up to approx. 90% coverage by geothermal district heating the remaining 10% are still outside known geothermal fields.This is however subject to changes, new geothermal wells are successfully being drilled within the so called „cold regions“ and heat pumps installations are gaining increasing popularity.

The Scandinavian countries started taking advantage of the HP technology already some decades ago. It is estimated that today some 13% of the total house heating demand of Sweden is brought about by „low-temp“ geothermal, associated with heat pumps.

The Vík example:

In the year 2014 the local authorities in Vík, S-Iceland decided to go for a HP solution to provide the local swimming pool and school buildings with heat and hot water. The HP installation was commenced the 1st of April 2015.

For operating parameters and visual illustration, please go online and check:

www.netbiter.net
User name: alvarr
Password: Skoli.vik

The compressor is speed regulated (load sensing) and so is the well pump. Considering the HP only, the COP is fairly constant over the load range, just about 4,3 kW/kW. Taking the well pump into account the average COP has been round about 3,6 kW/kW.

This in turn, means an energy savings of 72%

It is a pleasure being able to state that on the 27th Sept 2017 the accumulated energy saving – as compared with direct electricity – did break the 2 GWh boundary line (2 million kWh). That also means the HP installation has returned its total investment cost including:

- Project evaluation, design and related work.
- Drilling, well testing & completion with pump.
- Building of the HP, installation & run-in.

The Lund example:

Another and different installation worth pointing out is the thoroughly proven and successful heat pump in Lund, Sweden. The wells were drilled in the early 80´s and the heat pump subsequently brought in use by the mid 80´s. As can be seen from the picture below, this HP installation is based on several production & injection wells. Those are located sufficiently apart to avoid too much water level drawdown at the production side. The second consideration is to allow the cold injection liquid a suitable warm-up time on its passage through the formations.

The geothermal water in Lund has extremely high TDS and it´s hard to see how a liquid of that nature could be disposed of on the Earth´s surface, unless it was treated. However, by reinjection, the geothermal properties can be fully utilized without any sacrifices to Mother Nature. Some of those geowells in Lund are located within the city limits and some are located around the farms just outside the city. Cross contamination from the high TDS geo-liquid has never been observed in the fresh water wells within the area.

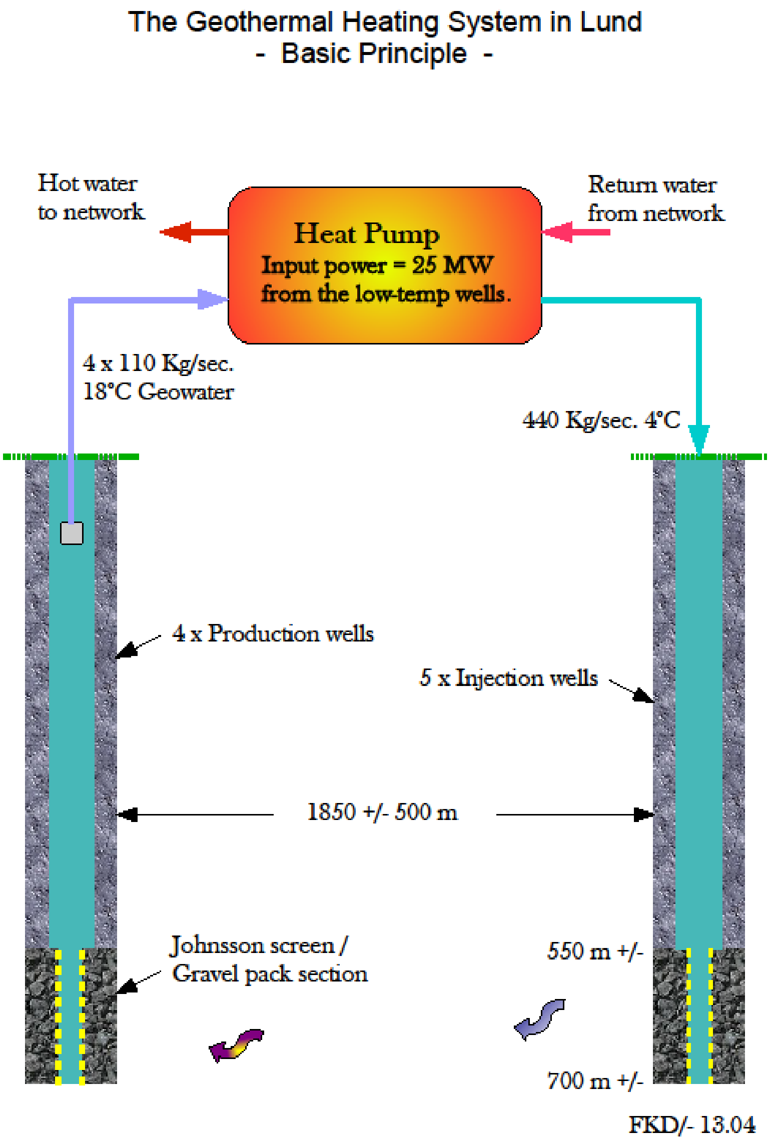


Fig. 5.9.1.5.The Lund heat pump principle

The heat pump system is based on a multiple production and injection wells. The ground as such is used as the energy source.

5.9.2. Drilling success of low-temperature wells in Iceland since the beginning

Executive Summary for chapter 5.9.2

- This report focuses on the success of Iceland in developing geothermal resources, in particular the financial mechanisms developed and drilling success. The key to success is a holistic approach where stakeholders perceive a win-win from all angles. Therefore it is quite important to consider all aspects of the process so that the development of geothermal resources successfully. OS is in the process of making a geothermal sustainability assessment protocol with the geothermal industry, which will serve this aim of mapping all aspects of the success of geothermal development. The aim of the protocol is its use will increase the overall success of projects and when a problem rises it will provide a framework to mitigate the effect.

- Good governance and communication with the public are important in addition to financial and asset viability, labour and working conditions, biodiversity and cultural heritage, to name a few factors. Aspects like geothermal resource management, and environmental and social issues often receive the most attention at the cost of other aspects. That has in some cases caused the development of geothermal resources to fail.

- Analysis of drilling success in Iceland reveals that two of every three wells drilled are successful. Productive wells last for a long time. Just for the low enthalpy wells the average age is 35 years with some wells over 50 years of age. Hence the cost of having one of every three drilled wells fail can be carried by the overall success rate and the long lasting yield. However, a mitigation fund is required, especially taking into account that the analysis reveals that the first well drilled has less than 50% chance of being successful in a greenfield. To mitigate this risk, Iceland introduced a financial mechanism in 1953 allowing the state to loan for the upfront risk but requiring those successful to pay back the loan. Overall the same mechanism has been continued until present.

- Drilling success on average in Iceland for the past 100 years is about 66%, after analysing the success of drilling 738 wells designed as production wells within 48 geothermal systems. The highest success rate is found in the high enthalpy geothermal systems where 74% of wells are successful (of 213 wells drilled in 5 fields). Success is 65% in 236 wells drilled in low enthalpy systems within 6 fields near the capital and 60% of medium enthalpy systems of 289 wells drilled in 37 systems. The first wells drilled have a lower probability of success which gradually increases with increased knowledge of the geothermal system.

- For low enthalpy systems there are in total 173 wells in 52 geothermal systems in use today by larger utilities with exclusive rights for distribution of heat within a given area. The average age of the wells is 35 years. They average 1055m in depth and are cased on average down to 223 meters. The average temperature is 88°C. This excludes statistics from close to 200 individual producers which data is of too low a quality to be included.

- Well design is important to minimize the risk of the project. OS operates a National Well Registry which is public and grants access to well logs and design. That access aids in preventing failures in the future. Using an online portal on a server, other entities can incorporate the Well Registry in their portals allowing the dissemination of information from different entities without the need to submit information between parties. Therefore it is now possible to visualize combined information on one portal from e.g. recent seismic data, wells, distribution networks for heat, water and electricity, tourist attractions, archaeological sites, planning and building drawings from various entities. Essentially whatever information one can think of and is relevant to combine on a portal and a party is willing to share. Each owner is though only responsible for his dataset and updates, so the information is updated across without any data submission.

- OS is in the process of stipulating rules for well design, registration, drilling, completion and permanent closure. In addition rules on reinjection have already been issued. This is developed with the industry and serves as a tool to mitigate risks. In addition resource indicators are incorporated within granted utilization licences. The two most important indicators are reduction of well production capacity (typically 3% on average over a period of five years) and pressure drawdown in the geothermal system. If either of those indicators surpasses levels stipulated in the license, a protocol is initiated to further understand and analyse appropriate actions to withhold a sustainable yield for generations to come.

5.9.2.1. Best practices and success in Iceland in drilling and explanation – recommendations for Poland

A sustainable approach to developing geothermal resources requires an overall strategic approach on various aspects beside those indicators related to the resource itself or drilling. OS is in the process of developing a Geothermal Sustainability Assessment Protocol (GSAP) with the industry in Iceland, applicable to both low and high temperature resources. The protocol takes on all aspects related to sustainable development and serves as a guide for best practices. The protocol is tailored for four stages, namely early stage, preparation, implementation and operation as illustrated in Figure 5.9.2.1 and addresses on a world scale what factors are important in developing geothermal resources. It uses the Hydropower Sustainability Assessment Protocol (HSAP) which is currently in use by the hydropower industry as a base for assessment and amends those topics as needed.

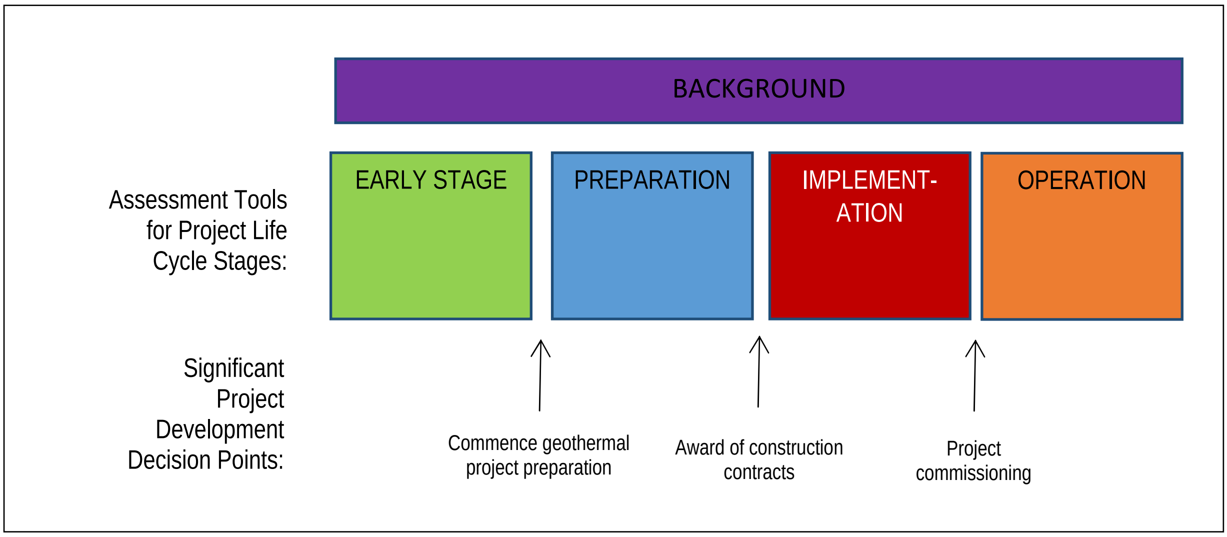


Fig. 5.9.2.1. Protocol Assessment Tools and Major Decision Points

The protocol is divided into topics with the following 17 subjects:

1. Communications and Consultation
2. Governance
3. Environmental and Social Issues Management
4. Geothermal Resource Management
5. Asset Reliability and Efficiency
6. Public Health and Safety
7. Financial Viability
8. Communications & Consultation
9. Community Benefits
10. Project-Affected Communities & Livelihoods
11. Resettlement
12. Indigenous Peoples
13. Labour & Working Conditions
14. Cultural Heritage
15. Biodiversity and Invasive Species
16. Induced Seismicity and Subsidence
17. Air and Water Quality

Fig.5.9.2.2. Sustainable development requires a focus given to economic factors as well as social and environmental with an overall balance (Ketilsson et al., 2011).

For low temperature district heating most of these topics are less relevant. However, when assessing the overall effect of a project it can be recommended to go through the topics and pick out those relevant and then look further into each as to what important indicators and best practices have been developed so as to make sure that no effect is left out. Issues for discussion in this chapter focus more on particular aspects such as resource management, induced seismicity, well registry and drilling success. To begin with the development of geothermal resources is reviewed to give an overall picture of development.

5.9.2.2. Introduction to Geothermal Resources in Iceland

Geothermal resources have a minor share in the worldwide generation of electricity but they have become of major importance in many volcanic regions. Leading countries in this development have been Italy, USA, New Zealand, Mexico, the Philippines, Indonesia, Iceland and Japan. In Africa, Kenya is the leading country but no development has occurred in S-America despite its large potential.

The initial build-up of capacity worldwide was slow but accelerated in the seventies due to rising prices of oil. In the last 25 years the capacity has increased on average by 250 MW per year. Compared to solar energy and wind power the development has been slow, despite considerable support from funds, public institutions and academic research. Science, technology and finance have not always succeeded in outlining to possible investors the barriers and risks involved, and how they can be mitigated.

The successful development of geothermal electricity generation in Iceland has raised interest. A country with 320 thousand inhabitants had in the year 2017 installed a capacity of 663 MW in geothermal power plants. This occurs in a country with a large potential in hydropower. Generally the risk in hydropower projects is considered less than in geothermal projects but the geothermal plants have the competitive advantage of serving a base load with full availability throughout the year. Power plants in Iceland have a total capacity of 2,725 MW, generating in total 18.55 TWh in year 2017. The share of hydropower is 73% and that of geothermal 27% in electricity generation. Oil is only used for electricity generation in emergency cases.

Iceland has an area of 103,000 km^2. Two thirds of the population live in the capital area in the SW-part. Other inhabitants are settled in a number of villages, mostly around the coast, and in rural areas. Electrification has been developed over the last century. The country has many rivers draining water from the mountainous inland and glaciers which provide a large capacity for hydropower generation. The electrification was initially in the hands of communities which erected small hydropower plants to serve their inhabitants but the networks were not interconnected.

Geothermal district heating started on a small scale in Reykjavík in 1930 and today Reykjavík Energy operates the largest municipal district heating system. The system serves about 195,000 people in the capital area with hot water. From 1998 electricity has been co-generated from geothermal steam along with hot water at Nesjavellir. However, about 70% of the energy used for district heating comes directly from low temperature geothermal fields, and about 30% from heating up cold water in CHP plants using geothermal energy as the primary energy source.

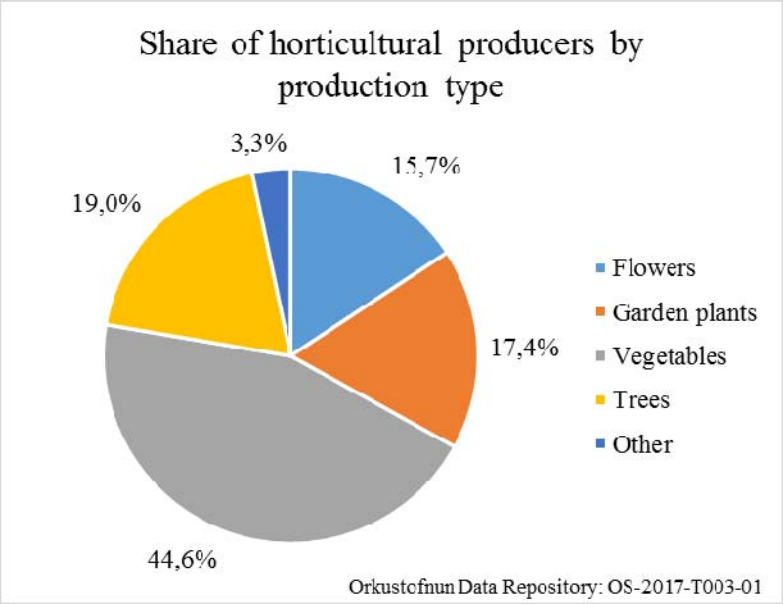


Fig. 5.9.2.3. Greenhouses are one of few uses of geothermal resources. This enables Iceland to grow domestic vegetables, fruits and flowers which otherwise would be impossible.

A major change occurred in 1965 when the State and the capital Reykjavik established Landsvirkjun (the National Power Company) with the aim of building larger power plants and interconnecting the countrywide electrical networks. The company built a hydropower plant of 210 MW to provide electricity for an aluminium smelter in 1969, with financial support from the World Bank. Landsvirkjun has continued developing hydropower and geothermal power to serve energy intensive industries. The installed capacity in hydropower in Iceland is now 1,895 MW. The company also operates geothermal power plants, which a combined capacity of 111 MW.

Other major power companies are Reykjavik Energy with 423 MW_e installed in two geothermal power plants and HS Orka operating two geothermal power plants of a combined 176 MW electric capacity. Three of the geothermal plants combine generation of electricity and production of hot water for space heating. Smaller companies operate hydropower plants with a total capacity of about 80 MW.

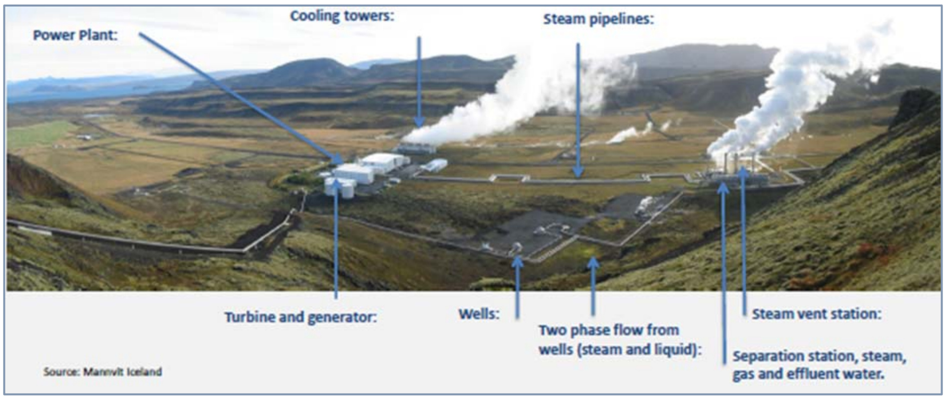


Fig.5.9.1.4. The Nesjavellir Geothermal Power Plant in Iceland.120 MW_e and 300 MW_{th} for Space Heating

The state and municipalities own 93% of the installed capacity and 7% are in the hands of the private sector. The electricity market is dominated by a few energy intensive industry companies which buy 77% of the production. The risk of having few customers is balanced by power purchase agreements (PPA) which ensure the steady use of energy and sales over decades. This leads to high utilisation factors in the power plants, about 75% in the hydro power and 90% in the geothermal plants. Long term contracts with trustworthy companies have also eased financing of the power projects.

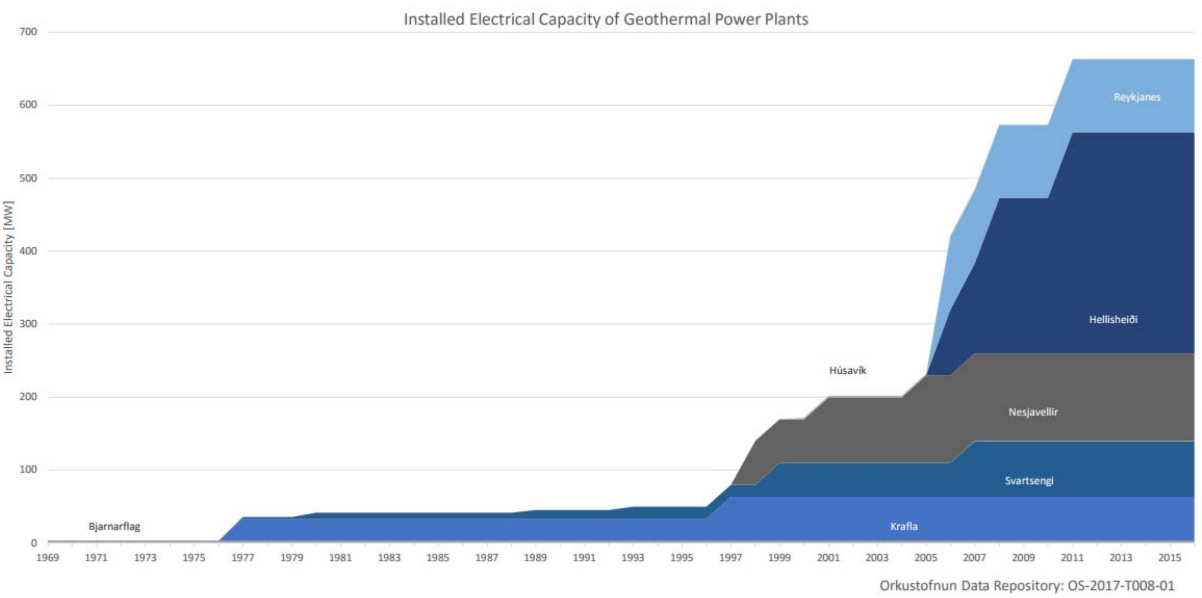


Fig. 5.9.2.5. Installed electrical capacity of geothermal power plants in Iceland until 2016

5.9.2.3. Drilling for Geothermal Water and Steam

First attempts to drill wells in geothermal areas in Iceland began as early as in the year 1755 when exploration wells were drilled in search for sulphur near the Laugarnes hot springs in Reykjavík and in the high temperature field Krýsuvík on the Reykjanes Peninsula. In Krýsuvík the hole reached 10 m depth and erupted a mixture of steam and clay. Drilling with percussion rigs for potable water in Reykjavik shortly after 1900 was not successful but rumors that the boreholes had encountered traces of gold led to the purchase of a new percussion drilling rig which was nicknamed the “gold drilling rig”.

The Reykjavik Electricity Service became interested in drilling as they learned of successful drilling for steam in Lardarello in Italy to generate electricity. They bought the “gold drilling rig” and used it to drill 14 wells in the hot spring area of Laugarnes in Reykjavík 1928–30. The deepest well was 246 meters. No steam was found but the wells yielded significantly greater artesian flow of hot water than the hot springs prior to drilling. This success led to the first step in geothermal heating of houses in Reykjavik in 1930.

Until 1986 nearly all drill rigs were operated by the State Drilling Company. The emphasis was on discovering hot water for space heating all over the country. The wells were located near hot springs and also in regions where exploratory surveys and drilling indicated a high geothermal gradient. Some drilling also took place in the high temperature fields. Exploratory wells were drilled in Reykjanes to provide hot brine for a sea chemicals factory.

Drilling for cogeneration of hot water and electricity took place at Svartsengi and Nesjavellir and wells were drilled in Krafla to provide steam for the generation of electricity. There the drilling ran into difficulties because volcanic activity caused an influx of corrosive gases into the geothermal reservoir. The drilling company was privatized in 1986 and now operates as Iceland Drilling Ltd but several other smaller drilling companies have also been established.

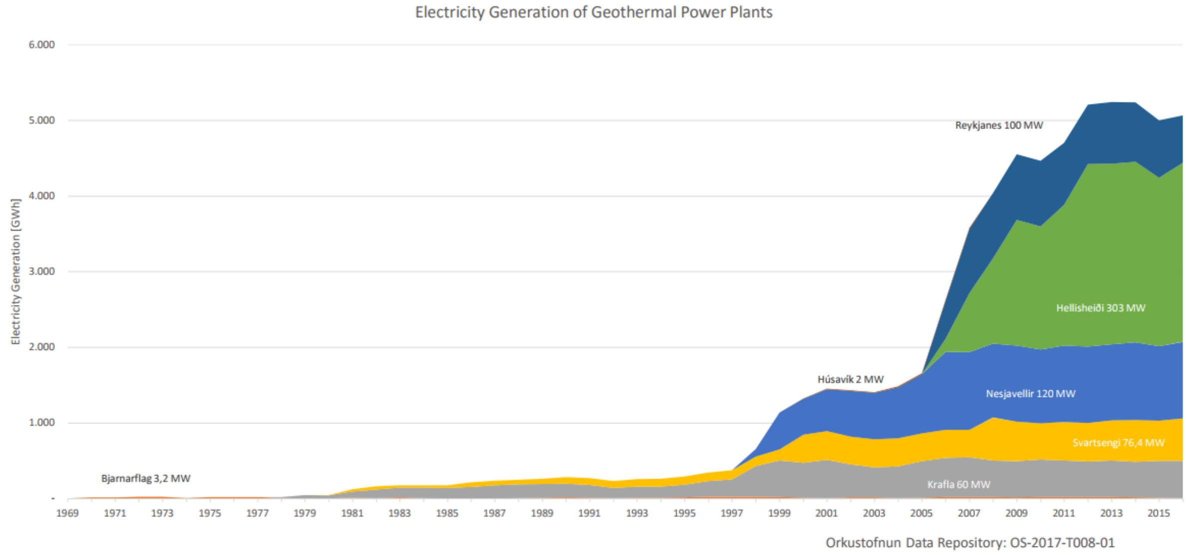


Fig. 5.9.2.6.Generation of Electricity using Geothermal Energy 1969-2016.

These smaller firms have overtaken most of the drilling in hot spring areas whereas Iceland Drilling Ltd has emphasized drilling boreholes in the high temperature fields. Among recent innovations in drilling technology are downhole hydraulic turbines that are driven by the circulation fluid and can rotate the drill bit much faster than the rotating string.

This technique yields a faster penetration rate and also allows for inclined directional drilling to intersect targets off the drilling platform. A cluster of wells can thus be drilled to different directions from the same drilling platform. Another novelty used in shallow holes is pneumatic hammers implanted with carbide balls that hammer the whole bottom several thousand times per minute and give a penetration rate of 10–30 m/hour.

The first geothermal unit for electricity was a 3 MW back pressure turbine installed in Bjarnarflag in 1969. The Krafla plant (2x30 MW) was constructed in 1975-1977 but volcanic activity injected reactive gases into the reservoir and made the best part of it unexploitable for the next 15 years. The first unit began operating in 1977 but the second unit was not installed until 1997. The project was financed by the State with the purpose of providing electricity for the northern part of Iceland.

These difficulties were discouraging for further construction of geothermal power plants while there was more feasible potential available in hydro power. HS Orka installed several small units at Svartsengi for cogeneration with the production of hot water for space heating. This escalated with a 30 MW_e unit installed in 1999 and another in 2007, bringing the total electrical capacity up to 76,4 MW_e. Reykjavik Energy also began cogeneration with hot water production at Nesjavellir with 2x30 MW_e units installed in 1998, and two more 30 MW_e units in 2001 and 2005.

Until 2003 only Landsvirkjun could sell electricity to the energy intensive industry but this changed with the new Electricity Act in 2003 which opened the door for competition between Icelandic energy companies serving that industry. Increased demand from the aluminum industry led HS Orka to build a 100 MW geothermal plant at Reykjanes in 2006 and Reykjavik Energy to build the Hellisheidi plant of 303 MW between 2006 and 2011. Without this increased demand from the aluminium industry the development of geothermal power plants in Iceland would have been much slower as the domestic market did not call for more than a minor increase in generation. Nowhere else do aluminium smelters rely as much on geothermal plants for electricity as in Iceland.

More than 300 wells have been drilled in high temperature fields for production. Of those 208 are deeper than 500 m, 36 reach more than 2.000 m and six beyond 3.000 m. In low temperature fields about 860 production wells have been drilled, thereof 291 are deeper than 500 m, 19 reach more than 2.000 m and one beyond 3.000 m. Wells drilled in search of high temperature gradient are more than 2.600. Most of them are shallower than 100 m but some exceed 1.000 m in depth. These wells are rarely intended for production. Steam field drilling for generation of electricity has dominated in the last decade.

5.9.2.4. Success of Geothermal Wells in Iceland

OS has conducted research on registered wells in Iceland. The work has been concluded on high and medium enthalpy wells but is still ongoing for low enthalpy wells. The results are reviewed here for each category by itself. However, overall it does indicate the expected success of drilling and in particular how the success rate increases with each well drilled in the same area.

Success of High Enthalpy Geothermal Wells in Iceland

For high enthalpy wells(T>200°C) 213 wells were analysed in five geothermal systems where a geothermal power plant is in operation, 158 or 74% were deemed to be successful. None of the fields analysed have a success rate below 50%. About 6% of the total wells failed because of drilling problems, 4% found inadequate temperatures, 10% could not be operated at high enough static pressure, 3% had too low permeability and 3% were so shallow that they did not reach the reservoir.

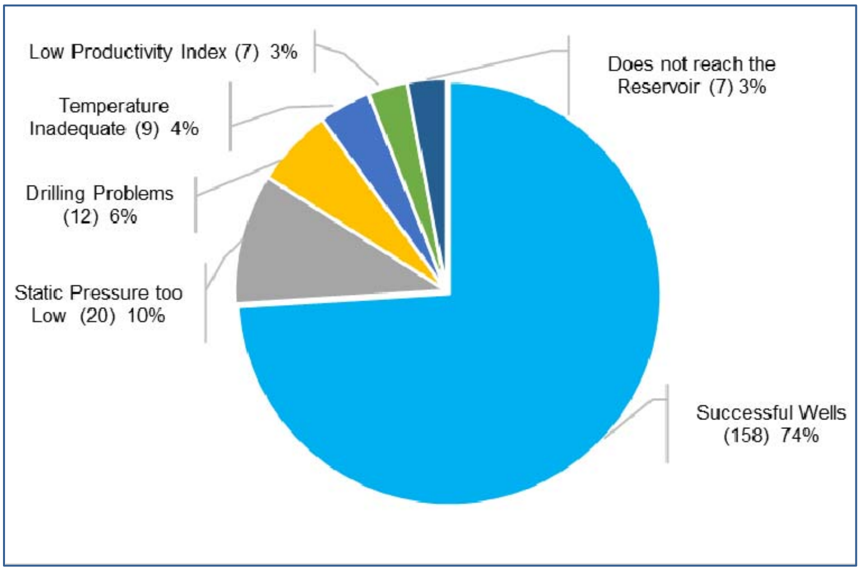


Fig. 5.9.2.7. Success Rate and Problems of high enthalpy wells

The average success rate improves from 43% for the first well to 60% for the first five wells and reaches a plateau of 74% after the fifteenth well. The first five wells drilled in a field are classified as Exploration Phase, the next 25 as Development Phase and wells drilled thereafter as Operation Phase. The Exploration Phase has the most variable well success rates, which has though improved in recent decades. The probability of successful wells in the Development Phase is nearly 80%. It increases until the year 2000 but declines after that. The same trend is observed for wells drilled during the Operation Phase. The reduction in the success rate may reflect step-out wells or rapid development where adequate results did not arrive in time to impact the drilling plan. The average capacity of all 213 drilled production wells is 4.9 MWe but 6.7 MWe for the 158 productive wells. The capacity has a lognormal distribution with a mean and most likely value of 4.8 MWe and a standard deviation of 2.3 MWe. The cumulative average capacity increases from 2.5 to 4.8 MWe during the Development Phase, and reaches 4.9 MWe during the Operation Phase.The five main operating geothermal power plants in Iceland have a ratio of installed capacity divided by number of drilled production wells ranging from 1.3 to 5.3 MWe/well and a weighted average of 3.5 MWe/well. Wells of 2,000–2,500 m drilled depth have the highest average capacity of 5.8 MWe followed by wells of 1,500-2,000 m with an average capacity of 5.5 MWe. Wells with a regular production casing diameter of 200–250 mm have an average capacity of 5.5 MWe whereas wells with a large casing diameter of 300–350 mm have a capacity of 8.9 MWe. The average capacity of directionally drilled wells is 6.1 MW_e compared to 4.0 MW_e in vertical wells. There is a clear increase in capacity with increased enthalpy. Wells drilled into steam caps above two-phase reservoirs at 230–240°C have the highest capacity of 11.0 MW_e and a 100% success rate. Wells in two phase reservoirs with T>300°C, are with an average of 6.2 MW_e and 86% success rate.

Success of Medium Enthalpy Geothermal Wells in Iceland

For medium enthalpy wells (100°C<T<200°C) 655 wells drilled between 1928 and 2014 were analysed. The wells are in 37 geothermal systems. The production wells were 289, ranging from 10-3,085 m in drilled depth, average 650 m. About 60% of them were productive after drilling, and 62% of those are still in use. Data on yield are available from 132 productive wells and 54 not productive wells. The average yield for these 186 wells is 12.1 l/s. Of the total, 193 wells, that found temperature above 90°C, were subjected to further analysis from the viewpoint of medium enthalpy utilization. They range between 52-3,085 m in depth, average 861 m. In this group 77% were productive after drilling, 70% of those are still in use. The average yield of 132 productive and the 44 not productive wells is 13 l/s. About 89% of the main feeders are in the uppermost 1,000 meters, with a broad range in flow values, within 62 l/s except for 2 wells; of 100 l/s and 110 l/s. Feeders below 1,000 meters give a more limited flow, generally below 20 l/s. At those depths only three wells have a flow above 18 l/s. Wells with a discharge temperature above 80°C are considered successful for space heating. Successful wells in the aspects are 132 out of 193 or 68%. Wells with a discharge temperature above 95°C are considered successful for electric production. Successful wells are 109 out of 193 or 56.5%. The analysis indicates that the 37 medium enthalpy systems have an aggregate thermal potential above 35°C of 935 MWth or an electric potential of 44 MWe, using an organic Rankine cycle, yielding aggregate 494 MWth of remaining thermal potential of 80°C effluent water for cascaded direct use. The ten largest systems have a range of 37 to 132 MWth and 1.0 to 7.4 MWe.

Success of Low Enthalpy Geothermal Wells in Iceland

The number of geothermal systems in this category is by far the largest. To begin this analysis focus has been put on geothermal systems producing geothermal heat for utilities with a natural monopoly license. In total OS has analysed 52 geothermal systems of this type. Production wells in use are 173 and in addition 9 springs. Injection wells are 5. The average age of the wells is 35 years. They are on average 1055m deep and cased down to 223 meters. The average temperature is 88°C. The success of drilling varies more for low enthalpy wells in comparison to high and medium enthalpy wells. The national average of a success rate is yet to be estimated. As a first milestone geothermal systems within the capital region have been analysed. In total 236 wells have been drilled in the greater capital region including 14 at Seltjarnarnes, 47 at Laugarnes, 45 at Elliðaár, 4 at Digranes, 81 at Reykir and 56 wells at Reykjahlíð. In total 154 wells have been productive or 65% of the 236 wells drilled in total. Beside the heat utilities with exclusive rights there are over 200 registered operations many of which received funding from the state in the past and heat up swimming pools, greenhouses, fish farms, public buildings and farms across the country. This statistical analysis excludes information from those areas due to the lack of reliable and up to date information. However the well registry does include information on many of those wells design, just not their current status.

Table 5.9.2.1. Overview of success rates for three types of geothermal systems based on enthalpy. On average the success rate is 66% in Iceland within 48 geothermal systems analysed.

Classification of a geothermal system	Success Rate
High enthalpy wells (213 production wells in 5 geothermal systems)	74%
Medium enthalpy wells 289 production wells in 37 geothermal systems)	60%
Low enthalpy wells (236 production wells near the capital in 6 geothermal systems)	65%
Average (738 production wells drilled in 48 geothermal systems)	66%

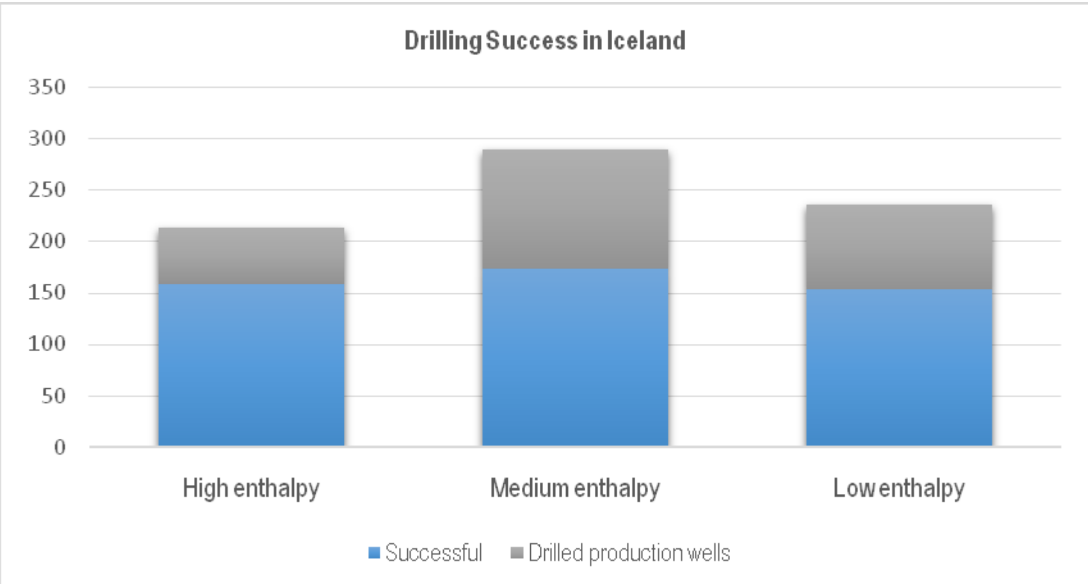


Fig. 5.9.2.8. Drilling success in Iceland in 48 geothermal systems after analysing 738 wells designed to be production wells. Highest success rate is 74% for high enthalpy wells, then low enthalpy with 65% and finally medium enthalpy with 60% of the wells successful. Overall this reveals that about two of every three wells drilled are successful on average in Iceland. Further analysis has been made as to at what depth the feed zones have the highest probability of giving economical yield.

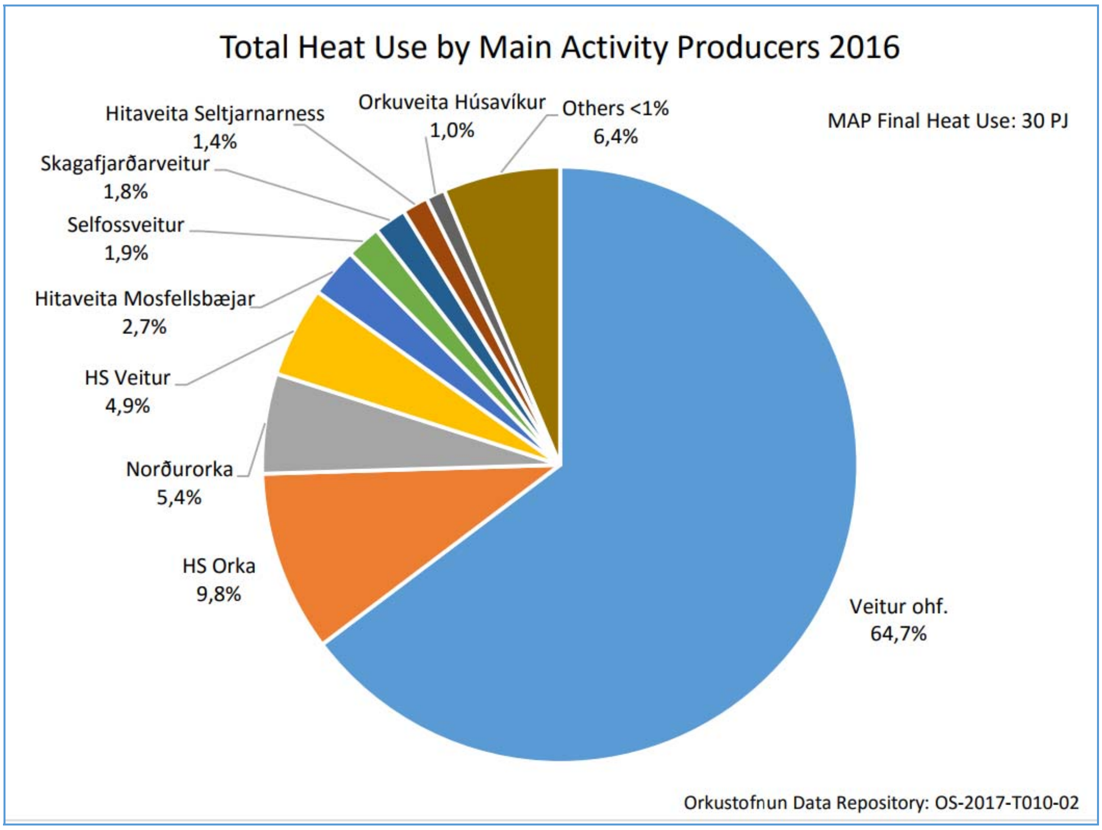


Fig. 5.9.2.9. Total heat use by heat utility in Iceland in year 2016. In addition close to 200 auto-producers use geothermal directly for local uses

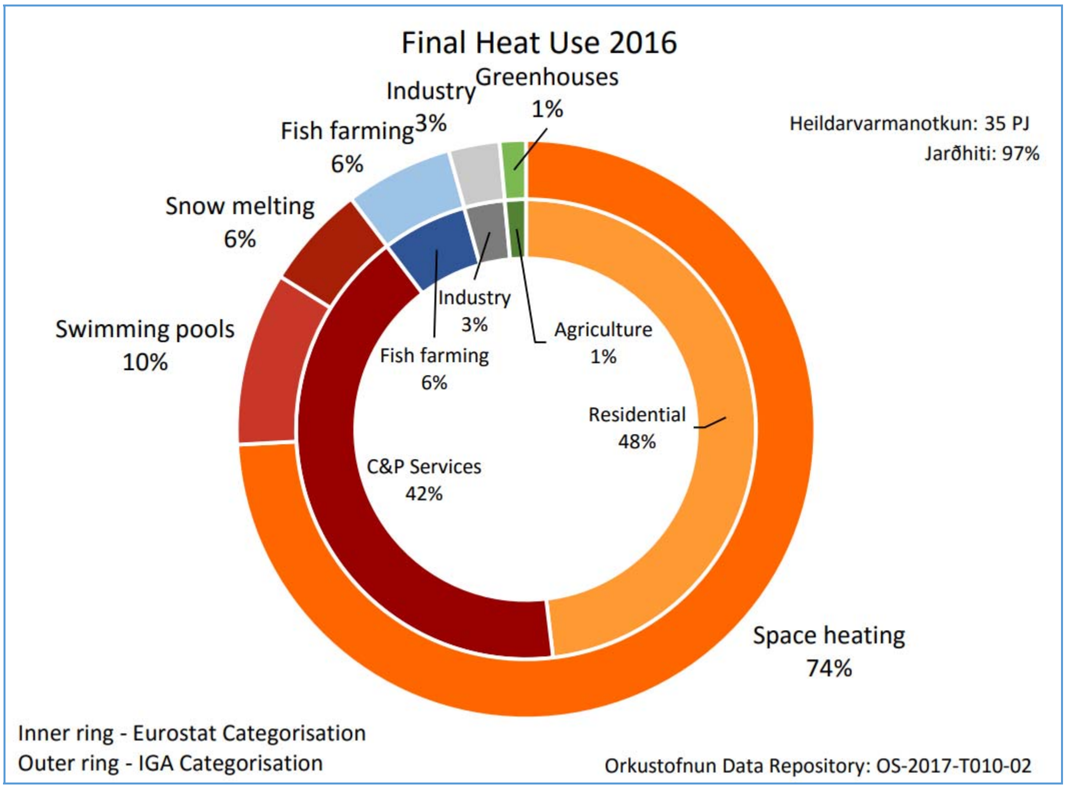


Fig. 5.9.2.10. Total final heat use 2016 in Iceland. Space heating is by far the most common use

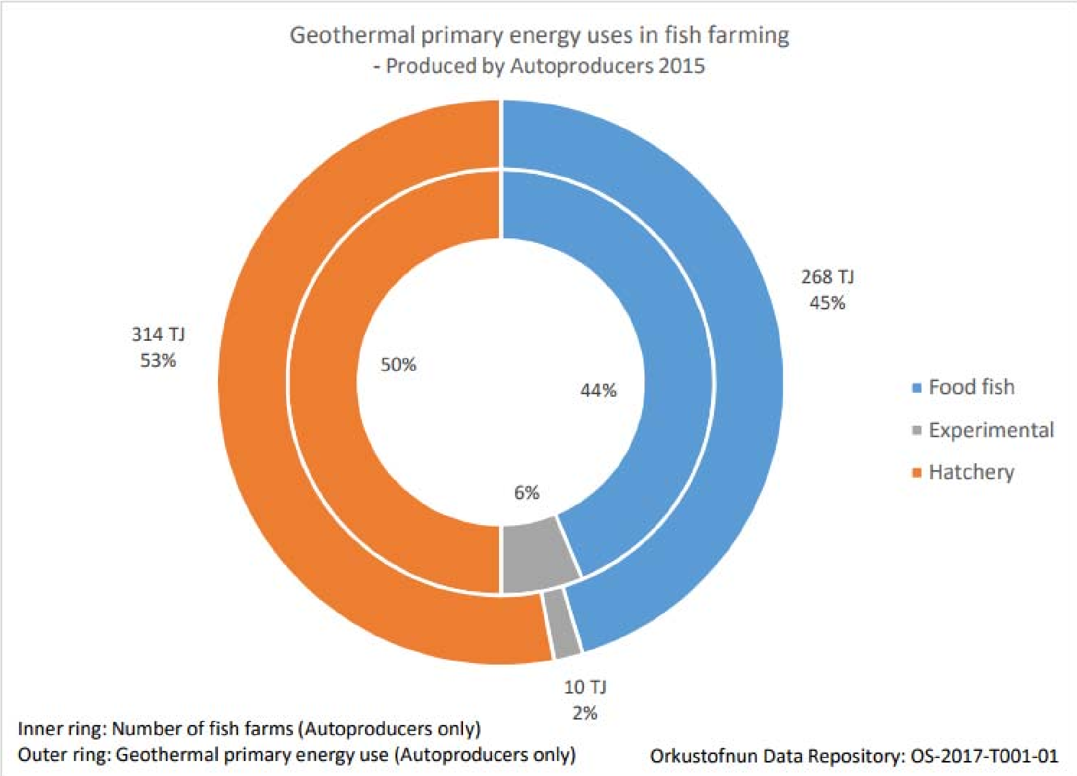


Fig. 5.9.2.11.In fish farming geothermal water is important to regulate the temperature. In the heat forecast until 2050 fish farming is estimated to increase the most of the various uses of geothermal water beside space heating with the gradual population increase

5.9.2.5. Best practices in drilling and rules for good well designs

There are various aspects to take into account when designing and constructing a well. An obvious but important feature is the anticipated role of the well. If there are plans for extraction of water (hot or cold), issues like temperature, pH, salinity, oxygen concentration and other physical and chemical characteristics play an important role in determining which technology and equipment are needed for the job. Apart from those features, external factors also have to be reflected upon. In that aspect, subsurface strata, groundwater level and the characteristics of the groundwater play an important role in the successful construction and usage of the well.

It is also highly important that the ownership and responsibility of the well is accurately defined and registered, especially when approaching the end-of-life of a well or after usage is terminated. An ill-maintained or neglected well can lead to harmful consequences for the natural resources it harnesses, other subsurface natural phenomena (e.g. groundwater quality, strata stability), as well as the environment on and above the ground. Furthermore, deterioration of well head and related instruments and piping can be dangerous for people and animals around. When the well is no longer in use, it has to be closed and decommissioned in such a manner that it does not pose any harm in the future.

Well defined and registered responsibility of a well is an essential factor for the relevant authorities in order to regulate the usage and maintenance of the well, as well as the safe decommission of the well after use. It is also important to document the location of such wells as future planning and construction projects in the area can be affected by the structure.

In order to assess these issues, OS has prepared a set of criteria on design, drilling and completion of wells, and on data submission for wells. Such criteria can be put forward in a set of administrative rules, or regulation(s). However, in Iceland, they have evolved via co-operation and collaboration between OS, energy companies, drill contractors and other relevant entities. It is under consideration to formalize them in a set of rules in order to ensure stability in data handling, consistency in requirements and safety for the future utilization of subsurface natural resources and environmental protection.

OS manages and runs a special directory on all wells in Iceland. The National Well Directory is accessible on a website (www.map.is/os) showing where wells have been drilled. For each well basic information is given on total depth, casing depth, purpose, type, year of drilling as well as whether or not the well log is stored at OS and can publicly be accessed.

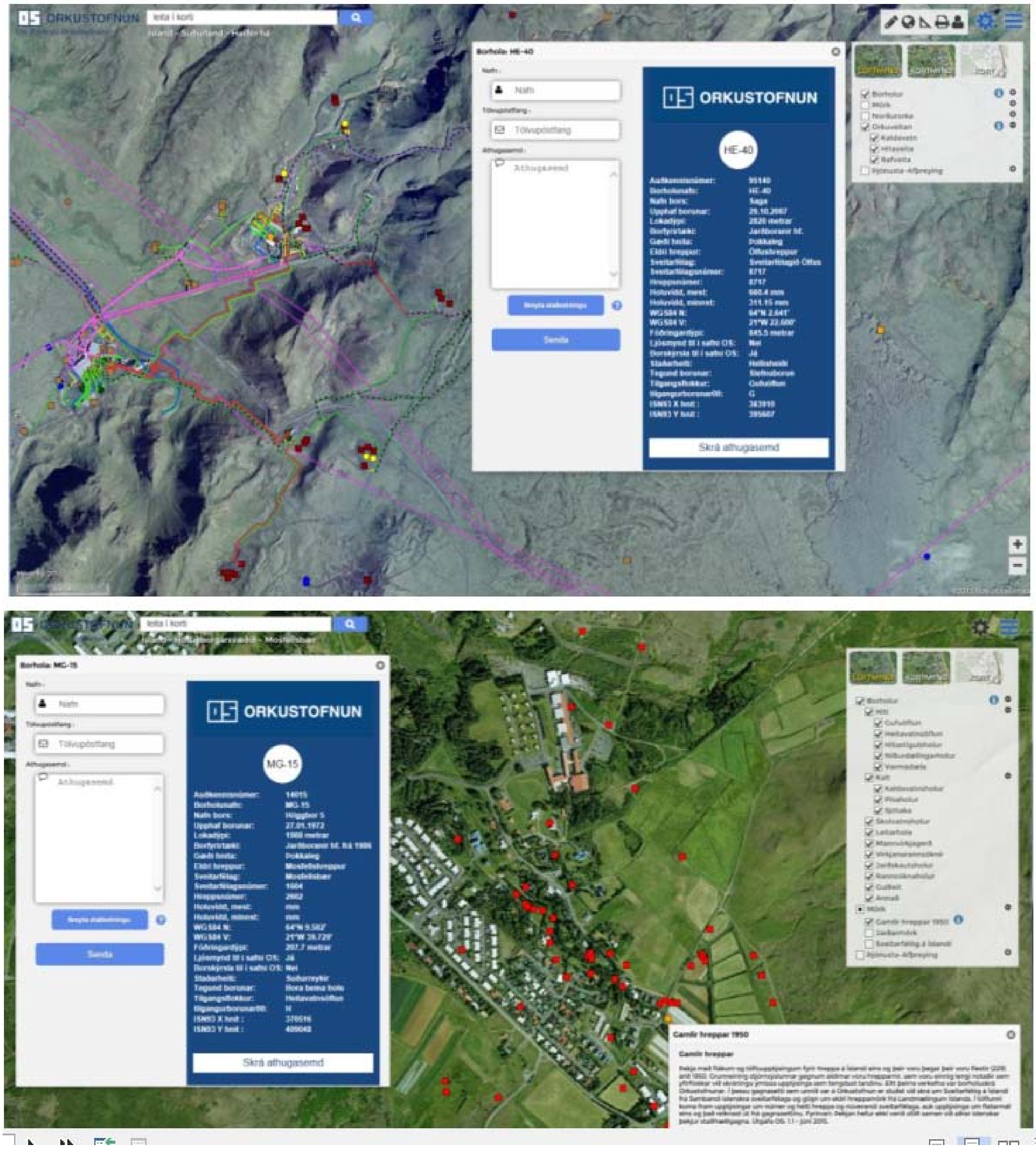


Fig. 5.9.2.12. Well registry in Iceland showing location and further information on registered wells

The portal is able to show in addition to information from OS, spatial datasets from other users like the utility companies, other public institutions and private entities. Each contributor stores the information on their own server and can therefore update it locally but also see the status of the dataset from other users. This is quite convenient and allows data sharing without requiring accumulation of data across institutions and utilities. This allows the public not only to see wells registered at OS well registry but also the distribution network of the district heating utility company in addition to various other information.

5.9.2.6. Main factors for criteria on well drilling

Well registration

Prior to drilling, a notification of a planned ground drilling and other major related construction work has to be submitted to OS. The notification shall include detailed information on the well, its intended use, and on the entity responsible for the drilling (company or person, e.g. landowner).

Upon receipt of notifications, OS allocates a fixed identification number and registers the well in the National Well Registry.

Well drilling

Well drilling is subject to environmental licences issued by the local health inspectorate in order to minimize pollution and to ensure safe and sound drilling procedures. Drilling contractors shall ensure that the drilling does not cause harm to humans, livestock or other animals. The well shall be drilled so as to minimize the potential effect on other subsequent utilization.

During drilling, the contractor is required to list his activities in a logbook, and if the OS so requires, to collect and preserve samples of cuttings or cores from the well. No later than one month after the end of drilling, the drilling contractor shall send the OS a preliminary summary of the drilling operations.

Well completion

At the end of the drilling process, the wellhead must be secured in a safe manner and marked prominently, so that there is no danger or significant discomfort for traffic. The surrounding environment should furthermore be left in such a state that the risk of accident to people and animals can be minimized, such as protection against fall into the borehole cellar.

Permanent closure of wells

When wells are no longer in use, the well and wellhead should be in a satisfactory state in order to ensure that is sealed and definitively closed. If the casing or other equipment is left in the borehole, the position of the well must be marked permanently to ensure safety to by-passers.

The permanent closure and decommissioning of a well should be reported to OS, and the notification shall indicate how the well was sealed, whether the casing or other equipment has been left behind and how the wellhead and surrounding surface was marked, together with markings if applicable.

5.9.2.7. Resource Management

At the operation stage the capacity of the resource needs to be continually evaluated scientifically and technically on the basis of chemical, geological and geophysical monitoring as well as testing of wells. For the project to be within the limits of sustainable yield, the production needs to be within the limits that can sustain the long-term steady energy production from the system. Re-injection of geothermal fluid into the geothermal reservoir can support long-term utilization. Models for re-assessment of the production capacity are maintained on the basis of continuous data obtained during operation. Operation of the geothermal resource may be conditioned by regulatory requirements.

If the operating geothermal facility is reliant on geothermal resources that can have an effect beyond the jurisdictional boundaries in which the facility is located, the implications of this would need to be fully considered. Technical considerations for generation operations examples include: geothermal reservoir characteristics; turbine type, number and characteristics, safety issues, adherence to acceptable limitations to pressure drawdown and cooling in the geothermal reservoir, monitoring for changes in physical characteristics and updating of reservoir assessment models, maintenance of wells and make-up well requirements, re-injection of geothermal fluid if applicable, location of make-up wells and maintenance and adoption of steam or water supply system to name a few.

Energy system opportunities and constraints examples include: patterns of demand for energy (e.g. base vs peak load), energy prices, other generators and their capacities and constraints, transmission issues, etc. It is important to fully optimise and maximise efficiency of the geothermal resource, i. e. to maximize the utilization of the available geothermal energy given the opportunities and constraints relating to scientific, technical, social, economic, environmental, financial considerations are based on an iterative and consultative process. Efficiency can be directly related to the technical installations, e.g. efficiency of geothermal supply system and turbines. Efficiency can be estimated by an assessment of the exergy efficiency and primary energy efficiency. Multiple use and/or cascaded use and re-injection into the reservoir affects this assessment.

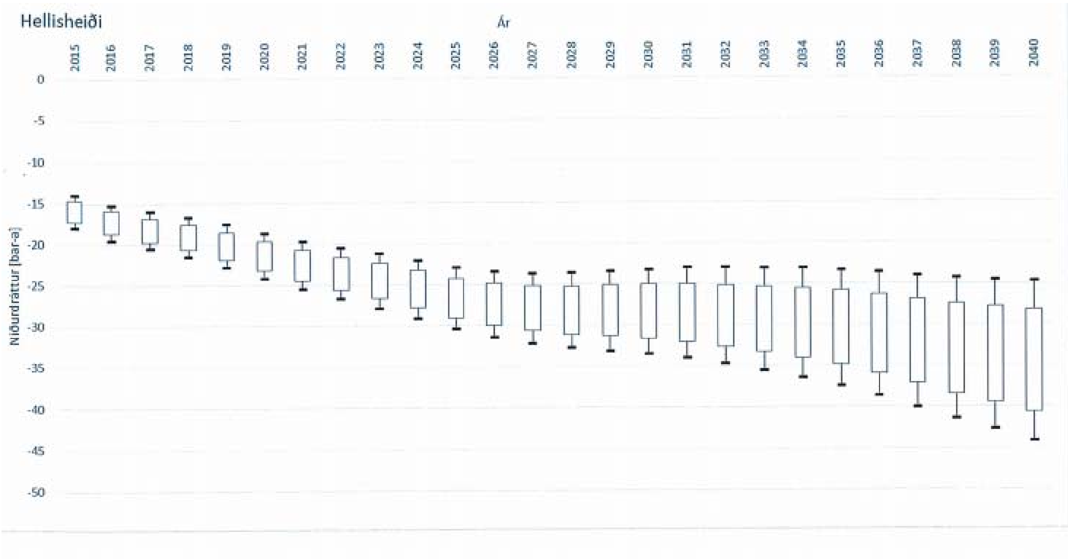


Fig. 5.9.2.13. Pressure changes allowed according to the utilization license of Hellisheiði Geothermal Power Plant which is the largest plant in Iceland. If drawdown exceeds estimates a protocol is initiated to firstly recalibrate and reassess based on an updated numerical model. In addition to drawdown well production decline measurements are taken and if they are above 3% per year on average over a five year period it is considered a warning sign that needs to be analysed.

Rules for reinjection

OS in collaboration with stakeholders published rules regarding preparedness and reactions to seismic hazards due to fluid injection into the ground via wells. These rules could be reviewed in Poland as far as they are relevant. The objective of these rules is to minimize the danger of bodily harm, damage to man-made structures and inconveniences due to earthquakes related to the injection of fluids into the ground via boreholes. The rules are also intended to restrict and explain the duties, roles and involvement of licence holders, OS and other parties in each situation and promote the right focus on the preparation and execution of the injection.

Geothermal areas can in some cases be geologically active and such areas are likely to experience many types of seismic activity. Fluid withdrawal and fluid injection into the ground accompanying geothermal utilization cause changes of the stress field in the earth's crust in production and injection areas. Research on fluid injection into the ground in geothermal areas has shown that in active geothermal areas in Iceland it may stimulate some microearthquake activity. On the one hand there are microearthquakes as a response to this change in the stress, but on the other hand it may bring forward earthquakes that would inevitably take place later. The most common reason is a change in injection rate, e.g. if injection is for some reason temporarily stopped, the probability of microearthquake activity is increased. In general these earthquakes are not felt at the surface but in specific cases there is a considerable probability that increased fluid pressure due to release has triggered larger earthquakes.

The injection of geothermal fluids into the ground is an important part of the utilization of geothermal energy, on one hand to dispose of fluids, but on the other to counteract pressure decline in geothermal systems. In some cases injection is mandatory in accordance with a utilization licence and/or an operation licence according to Act No. 7/1998 on hygiene and pollution control, and is practiced from the start of operations. In other cases it has been initiated after some time of operation. Geothermal energy is however widely harnessed without injection into the ground.

The effects of earthquakes in relation to injection are twofold, on the one hand a risk of damage to man-made structures and bodily harm, but on the other hand inconvenience due to repeated microearthquakes. When preparing for injection the operators may consult standards concerning the subject with reference to effects and consequences of earthquakes for the environment. Building codes stipulate the acceleration buildings are expected to stand with reference to areas and the use of the buildings and the recurrence time of that acceleration. Regarding inconvenience due to microearthquakes no set of guidelines exists in Iceland but a standard dealing with the design of man-made structures with reference to the effect of vibrations, ISO No. 10137/2007, may be consulted to analyse and estimate their effects.

The extent of fluid injection into the ground connected with the utilization of geothermal energy is steadily increasing. With reference to the risks described here OS has issued rules on the preparation and execution of fluid injection into the ground via boreholes (No. OS-2016-R01-01). The objective of the rules is to minimize the risk of bodily harm, damage to man made structures and inconvenience due to earthquakes in connection with fluid injection to the ground via boreholes. Furthermore they are intended to restrict and explain duties, roles and involvement of the licence holder, OS and other parties as applicable in each instance, and to promote the proper emphasis during the preparation and execution of the injection.

The objective of setting forth the rules is twofold. The chief objective is to provide information to applicants for production licences according to the Electricity Act No. 65/2003 and utilization licences according to Act No. 57/1998 on exploration for and utilization of ground resources (The Resources Act), due to power production or other utilization of geothermal energy, regarding the requirements considered upon the publication and revision of these licences with reference to the provisos of Item 7, Article18 of the Resources Act and Item 4, Para 1, Article 6 of the Electricity Act. By publishing the rule's the material that Orkustofnun considers the optimum codes of practice, and holders of current utilization and production licences and other holders of rights regarding the utilization of geothermal energy are encouraged to keep them in mind when preparing or executing fluid injection to the ground via boreholes.

The present guide is intended for explanation of the topics of specific paragraphs in the rules and to facilitate the preparation and execution of fluid injection into the earth for the licence holders, including the topics and execution of a preliminary assessment, a research plan, monitoring, supervision and a contingency plan. Furthermore there are examples in the guide of items that holders of geothermal utilization licences may keep in mind during preparation and execution of fluid injection into the ground via boreholes.

References to specific articles in the guide is a reference to the relevant items in the rules regarding preparedness and reactions to seismic hazards due to fluid injection into the ground via boreholes.

There are four sections in the rules to assess the risks and suggest mitigation measures. Firstly a preliminary assessment that serves the purpose of assessing the overall risk. Then if needed a research plan should be presented after which supervision and monitoring occurs having a contingency plan in place regarding the risk of earthquakes and how to react.

5.9.2.9. Conclusions

From the above overview for the Iceland there are some recommendations we can make:

- Good governance and communication with the public are important to ensure the success of geothermal projects.
- It is important that the regulatory framework supports the sustainable utilisation of geothermal resources.
- It is important that there is an overview of the wells that have been drilled in the country, such as the National Well registry in Iceland.
- There should be a comprehensive regulatory framework to ensure the safe drilling, operation and decommissioning of wells.
- The key aspect of this framework would be to determine the owner of a well who is responsible for it being safe and does not harm the environment or people.
- It is important that drilling activities are subjected to rigorous standards in order to ensure the minimum impact on the environment, that the staff is safe and that the well does not pose harm to its environment.
- Information about wells should ideally be public, and accessible to everyone who is interested via a web tool, such as the Orkustofnun map portal. In addition, the possibility of combing information on wells, with other datasets such as infrastructure which can be informative.
- Analysis of the success of drilled wells is a helpful tool to see how successful the drilling has been, if it has changed over time and if there are improvements to be made.
- In Iceland it became necessary to make rules regarding the reinjection of geothermal fluids, due to induced earthquake activity. Induced earthquakes have been controversial in other countries where geothermal development has taken place and this matter should be considered carefully in order to maintain the public approval of geothermal development.

5.9.3. Well register in Iceland and the rules of wells' design and data submission

The Well Registry in Orkustofnun contains a record of almost all drilled boreholes in Iceland. Currently there are just under 14.000 boreholes on record. There are three main groups of boreholes: Cold Water, Geothermal and Others. Each of those groups is about a third of the total number.

- The Cold Water group contains boreholes that were drilled for utilisation of cold water as well as seawater. This group also contains boreholes that were drilled to explore and monitor groundwater levels.
- The Geothermal group of boreholes includes different types of geothermal drilling; High enthalpy (above 100°C) and low enthalpy (below 100°C), reinjection wells as well as expletory drilling. The latest addition to this group is boreholes specifically drilled for installation of Heat Pumps.
- The Others group consists of variety of records. The majority is related to hydropower projects and construction sites. There is also a small number of records relating to general exploration of minerals, metals or other geological features.

The collected data is primarily focused on storing records of geological formations as well as water flows and temperatures. In some cases other tests have been made such as chemical analysis and radiation measurements.

Data collection is conducted through a Web portal, but also through email and other means. Orkustofnun also has extensive historical records in paper format (Fig. 5.9.3.1) which is being scanned so that it can be accessible to all.

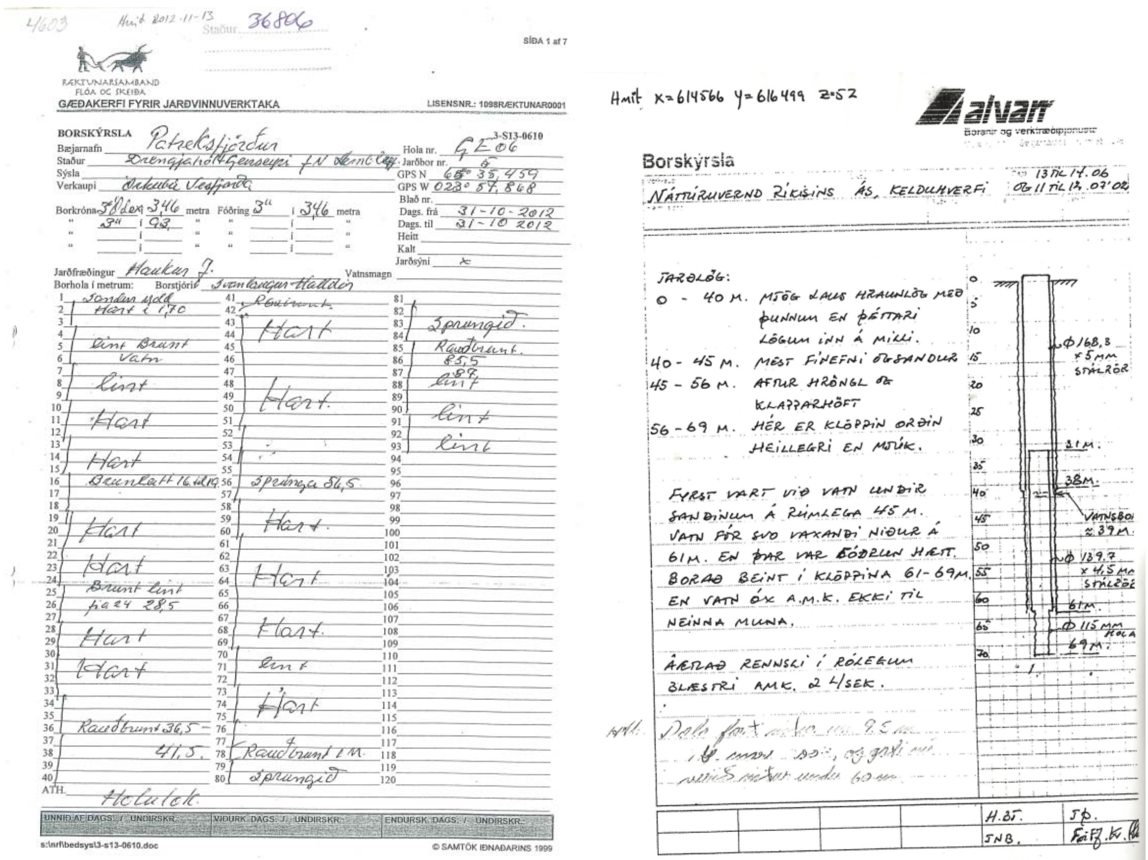


Fig. 5.9.3.1. Sample paper records of drilling operations.

Data has been collected at Orkustofnun for a number of years, and in 1989 a database was formed to keep track of all the records. The previously mentioned paper records form the basis of that database. There are also other reports (Fig. 5.9.3.2), articles and technical papers that have been searched for information.

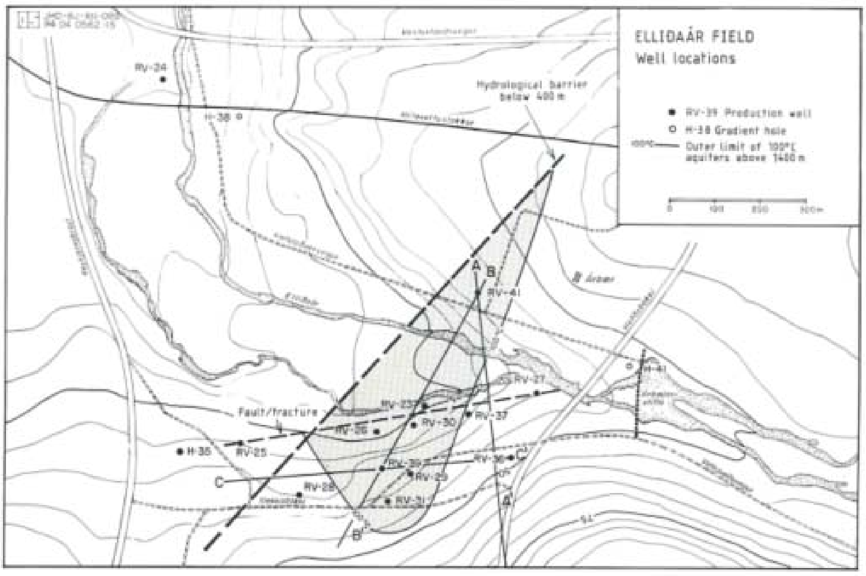


Fig. 5.9.3.2. Sample map from a technical report.

These have proved invaluable in filling out missing information and making the data records more complete.

Over the last few years a concentrated effort has been made to find better coordinates for all known boreholes. This is quite an undertaking as the landscape has changed a lot in places and some boreholes have been covered over. Almost all boreholes in the database have now been assigned coordinates which makes them viewable through the Orkustofnun map server (http://map.is/os) The quality of the coordinates varies, but even so it has proven to be of great value to people in the field. They are able to visualize all known drilling operations in a particular area and use that information to plan more effective drilling.

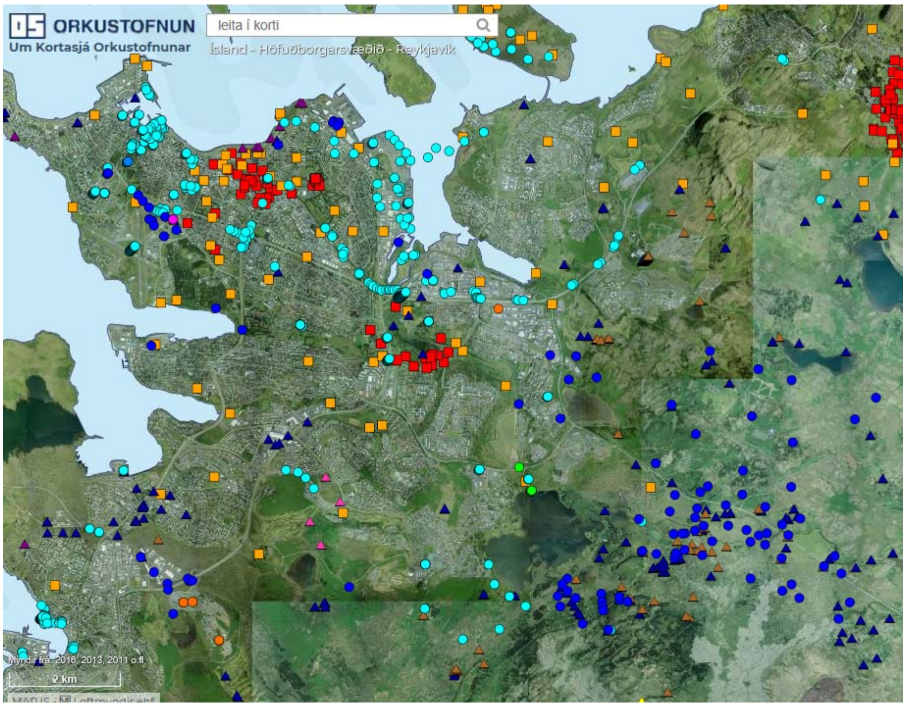


Fig. 5.9.3.3. Sample view from Orkustofnun's map server

References:

Sveinbjörnsson, B. M. (2014). Success of High Temperature Geothermal Wells in Iceland.
Geothermal Policy,Options and Instruments for Ukraine Based on Icelandic and International Geothermal Experience. Orkustofnun, 2016.

5.10. Heat pumps in geothermal heating in Norway and Iceland – recommendations for Poland

5.10.1. Norwegian best practices in heat pumps' application in geothermal sector – recommendations for Poland

Introduction

People need houses and houses need heating. Until the industrial revolution heating was done by passive solar energy or by burning biomass. After the industrial revolution and up to today fossil fuels have in different ways been a major heat supplier. In Poland, roughly 50% of the heating demand for the residential sector is covered by local heating systems with the combustion of coal, while 41% is covered by district heating (Euroheat & Power 2017c). The energy supply composition for district heating is 75% from coal, 12% from oil and gas, leaving a share of 13% to renewables, and recycled heat (Szymczak and Olszewski 2017).

There are several issues with using fossil fuels, like coal, for heating or other purposes. Combustion of fossil fuels is the single largest factor in global warming and has massive local emissions, which leads to health problems (IPCC 2014). Fossil fuels are also a problem for energy security since it is not evenly distributed around the world. Fossil fuels can thus be used by a country or cooperation to gain leverage over another (Verrastro and Ladislaw 2007).

For heating purposes, low-temperature district heating (DH), supplied with renewable energy, has been addressed as one benign option to tackle the above-mentioned challenges and problems. The fact that the energy efficiency of buildings improves, means that a low-temperature DH system easier can supply the heating demand. New houses also create a new need for cooling, which potentially can be integrated with an existing DH system, strengthening the position for district heating.

As an energy source for the district heating system (DHS), geothermal energy together with a heat pump is a viable option in many cases and will be the scope for this state of the art report. Firstly, the Norwegian housing stock will be evaluated through the governmental building legislation called TEK - technical building regulations, and other influencing trends. This will form a picture of the development of the housing stock, to better understand the need for heating. Then a segment on heat pumps will follow, focusing on large-scale heat pumps and key parameters for evaluating them. Lastly, the district heating system will be studied, both generically, and for Scandinavia and Norway, with a detailed look at Norwegian district, and local heating systems using geothermal energy and heat pumps.

References:

Euroheat & Power. 2017. "District Energy in Poland." *Euroheat & Power*. May 1. https://www.euroheat.org/knowledge-centre/district-energy-poland/

IPCC. 2014. *Climate Change 2014: Synthesis Report*. Edited by R. K. Pachauri and Leo Mayer. Geneva, Switzerland: Intergovernmental Panel on Climate Change.

Szymczak, Jacek, and Andrzej Olszewski. 2017. "POLAND Euroheat and Power." *Polish District heating - chamber of commerce*. Accessed September 25. https://dbdh.dk/download/member_contries/poland/POLAND%20Euroheat%20and%20power.pdf

Verrastro, Frank, and Sarah Ladislaw. 2007. "Providing Energy Security in an Interdependent World." *Washington Quarterly* 30 (4): 95–104.

5.10.1.1. The Norwegian House

To understand and plan for the heating of houses, one must start by looking at the development of the houses. In Norway, this progress has been easy to track since 1969 and up to today. This is because the first governmental technical building regulation (TEK) got introduced in 1969, and the TEK has later been followed to the minimum by entrepreneurs and builders. One can thus study the development of the Norwegian house from 1969 and up until today, just by looking at the TEK.

The first TEK in 1969 only had requirements for roof and wall insulation, and U-values for windows and the specific heating demand for a building was around 205 kWh/m^2, on average. Up until 1997, there had only been improvements in insulation thickness and U-values, while TEK97 also had requirements for ventilation and heating, lowering the heating demand to an average of 127 kWh/m^2. TEK10, from 2010, was at its time seen as the strictest mandatory building regulation in Europe and possibly the world (Bronzini 2017), with the additional requirements for the specific energy performance per building with 100 kWh/m^2 for residential buildings, and 115 kWh/m^2 for office buildings as examples. TEK10 also states that all buildings above 1000m^2 must facilitate for a low- temperature heating solution with temperatures below 60^{O}C, where the use of fossil energy is not allowed. This creates a better market for district heating, since, within a district heating concession area, this would be the easiest and sometimes only allowed heating available (Bronzini 2017).

On the question of where the path goes from here, there is a new factor to take into consideration. Being environmental friendly is now seen as attractive and is thus a valid sales argument, and we are seeing that the proprietor now demands that a building is performing above the TEK standard (Sweco and Zero 2017). Standards like BREEAM has developed as a result of this, making a better framework for planning, building and operating buildings in an environmentally friendly way. While BREEAM is a commercial standard of today, delivering houses with a relatively low heating demand and climate footprint, Norway has also a leading role in the research for zero emission buildings (ZEB) and zero emission neighborhoods (ZEN). ZEB and ZEN is an initiative from the research center SINTEF, where the goal is not just to have a low heating demand and climate footprint, but to create houses and neighborhoods that during their lifetime will have a net zero emission of greenhouse gasses (Woods and Samdal 2017). ZEB started in 2009 and finishes now in 2017, and has been a showroom for new technologies and innovation connected to buildings. On the topic of energy supply the focus has been on moving from large energy systems as we have had in Norway the last century, and down to smaller units, local resources, less distribution, resulting in lower losses (Frydenlund, Djuric, and Haase 2010). The next step is to use experiences from ZEB, to create zero-emission neighborhoods. Figure 1 displays the development of the specific heating demand for Norwegian houses from 2010, towards 2030 with plus energy houses that has a net delivery of energy during the lifetime.

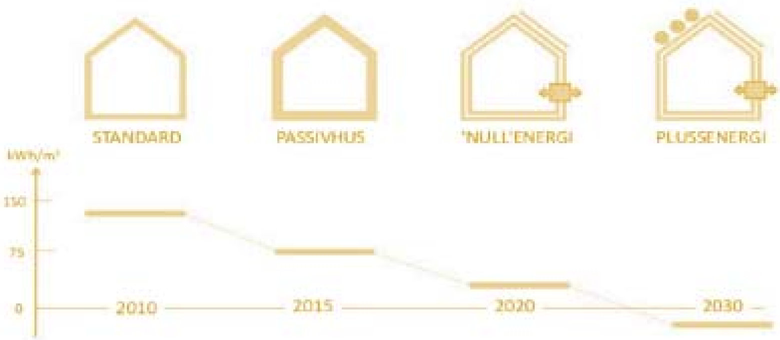


Fig. 5.10.1.1. Zwiększone zaptrzebowanie na ciepło w budynkach mieszkalnych w Norwegii

The reason for discussing the Norwegian housing stock and its development is to better understand the changing need for district heating. Where we did heat our houses with electricity and had a specific heating demand of over 200 kWh/m^2 fifty years ago, we now build houses that have a lower heating demand and also have strict regulations on what type of energy they can use. District heating has in this context become more benign, compared to direct electric heating, especially for offices and other large buildings, with the added possibility of delivering cooling as well.

References:

Bronzini, Andrea. 2017. "TEK10, TEK15, Husbanken and NS3700 (Passivhaus Standard) - How Norway Is Leading the Energy Efficiency Revolution." *Qhaus Prefabricated Wooden Element Houses*. Accessed September 12. http://qhaus.eu/articles/151-tek10-tek15-husbanken-ns3700-passivhaus-standard-hownorway-is-leading-the-energy-efficiency-revolution

Frydenlund, Frode, Natasa Djuric, and Matthias Haase. 2010. "Survey of Available Technologies for Renewable Energy Supply to Buildings." *Technical Report*. SINTEF.

Sweco, and Zero. 2017. "Energisparing i Norske Bygg Mot 2030."
http://swecomoment.no/wpcontent/uploads/2017/03/Sweco-Energirapport.pdf

Woods, Ruth, and Morten Samdal. 2017. "ZEB Final Report."
http://zeb.no/images/ZEB_Mag_20x28cm_Final_Single_WEB.pdf

5.10.1.2. Heat Pumps

A heat pump is defined as "a device which enables heat to flow from a colder heat source to a warmer heat sink" (Frydenlund, Djuric, and Haase 2010). By using a heat pump, you can increase the temperature of a system, utilizing the feature of evaporation and condensing of a certain fluid, known as a refrigerant. The two main heat pumps used today is the electrically driven and the heat-driven heat pumps. The electrically driven uses electricity to run a compressor, while the heat-driven does not have a compressor, but rather uses the effect of adsorption or absorption to fuel the process (De Kleijn Energy Consultants & Engineers 2017a). In this chapter, the two main heat pumps will be presented on a technical level, together with the third option, a hybrid heat pump that uses a combination of the other two. An overview of ground source heat pumps in Norway will then be presented. Lastly, the potential climate change mitigation effect of using heat pumps will be discussed.

Mechanical heat pumps

A mechanically driven heat pump has in theory only four components: evaporator, compressor, condenser and expansion valve. In addition, the heat pump uses a working fluid, called a refrigerant, that circulates through the system. The goal of the heat pump is to export heat from the heat source to a heat sink, for example from ambient air or from the ground through a borehole, to the inside of a house. The evaporator is placed at the heat source, and the first step (4-1) of the process is that the refrigerant evaporates (goes from liquid to gas) when exposed to the heat source, extracting heat in the process (Q_{in}). The refrigerant is then pressurized by the compressor (1-2). This increases the energy content and the pressure of the refrigerant. The refrigerant enters the condenser (2-3), which is placed in the heat sink. In the condenser, the refrigerant condenses (goes from gas to liquid) and releases heat ($Q_o$ut), which heats the heat sink. The refrigerant goes through an expansion valve (3-4), lowering the pressure and thus the temperature of the refrigerant. The refrigerant is now ready for a new cycle (Frydenlund, Djuric, and Haase 2010).

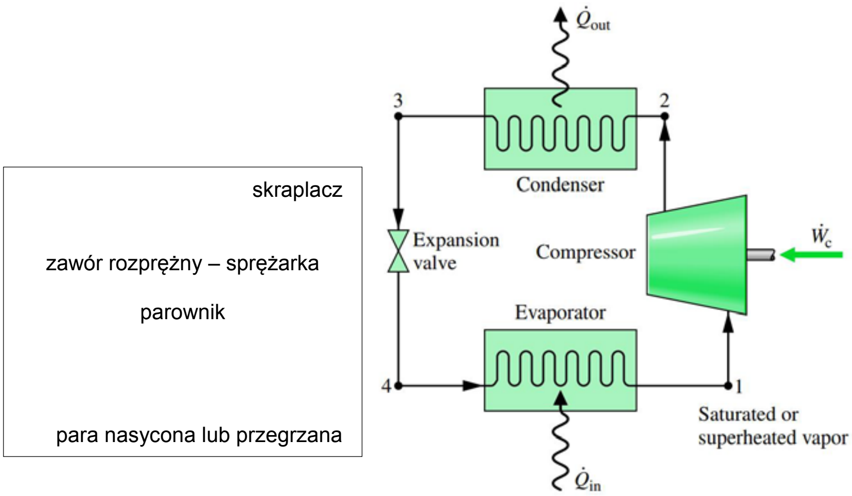


Fig. 5.10.1.2. A simplified schematic of a mechanical heat pump (Moran and Saphiro, 2004)

To assess the performance of a heat pump, the relationship between the energy that is put into the system in the form of electricity is compared to the energy one gets out of the heat pump in the form of heat. The indicator is called the coefficient of performance - COP. For an air-to-air heat pump used at home, one can expect a COP of 3-5, while for industrial pumps a COP of 10-30 can be achieved (Frydenlund, Djuric, and Haase 2010).

The COP is affected by the size of the heat pump and takes advantage of "economies of scale", but is also heavily dependent on the heat source. By using a heat source with a higher temperature, like geothermal heat instead of ambient air, the COP will increase.

A heat pump can extract heat out of several heat sources. For residential use, it is normal to use an air-to-air heat pump that extracts energy from the ambient air outside. For larger systems, either industrial heating, larger buildings or for district heating, groundwater, geothermal energy, sea water or waste heat can be good options, compared to ambient heat/air. These are often both more stable and have a higher temperature, thus increasing the COP.

An important characteristic of the heat pump is that it can be used in reverse and used as a cooling machine instead. This is useful for systems that demand both heating and cooling. The ability to produce both heating and cooling also creates an opportunity to store energy. More on this in the coming chapters.

Compressor types

There are two main types of compressors: positive displacement and dynamic. For this report, only positive displacement compressors will be assessed, since they are the ones normally used for heat pumps. Out of the different positive displacement compressors, screw compressors, scroll compressors, and reciprocating compressors will be presented, due to their relevance as compressors for heat pumps.

The reciprocating compressor also called the piston compressor, resembles an internal combustion engine, using a cylinder as a chamber, where a piston compresses the air in the cylinder, see Figure 5.10.1.3. The design and manufacture of the compressor is easy, with the main components being the piston and cylindric chamber, but due to the need of many other moving parts to make the compressor function, the operation is complex and must have a good system for maintenance to avoid the potential of failure. Especially the valves, controlling the flow through the compressor, is sensitive to wear, and in particular to droplets in vapor or oil. It is hence important to both keep the gas in the superheated state and to have a thorough maintenance program for the compressor. The compressor also has the issue with dead space, meaning the gas still in the cylinder, when the piston is at the top and the pressurized gas is out. This air must be expanded when the piston returns down, thus doing work that will decrease the efficiency of the machine. The volume flow of the piston compressor is also highly dependent on the pressure ratio. It can compress large amounts of gas, if the difference in discharge and inlet pressure is low, while if its high, only smaller amounts of gas can be compressed. On the other hand, a large advantage with the piston compressor is the ability to serve a variable load, by turning on or off one or several pistons, and thus regulating the amount of compressed gas.

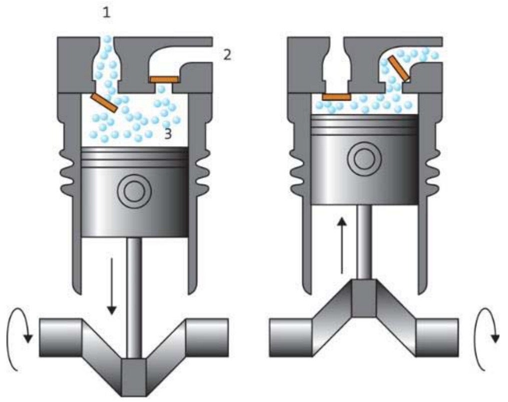


Fig. 5.10.1.3. Reciprocating compressor (*Rate Air Compressor* 2017)

The screw compressor normally consists of two rotors, one screw (male) and one slide (female), see Figure 5.10.1.4. These two are the only moving parts on the compressor, making it a durable component with a low need of maintenance. This construction also makes it hard to regulate the built-in volume of the compressor. To achieve good performance, the leakage between the different gas chambers have to be minimized. This can be done by either using oil as a sealant, which also works as a lubricant for the compressor and has a cooling effect. Alternatively, synchronizing gears can be used to keep the two rotors at optimized positions relative to each other. With this alternative, one can avoid the use of oil but will have an increase in price. Unlike the piston compressor, the screw compressor has no dead space, while it is harder to regulate to handle a variable load, and such a characteristic is expensive. It is also little influenced by the pressure ratio, concerning volume flow, in contrast to the piston compressor.

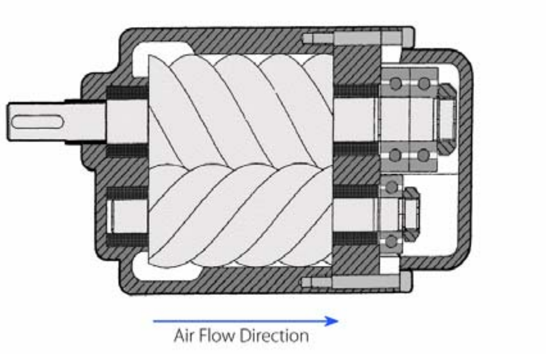


Fig. 5.10.1.4. Screw compressor (*Engineer student* 2012)

The scroll compressor is made up of two parts, one rotating scroll, and one orbiting scroll, see Figure 5.10.1.5 for details. The compressor is fairly quiet, vibrant free and reliant, and contrary to piston compressors, insensitive to liquid droplets. Its volumetric efficiency is also high, meaning that the volume flow rate is nearly unchanged by increasing pressure ratio (discharge pressure divided by inlet pressure).

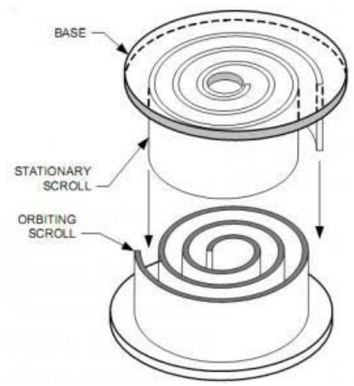


Fig. 5.10.1.5. Scroll compressor (van de Beld 2017)

Types of refrigerants

In the beginning of the twentieth-century ammonia, carbon dioxide, sulfur dioxide, and water were used as refrigerants at industrial scale, but there was no alternative for household appliances. In 1928. Thomas Midgley presented R-12, a chlorofluorocarbon (CFC) as the new refrigerant for household appliances, as it was nonflammable and non-toxic. It was later discovered that CFCs depleted the ozone layer, and the world united forces and planned to phase out CFCs and other gasses to protect the ozone layer through the Montreal Protocol in 1987. The alternative presented to replace CFCs was hydrofluorocarbons (HFCs), and hydrochlorofluorocarbons (HCFCs), which had no ozone depletion potential (ODP), while instead have a global warming potential (GWP). There is now an ongoing work to phase out the HFCs as well through the F-gas directive, and at the same time try to find alternatives, together with better routines so that leakage of refrigerants is minimized. The focus on leakages is due to the fact that the refrigerants do no harm when trapped in the heat pump or cooling machine, but become a problem if there is a leakage in construction, operation or demolition phase (Forsen et al. 2005).

The most common refrigerant types for heat pumps are R134a, R407c, R410a, R600, R600a, R717, R477 and R718. This is a mix of natural and chemically prepared refrigerants, with different properties that make them more or less suited for different heat pump applications. The following paragraphs will present shortly the characteristics of the different gasses.

R134a is a refrigerant of the type HCFC, that normally is being used at medium and large heat pumps. The efficiency of the gas is assessed to be quite high, being better than R407c and R410a, while not as good as R717. R134a has a relatively low pressure. This results in large volumes needed to be compressed, thus an increased investment cost for installation (De Kleijn Energy Consultants & Engineers 2017c). R134a is not flammable, but if the gas is cold it can cause frostbite and dangers can occur upon inhalation (National Refrigerants 2012). The refrigerant has zero ozone depletion potential, but a rather large global warming potential (GWP) of 1 300 kg CO2eq/kg (UNEP 2006).

R407c and R410a are both HFCs and used in smaller and medium-sized heat pumps, and often chosen if the heat pump also shall work as a cooling machine. These two gasses are a part of the refrigerant category called R400- series. Gases in this series are zeotropic mixtures, meaning they are a mix of gasses with different boiling points. This results in a temperature interval, not a specific temperature, where the gas reaches supercritical conditions. They are both suited for low-temperature systems. Having a relatively low volume, compared to R134a, it's easy to compress, resulting in lower investment cost, but it has a lower efficiency than R134a (De Kleijn Energy Consultants & Engineers 2017c). The gasses are not flammable and only slightly toxic. As with R134a, there is no ozone depletion potential for either of the two gasses, while they both have a high GWP of 1600 kg CO2eq/kg and 1725 kg CO2eq/kg for R407c and R410a respectively (Emerson Network Power 2017).

R600, known as butane and R600a, known as isobutane are natural refrigerants, used for both refrigeration installations and heat pumps with temperatures higher than 80^{O}C. At above 80^{O}C an issue with many refrigerants is a high pressure, which is not the case with R600 and R600a. The big issue with these two refrigerants is the flammability and explosion risk, which is fairly high, considering that they are also used as fuel (De Kleijn Energy Consultants & Engineers 2017c). Their relative GWP, compared to other refrigerants, is fairly low with 3 kg CO2eq/kg R600a (Linde Industrial Gases 2017) and 4 kg CO2eq/kg R600 (IPCC 2007).

R717 or ammonia, is a very good natural refrigerant, especially for heat pumps in an industrial environment. R717 can easily be used up to 80°C and expected to be able to tackle 90°C in the coming years, giving a high efficiency. Another advantage with R717 is that both the global warming potential and the ozone depletion potential is zero, while the downside is that it's both explosive and toxic. It is still quite easy to detect a leak, due to the characteristic and strong odor of ammonia fuel (De Kleijn Energy Consultants & Engineers 2017c).

R744 is the refrigerant code for CO2, which can be used as a refrigerant, often in combination with ammonia to reduce the amount of ammonia in the system. CO2 has a transcritical temperature of 31°C. Above this temperature, the condensation of CO2 does not happen at a constant temperature, but rather over a temperature range. This means that it can only be used as a refrigerant if the heating can happen at a non-constant temperature (De Kleijn Energy Consultants & Engineers 2017c). CO2 has per definition a GWP of 1, while zero ozone depletion potential. CO2 is neither flammable or toxic but can lead to chocking in high concentrations (Linde Industrial Gases 2017).

R718 or water, can in some applications be used as a refrigerant at temperatures above 100°C. The positive sides of using water include good availability, no damage to environment or people, while on the negative side has a low density in a gaseous state and thus needs a high compressor capacity (De Kleijn Energy Consultants & Engineers 2017c).

Thermal heat pumps

There are basically two different heat pumps that are driven by thermal energy, the adsorption heat pump, and the absorption heat pump. The adsorption system uses a solid sorbent, while the absorption system uses a liquid sorbent. Thermodynamically they are similar, with analogous basic configurations. The heat pump consists of four main components: a reactor called generator, a condenser, an evaporator and a reactor called ab/adsorber, see Figure 6. The first step (4-1) is to heat the refrigerant in the evaporator by energy from the environment *(Q_{in})*. Then, instead of going through a compressor, the refrigerant is absorbed in the absorber (1-a), by cooling the refrigerant down, mixing the refrigerant and absorbent. The mixture is then pressurized through the pump and transported to the generator (a-b). By adding heat from a high temperature source *(Q_G)* the refrigerant and absorber is separated, and the absorbent goes back to the absorber through a valve (c-a). The refrigerant releases heat *(Q_{out}).* In the condenser (2-3) and then enters the expansion valve (3-4), lowering both pressure and temperature of the refrigerant. (Kerr 2017). Based on the scope of this report adsorption heat pumps will not be studied further, due to their high cost and size. Absorption heat pumps will be elaborated on further, to present an alternative to mechanically driven heat pumps, but since they are not in use in Norway, less emphasis will be put on them than on the mechanical heat pumps.

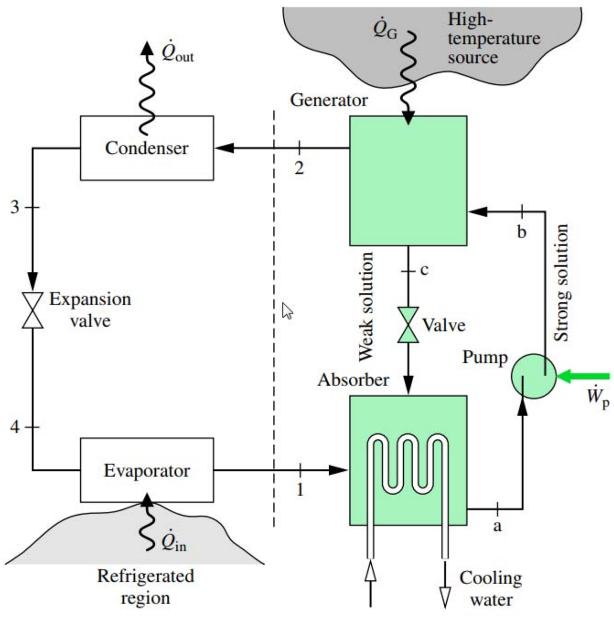


Fig. 5.10.1.6. Structure of an absorption heat pump/cooling machnine (Moran and Shapiro 2004)

Absorption chillers and heat pumps are well documented and tested and looked upon as a mature technology. They exist on the marked at high quality and are often driven by hot water, solar heat, district heating, waste heat from CHPs or gas-fired (Global CCS Institute 2017). Compared to mechanical heat pumps, the COP is generally lower at around 1,7. They can still be advantageous, given the use of a low-quality heat source, but the most used heat source today is fossil gas, which does not give a good environmental effect. Together with mechanical heat pumps, they are also well suited for delivering both heating and cooling for a given system (Moran and Shapiro 2004)(De Kleijn Energy Consultants & Engineers 2017a). Table 1 displays an overview of absorption heat pumps with different refrigerants and sorbents and their characteristics.

Table 5.10.1.1. Overview of absorption heat pumps, with respect to refrigerants, temperature of heat source, capacity, and COP (Global CCS Institute 2017)

Process	Absorption		
Refrigerant/sorbent	Water/LiBr single-effect	Water/LiBr double-effect	Ammonia, water
Temperature at heat source [ºC]	75-110	135-200	65-180
Capacity [kW]	10,5-20000	174-6000	14-700
COP heat pump	1,4-1,6	1,8-2,2	1,4-1,6
COP cooling	0,6-0,7	0,9-1,3	0,5-0,7

Hybid heat pumps

A hybrid heat pump is a combination of the regular mechanical heat pump and the absorption heat pump. Figure 5.10.1.7 displays a simplified model of a hybrid heat pump. The left side of the hybrid heat pump works as a regular ammonia heat pump, where heat is emitted in the absorber/condenser and heat is extracted from the environment in the desorber/evaporator. The difference lies on the right side, where a mechanical heat pump only would have a compressor, and an absorption heat pump would have a pump and a return valve. Instead, the mixture of water and ammonia is separated in the separator, ammonia is pressurized through the compressor and water pressurized through the pump. They are again united at the absorber, releasing heat (De Kleijn Energy Consultants & Engineers 2017b).

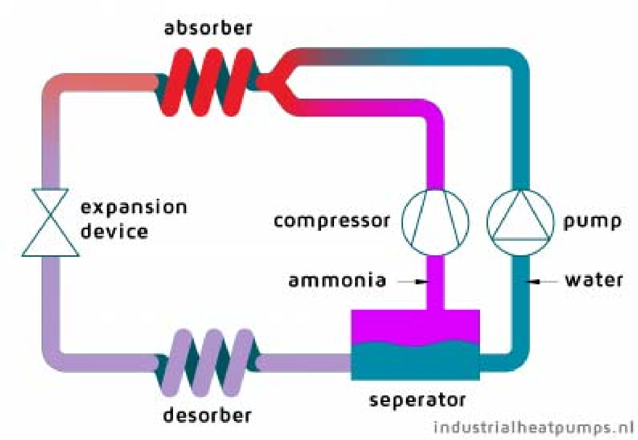


Fig. 5.10.1.7. Hybrid heat pump (De Kleijn Energy Consultants & Engineers 2017b)

The reasoning for using a hybrid heat pump is to be able to have a larger temperature lift than by using a normal gaseous refrigerant. This is achievable because the condensation temperature of the mixture of water and ammonia is higher than conventional compressor machines. Which again is because of a lower saturation pressure for the mixture, than for a regular gaseous refrigerant. Instead of reaching a higher temperature lift, one can alternatively reach a higher COP with a hybrid heat pump, than with a regular mechanical heat pump. (De Kleijn Energy Consultants & Engineers 2017b).

The drawbacks with using a hybrid heat pump are mainly connected to the availability and price. The technical complexity is high, and due to an increased temperature glide, the absorber and desorber have to be larger than normal, which both lead to higher costs. There are also few manufacturers delivering hybrid heat pumps. (De Kleijn Energy Consultants & Engineers 2017b).

Overview of ground heat pumps in Norway

When designing a heat pump system, one of the most important factors to evaluate is the heat source. A heat pump can draw heat from ambient air, a local river, sea water, groundwater, shallow or deep geothermal energy, or spill heat from industry as some examples, and the choice among these should take into consideration price, availability, stability, and durability. For medium to large scale heat pumps ground source/shallow geothermal energy is a good option, as it is stable throughout the season, long lasting, silent, economical in operation and available most places. The drawback of ground source energy is the investment cost of drilling and associated infrastructure.

Geothermal heat and ground source heat pumps (GSHP) have had a steady increase in popularity in Europe and the Nordic countries. In 2015, there was an installed capacity of more than 20 GWth from over 1.7 million installations in Europe. In Norway, 90% of the installed geothermal heat capacity is GSHPs with closed loop boreholes. One of the main issues with extracting heat from the boreholes is the thermal resistance, which affects both the efficiency and the cost of the investment. There is now research showing the potential of reducing the borehole thermal resistance with 50%, thus reducing cost and increasing efficiency of using ground source energy for heat pumps (Walnum and Fredriksen 2017).

An advantage with the GSPH system is the ability to utilize seasonal thermal energy storage (STES), using the ability of the heat pump to not only produce heat but also for cooling. The system can then both serve buildings with heating and cooling demand at the same time and also reduce the risk of delivery, due to low-temperature energy sources, by storing heat (Walnum and Fredriksen 2017).

The climate effect of using a heat pump

A motivation for using heat pumps for heating is to reduce the emissions of greenhouse gases like CO2, which is emitted when burning fossil fuels. To assess the total emissions from a heat pump during its life cycle a model has been developed, where the key parameters are the direct emissions due to leakage of refrigerant, indirect emissions related to electricity generation and direct emissions of the refrigerant at demolition. Calculated examples show that 97,8% of the total emissions are indirect and because of the production of electricity (Spath and Mann 2000). The potential emissions reduction potential for a heat pump is thus close to linearly to the emissions per unit of electricity used. Figure 5.10.1.8 shows the specific life-cycle emissions of CO2-eq per kWh for different electricity generation technologies. Coal is the most emission-intensive, with a median of 1 000 g CO2-eq per kWh, while hydropower is close to zero and biopower have the potential of having negative emissions using carbon capture and storage (CCS).

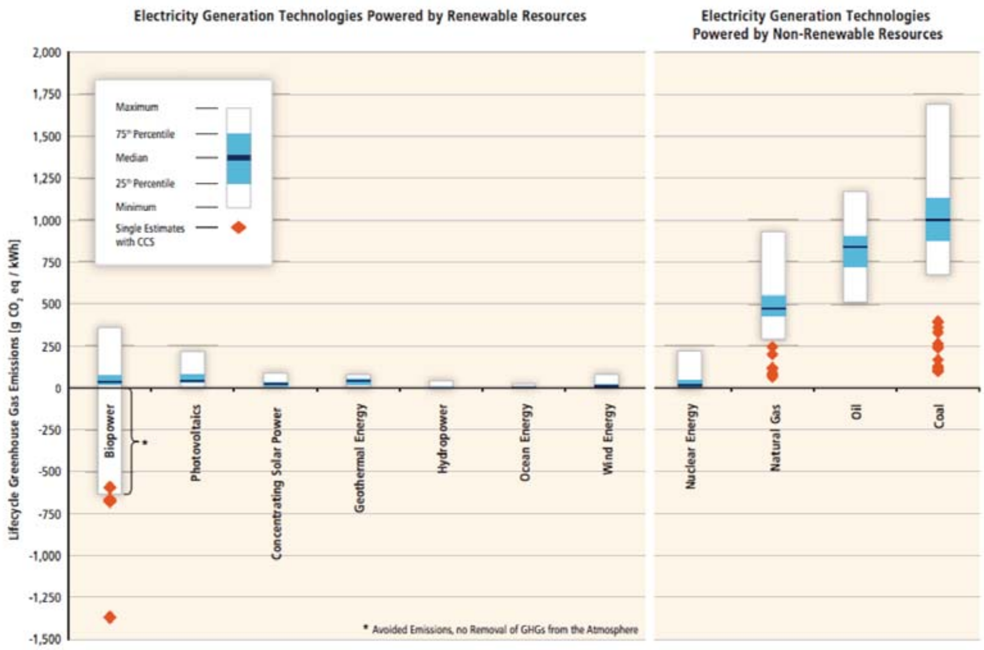


Fig. 5.10.1.8. Lifecycle greenhouses gas emission for different energy sources (IPCC 2011)

When emission intensity data is collected for each country, one can get a national emission intensity overview.

Figure 5.10.1.9 displays the emissions of CO2-eq per kWh electricity generated for the countries of Europe. It is from this graph visible that the use of a heat pump for heating in Norway would have much lower emissions than using a heat pump in Poland. On the other hand, the absolute global emissions reduction would be larger if heat pumps substituted coal-fired district heating in Poland than electric heating in Norway. It should also be taken into consideration that the energy mix is constantly changing and with EUs goals for emission reduction, one can expect that the specific emissions per kWh produced electricity will decrease in the coming years.

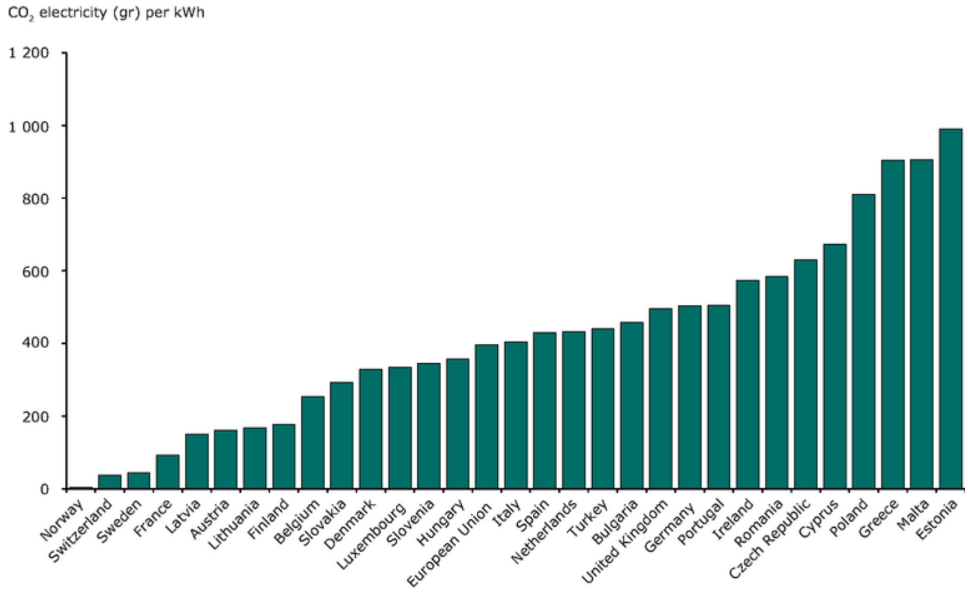


Fig. 5.10.1.9. Greenhouses gas emissions per kWh of electricity generated for European coutries (EEA 2013)

As an alternative to the mechanical heat pump, the thermal heat pump uses less electricity per generated unit of heat. In a climate perspective, the heat source for the thermal heat pump is relevant and today they are mostly powered by fossil gas. As an alternative, biomass and biogas might be an environmental option as a heat source. So, in a climate perspective absorption heat pumps can have the potential of cutting more emissions than a conventional mechanical heat pump, especially in a country with a dirty energy mix, but only given the use of a clean heat source. The use of biomass as a heat source has been tested in Italy with good results (Bibbiani, Campiotti, and Viola 2016).

References:

Beld, Cas van de. 2017. “The Scroll Compressor: Quiet and Easy | Air Compressor Guide.” Accessed October 3. http://www.air-compressor-guide.com/learn/compressor-types/scroll-compressor.

Bibbiani, Carlo, Carlo Campiotti, and C Viola. 2016. “Environmental Impact Reduction in Greenhouses Heating: Biomass-Fired Absorption Heat Pump Coupled with Wood Biomass Boiler” 17: 551–54.

De Kleijn Energy Consultants & Engineers. 2017a. “Absorption Heat Pump / Industrial Heat Pumps.”

http://industrialheatpumps.nl/en/how_it_works/absorption_heat_pump/

De Kleijn Energy Consultants & Engineers. 2017b. “Hybrid Heat Pump / Industrial Heat Pumps.”

http://industrialheatpumps.nl/en/how_it_works/hybrid_heat_pump/

De Kleijn Energy Consultants & Engineers. 2017c. “Refrigerants / Industrial Heat Pumps.”

http://industrialheatpumps.nl/en/how_it_works/refrigerants/

EEA. 2013. “CO2 (g) per KWh in 2009 (Electricity Only).” Figure. European Environment Agency. July 6. https://www.eea.europa.eu/data-and-maps/figures/co2-electricity-g-per-kwh

Emerson Network Power. 2017. “Technical Note - Comparing R407C and R410A as Alternatives for R22.” Dptechinc.Com.

http://www.dptechinc.com/PDFs/Technical%20Note%20-

%20Comparing%20R407C%20and%20R410A%20as%20Alternatives%20for%20R22.pdf

Engineer student. 2012. “Pneumatic Compressor Types.”

http://www.engineerstudent.co.uk/screw_air_compressors.shtm.

Forsén, Martin, R Boeswarth, X Dubuisson, and B Sandström. 2005. “Heat Pumps: Technology and Environmental Impact.” Swedish Heat Pump Association, SVEPR.

Frydenlund, Frode, Natasa Djuric, and Matthias Haase. 2010. “Survey of Available Technologies for Renewable Energy Supply to Buildings.” Technical Report. SINTEF.

Global CCS Institute. 2017. “Thermally Driven Heat Pumps.” Accessed September 14.

https://hub.globalccsinstitute.com/publications/strategic-research-priorities-cross-cutting-technology/43-thermally-driven-heat-pumps

IPCC. 2007. "Climate Change 2007: The Physical Science Basis." Agenda 6 (07): 333.

IPCC. 2011. Renewable Energy Sources and Climate Change Mitigation: Summary for Policymakers and Technical Summary: Special Report of the Intergovernmental Panel on Climate Change. Edited by Ottmar Edenhofer. New York. Cambridge University Press.

Kerr, Claire. 2017. "What Is Gas Absorption?" Robur Heat Pumps. Accessed September 22.

http://www.roburheatpumps.co.uk/what-is-gas-absorption/

Linde Industrial Gases. 2017. "R744 (Carbon Dioxide)." Linde Industrial Gases.

http://www.lindegas.com/en/products_and_supply/refrigerants/natural_refrigerants/r744_carbon_dioxide/index.html

Linde Industrial Gases. 2017. "R600a (CARE 10) Isobutane." Linde Industrial Gases. Accessed September 28.

http://www.lindegas.com/en/products_and_supply/refrigerants/natural_refrigerants/r600a_isobutane/index.html

Moran, Michael J, and Howard N Shapiro. 2004. Fundamentals of Engineering Thermodynamics. Hoboken, NJ: Wiley.

National Refrigerants. 2012. "Safety Data Sheet Refrigerant R134A."

http://www.nationalref.com/pdf/4%20SDS134a.pdf

Rate Air Compressors. 2017. "Best Air Compressor Reviews: Top 10 in 2017 (Buying Guide)." Rate Air Compressors. http://www.rateaircompressors.com/

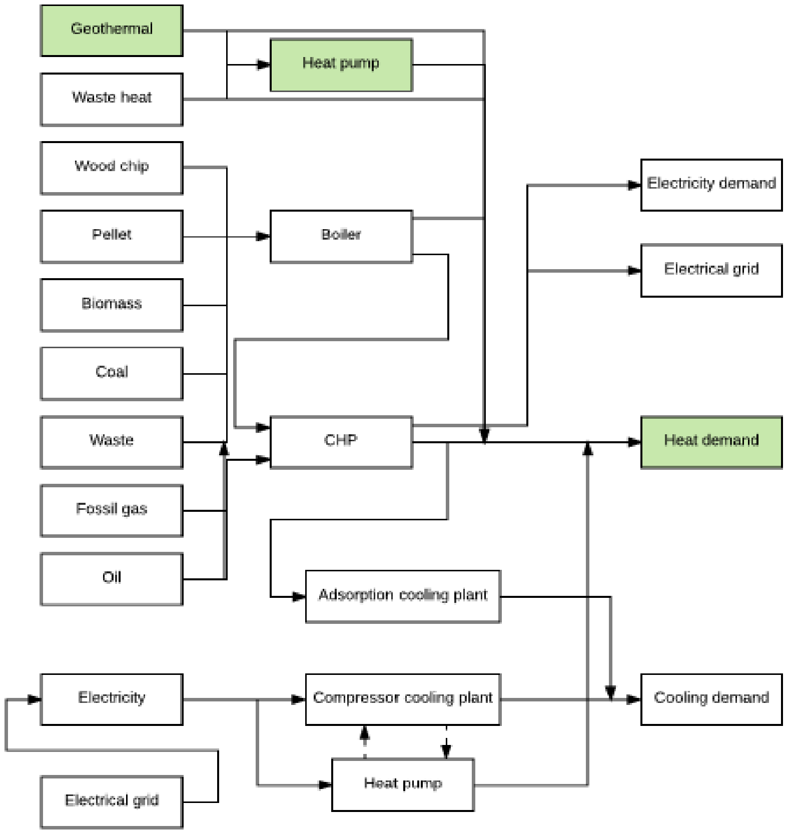
Spath, Pamela L, and Margaret K Mann. 2000. "Life Cycle Assessment of a Natural Gas Combined Cycle Power Generation System." National Renewable Energy Lab., Golden, CO (US).

UNEP. 2006. 2006 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee: 2006 Assessment. Nairobi: UNEP.

Walnum, Harald Taxt, and Eyvind Fredriksen. 2017. "Thermal Energy Systems in ZEN Review of Technologies Relevant for ZEN Pilots." Draft. SINTEF.

5.10.1.3. District Heating

District heating (DH) and district cooling (DC) is defined as *the "conversation of primary energy into distributed thermal heating and cooling"* (Frydenlund, Djuric, and Haase 2010). A DH system consists of three elements: (1) the energy input, (2) energy conversion, and (3) energy output. Figure 5.10.1.10 shows an overview of the different alternatives available for a DH or DC system.



Fif. 5.10.1.10. Energy flow for DH and DC system (Frydenlund, Djuric and Haase 2010)

District heating is a mature technology that has existed since 1877, where the first commercial DH system was established in New York. The first Norwegian thermal power plant was established in Oslo in 1936, and the excess heat from cooling the steam was used to supply the town hall and the national theater (Fornybar 2016). The DH system developed in New York in 1877 is categorized as a first-generation system and used water vapor as an energy carrier. This was assessed to be too high a risk and the second generation, that was installed from 1930 to 1970, and used pressurized water at 100°C instead. The third-generation DH system, that has been used from the 1980s and up to today uses pressurized 80°C water (Lund et al. 2014).

4th generation district heating sytems

Today the fourth generation of district heating (4GDH) systems are being rolled out (Fig. 5.10.1.11). The main focus with 4GDH is to reduce temperature levels in the network. This will lead to reduced heat loss, increased production efficiency and even more possibilities to use surplus heat recovery (Walnum and Fredriksen 2017). These systems are optimized to fit together with low-energy houses and smart thermal networks. They make it possible to connect energy sources with lower delivering temperature. In addition to surplus heat from buildings, also solar heat and geothermal energy. The ability to communicate with the buildings will also have a positive effect on consumption for new buildings, especially for buildings that are constructed for the passive house, zero emission building, or the plus house standards. The fourth-generation DH system will, in addition, increase the delivering security and flexibility (Lund et al. 2014) (Fornybar 2016) by allowing renewable energy to be integrated. The major change, compared to the third generation, is that the temperature is as low as 40-50°C (Walnum and Fredriksen 2017).

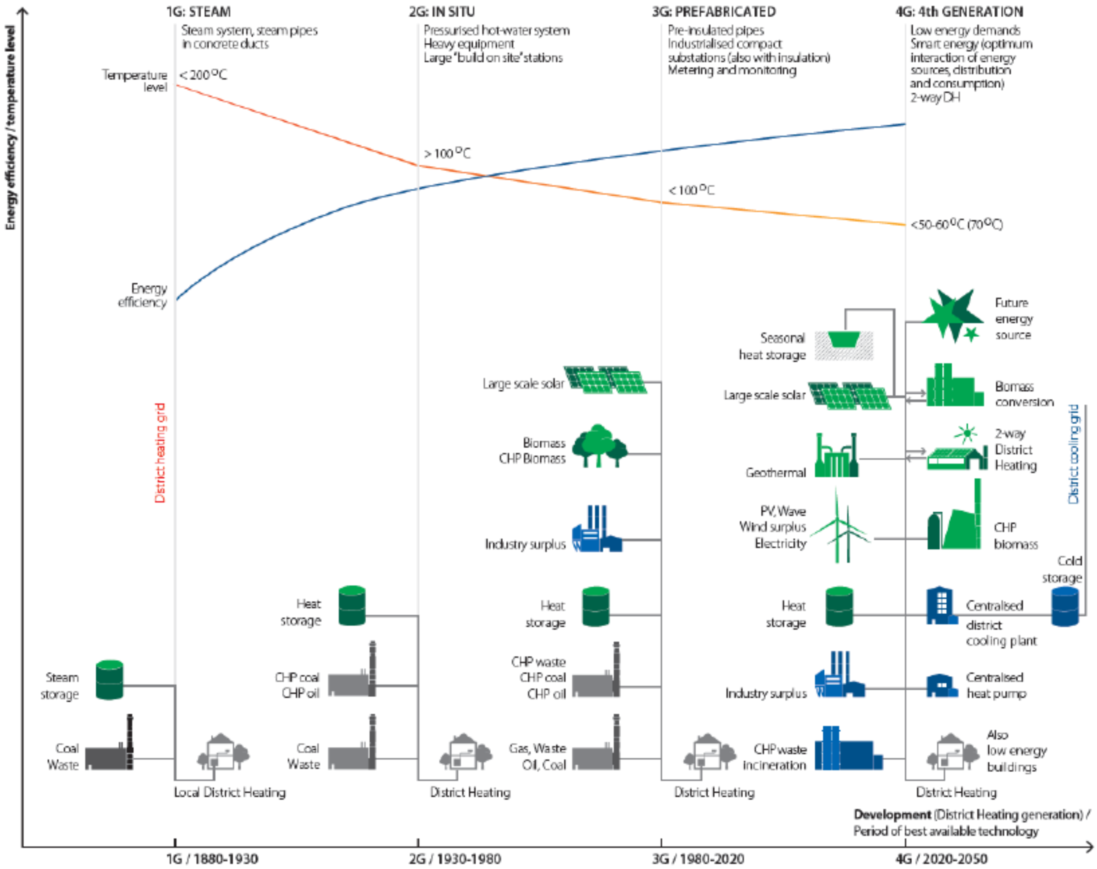


Fig. 5.10.1.11. The four generation of district heating (Lund et al. 2014)

By lowering the temperature of the district heating system, it creates an opportunity to utilize distributed renewable energy as a heat source. Which energy source and how to connect it again depends on the temperature level of the grid. The most promising technique, called the return-supply (RS) connection, is to heat the return water and inject it back to the supply line.

An issue that is occurring when converting a DH system to the 4th generation is that there usually is a mix of new and old buildings. The new ones have to fulfill standards to match a new DH system, while older buildings might not have a proper infrastructure and/or have a high-energy demand that is difficult to satisfy. Two options here is to either use two parallel systems or have a low-temperature system with the ability to increase delivery during cold periods.

District heating in Scandinavia

Both Sweden and Denmark have a well-established district heating system. Sweden has a heating market of 100 TWh. The residential sector is covered by 51% district heating, while 80% of non-residential buildings are supplied with district heating. 45% of the DH system uses combined heat and power (CHP), which again is fueled by 66% biomass and 18% waste, and cover 8.5% of Sweden's electricity needs (Euroheat & Power 2017d). In Denmark, 64% of households are heated with DH, and in the capital, Copenhagen 98% of all buildings are connected to the DH system. The amount of renewable energy used as an energy source has increased from 35% to 50% from 2005 to 2014, reducing the overall use of fossil energy in the DH system down with 20%. The main heat source for the DH system is CHP plants, which in addition to supplying the DH system also produce 57% of the electricity in 2015 (Euroheat & Power 2017a). The reason for Denmark's high share of DH is due to governmental incentives, resulting in a much larger DH share than neighboring countries with similar climate and physical structure. The DH structure is also a bit unusual, with several small systems all over the country, instead of e few major connected to big cities with population density (Frydenlund, Djuric, and Haase 2010). Compared to Sweden and Denmark, Norway has a low share of DH. While Norway's net DH production was at 5,2 TWh in 2017 (SSB 2017), Goteborg alone has a yearly DH production of 4,6 TWh.

District heating in Norway

Due to the geography of Norway, most of our electricity come from hydropower. Historically, the price for electricity has been low, and the availability high. Lately, the winters have been warm, and Norway has had an electricity surplus. As a result, district heating is not as big in Norway as in the rest of Scandinavia. Another reason for little use of DH is that our population density is low and it is arguably only economic incentives for using DH in the big cities. In 2015, DH only had a market share of 12%, 5.5 TWh of the total estimated heat market of 46 TWh in Norway. The energy source for most Norwegian DH systems is 90% renewable, from both direct renewable sources and recycled heat (Euroheat & Power 2017b), while fossil fuels are only used for peak load and reduced every year.

There are six arguments for an increased focus on district heating in Norway. (1) The availability of potential fuel in the form of incineration of waste. (2) Norway increases its capacity to export clean electricity to Europe. (3) Smarter energy use, meaning using electricity for motors and other equipment, while using low-quality energy for heating. (4) Experiences from Denmark show that also smaller DH systems are economically viable. (5) The electric grid quality in Norway. (6) All district heating systems with a governmental concession will automatically be able to deliver DH to new buildings since they have to connect to the DH system.

From the year 2009 the use of landfills for residual waste was forbidden (Avfall Norge 2017). This has resulted in an increase of incineration plants, which often supply heat for a DH systems as energy output. In 2015, Norway used 1 million tons of residual waste in incineration plants (Loop 2017), while we exported 1.7 million tons to Sweden (The Norwegian Environment Agency 2017). Leaving room for even more DH fueled by waste in Norway.

Norway has a history of using electricity as a primary heating source, with approximately 60% of the heat demand for residential sector covered by electricity in 2015. Lately, Norway has built several high voltage DC cables to Europe with the motivation of exporting electricity. It is expected that there will be built more of these because they are profitable, and it is predicted that Europe will need more Norwegian electricity to cope with variable production from new renewable energy. The result in Norway is an increased price of electricity, which makes district heating a better alternative for heating.

When working towards reaching the ambitious goal of maximum two-degree global warming energy has to be used in the most efficient way, to reduce losses and increase performance. When evaluating energy, exergy is the measurement of the quality of the energy and is measured in how much work a given amount of energy can do. Electricity is the purest form of energy that we have and thus has a high content of exergy, while heat has a lower exergy content. To optimize the usage of available energy, electricity should thus be used to do work, meaning giving energy to a motor or equivalent. Residual waste, which is hard to recycle or use for other purposes is better suited for incineration and heating.

As shown in the focus from the Danish government, it is possible to have economic functional smaller DH systems. This opens up for Norway as well, to increase its use of district heating.

In some of the major cities in Norway, the electrical grid is pushed to the limit, and with the increased use of electricity with everything from electric indoor equipment, to electric cars, the grid will get even more stressed. One alternative is to increase the use of DH, to take some of the load of the grid. This is especially efficient since the peak for the electrical grid is when the need for heating is at the top - during a cold winter day (Mellvang-Berg 2017).

The last aspect of the potential for district heating in Norway lies in the governmental concession all DH systems above 10 MW must apply for. If the concession is granted, all new buildings in the area have to connect to the DH system.

References:

Avfall Norge. 2017. “Bransjen | Avfall Norge.” Accessed September 11. http://kurs.avfallnorge.no/ombransjen1.cfm

Euroheat & Power. 2017a. “District Energy in Denmark.” Euroheat & Power. May 1. https://www.euroheat.org/knowledge-centre/district-energy-denmark/

———. 2017b. “District Energy in Norway.” Euroheat & Power. May 1. https://www.euroheat.org/knowledgecentre/district-energy-norway/

———. 2017c. “District Energy in Sweden.” Euroheat & Power. May 1. https://www.euroheat.org/knowledgecentre/district-energy-sweden/

Fornybar. 2016. “2. Varmedistribusjon - Fornybar.no.” May. http://www.fornybar.no/overforing-og-lagring-avenergi/varmedistribusjon

Frydenlund, Frode, Natasa Djuric, and Matthias Haase. 2010. “Survey of Available Technologies for Renewable Energy Supply to Buildings.” Technical Report. SINTEF.

Loop. 2017. “Restavfall.” Accessed September 11. http://loop.no/loopedia-avfallstype/restavfall/

Lund, Henrik, Sven Werner, Robin Wiltshire, Svend Svendsen, Jan Eric Thorsen, Frede Hvelplund, and Brian Vad Mathiesen. 2014. “4th Generation District Heating (4GDH): Integrating Smart Thermal Grids into Future Sustainable Energy Systems.” Energy 68: 1–11.

Mellvang-Berg, Trygve. 2017. “Fremtiden er elektrisk – men ikke bare.” VVS aktuelt, June 9. http://www.vvsaktuelt.no/fremtiden-er-elektrisk-men-ikke-bare-114908/nyhet.html

SSB. 2017. “District Heating in Norway.” Ssb.No. April 5. http://www.ssb.no/en/energi-ogindustri/statistikker/fjernvarme/aar/2017-05-04

The Norwegian Environment Agency. 2017. “Import og eksport av avfall.” May 23. http://www.miljostatus.no/tema/avfall/import-og-eksport-av-avfall/

Walnum, Harald Taxt, and Eyvind Fredriksen. 2017. “Thermal Energy Systems in ZEN Review of Technologies Relevant for ZEN Pilots.” Draft. SINTEF.

5.10.1.4. Geothermal heat pumps in Norway

In Norway, there are two district heating systems that use geothermal energy, together with heat pumps, as an energy source. These are the Kalnes energy central in Sarpsborg, and Nydalen energy central in Oslo. What has a larger prevalence is geothermal energy together with heat pumps that do not deliver the energy to a DH system, but rather use it locally. For this assessment, there will thus also be an assessment of similar systems to Kalnes and Nydalen that is not connected to the DH system. These are University college of Bergen and Vulcan energy central in Oslo. In addition, the district heating system in Drammen, that uses seawater as a heat source, will be evaluated.

Kalnes Energy Central

Kalnes energy central was constructed in 2015, with the goal to supply 0stfold hospital (85 000m^2) with 8 GWh of heating and 4,5 GWh of cooling a year, with an effect need of 4,5 MW of heating. The energy is used to cover hot tap water, room warming, and process- and room cooling. This is accomplished with one heat pump, one large cooling machine, one electric boiler, two bio-oil boilers, four small cooling machines and two dry coolers, supplied with heat from 100 shallow geothermal boreholes, at a depth of 240 m each. In addition, the heat pumps use the cooling energy from the hospital as a heat source for the heat pumps. The heat pumps can deliver 90% of the heat demand, while the peak load is covered by a bio-oil boiler.

Table 5.10.1.2. Data on the heating and cooling machnices at Kalnes Energy Central

Unit	Heat capacity max/min (kW)	Cooling capacity (kW)	Max el use (kW)	Working medium
Heat pump 1	1249/125*	844	405	R717
Cooling machine 2	1030/258	973	390	R134a
Electric boiler	3000/100	-	3000	-
Cooling machine x4	-	1052	340	R134a
Oil boiler x2	3000/300	-	-	-
Condenserx2	1017**	-	12	-

*10-100% frequency regulated
**dumps the heat to the outside via the dump circuit

Heat pump 1 is responsible for the base load and has always a top priority for delivering heating and cooling to the hospital. As a heat source, it uses both heat from the hospital and from the shallow geothermal boreholes. It can deliver a maximum water temperature of 60^{O}C. The refrigerant is ammonia. The cooling machine is modified to not dump heat to the surroundings, but rather have a water condenser at the condenser side, which heat exchanges with the heat pump. The cooling machine can also deliver heat when the out temperature is below 48^{O}C and can then deliver an in temperature of 50^{O}C from the condenser. The cooling machine is also used to regulate the temperature of the cooling grid when the heat pump only delivers heat (Ebnes and Hagen 2017).

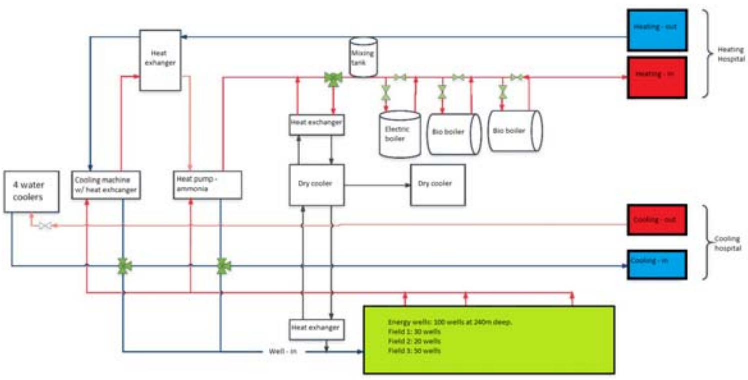


Fig. 5.10.1.12. Uproszczony proces eksploatacji w Kalnes Energy Central (Ebnes i Hagen 2017)

There are 100 shallow geothermal boreholes, with u-pipe collector with a depth of 240 m, and the bedrock consists of granite (Futurum Energi AS 2011). Key parameters are displayed in Table 5.10.1.3.

Table 5.10.1.3. Key parameteres for the energy wells of Kalnes Energy Central

Parameters	Value	Unit	Comment
Thermal conductivity	3.38	W/m*K (k)	(Futurum Energi AS 2011)
Number of shallow geothermal boreholes	100		
Depth of well	240	m	
Avg. temp. in boreholes	8	°C	(Futurum Energi AS 2011)
Max. temp. in boreholes	25	°C	
Area geothermal park	4200	m^2	7 m between boreholes
Volume geothermal park	1050000	m^3	
Volumetric heat capacity granite	666	Wh/ m^3*K	

The collector fluid HX35 is a mix of 35% ethanol and 65% water. After the evaporator, the fluid can be as cold as - 4°C in the heat pump. Key parameters are shown below in Table 5.10.1.4.

Table 5.10.1.4. Key parameteres for the collector fluid in the energy shallow geothermal boreholes of Kalnes Energy Central

Charakteristic	Data
Collector fluid	Water with 35% vol. ethanol
Density [kg/m^3]	965
Specific heating capacity [KJ/kg*K]	4.166
Freezing point [°C]	-17,5

Experiences from the first years of operation have, according to project developer Egil Erstad, been entirely positive. This is even though calculations on energy need for the hospital was 25% lower for heating and 22% lower for cooling than the actual need. This resulted in higher energy delivery from the energy central.

Nydalen Energy Central

Nydalen energy central and district heating and cooling system was established in 2003 in Oslo. The energy central delivered then heating to 170 000 m^2 and cooing for 135 000 m^2 through a local district heating system. The system is based on heat pumps, collecting geothermal energy through shallow geothermal boreholes and excess heat from the cooling systems around the area. The geothermal energy is collected through 180 boreholes of 200 m depth each, covering a total of 2 000 000 m^3 of bedrock. In 2014 they expanded the capacity by adding both a pellets- fired boiler and a heat exchange system with the river Akerselva, together with a gas boiler for peak load. This made the system able to deliver heat to 322 000 m^2 and cooling to 312 000 m^2.

The system takes advantage of the ability to store heat in the ground during the summer, by circulating hot water (25-40^{o}C) from cooling production down in the shallow geothermal boreholes, heating them from 7 to 15 ^{o}C. In the autumn, they mostly use the river as an energy source for heating and only starts using the geothermal energy from November, when the river starts freezing and keeps on using the geothermal energy throughout the winter. The collector fluid, water, and ethanol is pumped into the shallow geothermal boreholes with a temperature of 0^{O}C and returns at a temperature of 10^{o}C. In 2016, about 60% of the total heat production of 21 GWh was delivered from the heat pump system (Jansen 2017).

A talk with Bjorn Nygard revealed interesting aspects of the different phases of the project. The rest of this chapter is based on the talk with Bjorn. Firstly, the project was heavily dependent on governmental financial support. Out of the total investment cost of 60M NOK, 11 M NOK was given as financial support from the government and Oslo council. Without the funding, these investments would not have been done. Another key factor for increasing the profitability of the project was to include cooling together with heating. Offices are becoming more and more energy efficient, needing less heating than earlier, but they still have a cooling need. This is due to digitalization, meaning more electronic devices and a higher areal effectiveness, meaning more people per area. The adaptation to cooling is getting more important in a future perspective since plus houses and such have a low heating need, but still have a need for cooling, thus creating a new marked. Supplying cooling also means you produce heat during the summer, that can be stored in the ground, to be used in the winter. One issue, according to Bjorn Nygard, with supplying cooling is the lack of skilled workers for both installation and operation.

When planning a DH system one should be aware of the total demand for heating (and cooling) and try to predict the development of the future. It is also wise to construct a system of heat pumps that facilitate an incremental increase and decrease of effect, by having heat pumps of different installed effect, instead of adjusting the load of each heat pump, affecting the COP. Before installation, it is important to be present when the heat pumps and other machinery is tested, both at the factory and on site. This is to confirm that the given specifications match the actual performance. There should also be contracts in place that secure a guarantee period that include a full load test of both cooling and heating equipment. When placing the energy central, consideration of nearby buildings should be made due to the level of noise and vibrations the equipment can produce.

The operation is another important aspect, and a high level of maintenance and generally keeping everything clean is vital. The old heat pumps use refrigerant R134a, which the use of is heavily regulated in Norway due to its high ozone depletion potential, and global warming potential. If a leakage of R134a would occur, the fine from the government is high and increasing. The newer heat pumps are using ammonia as a refrigerant, which is poisonous. By keeping it clean, and having a high level of maintenance, one will not only keep the system running smoothly, but also avoid economic penalties, and avoid toxic leakages. Concerning the shallow geothermal boreholes, the collector fluid used must be able to withstand temperatures down to and below 0^oC, and a mixture of water and ethanol is thus often used. This fluid must be carefully monitored, since a leakage of air into the system can turn the refrigerant into acetic acid over time, eroding the pipes from the inside.

University College in Bergen

As a part of a large-scale collocation project for the University college in Bergen, it was chosen to use geothermal heat pumps, combined with cooling machines. The construction started in 2010 and finished August 2014, and delivers heating and cooling to 6 600 people at a 51 000 m2 area (including a garage of 3 650 m2). The annual cooling demand is at 1060 MWh, and the heating demand is 2 600 MWh (Dar 2014). The philosophy of the project was to keep the energy within the system boundaries of the building, and the surplus energy is thus stored for periods when a shortage of energy. For long-term storage, boreholes are used by dumping heat during the summer and extract heat during winter. For short-term storage, a cold storage for hourly regulation is also installed.

The system has an installed heating capacity of 2 830 kW, and a cooling capacity of 3 000 kW, using ammonia (R717) as a refrigerant. The reason for having a higher cooling capacity than heating, even though the annual heating demand is higher, is due to passive heating from the sun during summer, and a high number of internal loads, such as people and computers. To deliver the demanded heating and cooling, it is installed three heat pumps with a heating capacity of 343 kW, 511 kW and 788 kW and a cooling capacity, when used as cooling machines, of 292 kW, 438 kW and 671 kW respectively. Total capacity for the compressors is 300 kW. The heat pumps use 81 boreholes of 220m and the FlatICE™ cold storage tanks of 4 x 60m^3 (largest in Europe) to deliver cooling (Dar 2014). By using the cold storage tanks the avoided installation of 98 more wells, 1 600 kW of chillers and 400 kW of compressors is achieved. The cold storage tanks also made the planned dry coolers redundant, leaving the system better looking, less noisy and with a lower grade of maintenance. Since the cold storage also makes it possible to have a smoother operation, the operation conditions for the machines increase. The overall result is thus lower investments and a more profitable operation.

The cold storage tanks are filled with FlatICE™, which is a phase changing material (PCM) solution (salt hydrate) which has a freezing point of 10^OC. The PCM material is contained in sealed elements and stacked inside the tanks, with enough room between for water to flow through. The tanks contain 47 000 PCM elements, and the total cooling capacity is 11 200 kWh, given a 7 hours' discharge time


Fig. 5.10.1.13. An inside of storage tank with PCM elements (left) and set of storage tanks (right) (Dar 2014)

Fig. 5.10.1.14 shows a simplified schematic of the heating and cooling system for the University college in Bergen.

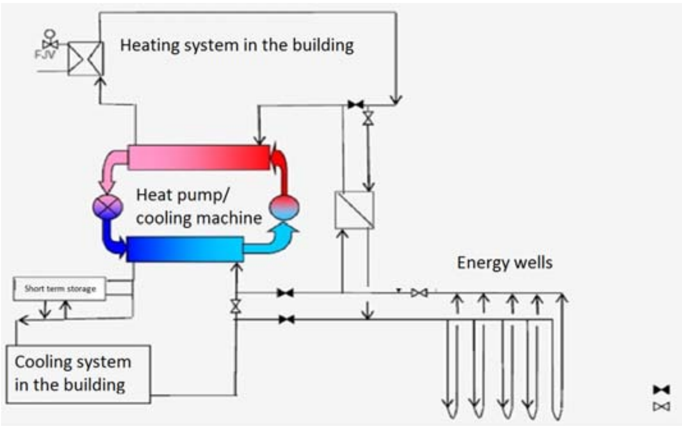


Fig. 5.10.1.14. Simplified schematics of the energy system (Dar, 2014)

Vulcan Energy Central

The Vulcan energy central delivers energy to seven major buildings, being two hotels, two office buildings, two combined apartment and grocery stores and one restaurant building. All buildings fulfill the passive house standard or the low-energy building standard (Stavset and Kauko 2015). The energy central can deliver 1 140 kW of heating and 1 130 kW of cooling, covering a yearly total energy need of 4,5 GWh cooling and heating (Joelson 2010). The central is build up of three heat pumps, 64 energy wells of 300m and solar collectors at the facade of one of the buildings. Water tanks are used for short-term storage of heat and ice banks are used as short-term storage for cooling. Out of the 1 130 kW of installed cooling, 200 kW is from the ice bank. During winter, the heat pumps can reach a COP of 3, while during summer the COP is around 1,5. The central is also connected to the regional district heating system.

The energy central has an operation strategy, consisting of three modes: heating, active cooling and free cooling. As a fourth option, the solar collector can be paired with all the other tree options. To optimize operation, these different alternatives can be combined. To use a combination can especially be efficient in periods with a high variation in ambient temperatures, such as during spring or autumn (Storas 2016).

A simplified sketch of the heating mode is shown in Figure 5.101.15. The energy is delivered through the heat pumps, from the energy wells and from the cooling circuit in Mathallen. If another part of the system also needs cooling, cooling from the evaporator side of the heat pumps can be used. The produced heat from the condenser side of the heat pump will accumulate in the hot storage tanks and be used if needed. Energy from solar heating is also stored in the hot storage tanks. Due to temperature restrictions for the heat pumps, the energy from the storage tanks is only used as pre-heating of tap water, while district heating is used to heat the water for use. For peak load, district heating is used (Stavset and Kauko 2015).

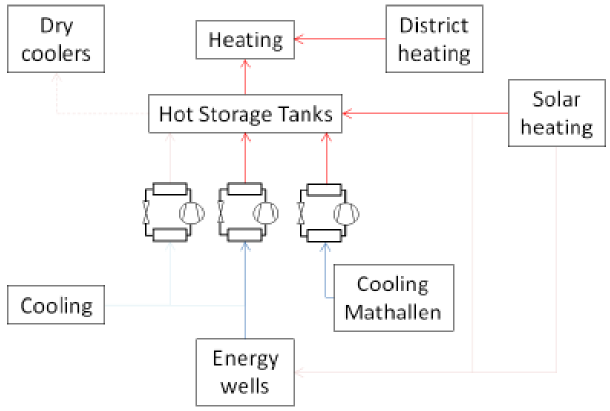


Fig. 5.10.1.15. Schematic diagram of the energy plant operating in heating mode (Stavset i Kauko 2015)

Figure 5.10.1.16 shows the schematics of the system in free cooling mode. This mode is used when the need for cooling and heating is fairly low and the energy wells are cold. This is particularly the case in the spring after the wells have delivered heat all winter. The collector fluid then flows directly from the wells to the cooling heat exchanger, and the only heat pump operating is the one that supplies cooling for Mathallen, which needs the energy to store the food. Heat is delivered as a combination of heat from the heat pump, solar heating, if available, and from the district heating system. When using this operation mode there is always a consideration between buying heat from the district heating grid or using the active cooling mode instead, and thus take advantage of surplus heat, that can deliver heating.

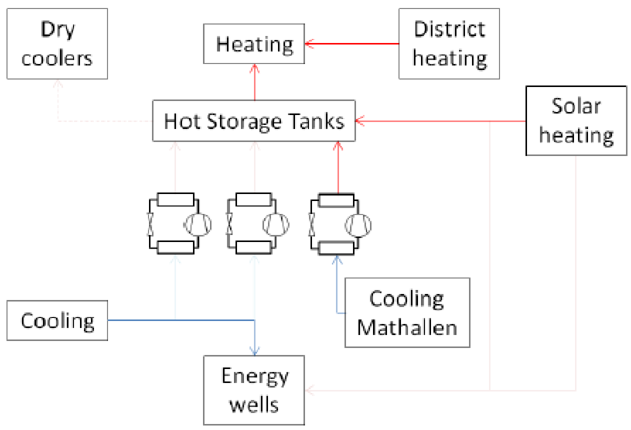


Fig. 5.10.1.16. Schematic diagram of the energy plant oparating in free cooling mode (Stavset and Kauko 2015)

Figure 5.10.1.17 shows the schematic diagram of the energy plant in active cooling mode. The heat pumps will now provide cooling for the buildings. The heat is used to heat the buildings, and to charge the storage tanks. If there is more heat available, it can be stored in the energy wells. Surplus heat can also be discharged in dry coolers if necessary. As for the heating mode, the district heating grid is used to heat the tap water to preferred temperature. The solar heating can either deliver heat to the storage tanks or to the energy wells.

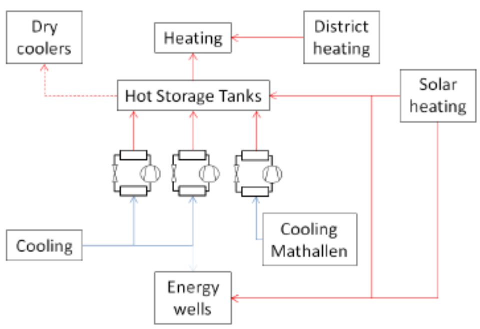


Fig. 5.10.1.17. Schematic diagram of the energy plant operating in active cooling mode (Stavset and Kauko 2015)

Drammen district heating

In 2011 Drammen district heating built the world's largest zero carbon 90ºC water heat pump (Star Refrigeration 2017) which uses sea water as a heat source and supply 14,3 MW of heat to 64 000 inhabitants. The system consists of 3 x 2 stage single screw compressor systems in series, with a heating duty of approximately 4.5 MW each. The system also has 2 x 30 MW gas-fired boilers for peak load during winter. The heat pump has a COP of 3.0 at 90ºC and a constant heat source temperature of 8ºC from the sea water. The refrigerant used is ammonia and was chosen out of a climate change perspective, since it has 0 global warming potential, unlike R134a and others (Hoffmann and Pearson 2011).

Figure 5.10.1.18 displays a typical heat load for the DH system in Drammen during winter. As seen, the HP will only work as a base load during the peak hours, but can still supply most of the heat. During winter, the temperature out of the energy central is at 120˚C, while being regulated down to 75ºC during summer, was the heating demand might be as low as 2 MW. The return temperature is always around 60-65ºC. When covering the peak load, the gas boilers work with a constant flow, heating the water 10ºC, and then mixed with the DH water, to reach the desired temperature. This process is optimized by having a variable flow system, taking water directly from the heating return line, achieving as much subcooling and as little overheating as possible (Hoffmann and Pearson 2011).

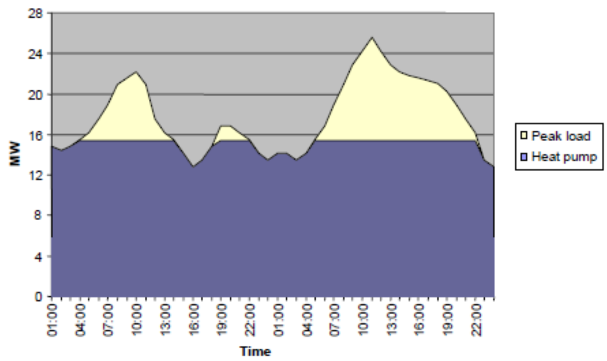


Fig. 5.10.1.18. Example of daily heat load variation in Drammen DHS (Hoffmann and Pearson, 2011)

Heat exchangers

When choosing heat exchangers for the system, shell and tube were chosen. The tubes for the district heating water are in stainless steel 304, while the evaporator tubes are in titanium. The heat exchangers have been chosen with the close approach, with the goal to optimize performance. The condensers and evaporates was chosen to only have a 2ºC difference from water outlet to condenser/evaporator temperature. For intercoolers, sub coolers, and oil coolers, they have all been chosen to be single pass and tube heat exchangers. These have counterflow, and the outgoing water temperature is higher than the outgoing refrigerant temperature (Hoffmann and Pearson 2011).

Compressor

The key component of the Drammen heat pump is the single screw compressor from Vilter (Emerson). This compressor is an upgrade from their normal refrigeration compressor for gas compression systems, to high- pressure systems. The single screw has balanced forces across the main rotor, both axially and radially. This is done by simultaneously compressing both sides of the rotor, canceling out the compression forces and balancing radial loads. The alternative, a twin screw, would compress only on one side of the rotor, creating a force trying to push the two rotors apart. The result of using the single screw instead of twin screw is an increase in bearing life with 120 000 hours, compared to regular refrigeration compressors (Hoffmann and Pearson 2011). The compressor is produced in three different pressure ratings: 76 bar, 52 bar and 36 bar, designed with a differential pressure up to 41 bar. The actuator operating the capacity and volumetric slides is operable up to a differential pressure of 26 bar. It is too expensive to do capacity control with an inverter drive on the 11 kW motors, so the differential pressure for each compressor is below 26 bar (Hoffmann and Pearson 2011).Sprężarki są produkowana dla trzech różnych ciśnień: 76 bar, 52 bar i 36 bar i przeznaczone do ciśnienia różnicowego do 41 bar. Siłownik obsługujący zawory mocy i objętości (zasuwy) działa przy ciśnieniu różnicowym 26 bar. Zbyt kosztowne byłoby sterowanie mocą za pomocą napędu falownikowego (inwertera) na silnikach 11 kW, tak więc ciśnienie różnicowe dla każdej sprężarki wynosi poniżej 26 bar (Hoffmann i Pearson 2011).

Another advantage, that makes it possible to operate at optimum conditions is the volumetric slides. Since there can be variations in both suction and discharge conditions throughout the year, the possibility to regulate volume increases performance.

System design

To have an optimal system it is of great importance to design the flow of water through the heat pumps to extract every kW at the right temperature. In Drammen, the three heat pumps work together to heat the water from 60–90°C, by working at three different temperature levels, where the first heats the water from 60°C to 69°C, the second from 69°C to 78°C, while the third from 78°C to 87°C. To increase the temperature from 87°C to 89°C the water stream is split into three, going through the high stage de-superheater for each system. In addition to the main stream, there are several separate streams going through different subcoolers, high stage and low stage oil coolers and intercoolers, absorbing heat on the way. The intercoolers are used for three reasons: they cool superheated gas that comes from the low stage compressors before entering the high stage compressors. This reduces the isentropic efficiency of the compression, and the lower suction temperature results in a lower discharge temperature, thus protecting seals from too high-temperature discharge gas on the high stage compressor. In addition, running the water flow through the intercoolers increases energy recovery of the system. The streams reach a temperature of 92-98°C through the coolers and is mixed with the main stream to heat the water the last degree from 89°C to 90°C. The three heat pumps work at different temperatures, but all have the same spec, meaning that if one fails, the remaining two can still deliver water at 90°C. The organization of the pumps, taking advantage of both series and parallel connection, reduces the average condensation temperature from 90°C to 80,5°C, which is a 10% improvement in efficiency for the ammonia heat pump system (Hoffmann and Pearson 2011). Figure 5.10.1.19 shows the operating conditions for each of the three heat pumps.

71.9 Condensing Circuit	Suction Pressure		Press Diff	Discharge Pressure		Discharge Temp	R717 Duty	Suction Temp	Discharge Mass Flow	Abs Power	Oil Cooling	System HOR	System Abs	System COP
Machine	bar A	°C	Psi	bar A	°C	°C	kW	°C	kg/s	kW	kW	kW	kW	
1201 Cast Steel	19.4	48.3	225	34.9	72.4	114.5	3888	64.0	3.412	484.9	120			
VSS2101	4.4	1.0	224	19.9	49.3	99.3	327	1.0	3.201	805.8	281	4,616	1,342	3.44
80.7 Condensing Circuit	**Suction Pressure**		**Press Diff**	**Discharge Pressure**		**Discharge Temp**	**R717 Duty**	**Suction Temp**	**Discharge Mass Flow**	**Abs Power**	**Oil Cooling**	**System HOR**	**System Abs**	**System COP**
Machine	bar A	°C	Psi	bar A	°C	°C	kW	°C	kg/s	kW	kW	kW	kW	
1201 Cast Steel	23.5	55.8	274	42.4	81.2	115.1	3754	64.8	3.367	493.8	135			
VSS2101	4.4	1.0	285	24.1	56.8	104.6	415	1.0	3.279	939.5	389	4,693	1,491	3.15
88.5 Condensing Circuit	**Suction Pressure**		**Press Diff**	**Discharge Pressure**		**Discharge Temp**	**R717 Duty**	**Suction Temp**	**Discharge Mass Flow**	**Abs Power**	**Oil Cooling**	**System HOR**	**System Abs**	**System COP**
Machine	bar A	°C		bar A	°C	°C	kW	°C	kg/s	kW	kW	kW	kW	
601 Cast Steel	26.1	60.0	347	50.0	89.0	117.7	3662	65.0	3.343	528.3	155			
VSS2101	4.4	1.0	323	26.7	61.0	107.2	471	1.0	3.328	1016.2	453	4,740	1,606	2.95

Fig. . 5.10.1.19. Operating conditions of each of the three heat pumps in Drammen (Hoffmann and Pearson, 2011).

References:

Dar, Usman. 2014. “Høgskolen i Bergen Energisentral.”

Ebnes, Kristian, and Emil Hagen. 2017. “Operational assessment of Kalnes energy central.” Master thesis. NMBU.

Futurum Energi AS. 2011. “Sarpsborg Nye Sykehus - Termisk Responstest Forprosjektering Av Geoenergianlegg.”

Hoffmann, Kenneth, and David Forbes Pearson. 2011. “Ammonia Heat Pumps for District Heating in Norway – a Case Study.” Case study. Institute of Refrigeration.
https://www.ior.org.uk/app/images/papers/2011_Ammonia%20heat%20pumps%20for%20district%20heating%20by%20K%20Hoffman.pdf

Jansen, Terje. 2017. “Nydalen Energisentral.” Avantor. Accessed September 20.
http://avantor.no/nydalenenergi/

Joelson, Av: Trond. 2010. “Vulkan Åpner Energisentral.” Bygg.No - Byggeindustrien. December 7.
http://www.bygg.no/article/66163.

Star Refrigeration. 2017. “BBC’s Take on World’s Largest Natural Heatpump - Star Refrigeration News.” Accessed September 26.

http://www.star-ref.co.uk/news/bbcs-take-on-worlds-largest-heatpump.aspx

Stavset, Ole, and Hanne Kauko. 2015. “Energy Use in Non-Residential Buildings-Possibilities for Smart Energy Solutions.”

Storås, Charlotte Storås. 2016. “Assessment of an advanced heating and cooling system with thermal storing.” Project thesis. NTNU.

5.10.1.5. Recommendations from Norway

The following section sums up the key findings of this report and presents it in the following three stages: laws and regulations, planning and construction, and operation and maintenance.

Laws and regulations

To facilitate for district heating and geothermal heat pumps there should be laws and regulations in place. In Norway, we have the technical building regulation (TEK) which is the minimum criteria when a new building is being constructed. By improving the TEK requirements, Norway has been able to start a shift away from fossil heating and direct electric heating, and over to the use of district heating and other more local energy systems, like geothermal heat pumps. There are also regulations in place to protect the interests of the owner of the district heating system (DHS), by demanding that houses being constructed within the concession must connect to the DHS. Experiences from Denmark also show that the use of strong governmental regulations can create a market for district heating, also for places that have been assessed as an uneconomic investment.

For both Nydalen and Bergen, financial support from the government have been important, and even essential. While Nydalen got funding for construction, Bergen received funding in the feasibility phase.

Planning and construction

When planning a new district or local heating system or refurbishing an old one, it is of the essence to have a good understanding of the demand, and the available energy sources. The demand should thus be calculated/measured, both for heating and cooling, and seen in the light of potential development in the area. This goes for both the number of new buildings and the quality of them since an increased quality shifts the heating and cooling needs of the building. The energy central at Kalnes, did calculations on the heating and cooling demand prior to the construction, and planned accordingly, but their calculations were wrong, resulting in a system that had to work harder than expected. There should also be an investigation into the potential energy sources for the system. Factors that must be considered, when choosing energy source is the temperature of the system, availability of fuel and price of fuel. By lowering the temperature system down to a 4. Generation DH system, it's easier to utilize renewable energy such as solar or geothermal, since they normally deliver lower temperatures than conventional combustion systems. When considering any sort of combustion system, it should be taken into consideration the availability and price of the fuel, both now and in the future. What we know is that fossil fuels probably will increase in price, due to their negative influence on the climate. On the other hand, biomass might potentially also increase in price due to an increased demand based on its benign climate effects. Mixing different sources of energy is nearly always both wise and possibly the only solution if the system should cover both base and peak load. By using a set of energy sources the system is also modeled with redundancy, which improves delivery security.

One option that nearly always will be relevant, when considering to build a district or local heating system is the use of a heat pump. When considering a heat pump there are again several aspects to take into consideration. The first step is to decide on what type of heat pump to use. While both hybrid and thermal heat pumps are potential alternatives, they often restrict themselves by being too expensive. The absorption pump also has the issue of finding a suitable high-temperature heat source with low cost and emissions.

When planning to use a regular mechanical heat pump, the most important aspects to consider are the heat source, refrigerant, compressor, part load regulation and temperature levels on the heating system. The choice of heat source should be based on the stability of the heat source, price, availability, and durability, and there might be opportunities to mix two or more of them to improve the overall efficiency of the system. As with Nydalen, they use the local river as a heat source, together with waste heat from the surrounding office buildings during summer, while using their shallow geothermal wells during the winter. Connected to the choice of energy source is also the alternative to store energy, both hot and cold. One option is to use the geothermal wells, by dumping heat from cooling production during summer, and extracting it in the winter, as done in Kalnes, Nydalen, the University college and in Vulcan. Another option, that has been used together with geothermal storage, is the use of short-term cold storage. University college in Bergen only had to build 81 wells by using the short-term storage tanks, contrary to 179 if they did not build the cold storage and dimensioned the geothermal wells on the basis of needed cold storage capacity.

The next step is to choose refrigerant. For large scale heat pumps ammonia is a good option concerning both efficiency, ozone depletion potential, and global warming potential while being both explosive and toxic. One alternative, being R134a, was by Nydalen seen as good when they installed their system, but now regret the decision based on the increased cost due to governmental regulations on the use of HCFCs. Such an experience is probably of value for Poland, since, if it's not already in place, the chances are good for new regulations, trying to limit the use of HCFCs by added fees.

When deciding on the compressor, the standard advice from Sweco is to use a piston compressor. They are good on price and the potential for regulation. For this study, it has been discovered that both Kalnes and Drammen have a screw compressor, with good results. These compressors are of high quality and expensive, giving them the ability to frequency regulate, to adjust for a variable load. In addition, Drammen predicts that it will give them 120 000 more operating hours per compressor. Instead of having very high-quality compressors, able to regulate and adjust to the load, it could be used several compressors. In addition to reducing cost, there is a security bonus by having several machines, thus having redundancy in case of emergency. An experience from Nydalen is to also not install several machines with the same capacity since it's easier to regulate and adjust to load if the machines have different capacity. The coefficient of performance (COP) will then also be increased, as the general compressor performs best at full load.

When the system is designed and the different machines and components have been chosen it is important to have all of the major machines and components tested, both at the factory and on site. Supervisors involved in the design and construction should be present at both tests, to evaluate if they perform as expected. This point was specified by Nydalen, that had a bad experience with not getting what they were promised. It is not always possible to run the machines at 100% just after installation, and if so, it should be given a deadline on when such a test should be done. This is to prevent the issue of testing the equipment too late, just to find out that it did not perform as expected.

Operation and maintanance

To be able to evaluate the actual performance of the given heating and/or cooling system it has to be monitored. This is easiest done with a good industrial control system (ICS) with sufficient measuring points in the system. A practice that was used in Nydalen was to do as much as possible manually in the beginning. This was to learn how the system functioned. Then slowly, more and more tasks and processes could be automated and programmed. Another option, that was used for both Kalnes and Bergen, is to have students do a thesis about optimizing the performance, or in general, use qualified personnel to optimize.

A lesson from Nydalen on operation and maintenance is to keep the entire facility clean and tidy. This makes it much easier to detect faults and leakages. A leakage can potentially be dangerous for workers and locals, expensive for the owners, and damaging for the ozone layer and the climate.

On maintenance, a potential issue was that the ethanol, which both Nydalen and Kalnes use, used in the wells might turn into acetic acid and rust the pipes from the inside. This can be avoided with regular controls and a high rate of maintenance.

Finding qualified personnel for both the heating and cooling side of the process was also highlighted as important to prevent a wrong installation and failures during the operation. And in general, one should seek competent personnel for all the steps of the process from the design phase, construction, operation, maintenance and decommissioning.

5.10.2. Success of geothermal heat pumps in Iceland (real data on electricity savings)

Introduction

Heat pumps are an interesting option in order to lower the cost of electrical heating. It can be lowered by 25-80% based on technology and difference in location circumstances. Due to that, heat pumps are an environmental friendly option that improves energy efficiency and lowers the cost of electrical house heating for people and the subsidization cost for the State considerably.

Geothermal heat pumps have been gaining ground on the Icelandic heat pump market in the last decade. The technology behind it has been evolving rapidly and knowledge of the function ability in Icelandic weather conditions has increased. Iceland is rich of geothermal energy at various temperatures, whichcan be found in different conditions around the country. In the later years, the installed geothermal heat pumps have better efficiency and a relatively high ΔT, i.e. can take in low temperature water and return high temperature water. Some types are able to take in water near the freezing point and return e.g. 40-50°C hot water, which is more than enough for a house with floor heating. In some situations where the temperature of the geothermal water is too low for direct heating of houses, a heat pump is installed to raise the temperature of the geothermal water. That has proven to be a good and simple solution to the problem.

In the past years, it has become known that some of the district heating systems, that use electrical boilers to heat the water, need a heavy refurbishment. The refurbishment is very expensive and the system has a high maintenance cost. As a solution to that, one company has decided to stop using the system and install instead heat pumps in every house (200 customers) and use only electricity to heat the houses in the system. This proves to be a much cheaper solution, estimated to save at least five million Euros, for both the customers and the company, over a 20 years period. The Icelandic State tends to take part in financing the instalment of the heat pumps with lump sum payments.

One municipality in Iceland is currently installing a seawater heat pump to replace an existing electricity boiler and produce suitable fresh hot water for the district heating. The boiler currently relies on low priorityelectric energy, which might not be available in the future on the terms that have been valid hereto. The Icelandic State supported the project with a 2.5 million Euros grant.

Executive Summary

- Some types of geothermal heat pumps are able to take in water near the freezing point and return e.g. 40-50°C hot water, which is more than enough for a house with floor heating.
- In some situations where the temperature of the geothermal water is to low for direct heating of houses, a geothermal heat pump is installed to increase the temperature of the geothermal water.
- The use of heat pumps in public buildings has been growing steadily in the past years and the share of geothermal heat pumps is constantly increasing. There has also been increasing awareness among the service industry, using geothermal heat pumps to lower their high electric heating cost.
- Residential houses share about half of the geothermal heat pump market in Iceland. There is a large potential for geothermal heat pumps across the country in regions where geothermal heating systems have not proven feasible.
- The State levels out cost of living around the country, where geothermal heating is not available, with subsidies that lower the cost of heating residential houses.
- A change in 2009 of the law Act No. 78/2002, made it possible for people to apply for a lump sum from the State to finance the purchase and instalment of heat pumps in exchange of lowering the subsidies in accordance with the electric savings resulting from the implementation. The lump sum is tax-free and can be fully used to install a heat pump. Over 400 residents with subsidized electrical heating have used this option.
- The total number of geothermal heat pumps installed in Iceland is unknown since there is no official regulation demanding that the companies selling heat pumps report records of the sale. However, the National Energy Authority collects electricity heating usage data for all the houses that have gotten a lump sum payment.
- The average saving ratio of geothermal heat pumps, according to the collected data, is close to 70% of the initial electric heating usage with the maximum up to 80% and the minimum roughly over 40%. This average share is equivalent to 21.9 MWh_e in savings for each house. The average time interval of the monitoring is 2.1 years, i.e. from the first day of usage until the last meter reading.
- A house owner, with a geothermal heat pump, is saving on average just over 1.2 thousand Euros annually, with VAT included, and the State is saving in reduced subsidies roughly 1.1 thousand Euros annually. Combined, this adds up to 2.3 thousand Euros annually that can be used on other issues within the Icelandic economical system.

5.10.2.1. Use of Geothermal Heat Pumps in Iceland

Public Buildings

The use of heat pumps in public buildings has been growing steadily in the past years and the share of geothermal heat pumps is constantly increasing. With better knowledge, experience and technology a greater diversity of public buildings has installed geothermal heat pumps to lower the electrical heating cost. The types of buildings using geothermal heat pumps vary from schools and municipality centres to swimming pools and sports centres. Some of the more modern churches in the country have installed geothermal heat pumps but the older ones made of wood and built a century ago are not suitable for such heat pumps. The same applies to other types of buildings of same age and with same structure.

Residential Houses

Residential houses share about half of the geothermal heat pump market in Iceland. Individuals who have access tosources of ground water, at temperatures near the freezing point, are more willing to install geothermal heat pumps in their homes than they were few years back. It has been proven that they do not need to go into expensive drillings or procedures and the risk is not as high as initially thought. Around 8% (ca. 10-11.000) of the residential houses in Iceland use electric heating and the number of geothermal heat pumps sold to individuals is counted in hundreds (Fig. 5.10.2.1). There is a large potential for geothermal heat pumps across the country in regions where geothermal heating systems have not proven feasible.

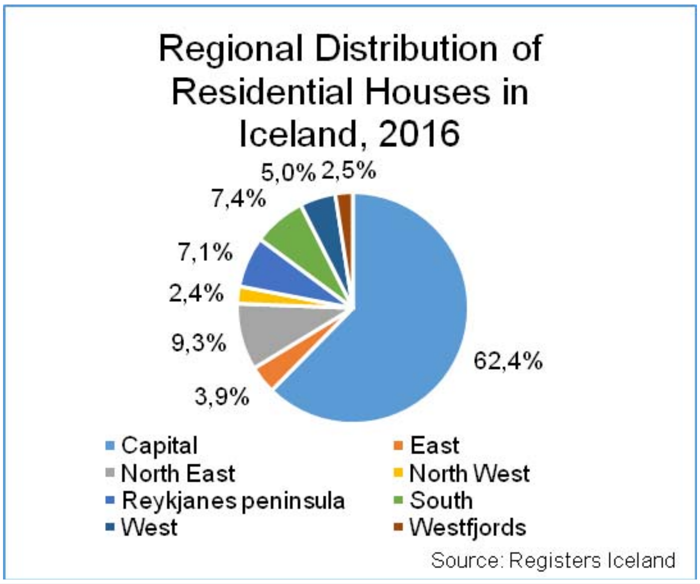


Fig. 5.10.2.1. Regional distribution residential houses in Iceland, 2016

Other Buildings

Summerhouses in Iceland are over 13,000 and distributed all around the country, mostly in the rural area where the main heating source available is electricity (Fig. 5.10.2.2).A majority of summerhouse owners has installed or is considering heat pumps in order to lower electrical costs. The average size of Icelandic summerhouse is 65 m^2, designed with a one large compartment and couple of small rooms. Therefore there is no need for highly productive or expensive heat pumps such as geothermal heat pumps. In most situations the cost of searching and drilling for geothermal waters to use for heating is too high for an individual. At least the cost does not match the gain in most cases. The summerhouse owners have therefore usually used air-to-air or air-to-water heat pumps to reduce their electrical consumption in the summer houses.

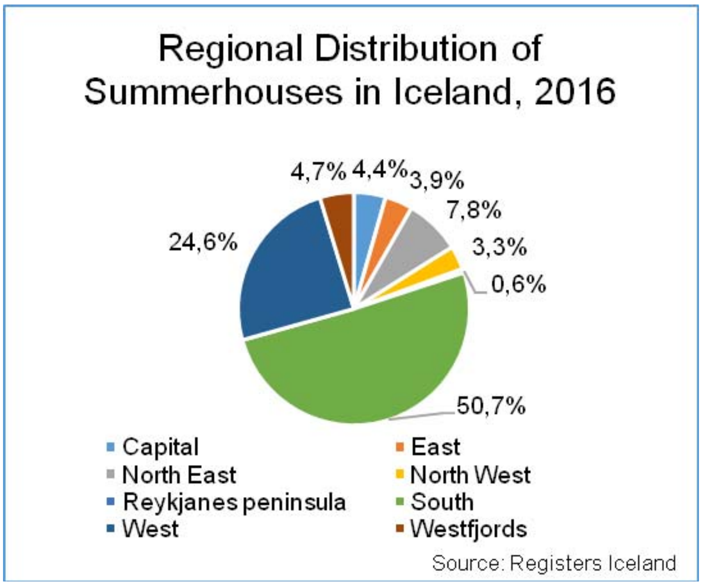


Fig. 5.10.2.2. Regional distribution of summer houses in Iceland, 2016

According to heat pumps sales companies awareness has increased among the service industry of using geothermal heat pumps to lower their high electricheating cost. In relatation to the rapid growth of the tourism industry in Iceland a lot of hotels has been built and refurbished around the country in the last few years.In the “cold areas”, where there is no geothermal heating available, a big part of that process has been to install geothermal heat pumps with good results in regards of electric efficiency. Even though the initial investment cost is rather high the investors look at it as a highly economical solution in the long run that pays back quickly the investment cost.

5.10.2.2. Public Support

Subsidy

Residents, who do not have access to geothermal heating, heat their houses with electricity or oil. Electricity and oil for heating houses is much more expensive than geothermal district heating. In order to level out living costs around the country the Icelandic State uses subsidies to lower the cost of residential house heating where geothermal energy is not available.

The subsidies on behalf of the State are substantial and the yearly contribution is about 1.7 billion Icelandic króna or 14.2 million Euros. It can be said that those who get subsidy are heating their houses in cooperation with the State. It is therefore in the common interest of the residents and the State to reduce the cost of electric heating. Heat pumps are certainly one option to look at. Subsidized electricity amounts to around 300 GWh_e/annum and a lot can be saved.

Further description of the terms of the law (Act No. 78/2002) regarding the subsidy:

- Heating with electricity: Distribution and transportation cost is fully subsidised up to 40,000 kWh/year for each residential house. It must have at least one person registered as a resident. Other public houses such as churches, museums and community centres are also eligible for subsidies.
- Heating with oil: The subsidies are equal to the most expensive distribution and transportation cost of electricity. The subsidies are limited to 4,500 litres of oil per year and subject to the same restrictions regarding the resident registration as the electrical heating.
- District heating with electric boilers: The subsidies are determined so that the heating cost is equal to the most expensive geothermal heating and subject to the same restrictions as the electrical heating.

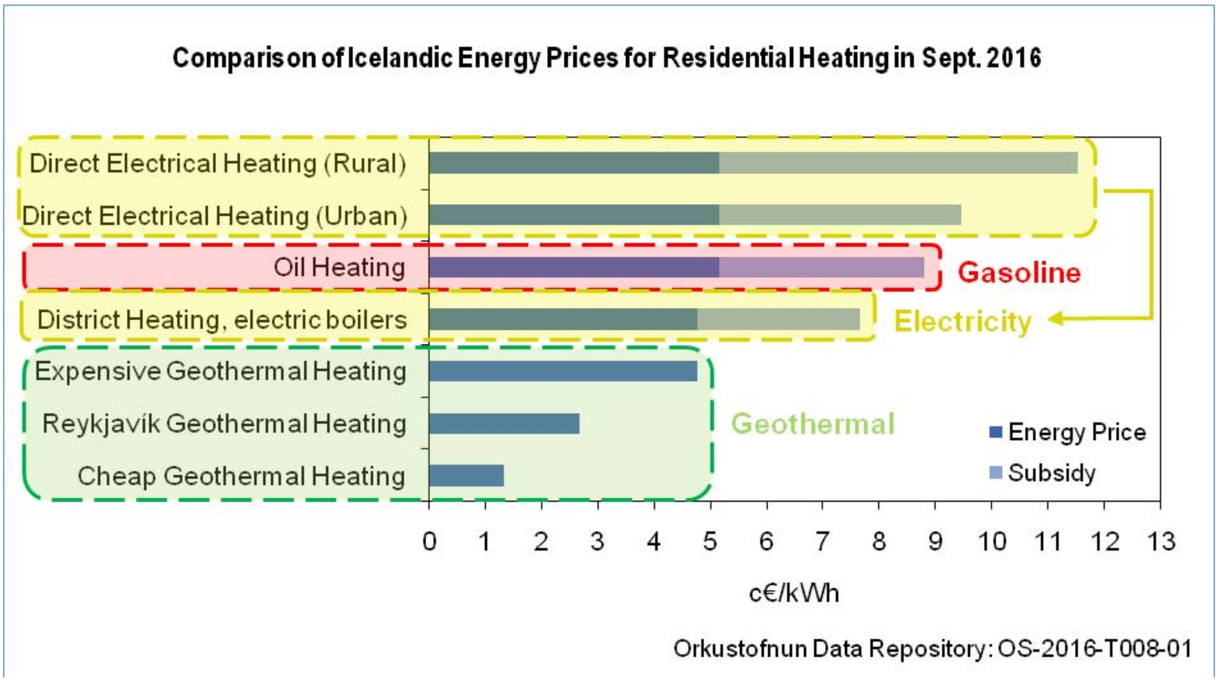


Fig. 5.10.2.3. Comparision of Icelandic Energy Prices for Residental Heating

Rural Contribution

The electricity distribution and transportation companies in Iceland offer different prices in the rural and urban areas. The prices are significantly higher in the rural areas. In addition to the subsidies, the State provides a rural contribution to balance out the electricity price difference between the rural and the most expensive urban areas. This contribution is financed with a tax, equivalent to 2.5 €/MWh, on all electricity usage, both for heating and everyday use. This contribution changes at least once a year, based on the national usage and price changes.

Tax Deduction

An individual who has invested in any type of heat pump can have the VAT of the heat pump itself refunded from the State. This is limited to the heat pump being installed into a residential house or other public houses that get subsidy. The lump sum (see next section) is tax-free and can be fully used to install a heat pump or other energy saving technology.

Lump Sum Payment

A change in 2009 of the law Act No. 78/2002, made it possible for people to apply for a lump sum from the State to finance the purchase and instalment of heat pumps in exchange of lowering the subsidies in accordance with the savings resulting from the implementation. The same applied for building of a small home-based power station, where suitable, and a connection to a private geothermal heating system. The lump sum is actually extrapolated subsidies and the period is based on how much subsidy the State will save. A person who intends to install a heat pump that is expected to reduce the electric heating usage by 50% can at most receive a lump sum based on a period of eight years. A person that changes to own electrical production from a home-based power station or connects to a private geothermal heating system gets a lump sum based on 12 years.

Over 400 residents with subsidized electric heating have used this option. It is known that many house owners of e.g. summerhouses and service buildings have invested in heat pumps, but theyare, according to the law, not eligible to get subsidy and lump sum. Therefore, it has been difficult to collect adequate information of the number of heat pumps in Iceland but the development of house heating in the past ten years shows that the electric usage has decreased significantly. In 2007, the electric heating usage was 750 GWh_e/annum but today it is between 600-650 GWh_e/annum.

Demo:

A house owner is using on average 35.000 kWh/annum of electricity to heat his house in the rural area. The owner decides to invest in and install a geothermal heat pump. He hands in an application for alump sum to the National Energy Authority and estimates to reduce the electricity usage for heating by 75%. According to the prices in figure 5.10.2.3 the lump sum would be 13.4 thousand Euros. This amount is tax-free and can be fully used to install the geothermal heat pump. In addition to that, the VAT of the geothermal heat pump is refundable.

The National Energy Fund

The National Energy Fund occasionally provides grants for geothermal exploration near public buildings in rural areas that get no subsidy and where there is only electric heating available. The goal is to find sufficient geothermal water for heat pumps to heat up the public buildings.

5.10.2.3. Statistical Information

The total number of geothermal heat pumps installed in Iceland is unknown since there is no official regulation demanding that the companies selling heat pumps report records of the sale. However, OS collects electric heating usage data for all the houses that have gotten a lump sum payment. By doing that, it is easier to monitor and have oversight on how productive the heat pumps are. Taking a closer look at the houses with geothermal heat pumps installed it can be seen they are efficient and are contributing, mostly, as estimated. There are some cases where there have been some minor problems occurring with operation, technology or calibration. It has usually been solved with simple procedures.

The average savings ratio, according to the data, is close to 70% of the initial heating usage with the maximum up to 80% and the minimum roughly over 40%. This average share is equivalent to 21.9 MWh_e in savings for each house. The average time interval of the monitoring is 2.1 years, i.e. from the first day of usage until the last meter reading. Compared to an average house in Iceland, which uses 30 MWh_e/annum, 21.9 MWh_e is equivalent to 73% decrease in energy usage. That is similar to the percentage decrease from the OS data.

The use of geothermal heat pumps in Iceland is not only beneficial for the residential house owner but it is also beneficial for the State. With more savings on electricity for heating residential houses the total amount of subsidies, the State has to supply, decreases. A house owner is saving on average just over 1.2 thousand Euros annually, with VAT included, and the State is saving in reduced subsidies roughly 1.1 thousand Euros annually. Combined this adds up to 2.3 thousand Euros annually that can be used on other issues within the Icelandic economical system (Fig. 5.10.2.3).

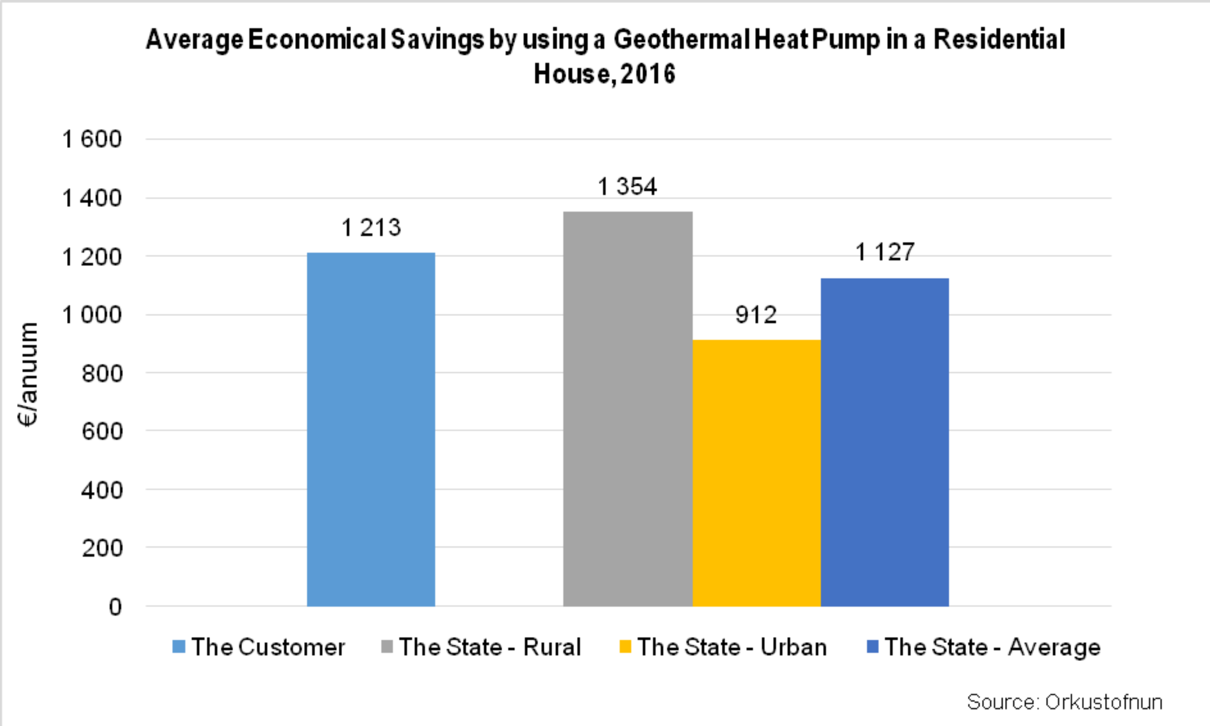


Fig. 5.10.2.3. Average economic savings by using a geothermal heat pump in a geothermal heat pump residential house

5.10.2.4. Conclusion

Even though the number of installed geothermal heat pumps in Iceland is currently unknown and the experience in using it, compared to e.g. Norway and Sweden, is significantly less, then it is a known factor that use of geothermal heat pumps in Iceland has a significant impact on energy savings and efficiency in heating houses.

The geothermal heat pumps have also proven to function properly in extreme Icelandic weather conditions, all year around. With improved technology and experience, increased awareness raising and support from the Icelandic State the use of geothermal heat pumps is expected to continue growing in coming years.

5.11. ATES and UTES technologies in Norway and Europe – recommendations for Poland

5.11.1. Introduction

This chapter gives an overview of technologies for underground thermal energy storage (UTES) in Norway and Europe. Focus is on large installations. UTES systems can be divided into three main types (see Fig. 5.11.1.1):

- Aquifer thermal energy storage (ATES). ATES uses aquifers (natural water in a saturated and permeable underground layers) as the storage medium. Thermal energy is transferred by extracting groundwater from the aquifer. In general, water is reinjected at a changed temperature at a separate well nearby to keep hydrogeological balance. ATES is the most economical and energy efficient alternatives of the UTES applications.
- Borehole thermal energy storage (BTES). BTES consists of vertical boreholes, typically with 50 to 300 meter depth, but deeper boreholes are also possible. The boreholes ensure the transfer of thermal energy to and from the ground (clay, sand, rock etc.). BTES are often used in combination with heat pumps.
- Cavern (or abandoned mine) thermal energy storage (CTES). CTES uses water in large, open, underground caverns to serve as thermal energy storage systems. CTES includes the use of manmade structures, like e.g. abandoned mines..

In addition there are other types of UTES which are less used, e.g. energy piles, duct storage and buried tanks.

The majority of UTES systems in Norway are BTES due to the geological conditions favoring this type of systems, with the remaining systems being mostly ATES. More than 90 % of the ground source heat pump (GSHP) systems in Norway utilize energy from boreholes in crystalline rock. In most of Europe, the majority of UTES systems are BTES, but in some countries ATES systems are predominant, e.g. in the Netherlands. UTES systems are sometimes augmented with other types of energy storage, e.g. phase change materials. This is for example done in the installation at the Western Norway University of Applied Sciences[1] (site visited during Norway visit).
BTES and ATES systems are described in detail in the sections below.

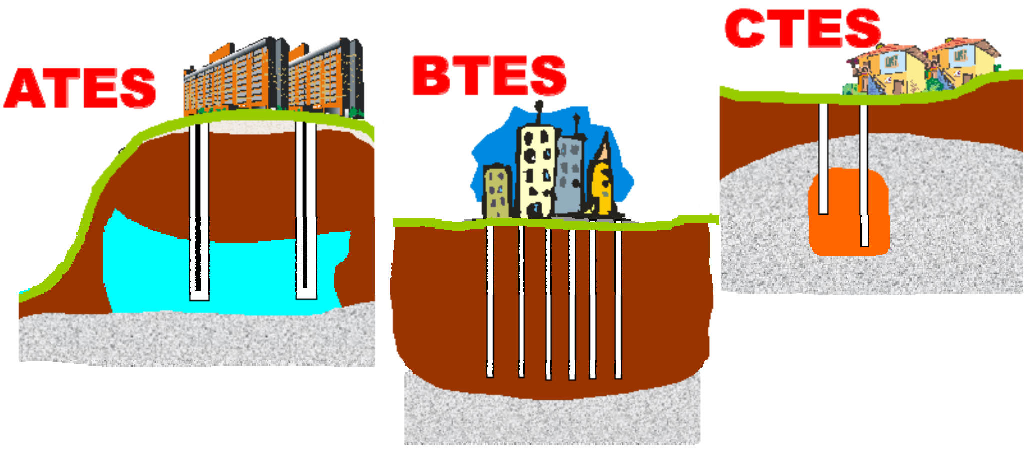


Fig. 5.11.1.1. UTES applications ATES, BTES and CTES (Paksoy 2007).

5.11.2. Geological conditions

Norway is located on the Fennoscandian Shield. The bedrock consists of Precambrian rocks with a belt of Caledonian rocks extending from south-western to northern Norway. Permian volcanic and intrusive rocks are found in the Oslo region. The porosity of the crystalline bedrock is low. A thin layer of glacial sediments or marine clay generally covers the bedrock, and in some of the larger valleys, there are groundwater aquifers in alluvial or glacial sediments (Midttømme 2005). The lithosphere is cool and thick and characterized by a low heat-flow density that is below the continental average (Kukkonen, 2002). The

[1] The Norwegian name for the Western Norway University of Applied Sciences is *Høgskolen på Vestlandet*, formerly known as *Høgskolen i Bergen* (until 2016)

median heat flow value for mainland Norway is around 58 mW/m2. An overview of heat-flow studies for Norway is given in Pascal (2015).

Geological conditions in Europe are varied compared to the uniform geology in Norway (seeFig. 5.11.2.1). A detailed description of the geology in Europe is outside the scope of this report, it should however be noted that in the Netherlands, Denmark and flat parts of Germany and Poland the geology is dominated by sedimentary rocks with sandstone aquifers of Jurassic and Cretaceous age.

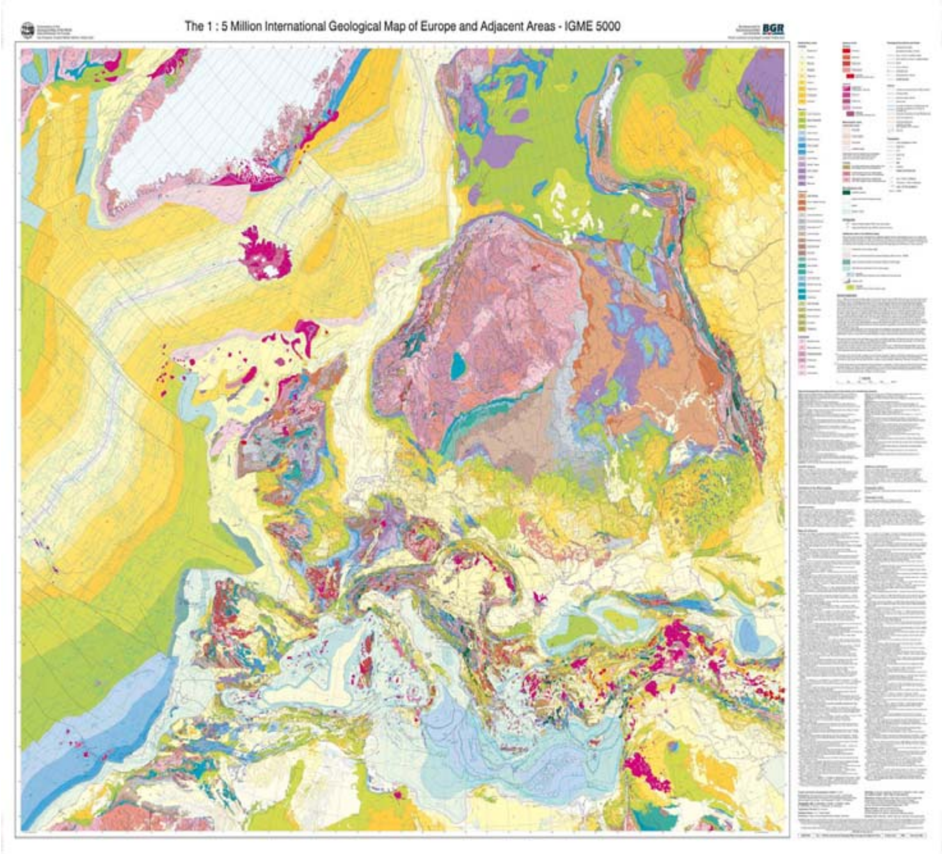


Fig. 5.11.2.1. Geological map of Europe. Source: IGME 5000.

5.11.3. BTES

5.11.3.1. BTES in Norway

BTES can be constructed wherever boreholes can be drilled, and are composed of one to hundreds of vertical boreholes which ensures the transfer of thermal energy to and from the soil and rock..

All BTES systems in Norway are vertical[2] closed-loop systems extracting heat and/or cold from crystalline rocks by use of borehole heat exchangers (BHE), and nearly all BTES in Norway utilize heat pumps. A typical Norwegian BTES is based on several boreholes with depths of 150 – 300 meters. A trend towards deeper boreholes has been observed the last 5–10 years, partially due to improved drilling technology/equipment and lower drilling cost for deeper boreholes. The average borehole depth in fields with 4 boreholes or more exceeded 200 meters for the first time in 2009, and increased further to more than 230 meters in 2014 and 2015.

Norwegian BTES systems with a total effective borehole length of more than 10.000 meters are listed in Table 5.11.3.1. From these statistics it can be seen that some of the largest systems installed the last years have an average borehole depth of around 300 meters; Nygårdsporten Bergen, Røyken Rådhus and Kongsberg Kulturpark. The first 500 m deep BHE was

[2] Some boreholes defined as vertical are set with a 10-20 degree borehole azimuth in order to better exploit the heat reserves.

installed in 2011 (Midttømme 2013), and in 2015 a BTES consisting of 9 BHEs with 500 m depth was established at Maudbukta in Asker (Hanstad 2017).

BTES has become an integrated part in the planning of energy systems of Norwegian buildings, in many cases introduced as an energy efficiency measure, reducing the energy demand for water heating and for cooling and heating of the buildings. This is partly due to the strong requirements related to reduce energy usage in buildings in Norway, regulated through the regulations on Technical Requirements for Building Works (TEK17). Buildings with more than 1000 m^2 floor space are required to have energy flexible heating systems covering at least 60% of the net heating demand, and use of low temperature heating solutions need to be facilitated.

These regulations, along with the trend towards passive house standard/Zero Emission Buildings and the push towards a desired high share of renewable energy, has increased the use of BTES in Norway significantly. This applies typically for larger buildings with combined heating and cooling demand such as shopping malls, health care centers, offices, schools hotels etc.

Most of the large BTES in Norway are designed for the cooling demand although the heating demand is usually higher. The buildings typically have additional heating source(s), like district heating (DH), gas or electrical boilers to cover the peak heat loads. Because of the unbalance with higher heating than cooling demand, additional charging of the BTES with heat is performed for balancing the operation. The most used methods for additional charging of heat includes using solar heated water from e.g. solar collectors, football fields or big parking lots, using excess heat from shopping centres, data centres or industry cooling or by utilizing other types of waste heat.

The space cooling is in Norway is mostly performed by direct cooling without use of heat pumps.In most BTES, the ground temperature is below 17°C which is sufficient for direct cooling Direct cooling is very cost effective due to the very limited use of energy for circulation of fluid (only the circulation pump), and a COP for direct cooling between 20 and 50 is common.

A BTES system comprising 52 BHEs of 150 m depth provides heating and cooling for an office building at Alnafossen, Oslo. Fig. 5.11.3shows the office building with facades of glass and the lawn where the boreholes are drilled. The graph shows the heating and cooling delivered from the BTES systems in the period October 2005– October 2006. There is a continuous cooling need through the year because of cooling of technical installations which matches the heating need from the fall to the spring.

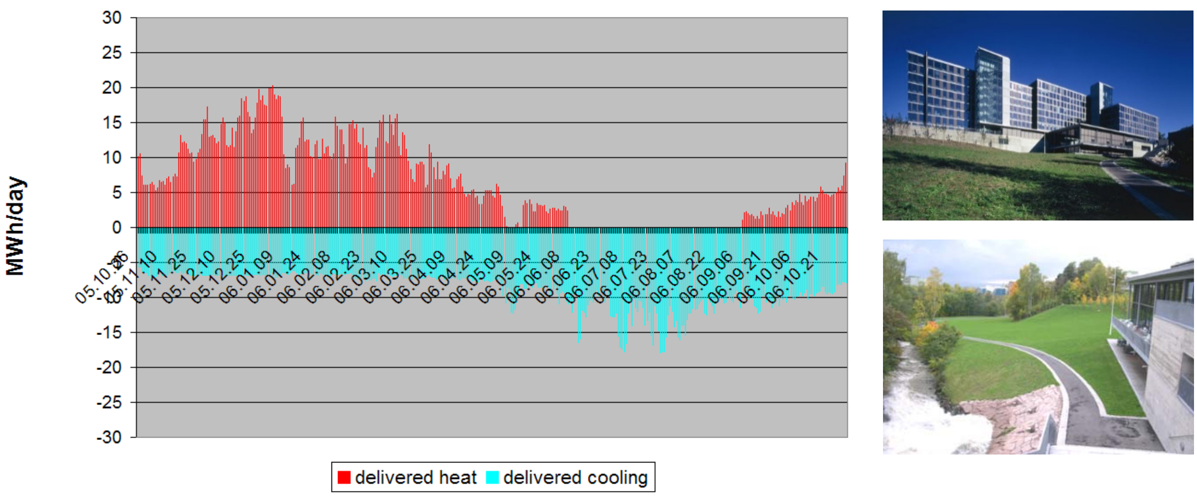


Fig. 5.11.3.1. Alnafossen Office building, Oslo. A BTES comprising 52 BHEs to 150 m depth is established at the lawn photo right bottom. The graph (left) shows delivered heat (red) and cooling (blue) in the period (Oct 2005-Oct 2006)

Table 5.11.3.1. GSHP systems in Norway with more than 10.000 effective borehole meters, compiled from (Midtømme et al. 2016) and updated with new installations after 2015.

Name	Category	Number of boreholes	Average depth [m]	Effective borehole meters	Year
Ahus hospital	Hospital	228	200	45 600	2007
Nydalen næringspark	Business park	180	236	42 500	2004
Sartor senter	Shopping centre	165	200	33 000	2013
Arcus	Industry building	91	300	27 300	2012
Sykehuset Østfold	Hospital	100	250	25 000	2013
Ullevål Stadion	Sport arena	120	200	24 000	2009
Coop Åsane	Shopping	112	212	23 744	2013
Stavanger Forum	Conference centre	85	250	21 250	2011
Haukeland universitetssjukehus	Hospital	77	250	19 250	2012
Sørlandssenteret	Shopping centre	90	200	18 000	2011
Postterminalen	Logistics	90	200	18 000	2010
Ørlandet kampflyplass	Airport	72	250	18 000	2016
Western Norway University of Applied Sciences	University college	81	220	17 820	2013
IKEA, Oslo	Shopping centre	86	200	17 200	2009
Høgskolen i Sørøst-Norge	University College	70	244	17 110	2009
Sandefjord lufthavn, Torp	Airport	60	250	15 000	2012
Speilen Mandal	Local heating facility	90	160	14 400	2011
Nygårdsporten Bergen	Business park	48	294	14 100	2015
Ericsson-bygget, Grimstad	Business park	56	248	13 872	2002
Ramstad skole	Primary school	45	250	12 650	2012
Røyken Rådhus	Town hall	41	300	12 300	2014
Kongsberg Kulturpark	Culture park	38	300	11 369	2014
Smedvig Eiendom	Business park	54	200	10 800	2011
Bjerkvik Tekniske Verksted	Industry building	50	201	10 050	2011
Scandic Airport Flesland	Hotel	50	200	10 000	2016

5.11.3.2. Regulations related to BTES in Norway

There are only limited regulations related to BTES installations in Norway. According to the Planning and Building Act of 2008, § 20-1 requires the landowner to apply for permission if there will be "significant encroachment on the terrain". However, according to today's practice, generally a BTES installation does not trigger the need for an application according this law as there are no significant encroachments on the surface; in most cases it is not possible to see the BHEs at all in the terrain. For large BTES systems the encroachments on the terrain may however be so significant that an application is necessary; either for the boreholes themselves or for the supporting infrastructure.

The Norwegian water resources legislation concerning the groundwater regulations do to a certain degree apply to BHEs. The groundwater regulations are included in the water resources legislation and are mainly managed by the Norwegian Water Resources and Energy Directorate (NVE). The groundwater regulations include an obligation to report all drilled wellsto the Geological Survey of Norway (NGU). The wells are archived in the national groundwater database GRANADA and the main information about the wells are available in the web-application[3]. There is, however, no need to apply for a license in order to drill a borehole. Also, there is no restrictions as to borehole depth.

In the municipality of Oslo, an application requirement has recently been introduced for drilling of boreholes due to the increasing number of underground installations in the municipality where boreholes can influence on the use of the underground for other applications. Although there is no formal application requirement in other parts of Norway, there may

[3] See website at http://geo.ngu.no/kart/granada_mobil/

be cases in which the underground is already used for other purposes or where there are plans for use of the underground for other purposes where it is not possible to drill a borehole.

5.11.3.3. Technical aspects

The Norwegian standard BHE has a borehole diameter of 115 mm (casing 139 mm) with a single 40 mm U tube installed. Some BHEs in Norway use alternative collectors, either coaxial collectors or collectors with a rougher surface that gives turbulent flow at lower flow-rates. Recent examples are Killingrud skole (secondary school, built in 2014) with 17 boreholes of 280 meter depth and Ørlandet Military Airport with 72 boreholes of 250 meter depth, both using the alternative single U BHE "Turbo-collector". Most of the BHEs in Norway are open and water filled with no grouting. Norwegian BTES are mainly low-temperature heat storage systems with storage temperatures of less than 20 °C. Some of the recent BHEs are equipped with fibre optics for distributed temperature measurements (DTS) ,see Fig. 5.11.3.2, in order to increase the understanding of the heat transfer and storage mechanism (Ramstad et al. 2017)[4].

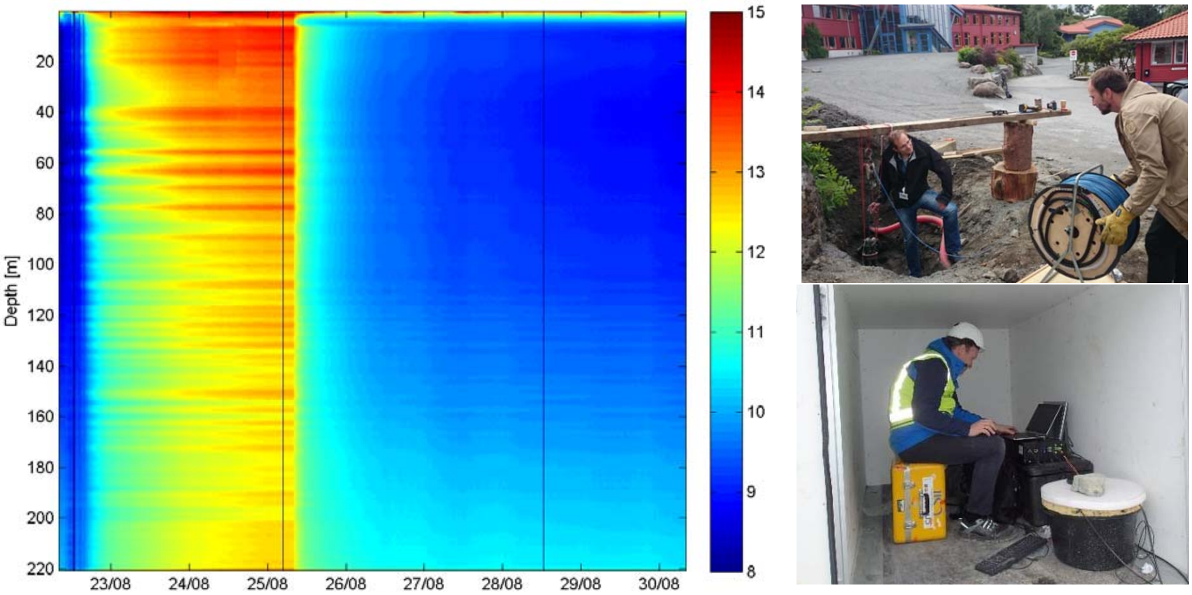


Fig. 5.11.3.2. Fibre optic temperature measurements (Distributed Temperature Sensing, DTS). Left: The plot shows DTS measurements in a BHE of 220 m depth during and after a thermal response test (from August 22 to August 25). Heat was injected into the BHE during the test. Right: the top photo show installing of fiber in a BHE and the bottom photo the DTS measurements. About 10 m of the fiber is put into water for calibrating of the measurements.

As discussed above, use of direct cooling is used in many BTES installations due to the energy efficiency of the method. There are two advantages by direct cooling: (1) The cooling is very cost effective, and (2) the excess heat from the building leads to an increased start temperature in the boreholes before the heating season, and thus an improved COP / increased profitability for heating as well. In most plants, the circulation fluid is cold enough and has a significant cooling potential. At the end of the summer, when sometimes the temperature in the BHE has risen so much that the potential for direct cooling is consumed, the cooling is produced by reversing the heat pump as a cooling machine.

The stricter building regulations in TEK17 and focus on Zero Emission Buildings / passive house technology, has also led to more focus on the energy system as a whole, and neighboring interaction by taking advantage of simultaneous heating and cooling demands. Another topic on the agenda is the role of BTES, and especially the role of large BTES with respect to peak-shawing and the potential for reduced demands for expansion of the electricity grid. The idea is that long-term and short-term storage of heat in low-peak periods, can be used for heating and peak-shawing in critical peak periods in the winter. This is particularly relevant on very cold days with high heating demand. The peak-shawing topic is gaining interest as highly relevant for reduced investment demands in some parts and larger cities of Norway. With the growth of variable renewable energy in Europe the coming years (wind, solar etc.), the European electricity prices will become more volatile, and peak-shawing is expected to become an important factor for cost efficient operation of BTES.

[4] Christian Michelsen Research AS has installed DTS in several BHEs in 2016-2017, results will be published based on measurements over time

5.11.3.4. BTES in Europe

BTES systems in other parts of Europe generally use similar technical solutions as in Norway, except that grouting is required. For example, in the MCS MIS 3005 standard used in the United Kingdom for design of BHEs, a borehole diameter of 130 mm and use of a single 32 mm U tube is prescribed. Generally a range of different borehole diameters are used, and the inner tube may be either single U tube (with varying diameter), double U tube or coaxial. BTES storage temperature is typically relatively low, but there are some medium and high temperature storage solutions like e.g. the Emmaboda installation in Sweden which is discussed in more detail below.

With respect to large BTES systems, the Norwegian installations are among the largest in Europe, with 3 installations on the Europe Top 20 list (Tab. 5.11.3.2). Installations larger than the Ahus hospital installation in Norway includes one installation in Romania, two in Finland, three in Switzerland and one in Sweden.

Table 5.11.3.2.20 largest GSHP systems in Europe as a function of effective borehole meters. From EGEC Geothermal market report 2016 (EGEC 2016).

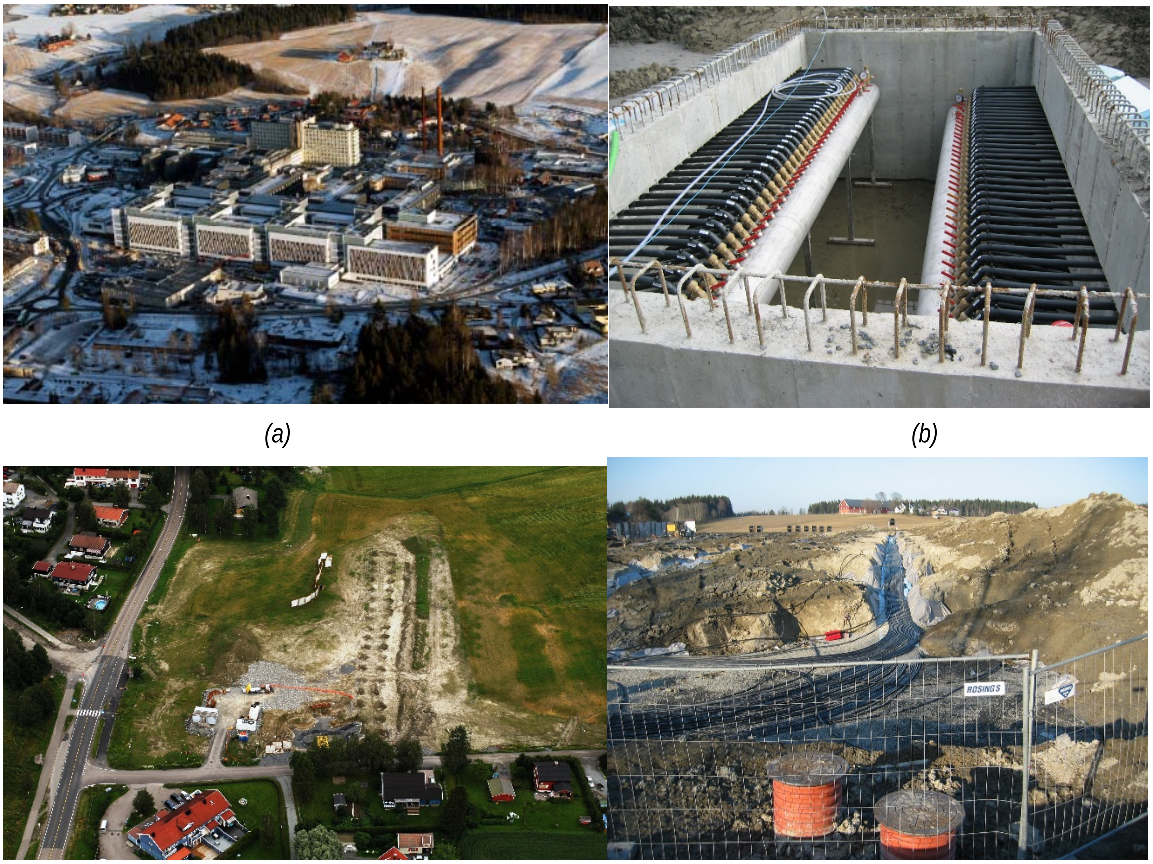
City, Name	Country	Number of boreholes	Average depth [m]	Effective borehole meters	Year
Magurele near Bucharest, ELI-NP	RO	1080	125	135000	2015
Sipoo, SOK Logistics Centre	FI	300	300	90000	2012/2016
Zurich, ETH-Campus Hönggerberg	CH	435	200	87000	2014-16
Rotkreuz, Suurstoffi 2	CH	193	280	54040	2015
Espoo, Lippulaiva shopping centre	FI	148	350	51800	TBD
Wallisellen, Richti-Areal	CH	220	225	49500	2012
Karlstad, Campus Karlstad	SE	204	240	48240	2014
Lørenskog, Ahus hospital	NO	228	200	45600	2007
Zurich, Neues Wohnquartier Freilager	CH	205	220	45100	2013/14
Zurich, FGZ Friesenberg, BHE-field Grünmatt	CH	179	250	44750	2015
Lund, IKDC / Chemical Inst.	SE	165	230	37950	
Basel, Novartis Campus	CH	170	220	37400	2012
Oslo, Nydalen næringspark	NO	180	200	36000	2004
Cambridge, Astra Zeneca new HQ Building	UK	176	200	35200	TBD
Stockholm, office Skanska Lustgården	SE	144	230	33120	2014
Rotkreuz, Suurstoffi 1	CH	220	150	33000	2014
Stockholm, NKS Hospital	SE	150	220	33000	2015
Bergen, Sartor shopping center	NO	162	200	32400	2014
Lübeck, IKEA Dänischburg	DE	215	150	32250	2013
Corsico (near Milano), IKEA	IT	304	106	32224	2008

5.11.3.5. Example BTES installations

Ahus hospital

The BTES installation built at the Akershus University Hospital (Ahus) in Oslo is the largest BTES system in Norway (Fig. 5.11.3.3). The building has a total floor area of 137 000 m^2. The annual heating demand is 26 GWh and the cooling demand 8 GWh. A BTES system comprising of 228 BHE of 200m depth was drilled in winter 2007. The system became operational in May 2007. The boreholes were drilled in dioritic rocks with 5 -40 m clay cover. The thick clay cover increases the drilling cost. A combined ammonia-chiller and heat pump system was installed. The total cost of the BTES and the heat pump system was 19.5 Mill USD.

It was originally planned to drill the boreholes close to the hospital, but seismic geophysical surveys and test drillings showed a high density of clay filled fracture zones. This observation suggested that full-scale drilling would be difficult and expensive. The proposed BTES borehole array was thus relocated to a field about 300 m from the hospital. Today the borehole heads are completely underground and the farmer is using the field to grow crops (Midttømme 2008).



(a) *(b)*

(c) *(d)*

Fig. 5.11.3.3. (a) Aerial view on Ahus hospital. The boreholes are located in the field in the background. (b) The BTES system at Ahus under construction in the summer 2007. (c) The pipelines from the boreholes to the manholes (d) Manholes for 114 of the boreholes. All photos Bærum fjernvarme

Western Norway University of Applied Sciences (site visit October 11th 2017)

The BTES installation at Western Norway University of Applied Sciences in Bergen consists of 81 boreholes in solid rock with average depth of around 220 meters. This makes the installation one of the 15 largest in Norway. The BTES is the main energy source for the campus at the Western Norway University of Applied Sciences. The spacing between the boreholes is 7.2 m, and the natural temperature in the ground is around 8–9°C. The geology is dominated by mylonite gneiss and mica schist. The groundwater level at the site is between 1.3 m and 2.8 m below the surface, and the probability for groundwater flow in the rock is low. The 81 boreholes are connected in parallel in a 9x9 configuration, and each borehole has four collector hoses that exchange the fluid (water/glycol) between the bedrock and heat pumps for both heating and cooling (Henne and Midttømme 2018, in preparation).

The campus for the Western Norway University of Applied Sciences at Kronstad in Bergen Norway was finalised in 2014, and has a gross building area of about 51 000 m², from where about 47 500 m² (BTA) is temperature controlled. The average energy consumption was estimated to 150 kWh/m², which is below the current national regulations (160 kWh/m² for universities and colleges), but 50% above the general requirements for low-energy buildings (100 kWh/m²) according to TEK 17. The campus is a combination of new and old restored buildings. The new buildings contain ordinary classrooms and auditoriums, but also a large number of special rooms and laboratories with specific requirements. The outdoor area is also partly heated during winter in order to melt snow and ice on the walkways, and the gutters are heated to prevent ice from blocking the roof drainage.

A water/glycol mixture is used as borehole fluid. Several measures have been taken in order to reduce the size of the BTES by reducing the peak cooling need from the BTES; most important is the inclusion of large cooling tanks with 11.000 kWh capacity using phase change materials (PCMs) and the use of adiabatic cooling. The building has a large number of energy meters (180) in order to be able to operate the energy system effectively.

The heating requirements for the campus could have been covered by the district heating system, but the large cooling requirements called for a heat pump solution. The peak cooling demands would however have required a very large and expensive geothermal installation, from which the maximum capacity is utilised only a small percentage of the time. The selected solution (see Fig. 5.11.3.4) combines a geothermal installation that covers about 50% of the peak load with an extra energy storage that covers the peak variations. Such a combination is more cost-efficient and has a smaller footprint than a \ full-scale geothermal system for 100% energy requirements. The heating and cooling system is thus a combination of long-term geothermal energy storage and latent energy storage in Phase Change Materials (PCM; four tanks with FlatICE elements, see Fig. 5.11.). District heating is used to cover peak loads during winter, but 80-90% of the heating demand is estimated to be covered by geothermal energy (Grønnesby 2014).

The storage tanks are cooled during night when the power requirement is low, and about 50% of the cooling requirement during the day is provided by the storage tanks. The cost of heating is significantly reduced when the investments for cooling can also be used to reduce the heating expenses. The core of the system is three heat pumps that exchange energy between the different parts of the energy system. The same heat pumps operates as cooling machines when cooling is required. The use of PCM tanks for short-term energy storage reduces the peak power required for cooling significantly as illustrated in Fig. 5.11.3.5. Another important benefit is that there is no need for traditional dry coolers or cooling towers.

Some figures for the boreholes and energy system (Grønnesby 2014):

- BTES 81 BHE á 220 m deep
- Thermal conductivity of rock 3.7 W/mK (measured in test boreholes)
- Thermal resistance in borehole 0.07 kW/m (measured in test boreholes)
- Heat extraction from boreholes is 1 700 kW
- Energy retrieved from boreholes about 1 200 MWh per year
- 3 heat pumps, 1 400 kW cooling power
- Energy storage tanks for about 11 000 kWh
- Heating water temperatures about 65/37 °C
- Cooling water temperatures about 7/17 °C
- Adiabatic pre-cooling of ventilation air

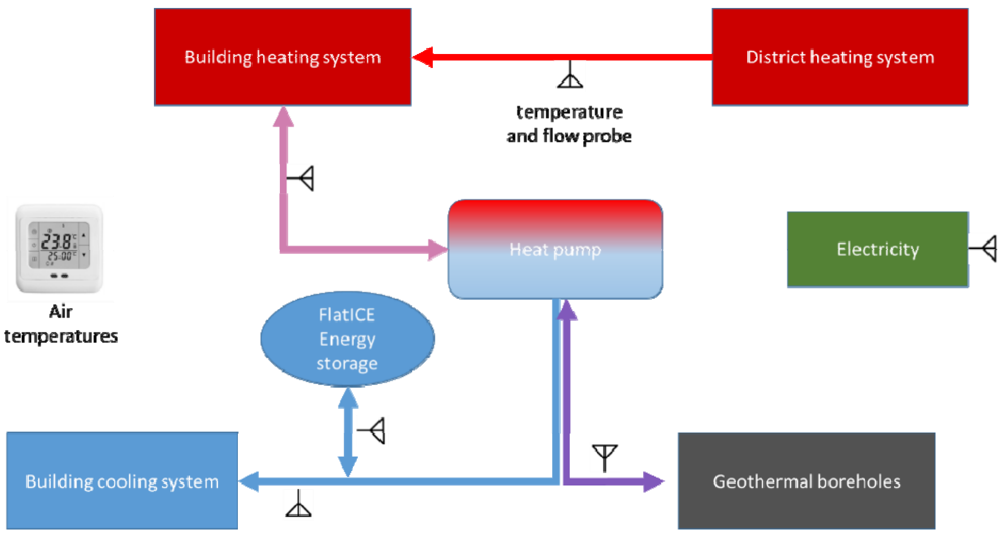


Fig. 5.11.3.4. Energy system principle Western Norway University of Applied Sciences.

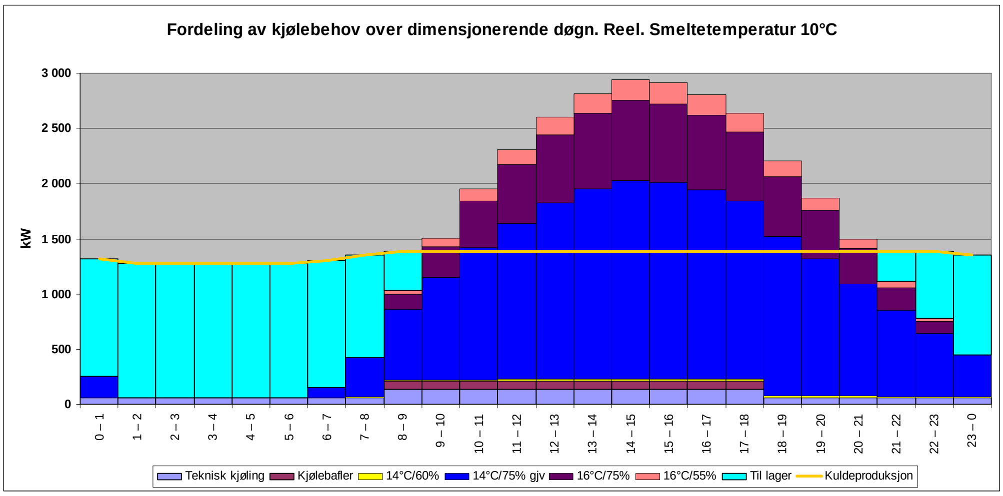


Fig. 5.11.3.5. Cooling requirements for day and night. The light blue rectangles in the figure shows the energy that is used for cooling the tanks during the night, and the yellow line illustrates the averaging power consumption for the cooling demands from the heat pumps (Grønnesby 2014)

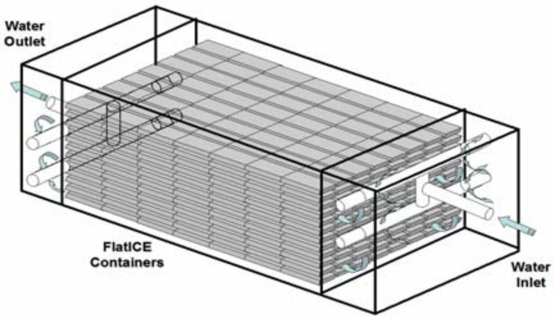


Fig. 5.11.3.6.(a) A typical Flat-ICE container (b) Installation of PCM tanks

Emmaboda (Sweden)

Whereas the majority of BTES installations are low temperature installations with storage temperatures below 20 °C, the BTES installation at Emmaboda in Sweden is a high temperature BTES with storage temperature of 30–40°C(Nordell et al. 2015).

The Emmaboda BTES consists of 140 boreholes, each 150 meters deep with 140 mm casing and 115 mm open hole. The holes are drilled within a rectangular field which is divided into seven sections of each 20 wells. The sections of the storage enable a better temperature stratification through which makes it possible to maintain a higher temperature in the center of the storage. The top surface is thermally insulated with a 0.4 m thick layer of foam glass. The border of the storage area, confining the boreholes, is 36 x 52 m.The system is designed in order to reverse the flow direction depending on mode of operation, charging or discharging the storage (fig. 5.11.37). One major delaying factor was a less drillable rock than expected. Water producing fractures and unstable cross zones became a time consumable factor for a large part of the boreholes. Some 30 % of the holes had an air-lift capacity of more than 500 l/min and had to be grouted to seal of the fractures. Some 5 % had to even be grouted twice, and another 6 % had to be redrilled due to problems at BHE installations.

The high temperature BTES is used to store waste heat from the process industry. After about five years of operation, the storage temperature had risen to around +40 °C – in this period of time the BTES was only charged (estimated to 10 GWh) and no heat was taken out of the storage.

Fig. 5.11.3.7. Installation of BTES in Emmaboda. Photo from xylemwatersolutions.com

5.11.3.6. Success and challenges

BTES-systems have proven to be an efficient way to implement large energy savings in Norway. The operational cost is low, and operation of BTES-systems is robust with few operational problems. A downside is the relatively high investment cost for drilling, but this investment is typically paid back through energy savings after less than 8 years operation.

Despite the prevalence of BTES, there is a lack of detailed understanding on how BTES systems are operating and how to dimension them. Measurements show that many installed Norwegian GSHP installations do not perform as well as they should; actual measurements show SPF between 1.52 and 3.95 (Haugerud et al. 2015), significantly lower than expected. With today's GSHP technology and proper designed systems, SPF above 4 can be achieved (Wemhoener 2016). Data from the new BTES at Scandic Flesland (Bergen) shows a SPF of 5.6 (Fondenes 2016). There is also a lack of published data on the utilization ratio (% recovery of the stored heat) for BTES. The limited data available shows big variations; from the BTES Infracity installation in Stockholm with a very good utilization ratio of 89 % (Dalenbäck et al. 2000) to the BTES in Drake landing in Canada with a significantly lower storage performance (36-41%) due to groundwater flow (Lanahan 2017). More high quality data is needed in this area, specifically also for Norwegian conditions.

Direct cooling of buildings (without heat pumps) is one of the most advantageous ways to charge the BTES, used in many cases in Norway, effectively giving nearly direct cooling of buildings while charging the BTES and securing higher storage temperature and thus lower cost heating in winter time. Other methods for charging BTES which are used successfully in Norway is the use of solar heated water from e.g. football fields or big parking lots. The use of excess heat from shopping malls and data centers has also proved to be very energy efficient. Some of the BTES-installations also use other types of waste heat to further increase the temperature of the BTES in summer time.

With the increasing advent of zero energy buildings and plus buildings, the need for cooling often is the main factor for dimensioning BTES, also in Norway with a relatively cold climate. This has led to a need for different ways of increasing the peak cooling capacity of the BTES in summer time; two successful ways of achieving this has been incorporated in the BTES at Western Norway University of Applied Sciences(see section 0) where a combination of big tanks with PCM and adiabatic cooling has been used to nearly halve the requirements for cooling.

Most BTES-installations in Norway are perceived to be successful, with significant energy saving for heating and cooling compared to traditional systems not utilizing BTES. However, for many of the BTES-installations the operation is often not fully optimized, and thus the full energy potential is often not realized. To achieve further energy savings it is necessary to follow-up the operation more closely, including using available sensors to measure temperatures and operating conditions. Practise has shown that it is a challenge to get building owners to focus on optimized operations, although there would be a significant cost saving and energy efficient potential. Another challenge when designing BTES-systems is the uncertainty with respect to geology which may lead to non-optimized design and operating if not appropriate measures are taken both during the design and operation.

5.11.3.7. Recommendations for Poland

In several areas of Poland BTES is a good alternative as an energy efficiency measure following the approach used in numerous cases in Norway, efficiently implementing large energy savings. In particular in the regions with crystalline rocks, e.g in the Sudety Mountains region, BTES is a very attractive alternative. BTES can also be an alternative in sedimentary rocks regions like the central and northern part of Poland, although casing of parts of the BHE might be needed in some areas, leading to increased investment cost.

The Polish climate is in general warmer than the Norwegian, making the cooling and heating demand more balanced than in Norway. As in Norway, many buildings in Poland require cooling in summer time combined with a need for heating in winter time, making BTES a very attractive solution with very low operational cost. The ground temperature in Poland is under 17°C which has been the maximum temperature for utilizing direct cooling in Norway. Thus it should be possible to use the very energy efficient direct cooling approach without heat pumps also in Poland, although this must be investigated on a case-by-case basis in the planning phase.

The challenge for Poland may be the up-front high installation cost for BTES-systems, typically requiring a large investment with return of investment period of 8-10 years. In addition, the regulations in Poland makes it necessary to get extra permission when drilling deeper than 100 meters; this leads to added complications and/or shallower boreholes which are less effective from an energy standpoint. Even with these challenges, there is a big potential for BTES in Poland.

The key to significant energy savings in conjunction with the use of BTES in Norway has been to look at the complete energy system as a whole, and understand how a BTES can become an integral part in solving the combined cooling and heating needs. This is important in order to dimension the BTES optimally – too many boreholes increases installation cost, too few boreholes increases operational cost due to too low capacity. Local energy solutions and seasonal and short term storage of energy in BTES can potentially reduce peak electricity demand and the need for investment, and should be investigated further. This also makes it important to understand the local ground conditions, including the groundwater flow. The need for skilled personnel in all phases (pre-investigation phase, building phase and operational phase) of BTES systems should be emphasized.

5.11.2. ATES

ATES requires presence of an aquifer. Further, the operating of an ATES is more challenging than a BTES due to potential problems with clogging, corrosion and water quality issues due to ATES being an open system (as opposed to closed loop BTES systems). This leads to higher operating costs, but on the other hand the installation cost is significantly lower and total cost per kWh extracted energy is typically significant lower for ATES than for BTES over the life span of an installation.

The power (kW) output from ATES and groundwater is a linear relationship between the extraction rate of groundwater (Q) and extraction of temperature (T) multiplied with the specific heat of water (C_{H2O}),

$$Power\ (kW) = Q \times \Delta T \times C_{H2O}\ . \qquad (1)$$

Here the specific heat of water, C_{H2O} , is 4,2 kJ/kg·K ≈ 1,17 kWh/m^3·K at 5°C. The linearity demonstrates the flexibility and potential in ATES by varying either the extraction rate Q, the temperature difference or both. For example, a groundwater well yielding 20 l/s (=72 m^3/h) and a temperature extraction of 4 degrees will produce approximately 340 kW of heat. Assuming a COP of 3 and 3000 operating hours per year, the heat delivered from the heat pump is approximately 500 kW, corresponding to 1.5 GWh/year. Increasing the temperature difference T by a factor 10, to 40 degrees, these figures rise to 5 MW and 15 GWh/year, respectively.

5.11.3.8. ATES in Norway

The geological conditions in Norway do only allow for installation and operation of ATES systems in a limited number of locations, and thus there are few ATES-systems in Norway compared to BTES-systems. The groundwater wells are typically established in quaternary deposits of sand or gravel of fluvial or glacifluvial origin, but high yielding groundwater wells in hard rock are sometimes used. In addition, a ground temperature of below 5 °C in high mountain regions and in the northernmost parts of Norway poses some challenges for ATES applications. Fig. 5.11..3.8 shows a principle drawing of a typical layout for a building using groundwater for heating. The installations commonly consist of a production well and an infiltration well to maintain the hydrogeological balance, thus extracting heat only from the aquifer. The infiltration well is important to maintain the hydraulic balance in the aquifer/groundwater reservoir, but still there are some cases also in Norway, where the plants only have a production well, and the water from the heat pump is returned to either a watercourse or a drainage pipe.

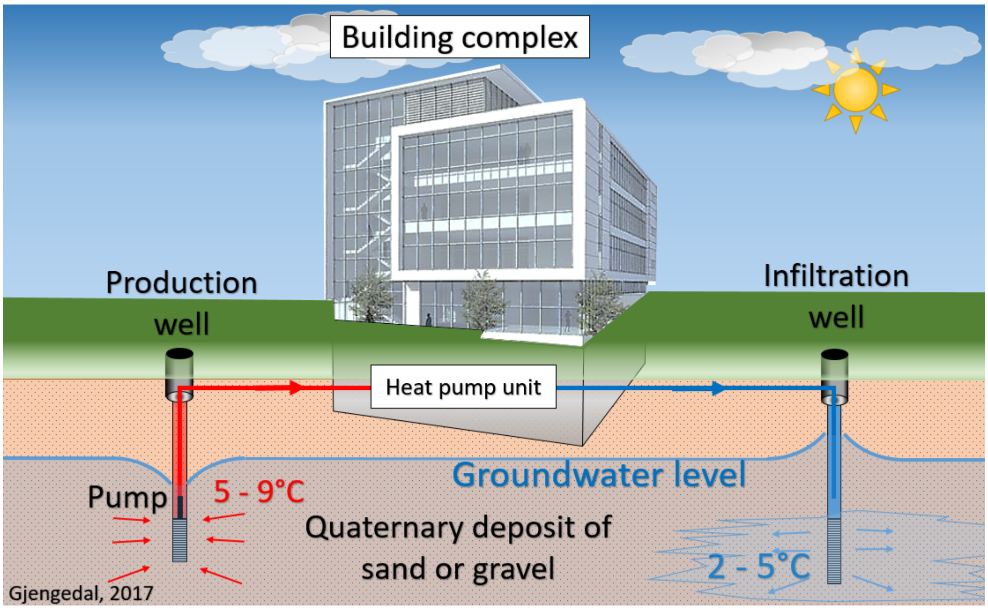


Fig. 5.11.3.8. Principle drawing showing the typical layout for a building using groundwater for heating in Norway. Due to the relatively low temperatures in Norwegian groundwater, e.g. 5-9°C the production well can be used for direct cooling as well. The wells are typically in quaternary deposits of sand or gravel of fluvial or glacifluvial origin

Due to the relatively low temperatures in Norwegian groundwater, typically 5–9°C, the production well can be used for direct cooling in addition to heating. In some cases such as for the Oslo Gardermoen airport (see section 5.11.3 for site description), the system is reversed such that the cold well produces cooling in the summer. To avoid freezing, the groundwater temperature is always kept above 0°C. The production capacity of a groundwater well in superficial deposits is typically 10-30 l/s and sometimes more.

The first known ATES in Norway was established in Seljord lysfabrikk in 1987 where a 10 meter deep well was drilled for heating and cooling. The largest ATES-system in Norway was installed at Gardermoen airport in 1998, and has been in operation since (see further details in section 5.11.3). The Gardermoen area features a large groundwater reservoir (sand and gravel aquifer) with low or no groundwater flow, making it ideal for thermal storage. Compared to the more than 200 boreholes in the Ahus BTES-system, the Gardermoen airport ATES has only 18 wells. At the center of Melhus south of Trondheim (see also section 5.11.3.12) there are 9 ATES installations within a few hundred meters distance. This is the largest concentration of ATES plants on a limited area in Norway. Similar to Melhus, there are also several ATES plants in the Gardermoen area indicating a “neighboring-effect” illustrating the spreading of a proven and a cost effective technology. Throughout the years, a certain level of expertise and experience for installing and operating ATES has been gained in both the Melhus and Gardermoen areas. The potential for ATES in Norway is theoretically estimated to be approximately 6 TWh/year (based on Ramstad et al. 2011). The numbers are based on mapped glacifluvial and fluvial deposits in areas with buildings having a heating and cooling demand. Realistic potential taking into consideration limitations such as groundwater level, soil thickness and size of the groundwater reservoir etc., the potential will be lower. The total number of ATES installations in Norway are uncertain, but is estimated to be around 100.

5.11.3.9. Regulations related to ATES in Norway

Correspondingly as for BTES as discussed in section 5.11.3.2, ATES-installation are to a certain degree addressed in the groundwater regulations which are included in the water resources legislation. Due to the extraction of significant amounts of groundwater for ATES, the groundwater regulations impose stronger requirements for ATES than for BTES. According to the law, extraction of groundwater higher than a certain yield and/or in vulnerable areas need a license from NVE. A license requires a detailed description of the hydrogeological conditions together with an evaluation on hydrologic and environmental aspects, e.g. influence on the water balance and biological vulnerability on local ecosystems. The procedure is to distribute the complete license application on hearing to relevant authorities somehow influenced by the specific extraction of groundwater. As for BTES, the drilled wells need to be reported to NGU for archiving in GRANADA.

The Norwegian water resources legislation concerning the groundwater regulations been changed recently, and the following changes apply from January 1st2018:

- § 43a: Duty of *general care* for the groundwater
- § 45: Notifiable extraction of groundwater (higher than 100 m^3/day $\approx$4.2 m^3/h$\approx$1.16 l/s) requesting an evaluation whether or not the extraction of groundwater requires an application for license.

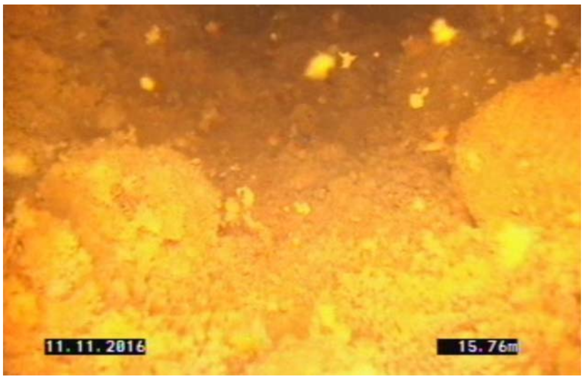
Previously, there has been some confusion related to groundwater wells used for energy purposes, where the main interpretation has been that there is no need for license when there is no net extraction of groundwater which is the case for plants with a set of production and infiltration well. However, though not decided yet, these wells are believed to fall into the category of notifiable extraction of groundwater. The change of the groundwater temperature in the groundwater reservoir are covered by the paragraph on *general care* for the groundwater (§43a).

5.11.3.4. Technical aspects

Some technical aspects related to ATES installations in Norway are included here in order to describe some of the issues specifically considered for Norwegian ATES installations:

- *Settling damages and clogging.* Special precautions need to be made in order to avoid settling damages and clogging. Both the production and infiltration well consists of a con-slot well screen. The slot opening is designed based on sediment sample analysis (grain size distribution analysis from pre-investigations) in such a way that the grain size in the formation match the slot opening. Improper design can cause production of fine sand, and over time causing settling damages around the production well and clogging the infiltration well. To create a natural formation filter outside the well screen just after installation, the well is flushed thoroughly to remove the fine particles. As a precaution to avoid air (oxygen) into the well screen, the submersible pump is recommended to be placed above the upper end of the well screen. Intrusion of oxygen in the system should be avoided due to precipitation of iron and manganese hydroxides, and sometimes iron bacteria, which is a common problem. When ions of iron and/or manganese are solved in the groundwater (anoxic conditions), and the intrusion of oxygen in the groundwater leads to precipitation and clogging of one or more parts (well screens, pump, pipes and heat exchanger) in the plant. For the same reason, these open groundwater system always has an extra heat exchanger before the heat pump.
- *Airtight closed loop between heat exchanger and evaporator.* The maintenance of, repair or replacement of a heat exchanger has lower cost than solving problems in the evaporator in the heat pump. The closed loop between the heat exchanger and the evaporator in the heat pump is often filled with glycol. To avoid intrusion of oxygen and iron and manganese problems, the system should be operated free of oxygen. To keep the system airtight, special precautions must be taken in order to always have the submersible pump and infiltration pipe several meters below the groundwater level, and also designing all the remaining parts (valves, filters, fittings and heat exchanger etc.) in such a way that oxygen is prevented from getting into the system. It is often difficult to get rid of iron- and manganese precipitation when the problem is present. Thus the effort is related to avoid the precipitation challenges to arise. To some extent, physical-chemical groundwater analysis in the pre-investigation phase reveals the potential for iron- and manganese precipitation as well as corrosion and precipitation of other minerals, e.g. carbonates.
- *Sensors with alarm functionality.* Both the production and infiltration well should also have sensors logging the groundwater level and alarm functions for low or high groundwater level in the production and infiltration well,

respectively. The aim of monitoring the groundwater level is to avoid problems by detecting potential deviations from normal operation occurring over time, such as lower extraction and infiltration rates, lowered groundwater level etc., which in turn can be caused by clogging somewhere in the system. Video inspections of the groundwater wells is also recommended with respect to documentation and for troubleshooting when the wells have a deviating behavior. Fig.5.11.3.9 shows an example of video inspections with clogging caused by iron precipitation and bacteria (a), and a new well screen without any clogging (b).



(a)

(b)

Fig.5.11.3.9. Video inspection of two well screens. Here the slot opening is 1 mm.(a) The well screen is clogged with iron oxides and iron bacteria.(b)A new well screen where the sand and gravel particles in the natural formation filter outside the screen can easily be seen. Pictures by Gjøvaag AS in the ORMEL-project.

5.11.3.5. ATES in Europe

The Netherlands, Sweden and Belgium are the countries with the largest number of ATES-installations in Europe, with some installations also in Norway, Germany, Denmark and the UK (Lee 2013).

The Netherlands has the largest number of ATES-installations in Europe with more than 3500 systems installed per 2015 which together save up to 3500 TJ of Energy (Heekeren and Bakema 2015). The Netherlands has very favourable ground conditions for ATES installations, with sand aquifers that can typically produce up to 250 cubic meters per hour (m^3/h), and typical temperature ranges for storing energy are between 7 – 17 °C. Heating is done in combination with heat pumps. Around 70% of the ATES-installations in the Netherlands are commercial and public buildings while the remaining 30% are housing developments, and industrial and agricultural applications (Cabeza 2015). The largest ATES project supplies cooling and low temperature heating to the buildings and laboratories on the campus of the Eindhoven University of Technology. In neighbor country Belgium the number of ATES-installations was estimated to be around 1200 as of 2015 (Loveless et al. 2015).

In Sweden there were around 150 ATES system plants in operation per 2015 (Gehlin et al. 2015). The systems are described as highly efficient, and have generally low pay-back times, often less than 3 years. The wells are normally designed with a double function - both as production- and injection wells. Energy is stored in the groundwater and in the grains (or rocks mass) that form the aquifer. Typical Swedish ATES operation temperatures are 12-16°C on the warm side and 4-8°C on the cold side of the aquifer. The largest ATES system in Sweden is the Stockholm Arlanda Airport ATES plant, used for free-cooling and pre-heating of ventilation, and for de-icing of gates. It has been designed to a capacity of 10 MW and uses no heat pumps. There is a steady market growth for larger systems for residential buildings as well as for larger ATES and BTES systems in the commercial and institutional sector in Sweden.

The number of ATES-installations in other parts of Europe are more limited, partly due to ground conditions and partly due to regulations. One of the ATES-installation in Germany is noteworthy; the district heating and cooling scheme the renovated Reichstag building and of the connected neighbouring large office buildings of the Parliament include a shallow and a deep aquifer, with a cold store in a depth of about 60 meters and a heat store in a depth of about 300 meters (Lee 2013). The deep aquifer is charged in summer with surplus heat of 70 °C from the combined heat and power plants. These plants are operated dependent on the electricity demand of the connected buildings. According to the design calculations, about 60% of the stored heat can be recovered during the heating period from the aquifer in the temperature range between 55 and 70°C and can supplement the absorption heat pump system. The groundwater of the shallow aquifer is used at ambient temperature for the air conditioning of the buildings.

In Denmark there are a few ATES used for heating, cooling or seasonal storage (Røgen et al. 2016). However, the three geothermal plants with wells of depth between 1.2 km and 2.6 km producing heat for district heating from aquifers with temperature between 43°C and 74°C (Røgen et al. 2016) may be more interesting for Polish conditions, although these installations are not actually ATES as they are only used to pump up heat with no storage component. These three installations which have been in operation from 1984, 2005 and 2013, respectively, have several features in common with the type of Geothermal installations which could be built up in Poland from the aquifers with temperatures around 60 °C. The plants have capacity of 7 – 12 MHw, with one production and one injection well producing heat from the sandstone reservoirs through heat exchangers and/or LiBr based absorption heat pumps, where the driving heat primarily comes from biomass boilers for heat and/or combined heat and power production.

5.11.3.6. Examples of ATES installations

Gardermoen[5]

Gardermoen is the largest groundwater reservoir in Norway. The groundwater in the glaciofluvial delta deposited 10 000 years ago is used for heating and cooling of Oslo Airport. The total building floor is 180.000 m2, and the buildings are equipped with large glass walls which increase the cooling demand in summer and the heating demand in winter. The aquifer thermal energy storage at the airport (ATES) consists of 18 wells, 9 warm and 9 cold wells, each with diameter 450 mm and depth 45 m. Each well is supplied with its own ground water pump and its own injection pipe. The cold wells are located 150 m east of the warm wells. The wells are connected to the heat pump / refrigeration system.

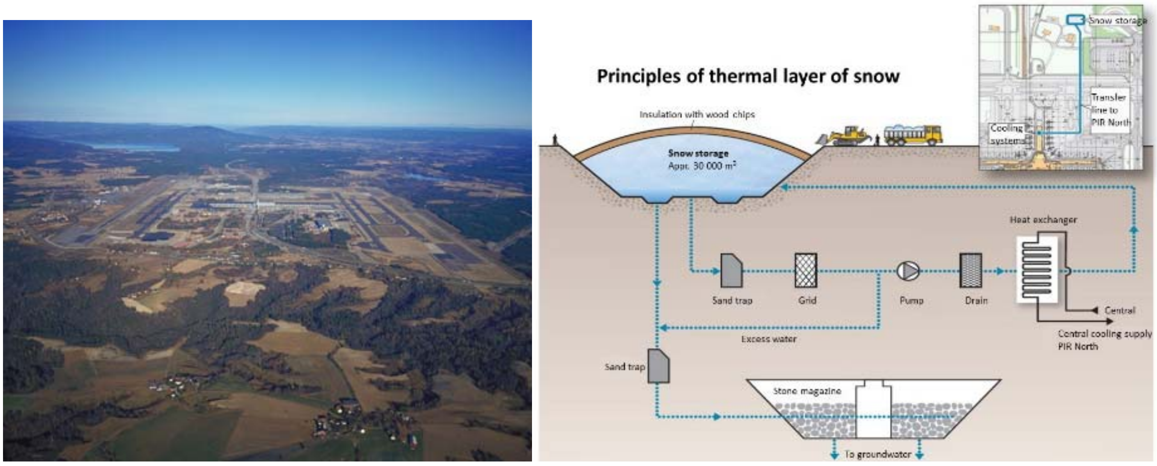
Oslo Gardermoen Airport (Fig. 5.11.3.10) was opened in 1998, and the ATES system has been in operation since then. There have been significant problems connected to clogging in the wells due to iron precipitation and iron bacteria in longer periods, which in turn was initiated by the presence of oxygen in the system. The presence of oxygen in the system is suspected to be a result of too intense pumping in periods, and/or mixing of oxic and anoxic groundwater in the upper and lower part of the aquifer, respectively. Due to the problems with clogging, the airport has a regular cleaning process for the wells at regular intervals, with well screen washing and airlift pumping. Only 12 of 18 wells were in operation part of the year 5-6 years after the Gardermoen system was set into operation, and several of the wells are currently not in operation due to these issues.

The ATES system covers the total cooling needs of the airport, of which 25% (2.8 GWh/yr) is direct cooling via direct heat exchange with cold groundwater and 75% (8.5 GWh/yr) is active cooling via the use of heat pumps (Fig. 5.11.3.11). The annual heating provision from the heat pump is typically 11 GWh. Additional heat is supplied from a heat energy central with four oil heated boilers (12 GWh) and the district heating plant of Gardermoen Fjernvarme with biofuels as the primary energy source (17 GWh). The total cost of the ATES system was 2.65 USD and the payback time compared to traditional heating and cooling system was estimated to be less than four years.

In summer, ground water is pumped from the cold wells for cooling the airport buildings. The heated water is returned to the warm wells. In winter, the direction of the heat pump is reversed, so the heat is extracted from the groundwater and transferred to a warm space –heating fluid. The cold from the building is returned to the cold wells. The heat and cold from the energy central is transported through insulated district heat and cooling pipelines to the terminal building and other buildings including a hotel and a conference centre. In addition, heat is used for snow melting at the airplane setback areas. The heat is distributed as low-temperature fluid through a 40.000 m2 floor heating system. Most of these systems are also used for cooling in summer.

Ammonia was chosen as working fluid for the heat pump. It is a natural, environmental friendly and with excellent thermodynamic properties, but since it is poisonous, the energy plant was built in a separate building 1 km from the terminal building.

[5]The text is compiled from (Eggen and Vangsnes 2005) and (Vangsnes 2014)



(a) *(b)*

Fig.5.11.3.10. (a) Oslo Airport Gardermoen. Photo: Oslo Airport AS. (b) Revised energy system at Gardermoen international airport which includes a snow storage insulated with wood chips

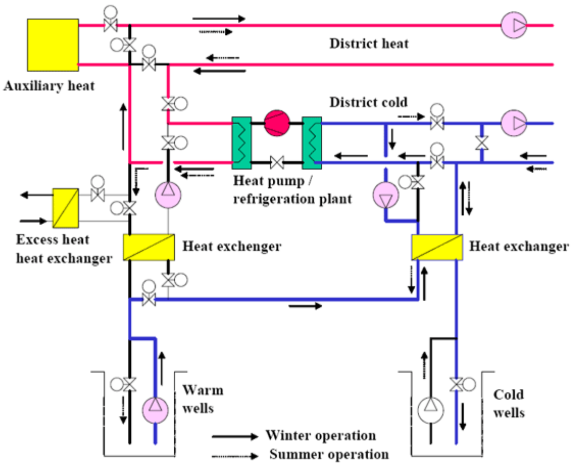


Fig.5.11.3.11. Functional description of the Gardermoen ATES. Illustration: COWI

Melhus and Elverum – the ORMEL research project

The ongoing ORMEL-research project (2015-2018) deals with ATES systems in Norway. ORMEL is an acronym for *Optimal resource utilization of groundwater for heating and cooling in the municipalities of Melhus and Elverum.* The main goal in the project is to provide a solid and sustainable basis for an optimal use and management of the groundwater resources for heating and cooling purposes in the central part of the Melhus and Elverum municipalities.

Both municipalities have large sand and gravel deposits and large groundwater reservoirs suited for groundwater extraction, and a total of 9 plants have been established within a distance of a few hundred meters in the center of Melhus (seeFig. 5.11.). Melhus is located around 20 kilometers south of Trondheim, Norway, while Elverum is located 140 kilometers northeast of Oslo. The project owner is Melhus municipality, while the department of Geoscience and Petroleum (IGP) at the Norwegian University of Science and Technology (NTNU) is the project leader. Other partners are Elverum municipality, the Geological Survey of Norway, department of Energy and Process Engineering at NTNU, and the consultant company Asplan Viak AS.

A PhD-student is working in the project and the main research topics are (1) mapping of the capacity and character of the groundwater resource, (2) iron and manganese challenges, and (3) follow up and monitoring of plants. The pairs of red and blue dots in Fig. 5.11. represents ATES plants with production and infiltration wells, respectively, while red dots are plants with only production wells. Green and purple dots are new and planned wells respectively by the ORMEL-project.

The total use of groundwater in the plants is 105 l/s, where the net extraction from the aquifer is approximately 50 l/s (Førde 2015, Riise 2015). Despite challenging groundwater chemistry with partly brackish water, dissolved iron and manganese, most of the plants are operating surprisingly well. The prevention of oxygen into the system seems to be a success criteria. Some other operational problems have also been revealed, e.g. production of fine particles / fine sand, corrosion of pipes, iron precipitation and iron bacteria in well screens (both production and infiltration wells), pipes, and heat exchangers. Some of the problems occurs as a result of lacking regular maintenance and monitoring of groundwater level and allowing a drawdown of the groundwater level to the water intake in the submersible pump, thus introducing air into the system and following precipitation and clogging problems. As can be seen in Fig. 5.11. the distance between some of the neighboring infiltration and production wells are quite short, and tendencies of short-circuiting the groundwater temperature has been observed. For the future ORMEL recommends that the heat and cooling should be organized in one larger unit, to control the aquifer as a whole.

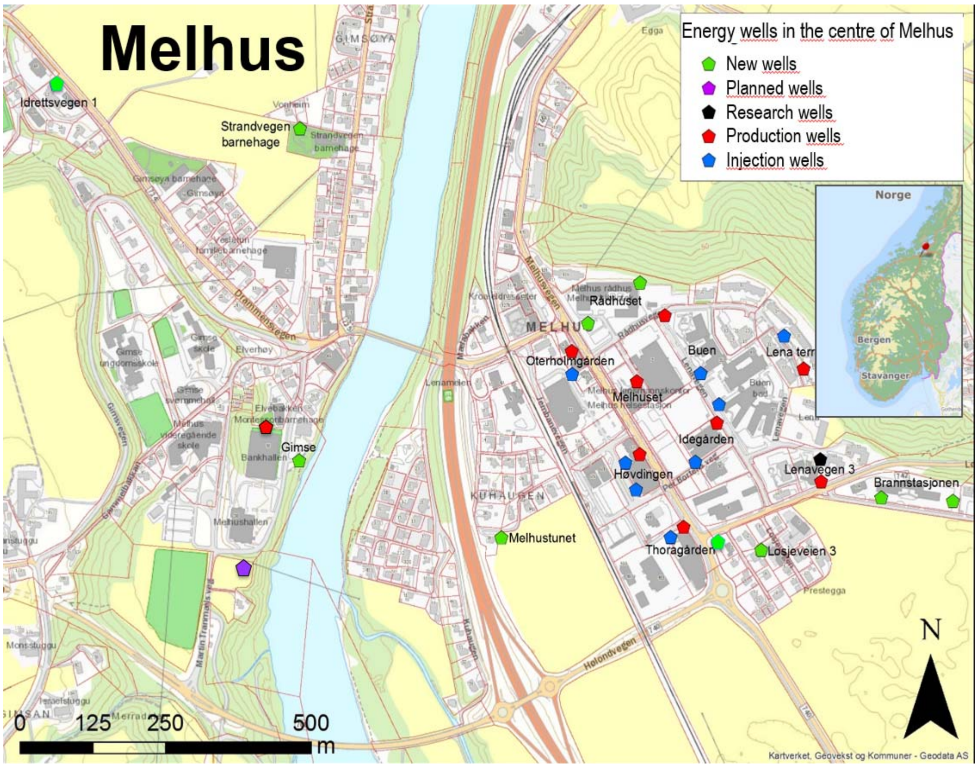


Fig. 5.11.3.12. An overview of Melhus, the centre in Melhus municipality south of Trondheim Norway. The pairs of red and blue dots represents ATES plants with production and infiltration wells, respectively. A total of 9 plants are established within a short distance

Eindhoven University of Technology (The Netherlands)

The largest ATES-installation in the Netherlands is found at the Eindhoven University of Technology where an ATES-based district heating and cooling system was installed in 2001. The ATES-system supplies direct cooling in summer as well as low-temperature heat in winter for the evaporators of the heat pumps. The heat pumps are located in the technical rooms of the buildings and can provide peak load cooling in summer as well. In order to be able to charge enough cold in winter, cooling towers are used to charge additional cold (Cabeza 2015).

The ATES-based district heating and cooling system also enables the users to exchange cold and/or heat by means of the distribution network. In this case the groundwater is functioning as an energy transport medium between the buildings. In the case of a net cooling or heating demand after the energy trade-off between users, groundwater is extracted from the cold or warm wells respectively, and transported to the users by means of the distribution network. As a result of this energy exchange between the buildings, the energy efficiency is further improved. The installation has a seasonal imbalance problem due to higher cooling demand than heating demand.

The soil conditions on the campus show a top layer of approximately 28 m in which a shallow phreatic aquifer is present. At a depth between 28 m and approximately 80 m below the surface, the ‘first aquifer’ is found with a transmissivity in the range of 1600 to 2000 m^2/day. Below this aquifer an aquitard is found of 60 m thickness with a hydraulic resistance of 20,000 days. Deeper aquifers are present and protected by the government as drinking water reserves and therefore these aquifers are not available to be used for ATES. The natural temperature of the groundwater in the first aquifer is 11.8°C. The groundwater is fresh with a chloride content of 10–40 mg/l.

5.11.3.7. Success and challenges

The most successful ATES-installation in Norway is the 18 well Gardermoen ATES installation, described in section 5.11.3.5, with annual heating and cooling provisions of around 11 GWh/year. The payback-time of the Gardermoen system was as low as 4 years. Gardermoen has now been in operation for nearly 20 years, but has had significant challenges with clogging in the later years, which has given maintenance challenges and additional maintenance cost. This highlights the fact that it is important to have a good plan for operation and maintenance from day one, based on a combination of experience from other installations and good knowledge of local conditions.

ATES-systems are the UTES-systems with lowest installation cost for a given installed capacity, making it possible to get short return of investment – the 4 year payback-time of the Gardermoen ATES-system is not an exceptional case. Thus if the ground conditions are suitable for ATES, the installation of an ATES is a very good investment, even with relatively low temperatures as is the case for Norwegian conditions (below 10 °C). However, the number of locations for which ATES-systems are suitable is small in Norway, leading to relatively few ATES-installations, and none in the same order of magnitude as the Gardermoen ATES.

A challenge related to ATES-systems is that there may be significant and unpredictable costs in the operational phase related to clogging, growth and corrosion. Potential problems with respect to these issues may be identified and handled already in the planning and pre-investigation phase due to e.g. water quality from test drilling. Whereas BTES-systems are nearly maintenance free, significant costs may be expected for ATES-systems for maintenance, and maintenance may also lead to some wells being non-operational for months if one does not apply an active maintenance program. The Gardermoen ATES-installation is an example; only 12 of 18 wells were in operation part of the year 5-6 years after the Gardermoen system was set into operation (ref. section 5.11.3.5). In the ORMEL project one has correspondingly found results of lacking regular maintenance and monitoring of groundwater level: Allowing a drawdown of the groundwater level to the water intake in the submersible pump introduced air into the system, and following precipitation and clogging problems. However, even including typical maintenance cost ATES-systems are often favorable compared to BTES-systems.

The key to successful design and operation of an ATES-system is to use skilled personnel all the way from the pre-investigation phase to the construction phase, operation phase and regular maintenance phase. It is also important to employ the experience from earlier installations in all phases, drawing on the experience from e.g. the Netherlands, Sweden and Norway. It should also be emphasized that ATES needs a multidisciplinary approach involving expertise in multiple fields like hydrogeology, drilling, heat pump technology and automatization. Documentation of the installation as well as follow up on critical operational parameters such as groundwater extraction and infiltration, groundwater level, groundwater chemistry, energy production, groundwater temperatures, COP etc. is also important. A recommended approach is to set up a periodic maintenance program in order to reduce the risk of problems, e.g. the Gardermoen ATES has a cleaning process of the wells which is performed at regular intervals to avoid problems with clogging caused by iron precipitation and iron bacteria. Systematic monitoring with alarm functions should also be used to understand when cleaning is necessary and to prevent oxygen getting into the system. Even though the groundwater quality can be challenging with high content of dissolved ions of iron, manganese and sometimes carbonates, keeping the system free of oxygen seems to be a success criteria in most ATES systems in Norway.

Another potential challenge for ATES-systems is to avoid thermal shortcut between the production and infiltration wells. Thermal shortcut could be as a result of high hydraulic conductivity in the aquifer. The groundwater flow (velocity and direction) should also be mapped thoroughly. Results from a test pumping and infiltration program performed in the pre-investigation phase will be sufficient to design the ATES with minimal risk of thermal shortcut.

5.11.3.8. Recommendations for Poland

Poland has very high potential for widespread usage of ATES with excellent ground conditions in large parts of the country. However, only a minor part of the potential has been exploited. In addition to low temperature aquifers which can be used for combined heating and cooling following the approach used for the Gardermoen and ORMEL cases described in section 5.11.3, Poland has higher temperature aquifers with temperatures up to 60 °C which depending on groundwater flow rate in the aquifer can be used either as high temperature storage or to only extract heat (see examples for Denmark in section

5.11.3). A combination of high temperature heat extraction from a deep aquifer and cooling from a shallow aquifer following the approach used in the Reichstag in Germany (see brief description in section 5.11.3) may also be a viable approach.

Equation (1) shows that the heat output in kW are linear the extraction of groundwater and heat. Thus the extraction of as much heat as possible per m^3 of groundwater is recommended. A maximum temperature reduction for heat production will save huge volumes of groundwater from being extracted from the aquifers. Extraction of groundwater is usually a limiting factor with respect to a sustainable exploitation of the aquifer to maintain the water balance. In addition to direct use of the warm groundwater, the remaining heat extraction, i.e. temperature reduction of the groundwater, should be done by using a heat pump. Today the electricity in Poland is mostly produced by coal fired power plants. Thus in the near future and according to the decarbonisation and introduction of more renewable power, the use of electricity driven heat pumps will be acceptable with respect to CO_2-emissions from the electricity generation. To reduce the CO_2-emissions as much as possible, the focus should be holistic and on system level. E.g. the potential for the use of heat pumps driven by electricity from solar cells should be considered and evaluated. Another important perspective on system level, is the investment needs in the electricity grid. Local energy solutions and seasonal and short term storage of energy in ATES (as well as BTES) can potentially reduce peak electricity demand and the need for investment, and should be investigated further. In some cases however, ad- or absorption heat pumps might be a right solution.

The need for skilled personnel in all phases (pre-investigation phase, building phase, operation phase and regular maintenance phase) of ATES systems should be emphasized. ATES requires a multidisciplinary approach involving expertise in many fields as discussed in the previous section. In order to ensure that more of the ATES potential in Poland is exploited in the future, one should focus on relatively large installations where one can have a short return of the investment. To exploit the resource fully, ATES should be used for both heating and cooling purposes, direct cooling included. The use of ATES must be according to the groundwater regulations.

References:

Hanstad N. 2017: Personal communication between Nils Hanstad (Båsum) with K. Midtømme.

Cabeza L.F., 2015: Advances in Thermal Energy Storage Systems: Methods and Applications, edited by L.F. Cabeza, Woodhead Publishing Series in Energy Number 66, Elsevier, 2015.

Dalenbäck, J.-O., Hellström G. and S. K., 2000: "Evaluation of the Borehole Heat Store at InfraCity, Sweden" TERRASTOCK 2000, 8th International Conference on Thermal Energy Storage, Proceedings, Volume 1.

EGEC, 2016: EGEC Geothermal Market Report 2016, published October 2016, accessed at October 5th 2017 from https://www.egec.org/media-publications/egec-geothermal-market-report-2016/.

Eggen G., Vangsnes G., 2005: Heat pump for district cooling and heating at Oslo Airport Gardermoen. Proceedings of the 8th IEA Heat Pump Conference, Las Vegas, Nevada, 30 May–2 June 2005.

Fondenes B., 2016: Personal communication with Kirsti Midttømme.

Førde, M., 2015:Numerisk 3D-modellering av kvartærgeologi og hydrogeologi i Melhus sentrum – En vurdering av uttakskapasitet, optimal utnyttelse og forvaltning til energiformål. Master thesis at Norwegian University of Science and Technology, department of Geology and Mineral Resources Engineering, 118 pages.

Gehlin S., Andersson O., Bjelm L., Alm P.G., Rosberg J.E., 2015:Sweden Country Update on Geothermal Energy, World Geothermal Congress 2015, Melbourne.

Grønnesby, E., 2014: Høgskolen i Bergen. (Egil Grønnesby, Sweco, Performer) Bergen University College, Bergen, Norway

Haugerud, L. P. and Lien I., 2015: Analyse av feltemålinger av varmepumpe i boliger Enova SF.

Heekeren, V.v., Bakema, G., 2015: The Netherlands Country Update on Geothermal Energy, World Geothermal Congress 2015, Melbourne.

Henne, I., Midttømme, K. 2018, in preparation: Integrated thermal energy storage combining PCM storage and borehole thermal energy storage - Western Norway University of Applied Sciences, Campus Kronstad, Bergen Norway , proceedings EnergStock, IEA ECES 14th International Conference on Energy Storage, Adana, Turkey 2018.

Kukkonen, I., 2002:“Finland” in Atlas of Geothermal Resources in Europe, European Commission.

Lanahan, M. and P.C, T.V., 2017: "Seasonal Thermal-Energy Storage: A Critical Review on BTES Systems, Modelling, and System Design for Higher System Efficiency." Energies.

Lee, K.S., 2013: Underground Thermal Energy Storage, Part of Green Energy and Technology Book series, Springer-Verlag, London.

Loveless S., Hoes H., Petitclerc E., Licour L., Laenen B., 2015: Belgium Country Update on Geothermal Energy, World Geothermal Congress 2015, Melbourne.

Midttømme, K., 2005: Norway's Geothermal Energy Situations. Proceedings World Geothermal Congress 2005, Antalya Turkey.

Midttømme, K., Banks, D., Ramstad, R.K., Sæther, O., Skarphagen, H., 2008: Ground-Source Heat Pumps and Underground Thermal Energy Storage— Energy for the future. In Slagstad, T. (ed.) Geology for Society, Geological Survey of Norway Special Publication, 11, pp. 93–98.

Midttømme, K., Müller, J., Skarphagen, H., Berre, I., Ramstad, R.K Sørheim, H.R., 2013: Geothermal Energy Use, Country Update for Norway European Geothermal Congress 2013.

Midttømme K., Henne I., Kocbach J., Ramstad R.K., 2016: Geothermal Energy Use, Country Update for Norway, in Proceedings of the European Geothermal Congress 2016, Strasbourg, France, Sept 2016.

Nordell B., Andersson O., Rydell L., Scorpo AL, 2015: Long-term Performance of the HT-BTES in Emmaboda, Sweden, Greenstock 2015, At Beijing, China, Volume: 13.

Paksoy, H.Ö., 2007: Thermal Energy Storage for Sustainable Energy Consumption. Fundamentals, Case Studies and Design, Springer.

Pascal, C., 2015: Heat flow of Norway and its continental shelf, Marine and Petroleum Geology, 66, (2015), 956-969.

Ramstad, R., 2011:Grunnvarme i Norge – kartlegging av økonomisk potensial. Report on commission nr 5/2011 by The Norwegian Water Resources and Energy Directorate (NVE). 88 pages.

Ramstad R.K, Holmberg, H., 2017: The most important results from the Føyka-project so far (Norwegian), presented at seminar.New solutions for explotation of geoenergy, Asker March 24th 2017.

Riise, M.H., 2015: Praktisk guide for grunnvarmeanlegg basert på oppumpet grunnvann – Hydrogeologiske forundersøkelser, etablering, drift og oppfølging med utgangspunkt i erfaringer fra etablerte anlegg i Melhus sentrum. Master thesis at Norwegian University of Science and Technology, department of Geology and Mineral Resources Engineering, 104 pages.

Røgen, B., Ditlefsen, C., Vangkilde-Pedersen, T., Nielsen, L.H. and Mahler, A., 2016: Geothermal Energy Use, 2015 Country Update for Denmark, in Proceedings of the European Geothermal Congress 2016, Strasbourg, France, Sept 2016.

Vangsnes, G. 2014: Personal communication with R.K.Ramstad.

Wemhoener, W., 2016: "Heat Pump Concepts for Nearly Zero-Energy Buildings: Final Report – Project outline and summary of main results.

5.12. Regulatory and financial incentive measures for geothermal development in Europe

5.12.1. Regulatory and financial incentive measures for successful geothermal development in Europe. Geothermal Risk Guarantee Fund. Recommendations for Poland

5.12.1.1. Regulatory and financial incentive measures for successful geothermal development in Europe

European energy policy and National strategies - European climate & energy framework

The European Climate and Energy Framework is the result of an extensive regulatory process and negotiations between European Institutions and Members States. The European Union was founded on energy related matters, even though it only meant coal in 1951[1]. In the Treaty on the Functioning of the European Union[2] (2007), the shared competency between Member States and the EU on energy is listed in article 194, which empowers European Union policies on the functioning of the energy market, ensuring security of supply, promoting energy efficiency and the development of renewable energy source and promoting the interconnection of energy networks. Member States retains many competencies on energy, notably the "*right to determine the conditions for exploiting [their] energy resources, [their] choice between different energy sources and the general structure of [their] energy supply*". This dual competency remains a lasting source of tensions between EU wide objectives and policies and national implementations.

The first major EU climate and energy framework is the 2020 package, proposing targets on energy efficiency, renewables and carbon emissions, which contributed to make the EU a pioneering ensemble on climate action and renewable deployment. It is followed by the 2030 framework, which is – as of 2017 – being debated by the EU institutions.

2020

The targets

The 20-20-20 targets for greenhouse gases emissions, renewable energy and energy efficiency to 2020 have proved to be a central tool to the EU's climate and energy policy. In details the targets, adopted in 2007 by the EU leaders and translated in legislations in 2009 entail:

- 20% reduction of greenhouse gases emission compared to 1990 at EU level, with binding national targets ranging from -20% to +20%according to national wealth;
- 20% of renewable energy in the EU's energy consumption with national binding targets ranging from 10% to 49%;
- 20% improvement in energy efficiency compared to a baseline with a reduction by 1.5% of national energy sales annually.

As of the 2017 report on the state of the Energy Union, the Greenhouse Gas target has already been met, with a 22% decrease compared to 1990 in 2015[3].The EU is expected to be able to meet its energy efficiency target by 2020[4], and same goes for the renewable energy target, provided Member States increase their efforts.

EU ETS

In order to meet its objectives in terms of carbon emission reduction, the European Union set up an Emission Trading Scheme[5] in which large installations in the power and industrial sectors and in the air transport sector must – as a whole – comply with an emission cap. The actors of the sector receive or buy emission allowances, and they may trade surplus allowances (or buy additional ones if they need to emit more carbon). The emission cap in the system decreases annually by 1.74%.The ETS covers 45% of the EU's emissions. The sectors covered must have 21% lower emissions in 2020 compared to 2005.

Within the ETS, the NER300 is a facility that aims at promoting innovative low carbon technologies. It is based on the use of the income from the sale of 300 million allowances to finance such projects. The geothermal sector has been a beneficiary

[1] Creation of the European Coal and Steel Community.
[2] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:12012E/TXT&from=EN
[3] European Commission, Second Report on the State of the Energy Union, 2016
https://ec.europa.eu/commission/sites/beta-political/files/2nd-report-state-energy-union_en.pdf
[4] European Commission, 2016 Energy Efficiency Progress Report
http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52017DC0056&from=EN
[5]European Commission, EU ETS factsheet, 2016
https://ec.europa.eu/clima/sites/clima/files/factsheet_ets_en.pdf

with projects in France, Croatia or Hungary. The facility provides grants which are refundable in case the projects does not deliver on its objectives.

The Renewable Energy Directive

The Renewable Energy Directive[6], or RES-D, is the main piece of European legislation governing the deployment of renewable energy sources in the EU energy system. The Directives lays out the EU renewable energy target of 20% in 2020, and introduces several measures to allow its completion.

As of 2017, only three Member States have deployed renewables at a levels below the trajectory towards their national targets (Netherlands, France, Luxembourg). If the EU is as a whole is above its planned trajectory for the RES target, deployment still needs to pace up to reach 20% by 2020 (Fig. 5.12.1.1).

Besides the targets, the Renewable Energy Directive established a set of new measures that allowed for a rapid penetration of renewables, notably in the electricity sector. These include the definition of support schemes allowed to promote renewable energy sources, and priority access and dispatch for renewables in electricity.

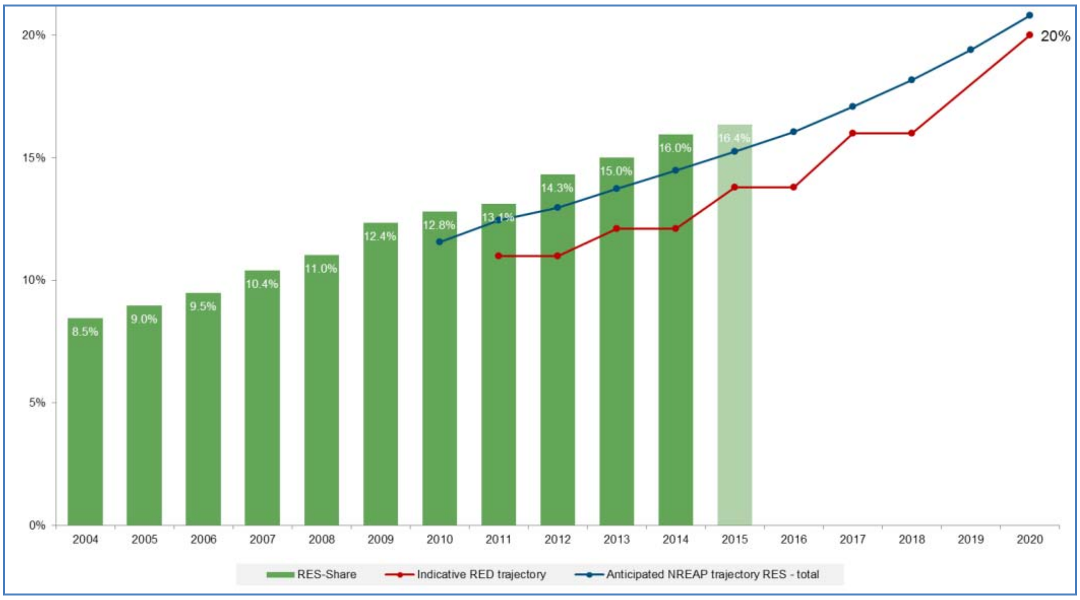


Fig. 5.12.1.1. Renewable energy shares in the European Union vs. Renewable Energy Directive and National Renewable Energy Action Plan Trajectories (Source: European Commission, Second Report on the State of the Energy Union, 2017)

For geothermal energy specifically, the RES-D introduced the definition of this energy source as "*energy stored in the form of heat beneath the surface of solid earth;*", which serves as a basis for the regulation of geothermal projects at the national level, and consistency in the regulatory framework for geothermal across the European Union.

Energy efficiency directive and EPBD

The Energy Efficiency Directive introduces the 20% energy efficiency target, and provides Members States with instruments to reach it, notably Energy Efficiency Obligation Schemes. A key measure of the EED is the annual mandatory reduction of 1.5% in the sales of energy Member States need to achieve between 2014 and 2020.

In 2016 final energy demand in the EU was 2.2% below the target for 2020, and only 1.6% above in Primary energy terms. As for progress at the sectoral level, energy consumption in buildings decreased by 0.7%/year from 2005 to 2014.

The EPBD introduced requirement for the energy performance of buildings, notably for all new buildings to be "Near Zero Energy", and for them to cover their remaining energy consumption with renewables.

Internal Electricity Market

The reform of the European markets for electricity aims at the creation of a unified European electricity market. It is defined by[7]:

[6]DIRECTIVE 2009/28/EC

[7]http://ec.europa.eu/energy/en/topics/markets-and-consumers/market-legislation

- Unbundling of networks:the grid is now operated by an independent TSO, and all electricity producers may access it without discrimination;
- Increased competition in the electricity production and supply: open the retail market to competition, allowing private, international and cooperative actors to emerge. It aims at yielding lower prices for consumers;
- Regulated electricity and gas prices are phased out – progressively – across the EU;
- Agency for regulators (ACER)to manage the opening of the European electricity market and ensure its stability.

2030

The guidelines determining the European climate and energy framework for 2030 were laid out in European Council Conclusions of October 2014[8]. As of November 2016, the European Commission proposed a Clean Energy for All European package[9] reviewing existing legislation or proposing new ones to set the post-2020 climate and energy policy.

The targets

The targets set by the European Council Conclusions of October 2014 for 2030 are:

- 40% greenhouse gas emissions reduction compared to 1990 levels(binding at EU level);
- Minimum 27% of renewables in the final energy demand (binding at EU level);
- 27% energy efficiency target compared to a baseline, with the possibility to consider a figure of 30%(indicative at EU level).

These targets are not assorted with binding national targets, which raises a new issue in terms of the governance framework that shall ensure EU level targets are met.

In its Clean Energy for all European package, the European Commission called for a binding 30% energy efficiency target.

EU ETS

The EU ETS is prolonged in the 2030 EU climate and energy framework[10], with several modifications aiming to increase the price of allowances, rendering the scheme more effective in driving investments in emission reduction.

- The rate at which the allowance cap decreases goes from 1.74% to 2.2%.
- Market Stability Reserve: introduced to withdraw allowances from the market to better control the price of carbon by avoiding oversupply of allowances.
- Innovation fund is introduced: (former NER300) use the income from 500 million allowances to support innovative low carbon projects across the EU, notably through financial instruments.
- Modernisation Fund[11]:help power and other energy system in emission reduction and energy efficiency in 10 poorest EU Member States. After 2020 this can be an outlet for district heating in Poland looking to develop geothermal projects in order to decrease their carbon emissions. It will allocate 310 million allowances (2% of the total cap of the ETS).

The Renewable Energy Directive

The proposal for a recast Renewable Energy Directive[12] introduces several changes likely to affect the deployment for geothermal energy post 2020. The core changes introduced by the Commission proposal are:

- Minimum 27% renewable energy target (at EU level);
- Support schemes to RES in electricity: awarded in the form of premiums, awarded through competitive, technology neutral processes. Member States may retroactively change support schemes, and must notify in advance any upcoming changes.
- Administrative procedures: one-stop-shop established in each Member States to centralise the application and authorisation process for renewable energy projects. Projects to receive an answer within 3 years;

[8] http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/145397.pdf
[9] http://ec.europa.eu/energy/en/news/commission-proposes-new-rules-consumer-centred-clean-energy-transition
[10] https://ec.europa.eu/clima/policies/ets/revision_en#tab-0-0
[11] http://europa.eu/rapid/press-release_MEMO-15-5352_en.htm
[12] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52016PC0767R%2801%29

- Article on "*Mainstreaming Renewables in Heating and Cooling*": Member States "*shall endeavour*" to increase the share of RES in H&C by 1 percentage point annually between 2020 and 2030;
- Article on district heating: district heating to disclose their share of renewable energy. Consumers have a (limited) right to disconnect from the network. The principle of "third party access" is applied to district heating networks.

Energy Efficiency Directive and EPBD

- Energy Efficiency Directive:
  - EU level binding target of 30% reduced energy consumption compared to a baseline;
  - Article 7: up to 25% of RES energy used in buildings may be discounted in the calculation of savings under article 7;
  - Primary Energy Factor[13]: proposal to decrease the general PEF used in the EED to 2.0 (from 2.5), in order to reflect an increased share of renewables in the electricity mix[14].

Internal Electricity Market

For the 2020-2030 period, focus on the integration of renewable energy sources and small actors in the electricity market. The European Commission proposal for a Regulation on the Internal Market for Electricity states that:

- All market participants hold balancing responsibility, except small (<500kW) and demonstration projects. They may all take part in the balancing market;
- Priority of dispatch is suppressed except for small (<500kW) and demonstration projects, and for existing projects benefiting from it;
- Member States may, following a resource adequacy assessment, introduce capacity mechanisms (aiming at setting a value on flexibility to offset the supply risk from variable renewables).

Geothermal state of play

Market report

The geothermal sector remains small at the European level and quite fragmented, being very dynamic in some states, less so in others. The availability of the resource in a given country's geology plays a role, but so does the existence of a suitable regulatory framework and sufficient political support.

State of the market in electricity

In electricity, Iceland, Italy and Turkey are by far the largest European players for geothermal. Italy, with 916MW of capacity is the largest geothermal electricity producer in the EU (Fig. 5.12.1.2). Iceland is well known for its extensive use of plentiful geothermal resources, which despites a small population allowed it to develop 663MW of capacity. Both these countries mainly use "traditional geothermal" generation, from very high temperature fields. Turkey however, where geothermal development is much more recent, makes extensive use of EGS resources and dual cycle generation. It has 853MW capacity in total.

[13]The Primary Energy Factor (PEF) is a value used to convert energy savings in electricity (final energy) into primary energy savings. The PEF should represent the conversion efficiency of the electricity system: a more efficient system means a lower PEF (as 1kWh of final energy is closer to amount to 1kWh of primary energy).

[14]By convention, a conversion efficiency of 100% is used for "non-combustible" RES for electricity production. Geothermal is the only RES which is not combustion-based not included in this convention: a conversion efficiency of XX% is considered for geothermal.

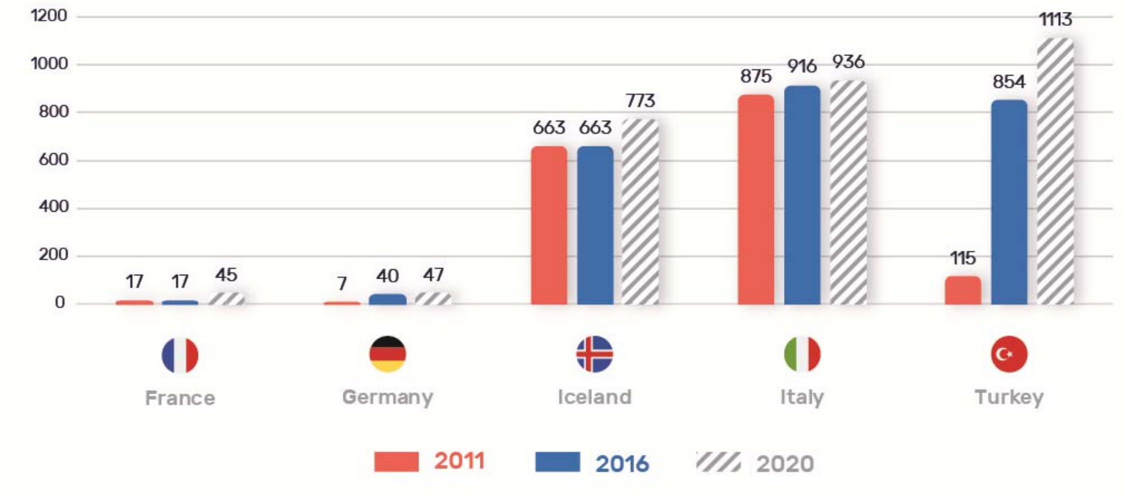


Fig. 5.12.1.2. Geothermal power: installed and projected capacity in select countries (MWe) (Source: EGEC 2016 Geothermal Market Report)

State of the market for district heating

The use of geothermal for district heating is much more widespread than for electricity. GeoDH capacity in Europe amounts to 4.8GW, including 1.7GW in the EU. It is a fast-growing energy source, at 10% per year in the EU (3% over Europe as a whole) over the last fast 5 years. Geothermal heat production for district heating amounted to 4.2TWh in 2015 in the EU alone. The leading countries in terms of installed geothermal district heating are Iceland (2169MW), Turkey (872MW), France (493MW) and Germany (301MW) (Fig. 5.12.1.3). In Poland, a country with a large share of H&C demand met through district heating, geothermal accounts for only 2% of district heating, and there have been few new developments in the 2012–2016 period.

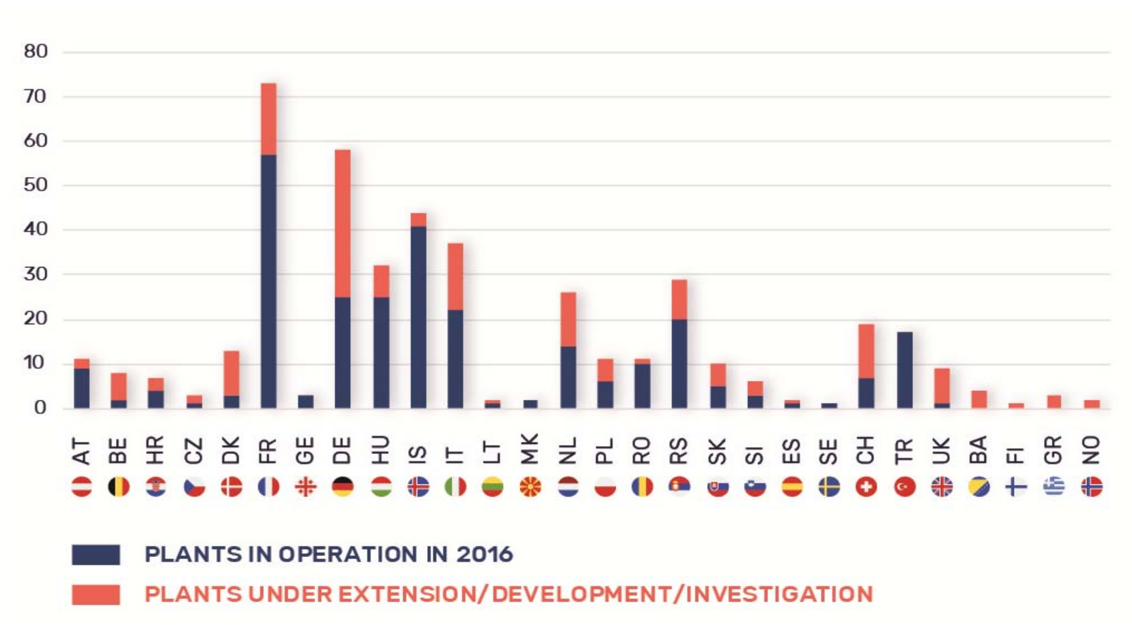


Fig. 5.12.1.3. Number of GeoDH plants in operation and in development in Europe by Country (Source: EGEC 2016 Geothermal Market Report).

State of the geothermal heat pump market

Across Europe, the total number of geothermal heat pumps (GSHP) amounts to 1.7 million units, with 1.3 for the EU alone. This market is dominated by Nordic countries, which total 44% of sales for 2015. Sweden is by far the biggest market for geothermal heat pumps (550,000 units installed, over 20,000 new units in 2015). Germany (over 300,000 units installed, 15,000 new) and France (200,000 units installed, 4,000 new) are also key markets, notably due to their size (Fig. 5.12.1.4).

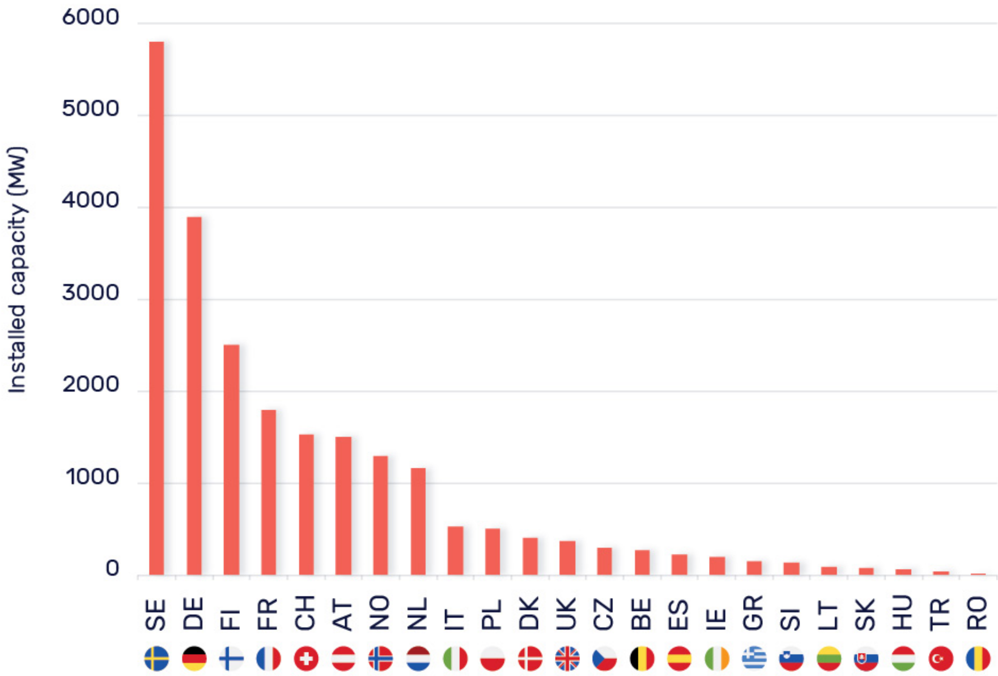


Fig. 5.12.1.4.Total installed capacity of GSHP in 2015 (Source: EGEC 2016 Geothermal Market Report)

Trends

Geothermal for Electricity

At the European level, geothermal for electricity has been growing at 10% per year (2% in the EU) over the last 5 years. Many investments are being developed with 26 plants planned in Europe, including 14 in the EU, most of which EGS. Over 100 plants are under investigation in the EU.

Geothermal projects for electricity are however being developed across the EU, carried by positive regulatory framework, financial support, notably from the EU, and the development of EGC technologies. France and Germany are among the main countries where this technology is being developed. Depending on the type of resources identified in the Sudetes region, such power production may be developed in Poland.

Geothermal for district heating

In the coming decade, the market for geothermal district heating will be structured by neighbourhood scale projects[15] which are integrated within the communities and connected to smart thermal grids. The high number of plants under investigation (136 in the EU, 164 in Europe) testifies to the value of this technology for local uses. All European countries are expected to use geothermal district heating by 2020. A very large potential remains untapped as more than 25% of the EU population lives in an area directly suitable for geothermal district heating[16].

Geothermal heat pumps

In terms of market dynamics, several countries are undergoing a rapid acceleration in the deployment of geothermal heat pumps. That is notably the case of Lithuania and Poland where units installed in 2015 account for 14% and 11.1% of the stock respectively.

Upcoming trends point the development of increasingly large systems, with borehole heat exchanger longer than 10km. Large installations are particularly suitable to meet the heating needs of the tertiary sector.

[15]EGEC, *Geothermal Market Report*, 2016.
[16]GeoDH Project.

Regulations

Geothermal projects are defined by long project development times, uncertainty concerns regarding resource availability in the early phases of investment, and they are usually regulated across several frameworks (water, energy, mining, etc.). It requires many authorisations, and procedures are usually lengthy. A sound regulatory framework for the development of geothermal needs to be transparent, fair and avoid unnecessary burdens.

Type of measures

Among the measures that may apply to a project for geothermal district heating, or more precisely deep geothermal projects – including power:

- Water regulations: Depending on different criteria, geothermal projects may be covered by water regulation. For instance, in Hungary a geothermal project above 2,500 meters depth is considered a water extraction project.

  The application of water legislation to geothermal energy differs between open or closed-loop system. Article 11 of the Water Framework Directive gives member states the option to authorise the reinjection into the same aquifer of water used for geothermal purposes if it does not compromise the environmental objectives of the directive. National governments have the competency to decide as to whether reinjection of the geothermal fluids is required.
- Mining regulations: Depending on criteria varying at the national level (depth, size, etc.), geothermal projects may be covered by mining regulations.
- Permitting process (well, building of the plant/DH network, etc.):Typically, the European framework grants license for exploration for 4 years, followed by 30 years exploitation licenses[17]. A key role of the licensing process is to avoid a double use of the resource.
- Environmental Impact Assessment, environmental permit: According to the Environmental Impact Assessment Directive, the national authority determines whether and which geothermal drilling projects should be subject to an environmental impact assessment. National or local regulations determine whether further environmental procedures are necessary, in compliance with EU requirements. This is notably the case when a project is proposed in a natural conservation area.
- Payment of royalties: Member States or regional or local authorities may impose the payment royalties to the operators of a geothermal project.

In cities, there is a diverse use of the underground (metro, parking, other networks) that make it more challenging to develop geothermal resources. Local heating and cooling plans are very rigid. Adding Geothermal DH in planning, requires information at an early stage about resources. This is the case in Italy or Hungary where local authorities manage authorisation for GeoDH. Article 13 of the Current Renewable Energy Directive and the Article 14 of the Energy Efficiency Directive have had positive influence on policies geothermal district heating, by mandating MS & regional authorities to assess they DH resources or include RES-HC in the planning of city infrastructure.

Geothermal heat pumps are usually not concerned by the same regulations, and building level regulations, notably – at the European level – the Energy Performance of Building Directive, Ecodesign and Ecolabelling, are the most relevant.

Assessment of existing measures

Considering the different types of regulations that govern geothermal projects, the assessment of the different measures as a whole is a difficult task. However, as highlighted in the Geoelec final report: "*Geothermal developers overtly abhor opaque, complex and lengthy licensing procedures. Deficient licensing rules can undoubtedly cramp investment in the geothermal […] sector in Europe.*"

The authorisation and licensing procedure of geothermal projects is tightly linked to the question of definition of geothermal energy. This has been settled in the Renewable Energy Directive where geothermal is defined as "*as energy stored in the form of heat beneath the surface of solid earth*." This definition plays a major role in the regulatory consistency and stability that allow predictability for geothermal project developers. This is notably crucial for developers of shallow or low enthalpy resources for district heating that may not meet criteria defined solely based on depth or temperature gradients.

[17] *Geoelec Final Report, 2015*

As situations vary greatly from one European country to another, the geothermal regulatory framework is not homogeneous. Besides, within a national framework, the wide array of regulation applying to geothermal leads to a high probability that if some best practices may be applied in some aspects of authorisations and licensing for geothermal, barriers may remain, hindering deployment.

Typical regulatory barriers identified by the GeoDH project are:

- Closed markets to new entrants;
- Burdensome administrative procedures;
- Lack of suitable regulation to give geothermal projects a status.

Regarding geothermal heat pumps, the framework laid out in the Renewable Energy Directive for the calculation of the geothermal energy from heat pump accurately represents the value of this technology. This allowed a political reckoning of GSHP and the setting of relevant support framework in several European countries, including in Sweden or Germany. In the latter case however, a shift in the support framework (MAP) contributed to halving the number of new heat pumps installed between 2008 and 2015 (other factors also contributed). Another change in this framework introduced in 2015 led the number of new GSHP to grow from around 17,000 that year to over 20,000 in 2016. This highlights the responsiveness of consumers to support frameworks, and to changing general context. Well design measures are of paramount importance.

Next steps

To continue the dynamism of the geothermal sector and to foster growth in new areas and countries, there are several measures that could be implemented across Europe. As was stated, these measures need to be consistent to develop a stable, transparent and streamlined regulatory framework for developing geothermal projects.

This can notably mean:

- Regulations and measures that are aligned with the 2009 Renewable Energy Directive, and the definition of geothermal it enounces;
- Single licensing authority for geothermal (which is consistent with the European Commission proposal for a recast Renewable Energy Directive);
- Better information of the public about geothermal, better training of civil servants – notably in local authorities that regulate geothermal for heating and cooling;
- Rules for GeoDH as adapted to the local context as possible;
- Include geothermal in national, regional and local planning for energy (notably heating and cooling strategies);
- A policy framework that guarantees that geothermal projects do not lead to a degradation of the environment, and that gives geothermal priority over other uses (nuclear waste, CCS…) for the use of the underground;
- Good information and development involving local communities and citizens (for instance through crowd funding[18]) to increase involvement and ownership of the geothermal resource and facility, and to decrease the risks of protests.

For geothermal heat pumps, consumer information needs to be improved. Consumers are not sufficiently aware of renewable heating and cooling solution for individual heating systems, notably geothermal heat pumps, which reduces the capacity to make such choice[19]. There, improving the training and awareness of professionals can also have a significant impact on support. Well-tailored incentive measures can also have a significant impact. However, considering the complexity of the heat pump market, these measures should be well designed not to incentivise inefficient appliances[20].

Conclusions

The geothermal market in Europe is undergoing a transition process. New investments, the development of new markets and the impact of innovative technologies support the growth of the sector and a change in the business models and organisations that allow these investments. This however requires suitable and consistent regulatory frameworks. The geothermal sector needs streamlined policies that result from a holistic approach to remove barriers that cause unnecessary frictions to project development. Moreover, due to the various uses that can be made of geothermal energy (electricity

[18]CrownFundRES project, 2016.
[19]FrONT project, Final Report, 2016.
[20]EGEC, *Geothermal, Air & Other Heat Pump technologies: market and efficiency*, 2017.

production, high or low temperature district heating, CHP, building heating, process heat for agriculture or industry…), and the tremendous differences between resources that can be utilised, there must not be a one size fits all approach to support, but flexible regulations that allow for diversity in projects. In that regard the definition of geothermal energy in Renewable Energy Directive is an important tool.

In the framework of sound policy support schemes aligned with the definition of the 2009 Renewable Energy Directive, state of the art environmental regulations, and integrating the specific challenges faced by geothermal projects, there can be a further deployment of geothermal energy in new markets and a diversification of uses and technologies.

Financing

Financing a geothermal energy project is often challenging because of the cost structure of geothermal projects that require large upfront investments while the viability of the project is unknown due to uncertainties on the quality of the resource before the well is drilled. Moreover, geothermal projects – notably for heating and cooling – are often undertaken by SMEs or public authorities, which have more limited finances or less capacity to take on debt.

Costs

Where high-temperature hydrothermal resources are available, in many cases geothermal electricity is competitive with newly built conventional power plants.

Binary systems can also achieve reasonable and competitive costs in several cases, but costs vary considerably depending on the size of the plant, the temperature level of the resource and the geographic location.

EGS cost cannot yet be assessed accurately because of the limited experience derived from pilot plants.

Geothermal heat may be competitive for district heating where a resource with sufficiently high temperatures is available and an adaptable district heating system is in place. Geothermal heat may also be competitive for industrial and agriculture applications (greenhouses).

As Geothermal Heat Pumps can be considered a mature and competitive technology, a level playing field with the fossil fuel heating systems will allow phasing out any subsidies for shallow geothermal in the heating sector.

Although geothermal electricity and heat can be competitive under certain conditions, it will be necessary with R&D to reduce the levelised cost of energy of less conventional geothermal technology (Table 5.12.1.1).

Table 5.12.1.1. Levelised costs of geothermal technologies (Update of Strategic Research Priorities for Geothermal Technology (2012, European Technology Platform on Renewable Heating and Cooling) – updated

LCo of Geothermal Electricity	Costs 2015 Range(€/kWh) Average (€/kWh)		Costs 2030 Average (€/kWh)
Electricity Conventional – high T°	0,05 to 0,09	0,07	0,03
Low temperature power plants	0,10 to 0,20	0,15	0,07
Enhanced Geothermal Systems	0,20 to 0,30	0,25	0,07
LCo of Geothermal Heat	Costs 2015 Range(€/kWh) Average (€/kWh)	Costs 2030 Average (€/kWh)	LCo of Geothermal Heat
Geothermal HP	0,05 to 0,30	0,08	Geothermal HP
Geothermal DH	0,02 to 0,20	0,06	Geothermal DH
Geothermal direct uses[21]	0,04 to 0,10	0,05	Geothermal direct uses[22]

[21] Directs uses are geothermal applications in balneology, greenhouses, agro-industrial processes etc.
[22] Directs uses are geothermal applications in balneology, greenhouses, agro-industrial processes etc.

Technology costs

Table 5.12.1.2. Technology costs for geothermal

Investment costs	Geothermal electricity development costs vary considerably as they depend on a wide range of conditions, including resource temperature and pressure, reservoir depth, location, drilling market etc. See below the capital costs per geothermal technology.
Operation and Maintenance costs	O&M costs in geothermal electricity plants are limited, as geothermal plants require few or no fuel. 1-2%/year
Commercial costs	Commercial costs associated with developments also need to be included in costing a geothermal project. These include financing charges (including establishment costs and interest), interest during construction, corporate overhead, legal costs, insurances. For geothermal, risk insurance is the main issue. It depends on the origin of the resources invested and the way they are secured, as well the amount of initial capital investment.

Capital costs, € million /MWe installed

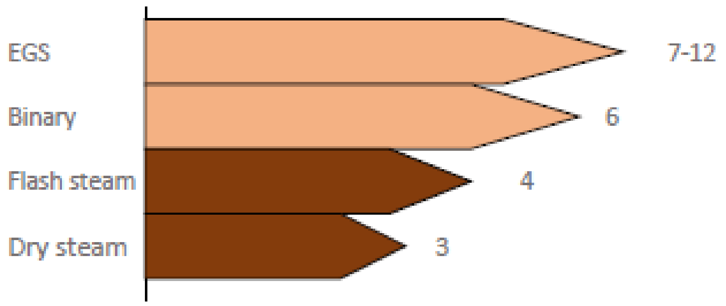


Fig. 5.12.1.5. Capital costs for geothermal electricity technology (million EUR/MWe)

Geothermal heat technologies are also capital intensive with low O&M costs.

Capital costs, € million /MWth installed

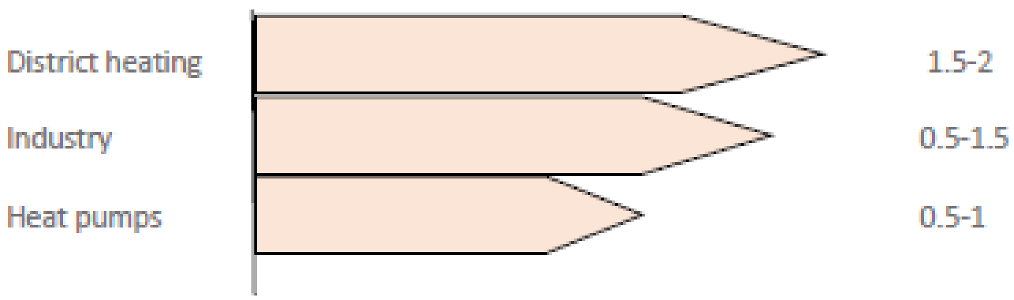


Fig. 5.12.1.2.Capital costs of geothermal heating and cooling technologies (million EUR/MWth)

Production costs

Table 5.12.1.3. Production costs for geothermal energy

LCoE & LCoH	Levelised generation costs of geothermal power plants vary widely. New plant generation costs in some countries (e.g. Tuscany-Italy) are highly competitive (even without subsidies) at ca. € 50/MWh for known high-temperature resources. They are largely depending on the main cost components: drilling which can be 30% for high-temperature plants 50% for low temperature and 70% for EGS. The very high capacity factor >90% (the highest of all energy technologies including nuclear) mitigates the capital intensity to render geothermal technologies competitive. To assess LC of h&c, several parameters must be assessed: - Climate conditions: in Europe we can assume 3 areas north, central, south to balance heating and cooling consumption - temperate level of the distribution system (50°C as an average) - N° of hours per year of h&c - Size of the buildings or demand from industry: m², kWth needed - Including or not domestic hot water
System costs	The geothermal power plant is assumed to be located in the vicinity of the national transmission network, so systems costs are very low. A reliable arrangement for the interconnection of a power plant to an existing transmission line is through the deviation of the transmission line into the power plant switchyard. Given the cost estimation of a 1 MWe power plant, the transfer station will cost about 80,000€ to 85,000€. In contrast to this, the costs for routing and cable installation are strongly related to the grid connection point assigned by the grid operator and therefore have site specific costs. Depending on the cable's diameter, a price of 100-150 € per meter is quite common. Geothermal energy is a renewable energy, producing 24h a day, everywhere; i.e. a local energy source with limited network needs. Moreover, it allows at balancing the grid, being both baseload and flexible.
Externalities	Geothermal has received very little R&D funding in comparison with other RES and conventional technologies. Moreover, geothermal is a renewable energy with very low GHG emissions so external costs of pollution damage are negligible
Business impact	Geothermal is affected like all other sources of energy by future change in legislation, but is immune from fuel price volatility.

Focus on drilling costs

Drilling represents from 30% to 50% of the cost of a hydrothermal geothermal electricity and heat projects and more than half of the total cost of Enhanced Geothermal Systems (EGS).

It is key to analyse the composition of the drilling costs, the influencing factors and the potential reduction of drilling costs.

A drilling cost includes the following elements:

- Drilling rig with all equipment incl. BOP
- Drilling tools incl. bits, fishing tools etc.
- Materials incl. cement, mud etc.
- Drillers : drilling crew, drilling supervisor etc.

Five generations of deep drilling techniques (Fig. 5.12.1.7) for geothermal have been seen since the first development of geothermal power in 1913 and of district heating mainly after the 1960s.The trend has always been to allow cost reduction and to improve efficiency and reliability. The first generation saw two vertical wells drilled from a two distant drill pads, while the second introduced deviated wells and single drill pads. The next generations were focused mainly on improving the design of deviated wells until deviated symmetric wells were developed. The fifth generation proposed for the first time (sub) horizontal wells for deep geothermal. This is, for example, the technology currently used in the Paris basin for new geothermal DH systems.

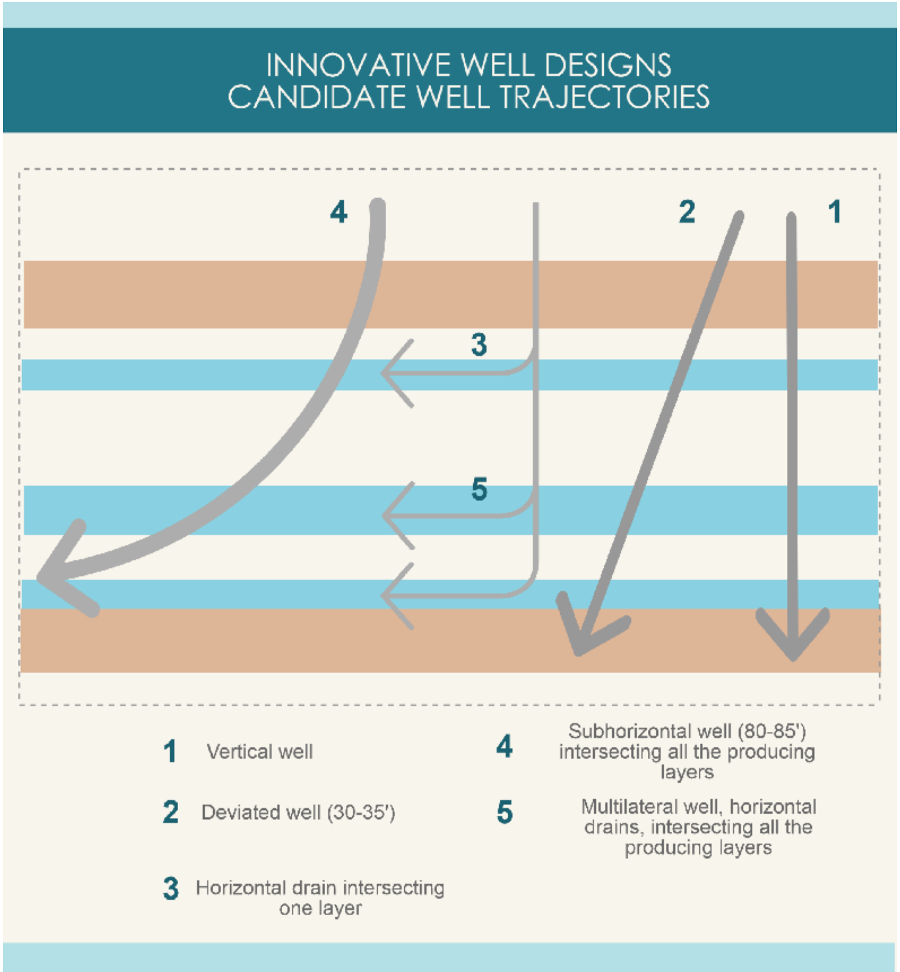


Fig. 5.12.1.7. Innovative well designs

Presenting the factors influencing the drilling costs is rather a complex task as they are numerous being technical, technological, regulatory, financial and economical.

The comparison of drilling costs is presented in Table 5.12.1.4.

Table 5.12.1.4. Costs review: Drilling costs comparison & recommendations (Source: EGEC)

<table>
<tr><th>Country</th><th>Drilling contract</th><th>Drilling price €/m</th><th>Ponderation factors</th><th>Other factors</th></tr>
<tr><td>Iceland</td><td>Integrated meter rates contracts</td><td>• A: 250 m fresh water / low-temp well, 60 to 100 €/m - Small rig
• B: 1000 m geothermal well 350 to 550 €/m - Medium rig
• C: 2500 m high-temp well 1.100 to 1.400 €/m - Large rig</td><td rowspan="6">Rig demand
Raw material cost</td><td rowspan="6">Market maturity : n° of geothermal plants, n° of drilled geothermal wells
N° of national drilling companies
Drilling market open or not to foreign competitors
Complexity of tender documentation</td></tr>
<tr><td>France</td><td>rig daily rate, lump sum</td><td>Under 1000m depth: 1000 €/m
Below 1000 m depth: around 870 €/m</td></tr>
<tr><td>Germany</td><td>metre rate, rig daily rate and lump sum</td><td>Below 2000m depth: 1100 - 1500 €/m</td></tr>
<tr><td>Hungary (and similar in the Pannonian Basin)</td><td>Lump sum drilling contract</td><td>• <2 km: 350-500€/m, with “small” capacity, “old” rig
• >2 km: 800-1000€/m, with “large” capacity rig</td></tr>
<tr><td>Netherlands</td><td>lump sum, rig daily rate</td><td></td></tr>
<tr><td>Italy</td><td>rig daily rate</td><td></td></tr>
</table>

On average the oil and gas industry drills 5000 m deep wells at a cost of about €2.5-3.0 million per 1000 m. Owing to the high energy density of oil and gas when compared to geothermal brine, the specific unit cost of a geothermal well (€/MWh) is significantly higher and geothermal systems must frequently have an associated re-injection well into the same hydrologic unit (IEA-geothermal August 2017). Depending on the characteristics of the subsurface and the market conditions, the drilling costs will be in the range of 1000 to 2000 euros per borehole meter, including the costs for the drill site, equipment rental, surveying, development, staff and energy. For example, in mature regions of the Bavarian Molasse Basin, the cost for a 3500 m deep well amounts to 5,250,000 euros assuming costs of € 1500 per meter drilled. In France, an estimation about an average drilling costs, with and drilling of 5-10 meters/hour will be EUR 4 million/well at 1800 m depth.

The typical components of drilling contracts in the geothermal drilling market in Europe are:

a. France: rig daily rate, lump sum
b. Germany: meter rate, rig daily rate and lump sum
c. Italy: rig daily rate
d. The Netherlands: lump sum, rig daily rate
e. Iceland: Integrated meter rates contracts
f. Hungary: Lump sum drilling contract

On average the oil and gas industry drills 5000 m deep wells at a cost of about €2.5-3.0 million per 1000m. Owing to the high energy density of oil and gas when compared to geothermal brine, the specific unit cost of a geothermal well (€/MWh) is significantly higher and geothermal systems must frequently have an associated re-injection well into the same hydrologic unit (IEA-geothermal August 2017).Depending on the characteristics of the subsurface and the market conditions, the drilling costs will be in the range of 1000 to 2000 euros per borehole meter, including the costs for the drill site, equipment rental, surveying, development, staff and energy. For example, in mature regions of the Bavarian Molasse Basin, the cost for a

3500 m deep well amounts to 5,250,000 euros assuming costs of € 1500 per meter drilled. In France, an estimation about an average drilling costs, with and drilling of 5-10 meters/hour, will be EUR 4 million/well at 1800 m depth.

The typical components of drilling contracts in the geothermal drilling market in Europe are:

• France: rig daily rate, lump sum
• Germany: metre rate, rig daily rate and lump sum
• Italy: rig daily rate
• The Netherlands: lump sum, rig daily rate
• Iceland: Integrated meter rates contracts

Day rate contracts are the most common, when turnkey contracts are used in smaller projects and water well drilling. We can see also integrated contracts with a mix of meter rate, day rate and turnkey contracts. The advantages of such contracts are that if everything is normal and the well is drilled as designed, the prize is then more or less fixed. The contractor is paid for each meter drilled. The contractor and the developer split the risk of damages in the hole up to a limit. So, the responsibility is greater on the contractor and the trust has to be between the parties. Unexpected delays related to hard rock, bad performance or weather condition is on the contractor. Hourly rate is paid for downhole problems due to difficult geological conditions by developer. The contractor is supplying all drilling services(casing running, cementing, directional drilling, logging etc.). The contractor is supplying all equipment's for drilling: drill bits, stab, DC, DP, mud motors, jars etc. The contractor is supplying all drilling consumables: drilling mud, cement, casing and casing accessories… These integrated contracts are recommended for small developers, new developers coming into the marked and operation in remote locations.

For the recently attributed drilling contract about the Þeistareykir Geothermal Power Project in Iceland, Landsvirkjun adopted a combined Integrated and hybrid-type drilling contract for ten wells. In top, we can notice some more specificity for this drilling contract. The call was an open tender published on EEA, in English, following the FIDIC terms. Non awarded bids 2, 3 and 4 received a financial compensation of $50.000 paid. The hybrid-type drilling contract had the following conditions:

▪ Meterage payments for drilling, casing run and casing cementing
▪ Day-rate payments for logging, stuck-in hole more than
▪Lump-sum payments for rig mobilization, installation of wellhead etc…
▪ Risk sharing for loss-in-hole, well direction etc.

Drilling costs reduce when more projects are developed in a given region, and when multi-well projects are developed. Such a cost reduction has been demonstrated by the project in Unterföring (Germany) developed by Erdwerk Gmbh (Fig. 5.12.1.8). In 2009, the first two wells in Unterföhringhad drilling costs of 1400€/mthen, two years after, a project in nearby Ismaning hada drilling costs of 1150 €/m; by 2014 when two new wells were drilled for the expansion of the Unterföringsystem, the drilling cost was 1100€/m. In five years, drilling costs were been reduced by more than 25%, principally through ‘learning by doing’.

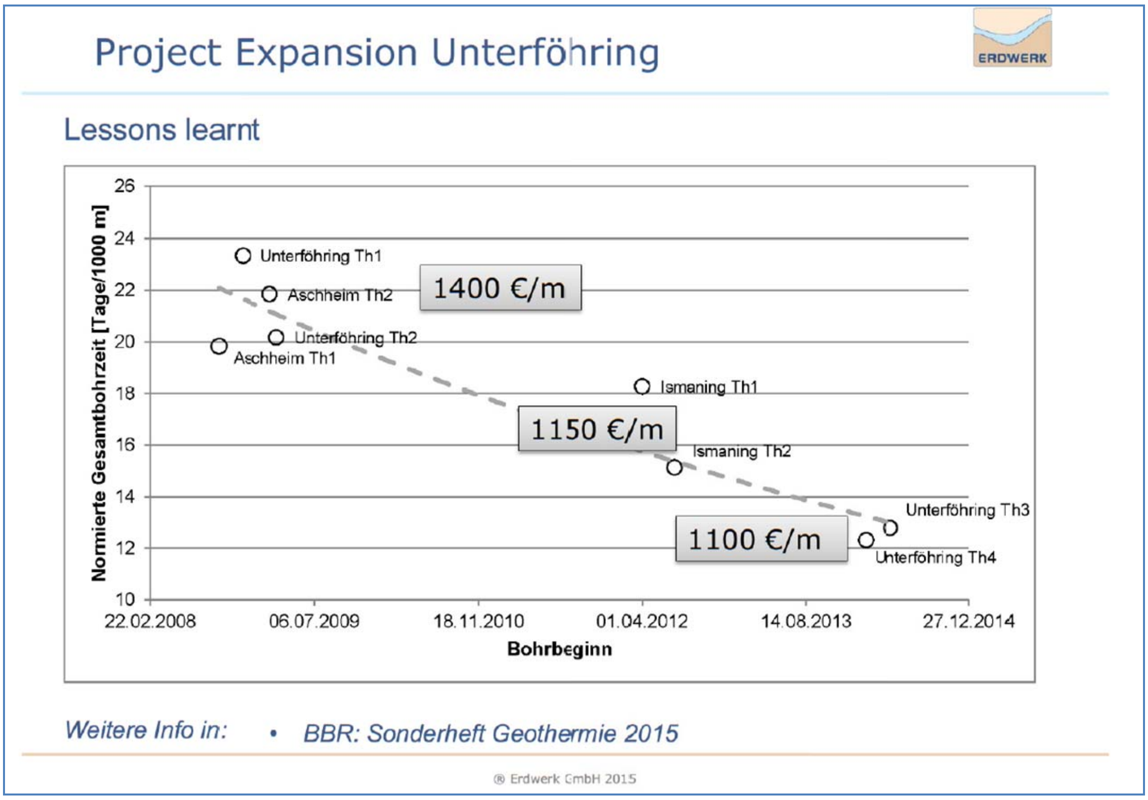


Fig. 5.12.1.8. Drilling costs. Project in Unterföring (Germany).

A briefing note on Deep drilling costs reduction can be found in annex to explore ways for having costs reduction of geothermal drilling.

Based on and EU survey on drilling costs, the results are as given in Table 5.12.1.5.

Table 5.12.1.5. Price range for geothermal drilling costs

Cost headings characteristic Detail of the service	Price range, in euros (pre-taxe price)
"Sub-surface"	
Civil works for access and drilling platform	8 – 10 M€ (estimation for doublet with two wells deviated at 2000 m)
Mob-demob drilling rig and auxiliary equipment	
Drilling	
Casing & installation	
Directional drilling	
Logging	
Stimulation, test and pumping	
Well head equipment	
Treatment and transportation of cuttings and waste material	
Engineering and supervision	
Insurance	
Unexpected (5%)	

Typical case study for geothermal DH in Western Europe:

Case study representing the cost estimates for a geothermal district heating plants in a small locality in Western Europe.

Table 5.12.1.6. Figures for case study on geothermal DH plant

Heating and cooling and DHW demand for 5,000 eq. inhabitants	40 000 MWh/year
Installed capacity requested	10 MW_{th}
Investment costs	EUR 22 million
• Wells and underground system (estimates for doublets with 2 wells deviated at 2000 meters)	EUR 10 million
• Heat plant (surface)	EUR 1-2 million
• District heating grid and substation (10km)	EUR 10-12 million
• Other costs (staff, engineering, permitting…)	EUR 1 million
Average investment costs	EUR 2.2 million/MW_{th}
Estimate for drilling costs (5-10 meters/hour)	EUR 4 million/well at 1800 m depth
Operation and maintenance costs (2 to 4% of investment)	EUR 0.5-1 million/year
Heat price	EUR 60/MWh
Efficiency	90-100%
Temperature	60-80°C
Lifetime (sustainability of 75 years)	25-30 years

According to these cost estimates, which are typically these for a 10MW_{th} project at 2,000 meters depth for 60-80 water – the type of conditions that could be developed in the Polish partner towns – a cost around EUR 2.2 million/kW_{th} can be considered.

Type of measures

There are different types of measures that ease the financing of a geothermal project.

For geothermal electricity, a possible approach is to provide feed in tariffs to power plants. These can be quite high in the case of demonstration projects, for instance in France they can be up to 0.28 EUR/kWh[23]. However, operational support is often not relevant for geothermal energy projects, whether electricity or heating and cooling, as they do not mitigate the risk for upfront investment. As was already noted, the key factor for financial uncertainty in geothermal project is not the price at which the energy can be sold, but the geothermal risk, that is the amount of energy – in terms of temperature, flow and sustainability of the reservoir – that can be recovered from a reservoir. A good measure reduces uncertainty in these areas.

As shown in Figure 5.12.1.9 below, a significant part of the investment into a project happens before there is any decrease in the level of risk associated to this project. In practice, before a first exploratory well yields satisfying data – which entails million-euro scale investment – there are no guarantee to the amount of energy that can be sold.

[23]JRC, 2015 Geothermal Energy Status Report

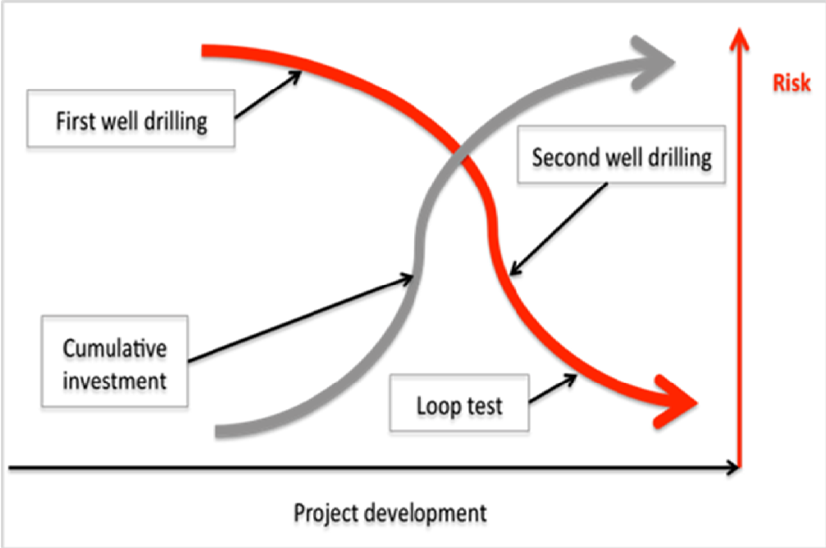


Fig. 5.12.1.9. Investment risk: a key challenge (representation of the level of risk of a geothermal project against cumulative investment)

Figure 5.12.1.10does illustrate that at different stage of market or project maturity, different financial instruments are relevant to promote geothermal energy. An extensive exploration phase requires upfront support that, from a private sector perspective, entail significant risk and potential for investment failure. There seed or venture capital projects are well suited. In markets where the geothermal sector is small or emerging, it is unlikely that private financial market will be drawn to geothermal exploration by themselves, and there, public incentives are necessary. Ideal forms of support for exploration include grants or public exploration. In the case of Poland, the availability of public geological data coming from oil exploration in the previous decades is a positive starting point for identifying geothermal resources.

After the exploration phase, and before the operation of the facility, for which Feed-In Tariff (FiT) or Feed-In Premium (FiP) are a widespread solution, the drilling and construction phrase require specific financial instruments. On a private sector perspective, the financing must be suited to project with higher risk. In mature markets, private investors are able to pool risk among different projects, and they can utilise data on existing installations. Products such as mezzanine debt that have lower payback certainty, but higher returns can be a solution when there is sufficient information. Private insurance for project developers or for financing actors can also be a solution to decrease the cost of financing, or increase the availability of financing for geothermal project. However, the emergence of such private insurance scheme requires a large enough pool of project that risk can be adequately assessed.

A key factor in the maturity of a geothermal market is transforming uncertainty into risk. On a financial point of view, uncertainty is intangible, and investors or project developers cannot assess the probability of failure before they have committed enough funds to drilling at least a well that will provide the needed information. Once there are enough installations in a large enough market, the private sector can provide the tools that allows to do so. Until then, support from the public sector is needed to allow geothermal projects to emerge. A solution to this end is the development of geothermal risk insurance facilities, which have been successfully implemented in several countries.

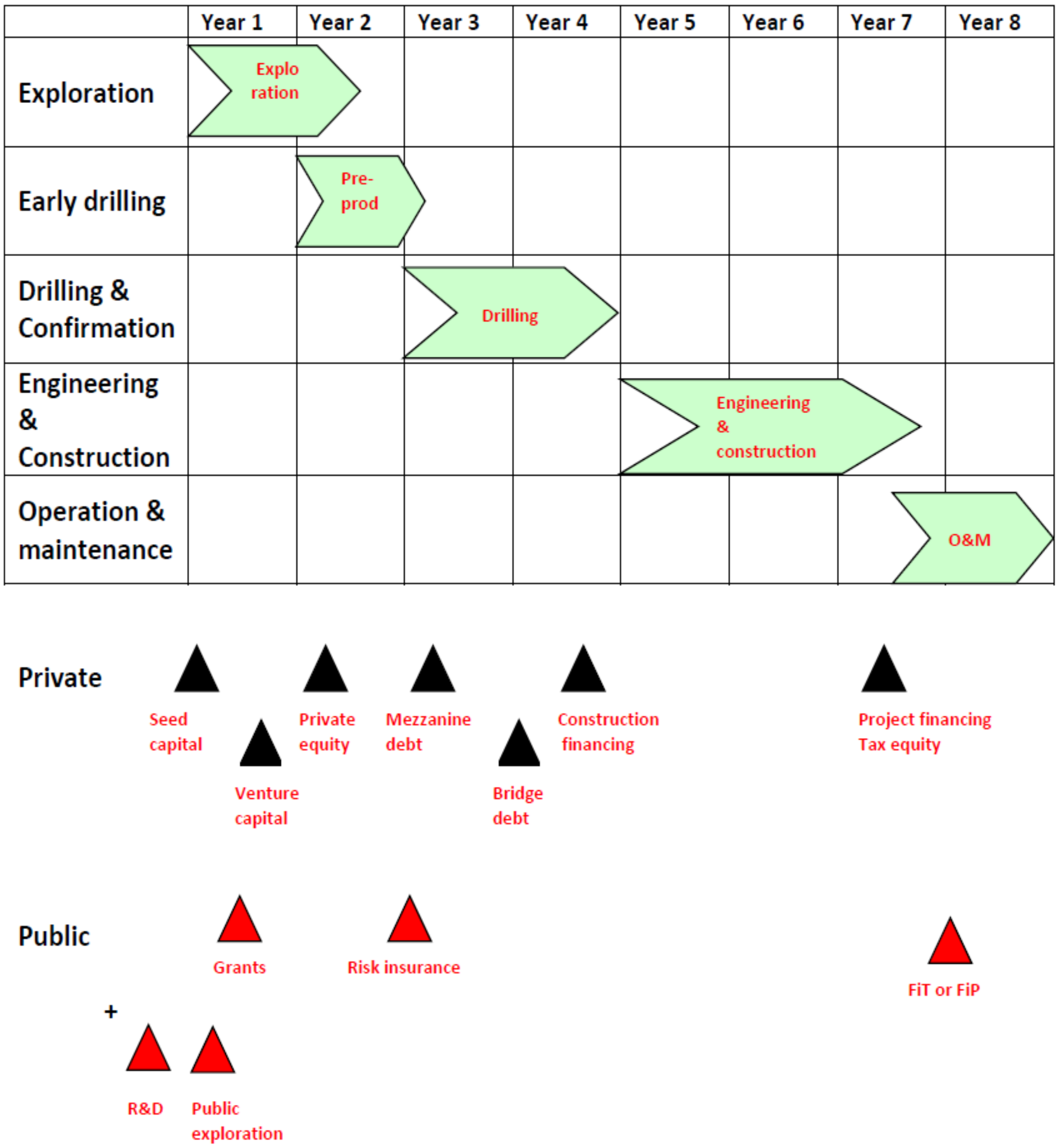


Fig. 5.12.1.10.Mechanisms for funding geothermal energy projects at different stages of projects development (EGEC)

Assessment of existing measures

Existing public-sector measures to promote geothermal energy can be divided in four categories: RD&I, risk insurance, support to electricity, support to heating.

- Research, Development & Innovation: a major actor in awarding support to RD&I in the geothermal sector have been the European Union. For the 2014-2020 programming period, the Horizon2020 facility – the EU's main vehicle for supporting RD&I projects – has allocated EUR 3.8 billion to projects in the "secure, clean and efficient energy" programme, of which EUR 664.3 million in 2016-2017. For geothermal energy, projects to improve the integration of geothermal in retrofitted buildings, the efficiency of borehole heat exchanges (BHE), further develop EGS or more generally improve the market uptake of geothermal and other RES technologies. The European Commission estimates that, as a whole, investment in RD&I relating to Energy Union priorities (which includes renewable energy, and thus, geothermal) amounted to EUR 22.9 billion[24]. The European Commission notably lists among its priorities for investment in RD&I the decarbonization of the building stock, for which geothermal energy is a viable solution for a large share of the European population, and strengthening the EU leadership in renewables, for which it is crucial to maintain a strong European know how to meet Europe's needs.

[24] European Commission, *Accelerating Clean Energy Innovation*, 2016,Com(2016) 763

- **Public risk insurance**: the countries that have implemented a public risk insurance mechanism for geothermal projects in Europe include: France, Germany, Iceland, The Netherlands and Switzerland;
- **Support for electricity**: feed in tariffs are available for geothermal electricity in several European countries, with limitation in some cases. However, due to a shift away from feed in tariffs across the EU, support for geothermal electricity is increasingly awarded through feed in premiums. This tends to decrease the certainty of geothermal power plants operators as to their cash flows – especially in the case of sliding premiums which are a fixed sum paid to the producer in addition to the wholesale electricity market price.

Table 5.12.1.7.Operational support for geothermal electricity in Europe (EGEC)

Country	Type	Eligibility period (years)
Belgium (Flanders)	Quota system	10
Croatia*	Feed-in tariff	14
France*	Feed-in Tariff	15
Germany	Feed-in Premium	20
Hungary*	Feed-in Tariff	N/A
Italy	Feed-in premium/ Tenders	25
Portugal (Azores)	Feed-in tariff / Feed-in premium	12
Romania	Quota system	
Switzerland	Feed-in Tariff	20
Turkey	Feed-in Tariff	10
UK	Feed-in premium (Strike price)	-

- **Support for heating and cooling**: geothermal for heating and cooling can be delivered through district heating (in which case some sort of feed in tariff or premium can be considered) or directly in a building. Many different solutions exist, from CHP to low temperature systems using heat pumps. Existing measures include[25]:
  - Investment grants (e.g.: France's Fond chaleur renouvelable, Poland'sNational Fund for Environmental Protection and Water Management)
  - Operational aid (e.g.: Feed in tariffs such as Italy's ContoTermico)
  - Tax incentives: reduced VAT (France), tax breaks…
  - Zero interest loans (e.g.: Spain with PAREER programme)
  - Carbon tax: Finland, Sweden, Denmark, France.

  The RE-Shaping project notably underlines that "*the success of some schemes will depend on the existing infrastructure, for example, the realization of renewable-based centralized heating systems can only be fully achieved if district heating grids exist*" and that stability is important for support to renewables in heating and cooling – including geothermal – to function.
- **Financial instruments**: whether at the European Union or national level, or provided by private institutions, specific financial instruments are increasingly important in the financing of renewable energy projects, including for heating and cooling. They can take different forms, from financial risk guarantee (e.g. European Fund for Strategic Investment), subsidized loans (e.g. National Fund for Environmental Protection and Water Management) to capacity building (e.g. ELENA). The main characteristic of such mechanisms is that a small amount of public funding is used to leverage private financing into a project (typically ratios between 15 to 20 are sought).

[25]FrONT, *Integrated Support Schemes for RHC, Assessment Report*, 2016.

- Energy Performance Contracting: energy performance contracting can be used for geothermal projects, notably when they are included in a wider programme that includes energy efficiency improvements. This is particularly suitable for instance for a project to improve energy efficiency and switch the heating and cooling system of a large building. With EPC, a company (ESCO) finances the project, which is then paid back periodically according to the terms of the contract (e.g. 10% of the total every year over 10 years). Following a European Commission Guidance[26] issued in September 2017, public authorities are now able to use EPCs to undertake renewable or energy efficiency investments without them being accounted as debt. This is quite significant for local authorities facing debt limitation but with clear prospect to decrease their energy expenditures by investing in geothermal energy projects.

Next steps

For further developing geothermal, particularly in heating and cooling, a stable and balanced policy framework is a requirement. Due to the varying climatic condition across Europe, and the different factors that affect the cost of installations (availability of skilled contractors, quality of resources, cost of financing, scale…), the market for geothermal heating and cooling is quite fragmented. Moreover, projects in this sector often face harsh competition from subsidized conventional fossil energy sources, notably the so-called "social tariffs" for natural gas or electricity – which often remains quite a carbon intensive energy carrier across Europe. Operational subsidies or tax breaks at different steps of the value chain of fossil energy sources should be phased out to ensure a level playing field with renewables. Meanwhile, emerging energy sources such as, in the case of Poland, geothermal, cannot be expected to stand on their own and a relevant support framework should be set.

On a longer term, public financial support framework such as grants for projects or public low (or zero) interest loans can be phased out provided there is a sufficiently large market for financing geothermal energy projects. When this happens, the public sector can retreat to providing information on resources – public geological resource information insures a level playing field and reduces the overall cost of the energy resources – and to providing insurance for the geological risk through a public geothermal risk insurance facility. As illustrated in the Figure 5.12.1.11, this insurance framework can be provided by the private sector at a later stage of market maturity.

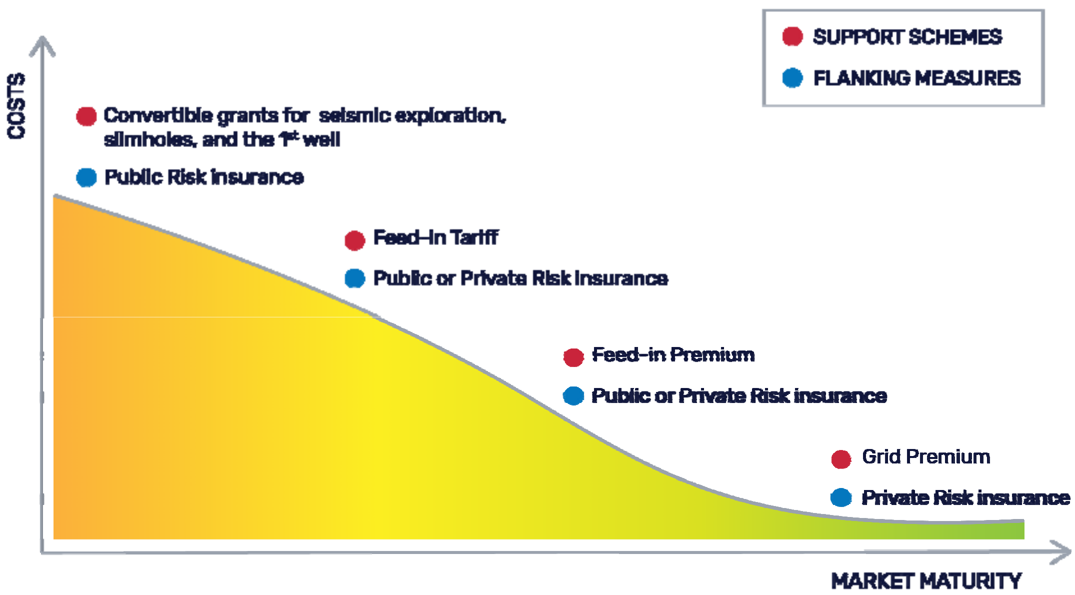


Fig. 5.12.3.11. Support schemes for geothermal adapted to market maturity

[26] http://europa.eu/rapid/press-release_IP-17-3268_en.htm

Conclusions

Considering the small number of geothermal projects in operation in Poland, with a suitable infrastructure and significant geological potential, the support framework should emphasise the mitigation of the geological risk and the development of expertise in the industry. Awareness raising for district heating operators and consumers as to the specific challenges and benefits of geothermal energy is also necessary, as the Front project has identified that lack of awareness is a major barrier in the development and the financing of RES projects for heating and cooling.

Initiating a geothermal risk insurance platform is a prerequisite to draw the private sector to the financing of geothermal project at a cost that does not prevent project development. Such platform could be national, which allows for an approach more suited to specific conditions. However, a European facility allows for a wider pool of projects, meaning a decreased risk at portfolio level – the projects are less likely to fail at the same time as they are set in different geological, political and economic settings.

Beyond such facility, investment grants such as the ones proposed by the National Fund for Environmental Protection and Water Management in Poland allow to develop so-called "flagship projects" that showcase the possible benefits from the use of geothermal resources. It is important that such a facility is prolonged until there is a sufficient depth of the geothermal market in Poland that allow project developers to build on past experience, and local authorities and district heating operators to be familiar with this energy resource.

In emerging markets, where "conventional" or fossil energy sources are still dominant, it is much too early to phase out grant based support to geothermal projects. If such projects can indeed be a factor of profitability and lower costs, this is unlikely to happen without some sort of public support.

Action Plan (Fig. 5.12.1.12)

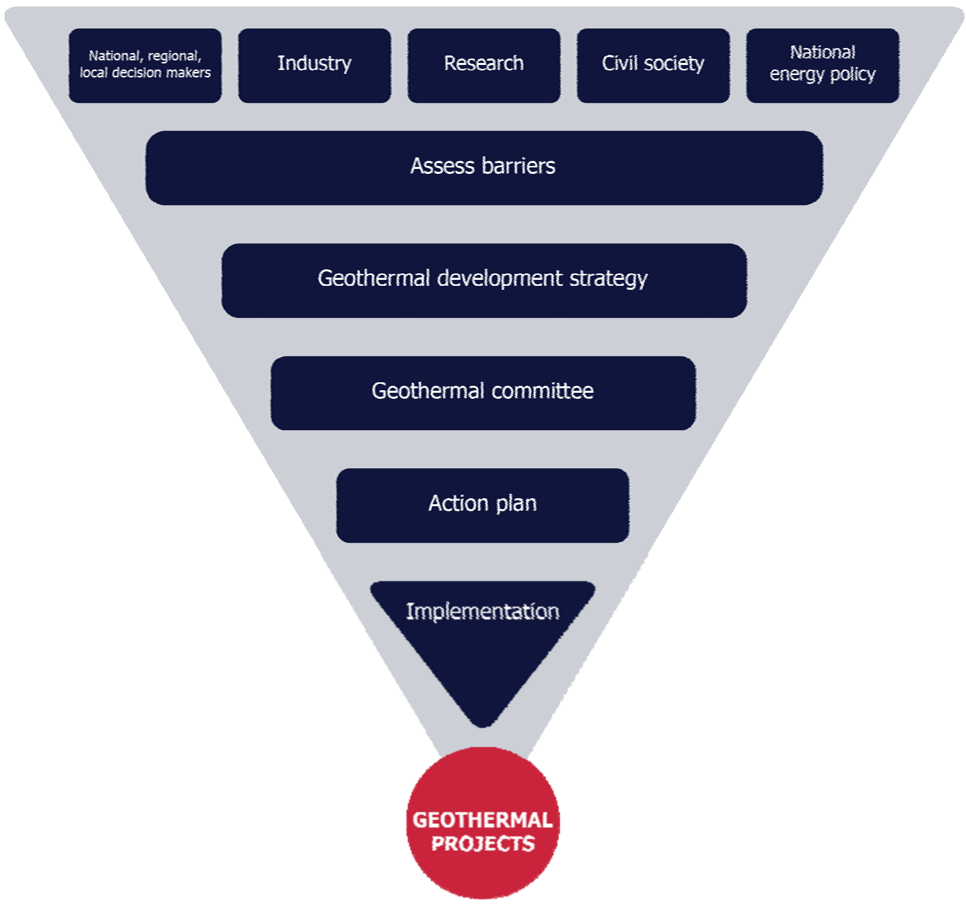


Fig.5.12.1.12. Representation of the steps for setting a framework enabling the development of geothermal energy

In Poland, there are circumstances conducive to the deployment of geothermal energy; there are resources, a market and commitment from the scientific community. However, policy makers should create substantially better conditions for geothermal deployment. Thus, the recommendations are as follows:

1) Create awareness amongst the public and decision makers about geothermal energy resources: More public and political support to promote, consider and initiate geoDH systems is needed, as is deepen knowledge and awareness among decision makers and politicians of various levels, local/regional administrations, DH designers and district heating companies. Some relevant activities have taken place conducted in the country but they should be done at more regular and wider basis.
2) Develop a suitable regulatory framework to increase the geothermal use and follow sustainable energy development. The recommendations propose a centralised and streamlined administrative process, that differentiates the requirements for permitting of small domestic or residential systems through a simplified online registration or notification process. A more complex permitting system comprising risk assessment, environmental impact assessment, permitting and subsequent monitoring is recommended for larger scale systems. Transparent, reliable, and coherent legal framework conditions and their implementation secures the investment in the sector. A reduction of legal barriers may be obtained by implementing clear/standardised administrative procedures to obtain licences.
3) Improve the financial framework

a) Earmark funds for the incentives for investment phase and production/sales stages: such as support schemes, fiscal measures. Since 2013 there are no dedicated support schemes on national level for geothermal resources' exploration drilling and subsurface parts of geoDH in Poland.
b) Establish Drilling/Insurance Fund
c) Phase out the regulated tariff for heat. The Tariff for heat and electricity must to be agreed with the Energy Regulatory Office; therefore it is not possible to make high profits from heat.
d) Refurbishment of existing DH network: Geothermal installations operating in Poland often supply heat to the already existing district heating systems in the consumer's buildings which were not initially designed to use geothermal energy.

4) Integrate shallow and deep geothermal as a key technology for smart cities and communities

   Shallow geothermal systems can be used in all parts of a city, at any scale, from individual single family houses to a whole city district as a part of a district heating/cooling network.
   Smart thermal grids can play an important role in the future smart cities by ensuring a reliable and affordable heating and cooling supply to various customers with renewable energy carriers like geothermal energy.
   Geothermal energy is a key technology for providing and balancing energy supply and demand in smart cities.
   Moreover, in smart cities, the smart electrical grid has to be combined with the thermal grid: here too, geothermal is a good solution by providing both heating and cooling and functioning also a storage technology with underground thermal energy storage (both in low and high temperatures and shallow and deep depths). Geothermal energy can provide heating & cooling for district heating, small and large buildings, and some other low and medium temperature applications.

5) Proposal for the launch of a national and regional geothermal committees in Poland:

   To develop geothermal energy in a sustainable way persisting barriers that can cause delays and increase the costs of geothermal projects must be removed. In this respect, it is important to take decisive steps towards, for example, disseminating geothermal data, mapping, and removing regulatory barriers.

   The long-term development of geothermal energy requires a stable regulatory environment as well as the direct involvement of all stakeholders, i.e. the State, the public and local authorities, NGOs, and employers and employees. To this end, we encourage the establishment of a permanent committee/forum on geothermal energy in Poland.

Briefing note on Poland with recommendations for selected Project's towns and Poland

Poland's energy sector is mostly defined by coal, which represents 94% of its electricity and 18.8% of the country's final energy consumption (not accounting for the coal used for electricity)[27]. This means that a large share Poland's heating and cooling demand is met by this highly carbon intensive energy source with well documented impacts on the health of populations exposed to its environmental effects. These effects are quite prevalent in Poland where "low exhaust" coal burning (in building scale ovens) is a serious environmental issue. However, lack of adequate regulation – or enforcement of this regulation – leads to the continuation of this trend. Promoting alternative solutions is key to improve the air quality in Polish cities and local communities (and therefore the health).

Alternative solutions must be considered carefully not to have unintended consequences. For instance, a switch to direct electric heating would, in the case of Poland – as the electricity mix stands – lead to an increase in coal consumption and not a decrease. Even the use of heat pumps with low efficiency (for instance and air heat pumps with a COP of 2.5) is not an ideal solution as this still represents an amount of coal primary energy similar to that consumed by the displaced oven[28]. In general, favoring high efficiency solutions with low seasonal variability in efficiency is important to avoid system risk when meeting heating and cooling demand by using electricity – albeit as an auxiliary energy source[29]. In that regard, geothermal heat pump, and the utilization of low temperature geothermal resource provides significant system benefits, often not reflected in the cost of a project.

The social and health implications of "low exhaust" coal are indeed well integrated in the heating policy and strategy planning of city council and operators. However, during the study visit, we could not see a thorough plan to the effect of the conversion of heating systems from low exhaust to DH. Extensive planning is needed to assist communities in the transition, prevent backlash and accompany them – this can for instance include financing schemes to assist poorer households in the case of Lądek-Zdrój where low exhaust coal is widespread.

The geothermal projects that are planned in the towns visited in the context of this GeoHeatPol Project are likely to be flagship that serve as model for local authorities and other communities eager to switch towards cleaner heating solutions. To this end, the projects should adhere to the highest environmental and safety standards, as one project with bad consequences can have dramatic consequences on the sector as a whole. The completion of these projects is a first step to the growth of geothermal in Poland. A sound support framework is necessary, notably considering the vast benefits incumbent technologies benefit from (amortised assets, being considered a strategic resources). Such projects are key to build technical know-how and knowledge of the resource, but a general framework is needed for deployment across the Polish Lowlands and the Sudetes region. In that regard, the support provided to geothermal projects by the National Fund for Environmental Protection and Water Management is valuable. A next step should be the development of a public geothermal risk insurance facility.

The high heat demand, and the different resources expected in the various localities allows for inventive use of the geothermal heat in order to maximise the investment and improve the business model of geothermal projects in Poland. Indeed, as was underlined in this report, the challenge for developing geothermal in Poland is to find the right business models, which allows for an optimal output for the heat and reduces the project financial uncertainty in terms of income. Examples such as those observed in Iceland where geothermal is also providing a marketing value to business partnerships can be explored in Poland. The specific constraints of geothermal projects should be considered, as for instance when considering the case study below, representing a typical geothermal district heating project in Western Europe.

[27]Eurostat, 2017 Energy balances

[28]That is when considering an efficiency for the oven of 90% and a coal plant efficiency around 35%-40% (standard for lignite installations), not accounting transmission and distribution losses

[29]EGEC briefing paper on heat pump technologies, 2017

Briefing note on deep drilling costs reduction

Deep drilling costs can be reduced:

- With RD&D activities
- With Learning by doing series of drilling
- With a better functioning drilling market

Research and Development (R&D) can improve geothermal drilling technologies in order to reduce its costs. R&D should focus both on novel drilling concepts and on improvements to current drilling technology, as well as for other ways to optimize the economics of drilling operations (horizontal, multi-wells etc.). Nowadays, drilling for deep geothermal energy is done using equipment originally intended for the hydrocarbon industry. The target is to reduce cost for drilling and underground installations in 2020/2025 by at least 25 % compared to the situation today.

By developing more deep geothermal projects in a region, and multi-wells project, the well fields will see a cost reduction of the drilling (Fig. 5.12.1.13).

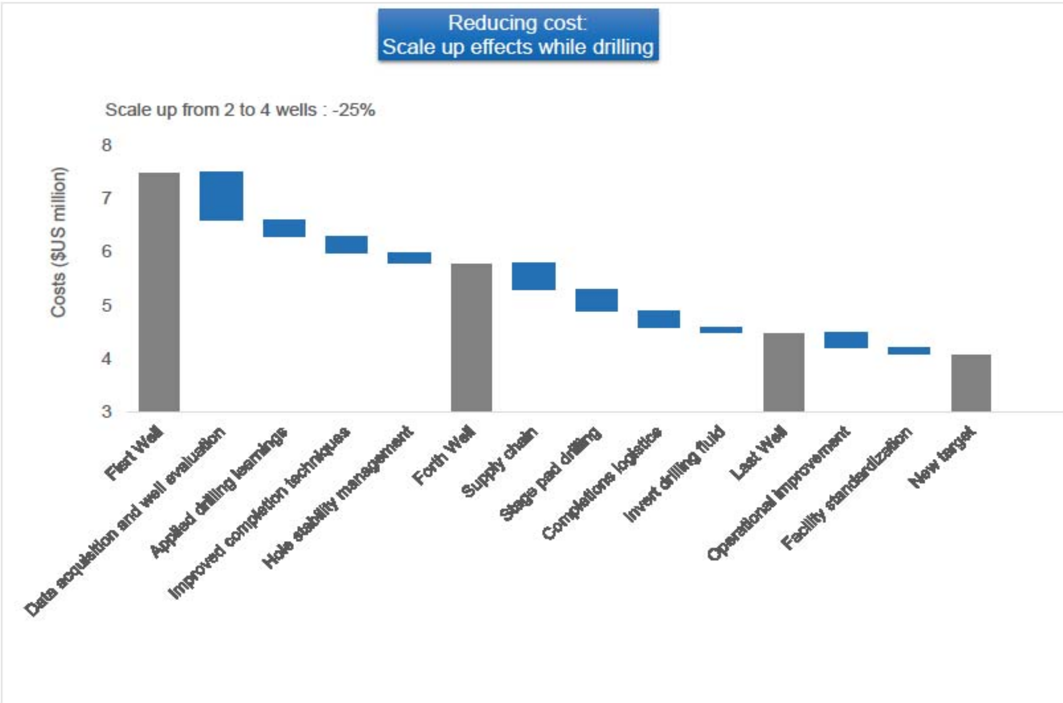


Fig. 5.12.1.13. Reduction of the drilling cost

Another challenge today is to improve market conditions for geothermal deep drilling. The deep geothermal drilling market could be more integrated with more access to available geothermal drilling cost data. Moreover, the interaction between project developers and drilling contractors could be improved.

Drilling market

During 2015, the Baker Hughes international rig count (Baker Hughes has issued the rotary rig counts as a service to the industry since 1944, when Hughes Tool Company began weekly counts of U.S. and Canadian drilling activity. Hughes initiated the monthly international rig count in 1975: http://phx.corporate-ir.net/phoenix.zhtml?c=79687&p=irol-rigcountsintl) showed that of the 2337 rigs used worldwide (on average),117 were used in Europe. Three quarters of the rigs in Europe were operating on land, and more than 70% drilled for oil and gas operations. It should be underlined that around4000 rigs are available for drilling worldwide.

Between one and three rigs have been used in France, Germany, Hungary, Iceland, Italy and Netherlands, and more than thirty rigs have been used for geothermal in Turkey. Still today, the geothermal industry uses the same rigs as the oil and gas industry. This is a key factor which influences the drilling market for geothermal. Geothermal drilling costs tend to follow the general oil and gas industry trend as depicted in figure 3 which exemplifies a total dependence on crude oil prices. This situation is likely to persist as long as the geothermal drilling sector does not build up a strong market share of its own.

The GEOELEC database of deep drilling companies active in the geothermal sector in Europe lists the main deep drilling contractors operating in Europe and further afield. Around 20 equipment manufacturer/provider and drilling service company and 20drillers/rig owners are operating in Europe

Drilling market conditions are different all over Europe. Firstly, drilling regulations have a national component which creates a barrier to the creation of a European market.

Fig. 5.12.1.14. Geothermal drilling index

In some countries, the number of drilling companies is not high enough to allow full competition and therefore competitive prices.

Another important parameter influencing the market is rig availability. Although the total number of rigs in Europe is enough for the geothermal operations currently developed, it can be the case that the rig required for a drilling is not available when needed by the project developers. The contractual relationship between geothermal developers and drilling companies is a key factor of the project and cost management. An innovative market approach has been recently developed in France. A specific drilling management contract has been developed by the French operator Fonroche Geothermie through a joint venture with Herrenknecht Vertical and Anger's & Soene, in order to build and operate an innovative a heavy land rig adapted to urban environmental constraints and deep targets (down to 6000m True Vertical Depth:TVD). This long term commitment brings price stability and availability for the ongoing development of deep geothermal exploration in France.

To sum up, drilling costs are dependent on:

- the rig demand (mainly for oil & gas, therefore dependant on crude oil prices),
- the drilling price (€/m),
- and the raw material cost.

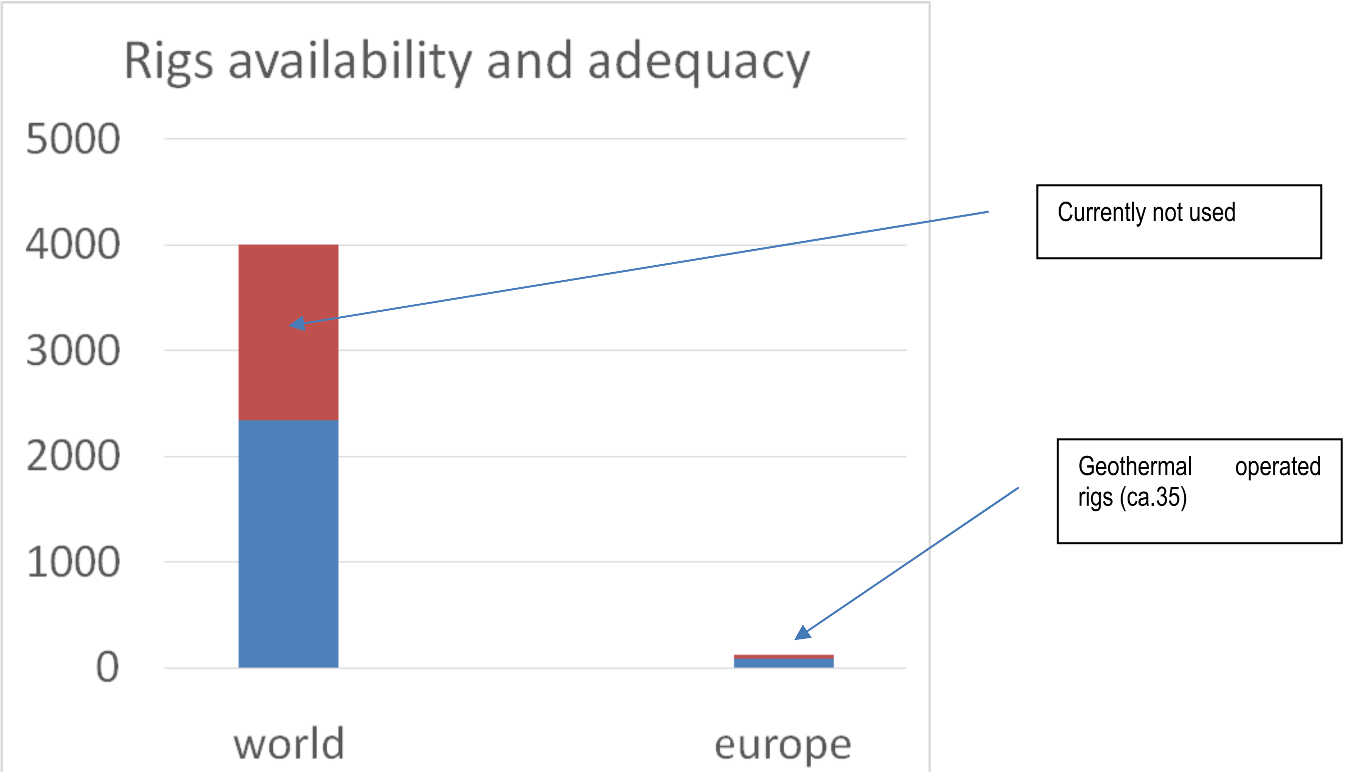


Fig. 5.12.1.15. Rigs availability and adequacy

Drilling cost

Acknowledging that drilling is the most costly phase of a deep geothermal project, between 40% and 75% in Europe, it is key to analyse the composition of the drilling costs, the influencing factors and the potential reduction of drilling costs.

A drilling cost includes the following elements:

- Drilling rig with all equipment incl. BOP
- Drilling tools incl. bits, fishing tools etc.
- Materials incl. cement, mud etc.
- Drillers : drilling crew, drilling supervisor etc.

They operate the following works:

- Rig mobilisation
- Drilling incl. directional drilling services
- Mud engineering
- Casing run
- Casing cementing.

Presenting the factors influencing the drilling costs is rather a complex task as they are numerous being technical, technological, regulatory, financial and economical.

On a technical point of view, using old or recent rigs, bits and other materials or having experienced drillers or young ones can change the costs. It is one reason for explaining the difference between Turkey and Germany for example. We can highlight the importance of having properly trained and experienced drillers.

On a technological aspect, it is clear that it is not the geothermal sector which influences the technological development and the costs but the oil and gas sector. But using the proper rigs and bits, traditionally operated for oil and gas, will influence substantially the drilling cost of a project.

One key factor, not enough considered, is about the regulatory conditions. We can there consider two dimensions: the nature of the regulations and its local or national aspect. The regulatory framework for drilling cover environmental rules, rules of mining authorities regarding protection and workers safety and mining permits. Standards and norms (ISO and API) are also regulating this sector. Competition rules are also important (see paragraph below on economics). Stricter regulations influence negatively the costs, but minimum rules are necessary for mitigating the environmental impact. Here it is important that the specificities and criteria of national rules are a barrier to the creation of a European drilling market and allow competition.

The financing of the drilling is not specific in it but is including in the project financing. Of course, it is the key phase as it is the most capital intensive one and due to its risk component. The financing has not the same cost being public or private, in a juvenile or a mature market. The interest rates propose for the drilling operation influence the costs as we underlined above, this phase of the project is capital intensive with a total costs ranging from 6 to 20 Mio €.

Finally, the drilling costs are influencing by the economic and market conditions. It relates here with the degree of competition between the drillers, the oil price and the project management. Many countries do not have national drilling companies, in others only few are operating. The contractual relationship between project developers the drillers, described above, is also influencing the drilling cost. The oil price influences the drilling costs for geothermal, as described with the graph on the drilling index. Drillers are proposing more rigs to geothermal when oil price is low. Finally, drilling costs can be reduced by saving time. This relates with drilling management onsite, work organisation and materials supply. Training, education and experience help to improve the drilling management.

The potential reduction of drilling costs should operate by working on these five factors.

The technical and technological development could lead to drilling costs reduction, but they will be largely influenced by the oil and gas sector. If improving current drilling technologies and concept will have an, impact at medium term, novel drilling technologies will only be available at the long term. At short term, one should work on technological development with learning-by-doing/drilling with a drilling operation covering several wells on a single project. Having more professionalised drillers would help in some countries to decrease costs.

We can consider together the regulatory, economic and financial conditions. The creation of a European geothermal drilling market and the adaptation of conditions according to the maturity of the market will help to mitigate drilling costs.

Conclusions

In the near future, the main driver for the reduction of costs of power and heat production leading towards grid parity will be the drilling cost. The drilling costs are expected to decrease firstly with learning-by-doing. The cost reduction will essentially be through better use of the current drilling rigs, a decrease in the number of hours to drill a well, and an increase in the number of wells per site (from two -four towards four-eight wells per site). This highlights the importance of engineering for the cost of drilling operations.

Current experiences in geothermal confirms that new technology and concepts in drilling help to save money. Because of the low market price of oil in 2016, drilling and service costs are lower than two years ago. Geothermal developers are starting to focus on saving time to further decrease costs. For example, performance and deviated wells drilling in geothermal are increasing in Turkey; and(sub) horizontal wells for deep geothermal will be developed in France in 2017. In Turkey, the expectation is to reduce the number of drilling hours for a well from ca. 300h to less than 130h, a reduction by a factor of more than two.

Further research and development to improve current technologies is expected to decrease costs by more than20% in the next ten years. Long-term cost reduction will be brought about by novel drilling technologies becoming mature.

The market conditions for geothermal drilling are, however, not expected to change dramatically until the development of a substantial number of deep geothermal projects and the creation of a proper geothermal drilling industry. In the geothermal drilling market, price elasticity will remain low.

The crude oil price and the demand or supply of rigs or wells drilled in the near future is hard to forecast precisely, and the impact on the drilling costs for geothermal are rather uncertain.

5.12.1.2. Geothermal Risk Guarantee Fund. Recommendation for Poland

Towards a risk coverage scheme in Poland – summary

Key recommendations for designing new and improving the functioning of existing public support schemes for geothermal include:

- Support schemes are crucial tools of public policy for geothermal to compensate for market failures and to allow the technology to progress along its learning curve. By definition, they are temporary and shall be phased out as this technology reaches full competitiveness;
- Market failures and unfair competition prevent full competition in the electricity and heat markets, while the current capital crunch obstructs the necessary private financing mobilisation to realise the enormous geothermal potential;
- Geothermal technologies hold significant potential for cost reduction. Dedicated support schemes should allow to reduce costs;
- Innovative financing mechanisms should be adapted to the specificities of geothermal technologies and according to the level of maturity of markets and technologies;
- Geothermal Risk Insurance Fund is seen as an appealing public support measure for overcoming the geological risk. As costs decrease and markets develop, the private sector will be able to manage project risks with, for example, private insurance schemes, and attract private funding;
- While designing a support scheme, policy-makers should take a holistic approach, which goes beyond the LCoE and includes system costs and all externalities. As an alternative, there is the chance to offer a bonus to geothermal for the benefits it provide to the overall electricity system: flexibility and base-load;
- Geothermal heat technologies are heading for competitiveness, but support is still needed in certain cases, notably in emerging markets and where a level-playing field does not exist.
- Given the level of maturity of innovative geothermal technologies and the negligible support received so far, it seems premature to talk about the need for more market-based mechanisms or even phase-out financial support for geothermal

With the notable exception of a few European market participants operating in well-developed geothermal regions, project developers have very little capability to manage the financial risk owing to the poor knowledge of the deep subsurface, lack of technological progress and high cost. In effect the probability of success/failure weighted net present values of project cash flows tend to be overly negative, thus effectively shutting out private capital from investing in geothermal energy.

However, with technology development (increasing the probability of success of finding and developing geothermal reserves) coupled with experience and thus reductions in cost, project developers will eventually be able to accept and, where appropriate, transfer project risks (technical, economical, commercial, organisational and political) in such manner that private funding will become available. Until then, a Geothermal Risk Insurance Fund (GRIF) is seen as an appealing public support measure for geothermal.

Although the geothermal market in Poland is ancient and that a national expertise exists, with less than ten projects in operation and less than ten under development, the polish market can still be considered in its juvenile phase.

The objective would then be to guarantee the cost of a well in case of partial or total failure. Firstly for such a juvenile market, (Convertible) Grants for seismic exploration, slimholes, and the 1st well are the most adequate support schemes. Subsequently when more wells have been drilled and dozen of deep geothermal projects are in operation, so for intermediate market, a public risk insurance is then seen as the most appropriate tool. It should be the case of Poland by 2020 or just after that date. Indeed, then the geology would be better known, more projects would be developed and be able to mutualise the risk all together, more financial institutions should be attracted. The geological risk should be easier to mitigate and more economical.

The governance of such a public national financial tool is shared between the Ministry, National Energy Agency, Geological Survey and a committee of experts. A State budget of 40-60 Mio € could help to launch this fund in Poland. This amount would indeed allow to cover the next 6-10 wells (3-4 deep geothermal systems), with a premium of 6-7% of the maximum guaranteed amount. It is a mutual insurance in order to develop projects in favorable regions and to have operations in new areas. The ultimate stage is when the market is considered enough mature to see private insurers proposing risk insurance at a competitive price.

If risk insurance is recognised to be a prerequisite for developing deep geothermal projects, financial subsidies for investment and operational support are also crucial.

The Risk insurance should cover the exploration phase and the first drilling (test). It means activities to be funded before financial institutions and IPP funding the confirmation drilling and surface systems. It appears clear that a risk mitigation scheme must be designed according to the market maturity of the sector (figure below):

- Investment aid in forms of Grants is seen more appropriate for juvenile markets. Starting with direct grants, this could evolve secondly to repayable grants in case of success and thirdly to convertible grant aiming at financing the second well.
- A Public risk insurance scheme would fit for intermediate market
- And Public-Private partnership for the risk insurance fund for pre-commercial technologies in a near mature market
- When market is mature and with a fair competition, this market will reward geothermal for its value and a fully private risk insurance scheme could be established

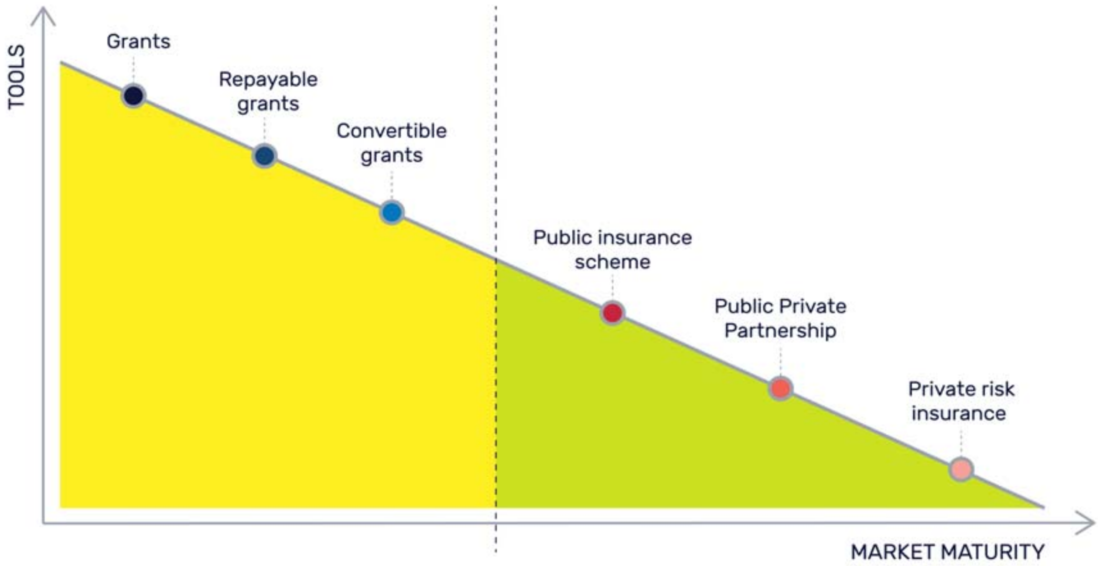


Fig. 5.12.1.16.Relevant investment support framework for geothermal projects per market maturity

Poland: state of play

The energy mix in Poland differs substantially from the one of the EU28, due to a much higher share of solid fuels (ca.54%). For the last 20 years, the share of renewable energy is increasing, more than the EU average, from less than 4% in 1995 to 12% of gross inland energy consumption in 2015. But during the same period, the share of gas also increased by 5 percentage points. The main decrease concerns the use of solid fuels (17 percentage points).

Poland has an overall low import dependency, although increasing, mostly due to the presence of national sources of solid fuels. However, import dependency is high for crude oil, and also above EU average as regards gas. Poland imports a significant share of its crude oil and gas needs from Russia.

The Polish energy sector is historically based on fossil fuels, which occur abundantly in Poland (ninth largest deposits in the world). In electricity production, two major fuels play a key role: hard coal and lignite, which produce nearly 90% of Poland's electricity.

In the heating and cooling sector, the share of renewables in Poland is about 14 %. Coal fired boilers and furnaces play a major role in Poland with more than 2 million of units installed (stock 2013). Moreover, Poland is one of the countries with higher installed district heating (DH) thermal capacity (57 GWth). Cogeneration (CHP) plays also an important role in Poland, with an installed capacity of 21 GWth. But for both DH and CHP the share of renewables (biomass, geothermal or solar thermal) is negligible.

In space heating and cooling in buildings, coal technologies still have a share of 36% in the total installed heating capacity in Poland. Gas, imported mainly from Russia (74% of gas consumed in Poland is imported), is also supplying a large share of the heating and cooling in buildings.

Table. 5.12.1.8. Energy consumption of Poland for electricity and heating (Source: IEA)

Production from	Electricity (GWh)	Heat (TJ)
Coal	132.962	242.947
Oil	2118	3406
Gas	6387	20167
Waste	75	711
Hydro	2435	0
Geothermal	0	0.1
Solar PV	57	0
Wind	10858	0
others	115	1290

The potential for fuel switch is large both in the heating and cooling sector and the electricity area, and geothermal could play a role to decarbonising these sectors.

- Coal is the main fuel for heating in Poland: in 2013, 36% of the heat demand in buildings was covered by coal fired boilers.
- Space heating and domestic hot water is supplied notably by 443 district heating systems, representing 41% of the heat demand.
- Less than 5% of the heat supplied in district heating is produced by renewables, and less than 1 by geothermal.
- District heating installations are ageing: the majority of district heating installations were built in the 1960's and 1970's in the large housing estates (panel blocks).
- Conventional coal and gas boilers operating in Poland are also old.

The geothermal resource based in Poland is very interesting for power and heat production but so far little progress in that sector was done in comparison with other European countries. Geothermal uses development in Poland has been moderate, especially in the heating sector. It means some barriers must be removed for tapping the great potential.

Most of the Polish territory is suitable for geothermal district heating, corresponding to areas where around 60% of the population lives (see map overleaf).

The geothermal HP market is still juvenile, but the development (initiated several years ago) is persisting. One may roughly estimate that in 2015 they reached at least 500 MWth capacity, and a production of and 714 GWh (2500 TJ)

Geothermal power plants demonstration projects should be launched for showing the potential based on low temperature resources.

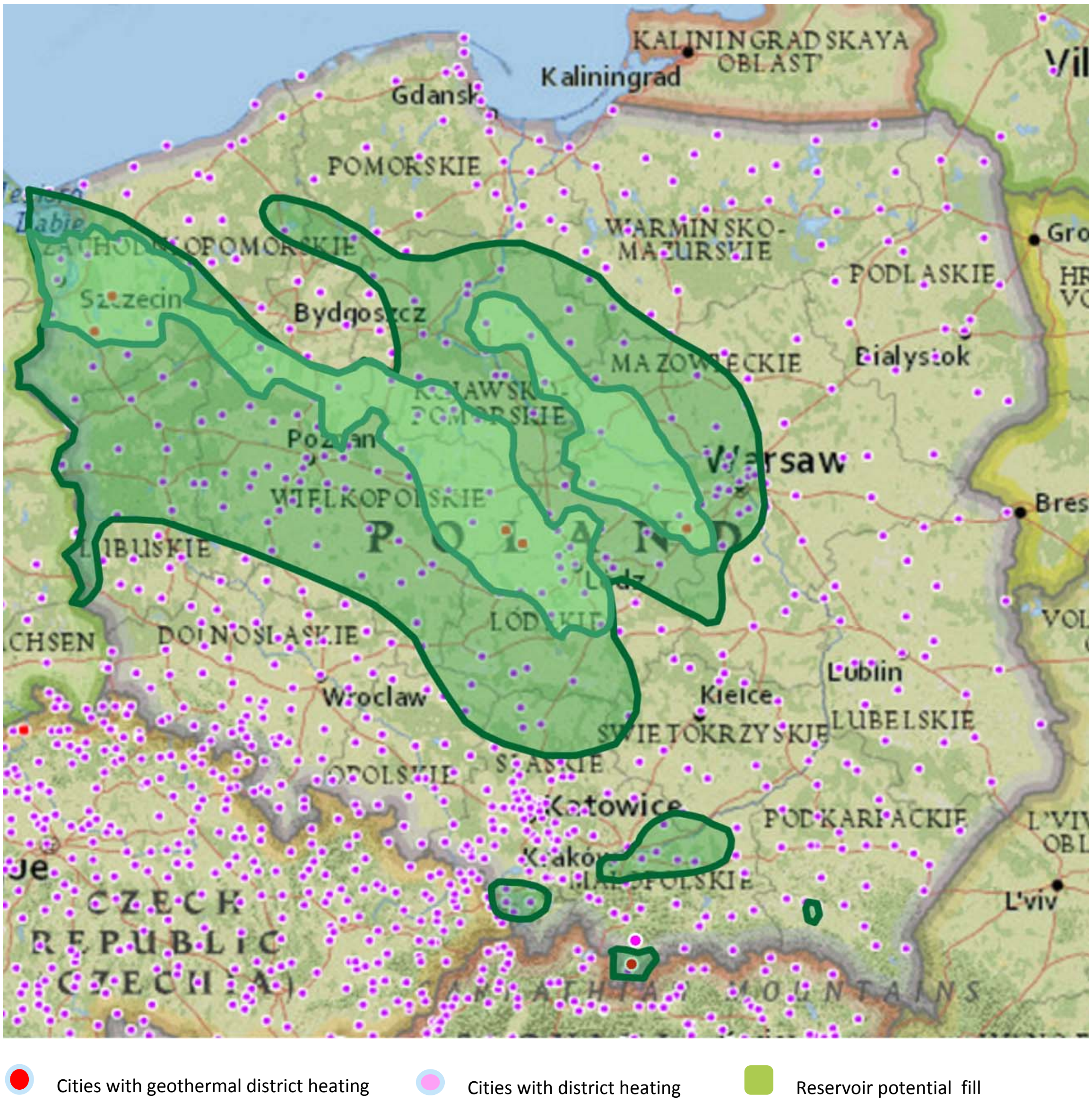


Fig. 5.12.1.17. Map of geothermal potential for geoDH in Poland. Based on GEODH Project results (www.geodh.eu)

Poland extends over parts of four major tectonic provinces: the East European Platform in the North East, the Mid-European Platform in the South West, the Variscan fold belt in the West, and a fragment of the Alpine belt, i.e. the Carpathians and Carpathian Foredeep in the South. The most important geothermal reservoirs for heating purposes lie in the Central and North Western Poland (the Polish Lowlands) and are mostly connected with the Mesozoic formations of the so-called Polish Trough (filled with Permian-Mesozoic sediments creating a cover of older formations).

In general, the aquifers hosted by Early Cretaceous, Early Jurassic and some Early Triassic formations have the greatest geothermal potential in the Permian-Mesozoic cover of the Polish Lowlands. Good conditions are found also in the Podhale region (part of the Inner Carpathians also in Slovakia) and, locally, in some areas of the Outer Carpathians and Carpathian Foredeep. In recent years (2006 – 2013) geothermal potential for prevailing area of the country was presented in a series of regional atlases (Górecki, Hajto et al., 2006, 2011, 2013: Górecki, Sowizdzal et al., 2012 Barbacki et al., 2006; Solik-Heliasz, 2009). These works extended and updated the knowledge given, among others, several years earlier in Geothermal Atlas of Europe (Hurter, S. and Haenel, R., 2002).

Euroheat and Power (2013) shows that in Poland there has been a significant increase in natural gas consumption in the preceding ten year period. However, due to new installations in DH and CHP an increase in the use of renewable fuels, in particular biomass is expected.

Coal is the main fuel in Poland. Around 76% of the heat supplied was produced by coal and coal products, while natural gas accounted for 6.77% and oil and petroleum products for 6.18%. Deep geothermal has almost the lowest share (0.09%) followed by geothermal heat pumps (0.02%) (EHP, 2013).

There were around 500 District Heating Systems installed in Poland as of 2011. Currently (2017) there are 6 geoDH plants; among them in Podhale Region with the highest installed geothermal capacity of 40.7 MWth (total ca. 81 MWth) and Pyrzyce, with installed geothermal capacity of 35.2 MWth (total ca. 48 MWth).

Table. 5.12.1.9. Cities with geothermal DH

Location	Capacity (MWth)
Podhale Region	40.7
Pyrzyce	35.2
Stargard	12.6
Mszczonów	6.4
Poddębice	3.8
Uniejów	3.5

The Geothermal risk – a resource risk

Geothermal project development has several risky components, the most important one being the resource risk. This concerns mainly deep geothermal projects, but some shallow geothermal open systems could also be included in this category of projects (Fig. 5.12.1.18).

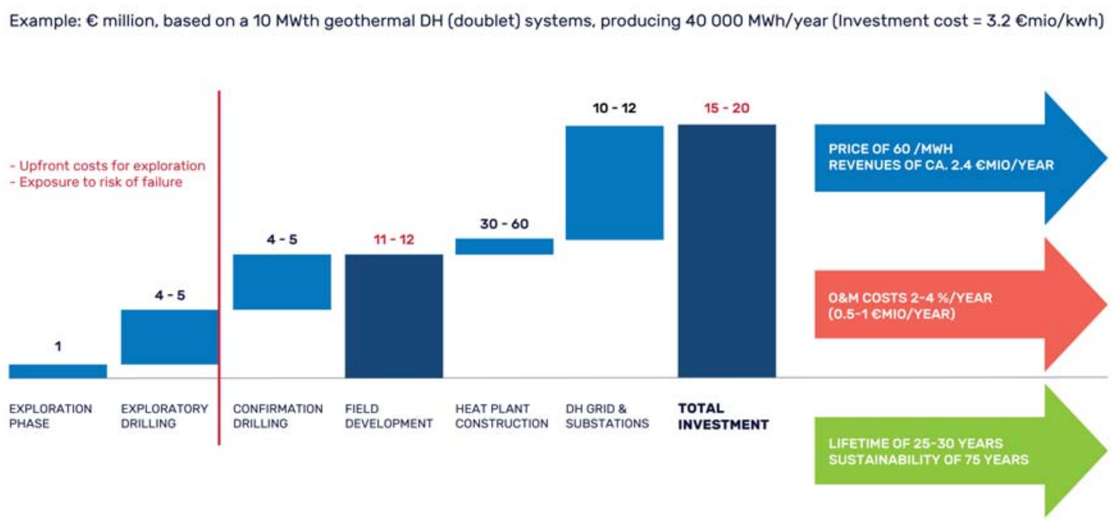


Fig. 5.12.1.18. Cost structure for a typical geothermal district heating project in Europe

Beyond exploration, the bankability of a geothermal project is threatened by this geological risk. The geological risk includes :

- The short-term risk of not finding an economically sustainable geothermal resource after drilling,
- The long-term risk of the geothermal resource naturally depleting rendering its exploitation economically unprofitable.

Available geological data help to find geothermal resources and give indications for their profitability but the only way to purge the geological risk and confirm the geothermal resource is to actually initiate the exploration and drilling work. This requires developers and investors to lay out significant amounts of cash beforehand without certainty as to the availability and perennity of the geothermal resource and hence the bankability of the project (Fig. 5.12.1.19).

For now, the fairly small number of deep geothermal operations in Poland does not provide a sufficient statistical basis to assess their probability of success. Therefore, geothermal developers struggle to find public or private mitigation schemes under affordable terms and conditions for the resource risk. In those circumstances, a Polish scheme would aim at alleviating the shortage of insurance policies for the resource risk and ease investments in geothermal electricity and heat projects.

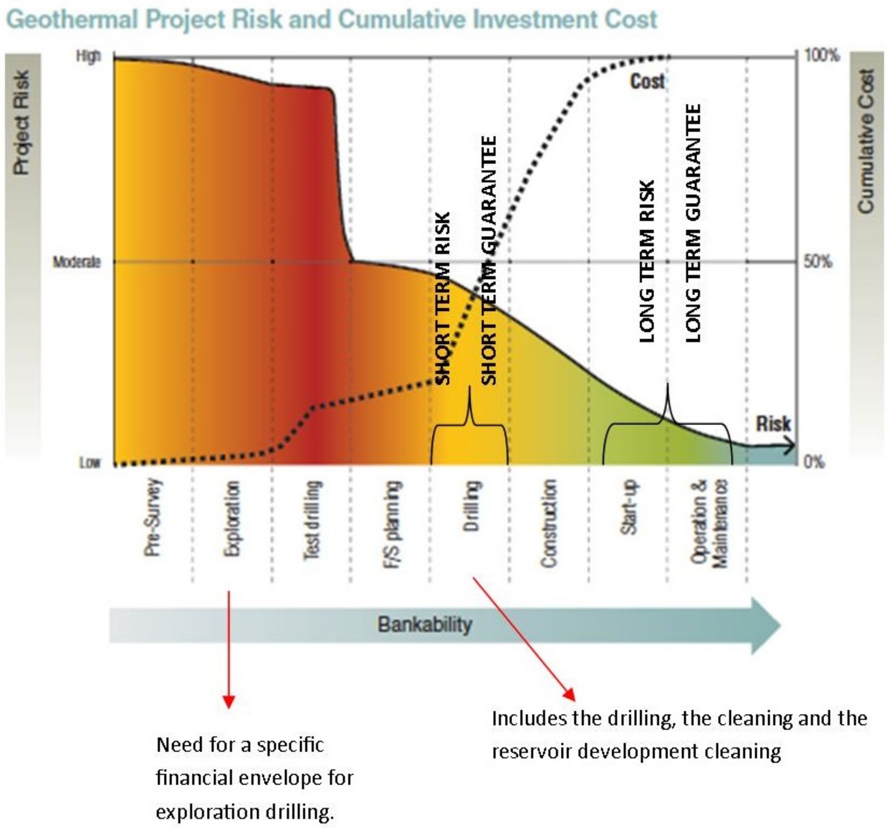


Fig. 5.12.1.19. Geothermal project risk and cumulative investment cost, modified from ESMAP, April 2012, GEOELEC

Until the first borehole has been drilled into the geothermal reservoir, developers cannot be sure about the exact parameters (temperature and flow rate) of the planned geothermal electricity or H&C project. Once drilling has taken place, in situ pump tests, temperature and hydrological measurements then reduce the resource risk and make it possible to attract external capital.

Risk insurance Funds for the geological risk already exist in some European countries (France, Germany, Iceland, The Netherlands and Switzerland). The geological risk is a common issue all over Europe. In countries where geothermal developers might not internalise the resource risk into the costs of their projects, they may resort to private insurance policies. In Germany for instance, insurance companies and brokers are engaged in obtaining experience in relation to the resource risk. They provide adequate insurance policies to geothermal developers. In the rest of Europe however, the private insurance sector stands back.

In this context, some governments have taken action to settle a national insurance Fund in order to further develop geothermal projects (France, The Netherlands, Germany, Iceland and Switzerland).Where such a Fund has been created, two insurance patterns may be distinguished, either:

- consisting of a post-damage guarantee;
- involving a guaranteed loan.

Technical details about the geological risk

The validation of geothermal resource through test drilling is capital intensive and its financing is hard to find due to this risky Commercial financing.

As explained in the first part, where knowledge of the geothermal resource is lacking, exploration is of crucial importance to collect relevant data before drilling. Beyond exploration, two risks threaten the bankability of a geothermal project: the risk not to find an adequate resource (short-term risk) and the risk that the resource naturally declines over time (the long-term risk).

In consequence of this resource risk is a much higher levelised tariff required mainly because the rate of return on equity is higher due to high risk premium of an early entry.

As for deep geothermal electricity and heat generation in Poland, the mitigation scheme shall be concerned with the exploration phase, the short-term risk and the long-term risk.

a) THE EXPLORATION PHASE

Here again, exploration aims at acquiring some data about the geothermal resource. This may be achieved through surface studies and/or exploration drilling.

The exploration drilling is not necessarily a production drilling. It is focused on data collection. However, if exploration proves favourable, the exploration well may be used as a production or injection well.

With exploration, there are no clear success and failure criteria. Success is determined on an empirical basis. This makes any insurance irrelevant in relation to exploration. Instead, exploration is usually supported by public financing.

b) THE SHORT-TERM RISK

With regard to the short-term risk, the insurance shall aim at covering the costs of one or several drillings in case of a geothermal resource being economically flawed (see infra ‘eligible costs and coverage ratio’).

Two types of insurance may apply: a post-damage guarantee or a guaranteed loan.

A guaranteed loan has the main advantage of serving as a source of financing while at the same time providing some insurance, as the loan is forgiven when the resource risk materializes. However, it requires an immediate disbursement of funds. This severely limits the financial flexibility of the Fund.

The post-damage guarantee does not serve as a source of financing for geothermal projects. Nevertheless, it proved to be an effective insurance design in EU Member States that provide it, as it allows geothermal developers to attract external capital. From an accounting point of view, the funds are frozen when the guarantee is granted but only released when the risk occurs. As such, it allows some financial relief to the Fund and this flexibility ensures that many projects can be covered at the same time.

With regard to the aforementioned considerations, a post-damage guarantee shall be favoured in relation to the Geothermal Risk Mitigation Fund

c) THE LONG-TERM RISK

With regard to the long-term risk, the insurance shall aim at covering the remaining depreciable value of the wells and the geothermal loop as well as the loss of geothermal resource (see infra ‘eligible costs and coverage ratio’).

The coverage of the “long term” risk should take into account some specific elements. Natural depletion is a standard technical risk that operators can deal with proper reservoir management. Offering the option to have insurance coverage for the “long term” risk should not set up a classic moral hazard situation where “unsustainable reservoir management” is an unintended consequence.

As previously explained, the Risk Mitigation Fund shall provide a post-damage guarantee for the long-term risk considering the accounting advantages of this option compared to the guaranteed loan.

Risk mitigation technical and non-technical measures

Several risk factors (e.g. technical, financial, and environmental) need to be carefully evaluated during the exploration phase while the subsurface model is not well understood, the resource not completely proven and the development scenarios not yet clearly defined.

Some of these risks can be mitigated by technological development with Research, Development and Innovation actions. Risks associated with EGS projects and ground deformation associated with exploitation of shallow reservoirs should be addressed and technological mitigation actions identified accordingly in stimulation planning.

It is assumed that in early exploratory stages a framework insurance policy would be promoted to mitigate the exploration risk. It should act as a stimulus until, after the initial high level risk be mastered, developers carry out exploration/development issues under their own responsibility and resources.

- Potential for technological development

The objective is to have better data collection and treatment to use high-quality public databases for the exploration phase.

It includes the development of advanced approaches, guidelines and tools addressing exploration risk assessment and mitigation easing the decision making process. Other topics for RD&I aim for economic optimisation of the exploration: slimholes, standard well exploration campaigns, approaches to early reservoir assessment/performance, guidelines for risk assessment/mitigation, methodology for economic projections and anticipated cost benefits.

A drilling campaign could be a flanking measure to further reduce risk by getting new geological data, and thereby promote commercial initiatives, by supporting secondary exploration through drilling of characterisation wells in prospective regions based on commercial initiatives.

In top of technological development, a technical improvement is expected with learning by doing or “learning by drilling”. The average drilling success rate is increasing with the number of wells drilled. In top, it is notable that drilling costs reduce when more projects are developed in a given region, and when multi-well projects are developed. Such a cost reduction has been demonstrated by the project in Unterföring (Germany) developed by Erdwerk gmbh. In 2009, the first two wells in Unterföhring had drilling costs of 1400€/m then, two years after, a project in nearby Ismaning had a drilling costs of 1150 €/m; by 2014 when two new wells were drilled for the expansion of the Unterföring system, the drilling cost was 1100€/m. In five years, drilling costs were been reduced by more than 25%, principally through ‘learning by doing’.

- Potential for regulatory and financial measures

Some practice on regulations is perceived as being pre-requisite or very favourable to the development of deep geothermal technology. This is the case, for instance, where:

- Information on geothermal resources suitable for deep geothermal systems should be available and easily accessible. In some countries, geological data are freely available to project developers (e.g. after a five year periodin the Netherlands).
- There is the need of a clear definition of procedures and licensing authorities (e.g. France, Poland and Denmark). A unique geothermal licensing authority should be set up.
- The rules concerning the authorisation and licensing procedures must be proportionate and simplified, and transferred to regional (or local if appropriate) administration level.
- Administrative procedures for geothermal licensing have to be fit to purpose – they should be streamlined wherever possible and the burden on the applicant should reflect the complexity, cost and potential impacts of the proposed geothermal energy development.
- Ownership rights should be guaranteed.
- Legislation should aim to protect the environment and set priorities for the use of underground: geothermal energy should be given priority over other uses such as for unconventional fossil fuels, CCS, and nuclear waste deposits.

With the notable exception of a few European market participants operating in well-developed geothermal regions, project developers have very little capability to manage the financial risk owing to the poor knowledge of the deep subsurface, lack of technological progress and high cost. In effect the probability of success/failure weighted net present values of project cash flows tend to be overly negative, thus effectively shutting out private capital from investing in geothermal energy.

However, with technology development (increasing the probability of success of finding and developing geothermal reserves) coupled with experience and thus reductions in cost, project developers will eventually be able to accept and, where appropriate, transfer project risks (technical, economical, commercial, organisational and political) in such manner that private funding will become available. Until then, a public Geothermal Risk Insurance Fund is seen as an appealing public support measure for geothermal.

Public fundings can be in form of several innovative financing such as grants: direct, repayable or convertible, insurances and guarantees (Fig. 5.12.1.20). They aim at financing the test drilling and so improving the economy of the projects. A public Geothermal Risk Insurance Fund can help to reduce the required levelised tariff by notably delaying the call to private investors by 2 to 4 years. The risk being lower, the rate of return requested is also lower.

Support schemes for geothermal adapted to technology maturity

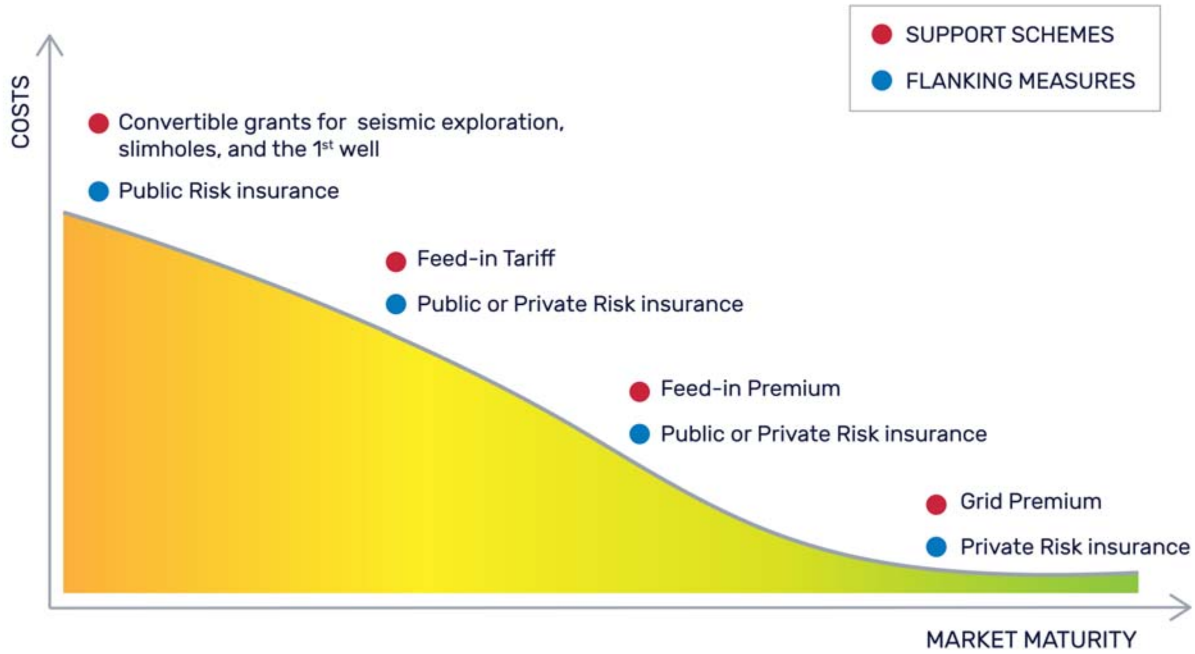


Fig. 5.12.1.20. Support schemes for Geothermal adapted to technology maturity

Towards a risk coverage scheme in Poland

In Poland, the public funding currently established do not allow to cover the resource risk. New funding programmes are needed. For now, the small number of deep geothermal operations for power and heat in Poland does not provide a sufficient statistical basis to assess the probability of success. therefore, geothermal developers struggle to find insurance (public or private) schemes with affordable terms and conditions for the resource risk. In those circumstances, a public fund aims at alleviating the shortage of insurance policies for the resource risk and ease investments in geothermal electricity and heat projects.

The Fund is meant to work through the pooling of the resource risk among geothermal electricity and H&C projects taking place in Poland. Public money should first support the risk mitigation scheme; when mature this could be phased out and replaced by private schemes.

Considering the importance of exploration for deep geothermal generation, a mitigation scheme shall provide some financial envelope to support exploration studies. This financial envelope shall take the form of a repayable advance. This would allow for some financing of exploration, without depleting the Fund as the advance would be reimbursed.

The insurance will cover risk in the short and long term. The main criteria for the level of risk will be a combined ratio including the flow rate and the temperature. The guarantee should cover the cost of a well in case of partial or total failure (partial up to 90 % compensation). It would be supported by Public and Private Funds and by subscriptions from project developers.

The advance could be granted, repayable or converted. it would have to be reimbursed or converted in case of production. In such a case, the amount to be repaid to the Fund shall be enhanced. A classical interest rate as well as a discount factor shall be applied. These shall be set contractually and modulated according to the estimated exploration risk. It shall cover the costs of exploration drilling and tests. Exploration costs specific to EGS shall also be considered.

Options for Eligibility criteria

Eligibility criteria shall enable an experts Committee to assess applications and claims in relation to each insured phase of a geothermal project. Eligibility criteria with respect to both applications and insurance claims are considered.

a) ELIGIBILITY CRITERIA FOR APPLICATIONS MADE TO THE FUND

Applications made to the risk mitigation scheme may vary depending on the coverage sought (repayable advance, short-term guarantee or long-term guarantee). Regardless of the phase concerned with the application, some requirements shall be common to each application.

The obligation to disclose the data collected

Any developer willing to benefit from the guarantees provided by the Geothermal Risk Insurance Fund shall engage to disclose to the Fund all data collected during his geothermal project. This data shall be in particular, but not exclusively:

- The temperature;
- The depth and thickness of the reservoir;
- The flow;
- The geology;
- The porosity;
- The permeability;
- The geochemical analysis of the fluid;
- The seismicity measurements.

The reference contract shall determine the data to be disclosed as well as the term when this data shall be made public. It shall also provide that any breach of the disclosure obligation shall lead either to the termination of the insurance contract or the review of the insurance, in particular of the coverage rate.The data shall be submitted by means of a unique and exhaustive report, with respect to the terms of the reference contract.The data collected shall be used in the establishment of a Public Geothermal Database.

Public and confidential information within the application procedure

Among the information submitted to the Fund, the reference contract shall set the one which shall eventually be made public and when it shall become public.

Besides, where the applicant desires to keep some information secret (e.g.: use of a specific industrial process) he shall submit this information under separate cover. The reference contract shall determine whether this information shall eventually be made public.

Criteria to benefit from the repayable and convertible advance

In order to apply for repayable/convertible advance, the developer shall submit the following information to the secretariat:

- A detailed presentation (identity, legal form, information on contractors and key personnel);
- The location of the exploration site;
- Detailed surface studies and any relevant document or piece of information proving the probable existence of a commercially viable geothermal resource;
- A detailed program of exploration work;
- Available financing and proof of financial capacity to achieve the whole exploration program;
- Legal permits and licences.

Specific case of EGS where EGS are considered, the developer shall in addition submit:

- The reservoir development concept;
- Seismicity studies;
- Stimulation modelling i.e. expected impact of chemical, hydraulic or thermal stimulations.

Criteria to benefit from the short-term risk guarantee

A developer shall be entitled to apply for the short-term guarantee whether he has benefited from the repayable advance or not. In order to apply for the short-term guarantee, the developer shall submit the following information to the secretariat:

- A detailed presentation (identity, legal form, information on contractors and key personnel);
- Whether he has benefited from the repayable advance;
- The location of the drilling site;
- A prefeasibility study as a result of exploration, which proves the likelihood of electricity and heat production for the considered geothermal project;
- A feasibility study, which should particularly insist on the expected flow rate and temperature;
- A detailed program of wells and tests;
- The power plant use concept (electricity generation/CHP) and the intended use of the energy. In particular, the developer shall submit a curve displaying the possible recovery of the energy (heat generation/CHP) according to the achieved flow rate and temperature;
- Seismic investigations and their analysis;
- Legal permits and licences required for exploitation and proof of compliance with legal requirements (e.g. environmental impact assessment, public information).

Where EGS are considered, the developer shall in addition submit:

- The degree to which the project involves technical innovation;
- The reservoir development program;
- The planned stimulation measures;
- The planned seismic monitoring.

Criteria to benefit from the long-term risk guarantee

A developer shall be entitled to apply for the long-term risk guarantee if he has benefited from the short-term guarantee only or if he may provide all relevant results of the drilling phase to the board. Where the developer has not previously benefited from the short-term guarantee, the board shall decide whether the developer may apply for the long-term guarantee on a case-to-case basis. In order to apply for the long-term guarantee, the developer shall submit the following information to the secretariat:

- A detailed presentation (identity, legal form, information on contractors and key personnel);
- Whether he has benefited from the short-term risk guarantee;
- The location of the geothermal site;
- The results of the drilling phase, in particular the achieved flow rate and temperature;
- The financial plan of the operational phase (e.g. return on investment, financing of the project, initial value of the well(s) and loop(s));
- The power plant use concept, the intended use of the energy in case of the resource depleting and a curve displaying the possible recovery of the energy according to the flow rate and temperature;
- Legal permits and licences required for exploitation and proof of compliance with legal requirements;
- The operations and maintenance program, including the frequency and method of control as well as the controlled parameters.

Regardless of the phase concerned with the insurance claim, some requirements shall be common to each claim.

The obligation to engage stimulations measures before submitting the insurance claim

Whether the project generates geothermal electricity and H&C using conventional technologies or EGS, the developer shall only be allowed to file an insurance claim where he has undertaken all relevant stimulation measures either to find a viable resource or to avoid its depletion.
Stimulation measures to undertake shall be determined by the board and supervise by the rapporteur.

Public and confidential information within the claim procedure

The reference contract shall determine which of the information disclosed by the developer in its insurance claim shall eventually be made public and when this shall be made public.

In this respect, the board and experts appointed by the board shall comply with confidentiality duties and shall not disclose any information until it is made public.

Its establishment

The Geothermal Risk Insurance Fund shall be made available to private and public organizations developing geothermal electricity and heat projects in Poland. The Geothermal Risk Insurance Fund shall be concerned with the exploration phase, the short-term risk and the long-term risk. In relation to each of these phases, the Fund shall cover some of the costs borne by the developer, where these are deemed eligible, and up to a certain level set contractually.

a) THE EXPLORATION PHASE

The costs considered as eligible regarding the exploration phase shall be the costs of the exploration well. These shall include in particular, but not exclusively, the costs relating to:

- Installing and breaking down the rig;
- The drilling itself;
- Tubing;
- The cleaning;
- Well testing and improvements;
- Drilling management.

Specific case of EGS: where EGS is considered, exploration may involve specific costs in relation to the reservoir development concept. These costs shall be eligible for coverage.

Eligible costs shall be specified in the reference insurance contract eventually signed between the developer and the Fund.

Regarding the exploration phase, a financial support taking the form of a repayable advance shall be provided to the applicant.

Depending on the risk assessed by the independent experts and the amount of the eligible costs, a certain amount would be released to cover the aforementioned costs. This amount shall be set contractually on a case-to-case basis. If the developer benefits from national subsidies with respect to the exploration drilling, these shall be removed from the amount of the repayable advance.

As the success and failure criteria cannot be determined exactly in the exploration phase, the advance shall be repaid when production begins. The reference contract shall specify the starting point and deadlines for reimbursement.

As for reimbursement, the amount to be repaid shall be enhanced. An interest rate as well as a discharge factor shall be set contractually.

b) THE SHORT-TERM RISK

The costs deemed eligible with regard to the short-term risk may differ depending on the kind of technology considered for geothermal electricity production:

Geothermal Heat and electricity production using conventional technologies

The costs deemed eligible shall be the costs of the first production/injection drilling. These shall include in particular, but not exclusively:

- Installing and breaking down the rig;
- The drilling itself;
- Tubing;
- The cleaning;
- Well testing;
- Drilling management.

Geothermal production using EGS

In addition to the aforementioned eligible expenses, where geothermal electricity is generated using non-conventional technologies, eligible costs shall also include in particular, but not exclusively:

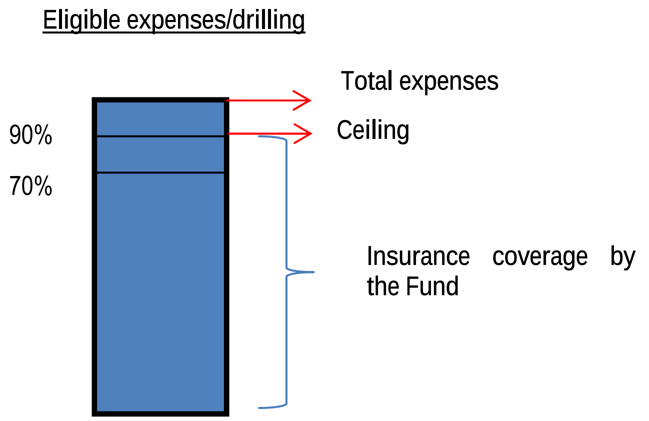
- The reservoir development (e.g. seismic sensors and modelling);
- The reservoir stimulation (e.g. hydraulic pumps, pumping costs, chemicals, seismic monitoring);

Eligible costs shall be specified in the reference contract signed between the developer and the Fund. Subsidised costs shall be excluded from the eligible expenses. The insurance provided in relation to the short-term risk shall work through a revolving mechanism: the first drilling shall be insured. When successful, the insurance provided may be reused to cover a following drilling. The insurance may be successively reused in this way to cover several drillings until one fails and the insurance be released.

As for the coverage ratio in relation to the short-term risk, the eligible expenses may be covered up to 70-90%. A ceiling shall apply for each drilling. In this respect, the costs insured shall be established on a case-to-case basis.

The rate eventually applied shall depend on the drilling being partially successful or unsuccessful. The rate shall also depend on the possible energy recovery, where for instance heat can be generated instead of electricity (see *infra* 'eligibility criteria').

In any way, the coverage rate shall be set contractually with respect to the above mentioned range of values. A franchise amounting to 100 000€ - 150 000€ shall be borne by the developers.



This option has pros and cons:

+ It provides a homogeneous rate for all developers;

+ It provides a generous rate encouraging the development of geothermal power and heat generation;

-The generous rate provided may lead to competition with existing national insurances.

c) THE LONG-TERM RISK

The costs deemed eligible in relation to the long-term risk shall be:

- The remaining depreciable value of the well(s) and the geothermal loop(s);
- The stimulation measures;
- The loss of the geothermal resource, as a percentage of the enthalpy multiplied by the flow rate;

These eligible costs shall be clearly specified in the reference contract. If national subsidies are available on the national stage in relation to the perennity of the geothermal resource they shall be removed from the eligible expenses.

The coverage rate for the long-term risk shall depend on the results of the previous drilling(s) ie whether the drilling(s) was (were) completely or partially successful. The rate shall also depend on the possible energy recovery in spite of the resource depletion (see *infra* 'eligibility criteria'). It shall be set contractually.

The long-term risk guarantee shall be provided for a period of 10 to 20 years, as set contractually between the developer and the Fund on a case-to-case basis. A franchise amounting to 100 000€ - 150 000€ shall be borne by the developer.

Its funding

The Geothermal Risk Insurance Fund shall rely on a strong capital and financial structure. This underlying principle raises the matter of reinsurance as well as the likelihood of a balancing of the Fund.

a) THE SEED CAPITAL

The seed capital shall have as many diversified sources as possible. Indeed, the more diversified the seed capital is, the more reliable the insurance system will be. The minimum seed capital shall be of 40 Mio – 60 Mio €.

The seed capital shall stem from all possible sources such as:

- The European Union; European Investment Bank (EIB), Modernisation Fund, Innovation Fund, Structural Funds, Horizon 2020 programme with InnovFin.
- The National level;
- The regional level authorities of the Member States;
- Insurance companies and brokers;
- Private and public financial institutions;
- Other reliable stakeholders;

In any circumstances, the distribution of the seed capital shall be made public and transparent.

b) OPERATING INCOMES

Among all possible incomes for an insurance system, the following shall be considered as suitable. They could apply cumulatively or not.

Fees

Insurance fees shall be charged in relation to each application made to the Fund (for the repayable advance, for the short-term guarantee and for the long-term guarantee).

In relation to each phase of the project, fees shall be charged according to the following ranges of values. These ranges of values are based on the existing insurance concepts for the resource risk in Poland:

– The exploration phase: a 6% to 8% interest rate could be charged as for the repayable advance;

– The short-term guarantee: a premium amounting to 3.5% to 5% of the eligible costs could be charged;

– The long-term guarantee: a fixed fee of 12 000€ to 13000€ per year could be charged.

These insurance fees might be modulated according the estimated resource risk. They shall be set in the reference contract signed between the developer and the governance.

c) THE FUND BALANCE

Aforementioned incomes may not be sufficient to allow the balancing of the Fund. In addition, when relying on these incomes, the balancing would mainly depend on the success of insured geothermal projects.

In this context, the Geothermal Risk Insurance Fund shall be able to exhaust and be replenished with available public and private funding. This would give the Fund more flexibility from an accountancy point of view.

d) REINSURANCE

Considering the financial stakes the Fund may face and the flexibility needed to insure as many reliable geothermal projects as possible, some reinsurance shall be applied to in order to provide the Geothermal Risk Insurance Fund with some financial relief. This shall be achieved contractually between the Fund and a reinsurer.

Country fiche: summary. Geothermal Risk Guarantee Fund

Country	Poland
Market deep Geothermal	– 2 geothermal co-generation plants under investigation – 6 geothermal district heating systems in operation – 5 geoDH projects under development (Extension existing networks) – Other direct uses with deep geothermal N° of wells drilled: 12-20 N° of wells to drill until 2020:15-20
Background	The technical factors determining the success or failure of a project depend on the exploitation of the subsurface (flow rate and temperature of the resource).After drilling, the risk that the geothermal resources will have insufficient production and/or temperature characteristics, rendering the operation unprofitable, is commonly known as the geological risk. Well costs at 3 Km: 6-8 €mio
Objective	The objective is to guarantee the cost of a well in case of partial or total failure.
Type of insurance (see details in the table below)	Firstly for juvenile market: (Repayable or Convertible or Direct) Grants for seismic exploration, slimholes, and the 1st well Subsequently for Intermediate market: Public Risk insurance.
Governance	Ministry, National Energy Agency, Geological Survey and a committee of experts
Capital and financial structure	State budget of 40-60 Mio €. To cover the next 6-10 wells (3-4 deep geothermal systems) Repayable/Convertible Grants or Insurance Premium of 6-7% of the maximum guaranteed amount. It is a mutual insurance in order to develop projects in favorable regions and to have operations in new areas
Beneficiaries	Public and private developers based in Poland.
Insurance scope	Heat and Power production. Two drillings (one production well and one injection well deeper than 500 meters).
Risks insured	Short-term risk (drilling) Long-term risk (reservoir)
Eligible costs	Drilling and test costs. Definition of success: fixed parameters or a formula
Coverage ratio	100% in case of grants and Risk insurance criteria for the level of risk: flow rate and temperature • Total failure: compensation up to 70-90% of the well costs • Partial failure: partial compensation
Eligibility criteria	The developer must provide a technical, legal and financial feasibility study. He must comply with schedules: the drilling must start within 6 months after guarantee approval, completed within 1 year after guarantee approval and lead to application of geothermal energy within 2 years. The developer has to abide by reporting and disclosure obligations.
Insurance process	Complete applications are evaluated in order of receipt. Geological Survey has an advising role, both in the application phase and in the assessment of results
Short additional description	Risk insurance funds for geothermal already exist in France, Switzerland and the Netherlands in the past also in Iceland)

5.12.2. Success of the Iceland Geothermal Energy Fund over 50 years. Recommendations for Poland

Introduction

The National Energy Fund (NEF) has been operational in one way or another for nearly 60 years, or since its predecessor were founded in 1961. Its main activity through the years has been offering loans for the exploration of geothermal heat in cases where it could reduce the society's cost in heating houses. In later years, the activity has turned more towards grants for special projects in the field of economical energy utilization and promoting the exploitation of domestic energy sources instead of fossils fuels. The role of NEF in developing the use of renewable energy in Iceland is a good example of how important and effective the public support is in the whole progress.

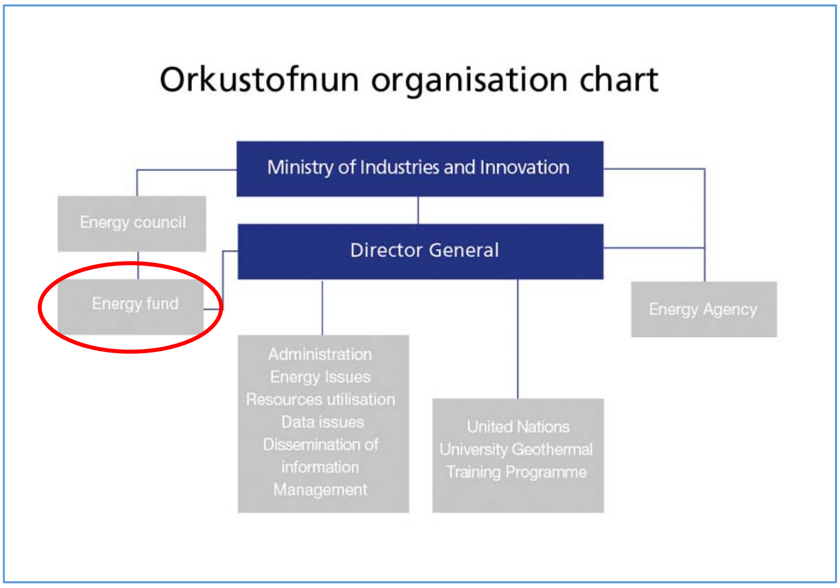
There is no doubt how good impact the use of geothermal for heating has had on the Icelandic society and the role of the National Energy Fund was a huge part of that. To be able to see how big factor the NEF was in the process, its loans need to be evaluated and put into measurable perspectives. The evaluation should also demonstrate situations where funding or exploitation is not feasible and not to mention the funding process.

Executive Summary

- A financial mechanism was created in Iceland with an Act in year 1953 allowing the state to finance up to 80% of the drilling and construction cost of heating services outside the capital region after the success of the first steps of geothermal based district heating in the capital. The state has kept the overall ideology of this financial mechanism similar since then.
- A Geothermal Energy fund was established in 1961 offering 60% of the drilling cost for exploratory and appraisal drilling. The fund was merged into the National Energy Fund when it was established in 1967.
- Between the years 1964 and 1998, National Energy Fund (NEF) provided approximately 350 geothermal heat exploration loans to investors, individuals, municipalities and others in search of geothermal heat. The total amount of the loans was 59 million Euros (extrapolated number).
- The oil crisis in the early 1970s caused Iceland to increase funding on research and development of domestic resources within the framework of the national energy policy from 1953.
- In 1975 to 1983, NEF provided 66% of all loans it offered in the years 1964-1998 and the amount was in total 49 million Euros or approximately 82% of the amount it offered over the total period. At this point, in 1983, the share of geothermal heating had increased from 40% in 1971 to 80%, i.e. it took only 12 years to double its share in regards of total space heating.
- In the approximately 50 years before 1971 there had been 15 geothermal district heating companies established in Iceland but in the next 12 years, 22 new geothermal district heating companies were added to that number. That is increase of nearly 150%. However, over the time, many of these geothermal district heating companies have merged and today are 22 geothermal district heating companies operational.
- The average annual savings, by using geothermal heat instead of oil for heating, in last 50 years, have been 2.6% of GDP and peaked at 7% in the period 1973 to 1985, and rose again up to 5.4% during the last years of the financial crisis, which started in 2008. In 2016, each savings percentile of GDP was equivalent to 551 € per capita and in accordance to the 2.6% average it would be equal to 1.433 € per capita.
- Cumulative savings of geothermal district heating from 1914 – 2016, based on real price (fixed price 2016) and 2% annual interest rate are estimated 21.8 billion €.
    - According to information from Registers Iceland, 21.8 billion €, is equal to 68% of the total value of all residential houses and apartments in Iceland which was estimated around 32.1 billion € in 2016.
- From 1982 – 2016 the majority of savings have happened after the geothermal district heating implementation and the cumulative savings are estimated about 17.6 billion €. This is equal to 502.5 million € per year, or 6.290 € per family, or about 520 € per month per family, before taxes.
- Important element of a geothermal heating project is to have options and possibilities of support from public authorities towards the exploration and the drilling stages. Without the support from NEF, the geothermal energy sector in Iceland would not have developed as much it has, or at least not as quickly.

5.12.2.1. The National Energy Fund

Introduction



The National Energy Fund (NEF) is a property of the state and is responsible for its obligations. The supervision is in the hand of the Minister but the National Energy Authority (OS) is responsible for the daily activities management. The Minister appoints three members into a National Energy Fund Advisory Committee (NEFAC) for the NEF and each council is to sit for four years at a time. The council presents proposals and recommendations to the Minister regarding loan grants and disbursements made by the NEF in accordance to its budget and payment plan.

The NEFAC shall issue its own operating procedures to manage the processing of NEF loan and grant applications. These procedures shall i.e. provide general guidelines employed by the NEFAC when decisions are made regarding proposals for NEF grants or loans. In addition, other conditions must be specified if the NEFAC finds them necessary. The NEFAC's operating procedures regarding disbursements from the NEF must be approved by the Minister and officially published.

Before a proposal can be made regarding NEF grants or loans, the NEFAC must request comments from the OS. In cases of comments regarding loans for geothermal heat exploration, the OS must provide an assessment of geological prospects, the production feasibility for success and the financial advantages of acquiring geothermal heat.

The role of the NEF is to promote efficient utilization of natural resources with special focus on reducing the use of fossils fuels by providing grants and loans. According to regulation no. 185/2016 for the NEF, there are three different paths it needs to follow in order to implement its duties.

1. Offer loans for the exploration of geothermal resources in cases where it could reduce the society's cost in heating houses.
2. Offer grants for special projects in the field of economical energy utilization, including educational and outreach purposes. The specific projects are categorised as follows:
    a. Projects that contribute to a decrease in oil consumption for house heating or production of electricity without the involvement of a utility.
    b. Projects that lead to lower costs of electric house heating of unsubsidized houses or buildings owned by municipalities.
    c. Projects that lead to energy savings.
3. Offer grants for projects that promote the exploitation of domestic energy sources instead of fossil fuels and strengthen international cooperation in such projects.

The NEF draws revenue from:

1. Interest income from the Fund's money
2. Yearly state budget appropriations

With the approval of the Minister, OS may enter into agreements with parties that have statutory authorization to keep and manage funds in trust. The NEF shall pay all of its own operating costs.

The OS supervises the projects funded by the NEFAC. It is mandatory to provide in advance satisfactory information regarding a planned undertaking and to provide OS the opportunity to keep informed of the project's progress. OS may impose such conditions regarding the project's performance as it sees fit in order to achieve optimum results. OS shall notify the Minister if conditions set by the OS are not followed. The Minister may suspend payments from the NEF to any project if these rules are not followed.

5.12.2.2. Grants

Projects can get up to 50% grant from the NEF but the NEFAC has authority to decide a specific maximum grant amount. The maximum amount has to be specified in the advertisement of the grants. In order to be able to pay grants to beneficiaries, the following items needs to be clear:

1. Ministerial decision on grants.
2. A written agreement between the NEF and the beneficiaries of the project.
3. A written confirmation that funding has been successful as expected in the application.
4. A written confirmation that work has begun.

The grants are paid in three, i.e. three equal payments when a written confirmation of the start of the project is available.

- First payment (one third): At the beginning of work on the project.
- Second payment (one third): When the beneficiary deems the work on the project half-finished and she/he/it sends a statement or progress report stating so to the NEF.
- Third payment (one third): When a beneficiary has submitted a final report on the project and the data been approved by the NEF.

5.12.2.3. Loans for Geothermal Exploration

The NEF has authority to provide loans for an exploration of geothermal resources where it is proven to be socially economical to lower the heating costs of houses. These are “soft loans”, which are meant to lower the financial risk of the initial investment costs related to the exploration and/or drilling and may be converted to grants, i.e. all obligations in regards of paying back are dropped fully or partially, if the project turns out unsuccessful. The granting of the geothermal loans applies as follows:

1. NEF loans are with indexation and linked to the Icelandic consumer price index (CPI).
2. NEF loans must collateralized by all the property of the planned hot-water supplier, including farms and/or other property deemed sufficient by the NEFAC.
3. The loan amount will be a maximum of 60% of the Fund-approved cost.
4. Offered loans are for a period of up to 10 years.
5. Loans interest rates shall take into account the Central Bank’s announcement of the general interest rates on indexed loans, acc. Act no. 38/2001, with 1.5% load.
6. The NEFAC evaluates the estimated eligible loan cost before being approved. Eligible loan cost is considered to be:
    a. Probable preparation cost for exploration of land, which has not been supported by public funds.
    b. Geoscientist’s consultancy cost, which has not been supported by public funds.
    c. Estimated cost of establishing facilities on drilling site.
    d. Estimated cost of the drilling itself.

Today, the interest rate on a NEF loan is 5.3%.

If a particular drilling project that received a loan turns out to be unsuccessful, or if its success rate is significantly lower than expected when the loan was granted, or if the costs involved are unreasonably high and the use of the drilling hole for geothermal heat production is therefore less beneficial than initially expected and the financial standing of the borrower is put at risk for any of the above reasons, the Minister may, after having received the NEFAC’s proposals, waive partially or completely the obligation of the borrower to repay the loan. Before the NEFAC assesses whether the above conditions have been met, it shall request the opinion of OS.

5.12.2.4. Risk and Financing of Geothermal Projects

It is generally recognized that geothermal exploration and development is a high-risk investment, due to uncertainty associated with a natural resource that cannot readily be observed or characterized without relatively large expenditures for drilling.

The long development time typically required to move a project from preliminary exploration through development to construction is an additional risk factor and many large geothermal projects (50 MW_e) have taken 10 years or more to develop. This is a long development and construction time for investment, with the added risk in the early phases of the project. From Figure 5.12.2.1 it can be seen that the risk profile is greatest during the preliminary surveying and exploration phases, but in that part of the project the cost is comparatively low.

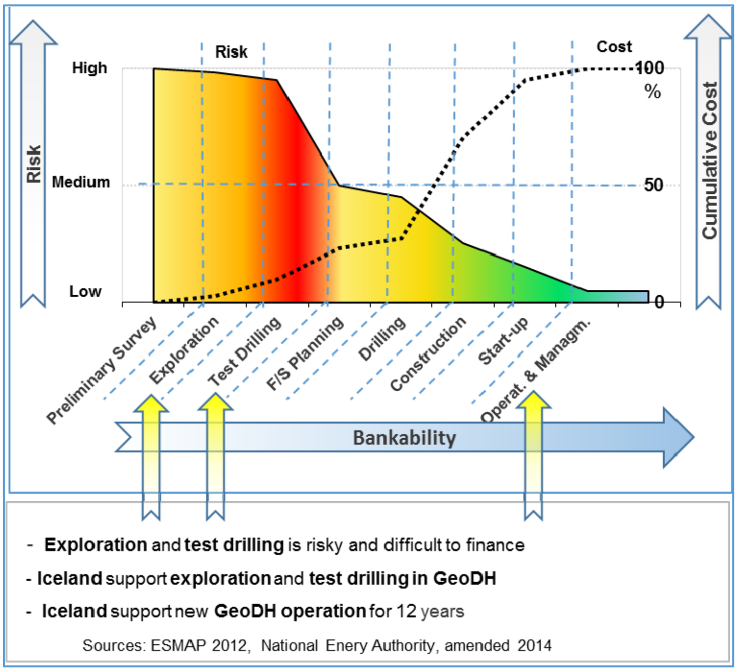


Fig. 5.12.2.1. Risk, bankability and cost of geothermal project

The test drilling phase requires a greater level of expenditure, although there is still a high level of uncertainty and risk involved and this step is frequently the biggest barrier for further development of the project. Therefore, numerous international aid agencies and governments around the world have recognized this as a barrier to the development of geothermal projects. Risk mitigation funds (private and public) have been established in some countries to assist projects through this exploration phase. In addition, more capital has also been spent on R&D in geothermal projects in recent years. Generally, funding is only committed to the test drilling part of project development if the investor believes there is an adequate financial return on investment ROI (in terms of a percentage of the committed capital per annum). In addition, risk mitigation funds (grant scheme) improve the predicted ROI by reducing the amount of capital invested by the investor. Usually, maximum ROI is only achieved if wells produce at or above their predicted outputs, and this result relies on high quality exploration methods and interpretation. Several mechanisms for supporting investments in geothermal energy exist around the world and at a national level. These financial mechanisms (public and private) can address different project stages and can come from different sources (Fig. 5.12.2.2). In Iceland, the National Energy Fund have provided grants and/or loans at early stages to help many projects with a good impact for nearly 60 years.

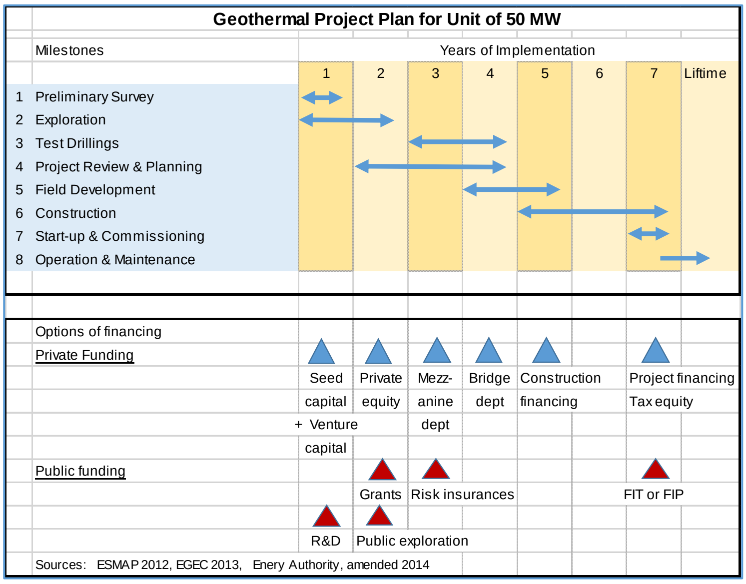


Fig. 5.12.2.2. Geothermal project plan and options of financing

5.12.2.5. Public Support of Geothermal District Heating

Public Support towards of Geothermal District Heating

Already by the 1940s, the State Electricity Authority promoted geothermal development and carried out a regional survey of geothermal areas suitable for space heating and explored promising fields with exploratory drilling. The capital Reykjavik obtained by law a monopoly on operating a geothermal heating service in the town and took initiative in production drilling and establishment of the first large geothermal district heating system. The State guaranteed loans for the construction of the system. In 1950 about 25% of families in the country enjoyed geothermal heating services, 40% used coal and 20% oil for heating. The cheap geothermal heating was attractive and intensified the flux of people from rural areas to the capital.

To balance that, the national parliament approved an Act in 1953 on geothermal heating services in communities outside Reykjavik, which permitted the State to guarantee loans up to 80% of the total drilling and construction cost of heating services. Further, to encourage the development, the State started a Geothermal Fund in 1961. The fund gave grants for reconnaissance and exploratory drilling carried out by the Geothermal Department of the State Electricity Authority and offered loans to communities and farmers for exploratory and appraisal drilling covering up to 60% of the drilling cost. If the drilling was successful, the loans were to be paid back with highest allowed interests in five years after the heating service was up and running.

If exploratory drilling failed to yield exploitable hot water, the loan was converted to a grant and not paid back. In this way the fund encouraged exploration and shared the risk. Within the next ten years many municipalities used this support and succeeded in finding geothermal water. In 1967, the fund merged with the Electricity Fund and named the National Energy Fund. The Electricity Fund had since the 1940s supported electrification and transmission in rural areas. By 1970 about 43% of the nation enjoyed geothermal heating, while oil was used by 53% of the population, and the remainder used electricity.

Space heating of residential buildings is subsidized by the state for those areas where geothermal based district heating systems are not reachable. The lump sum for 8-12 years of this state subsidization has been available to support homeowners to transform to renewable heating (Act No. 78/2002). This was recently increased up to a maximum of 16-year lump sum in special circumstances. In addition, if the project receives other grants it will not effect in any way this lump sum payment. This has stimulated new geothermal based district heating systems to be installed, like in the town of Skagaströnd, operated by RARIK, in 2013 or in Kjósarhreppur in 2016.

5.12.2.6. The Government's Role in Developing Geothermal Energy

The government has encouraged the exploration for geothermal resources, as well as research into the various ways geothermal energy can be utilized. As stated earlier this work began in the 1940s at The State Electricity Authority, and has been in the hands of its successor, The National Energy Authority, since its establishment in 1967. The aim has been to acquire general knowledge about geothermal resources and make the utilization of this resource profitable for the national economy.

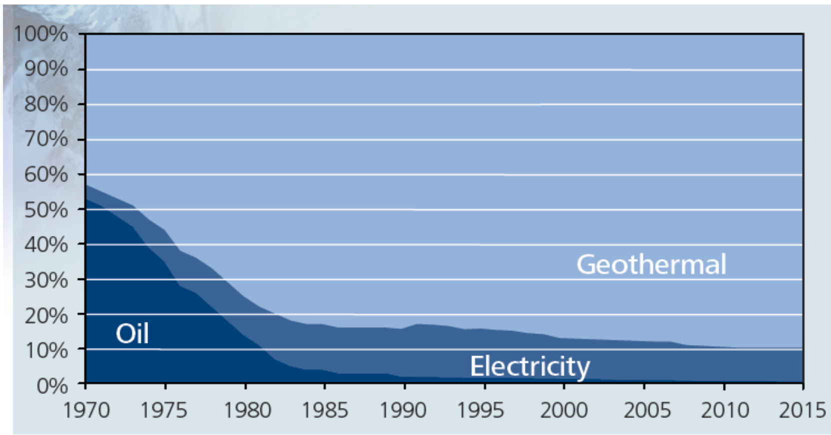
This work has led to great achievements, especially in finding alternative resources for heating homes. This progress has been possible thanks to the skilled scientists and researchers at the National Energy Authority. After the electricity market was liberalized with adaption to EC Directive in year 2003, OS only contracts research in the field of energy and a new state institute, Iceland GeoSurvey, was created which on a competitive basis takes part in projects mainly for the energy companies and heat utilities but also for OS. According to a new Energy Act in 2003, the National Energy Fund is under OS now.

5.12.2.7. Loans for Drilling

Statistical Information

Between the years 1964 and 1998, NEF provided approximately 350 geothermal heat exploration loans to investors, individuals, municipalities and others in search of geothermal heat. The total amount of the loans was 58.5 million Euros (extrapolated number). The first three years after the predecessor of NEF was founded, 36 loans were provided, all with relatively low amount – 1.5 million € in total. Then in 1968 four loans of total 0.86 million Euros were offered to the State drilling company to support search and establishment of geothermal heating in northern Iceland. Little happened the next few years until the oil crisis struck in the early 1970s, fuelled by the Arab-Israeli War, the world market price for crude oil rose by 70%. It caused Iceland to change its energy policy, reducing oil use and turning to domestic energy resources, hydropower and geothermal.

This policy meant exploring new geothermal resources, and building new heating utilities across the country. It also meant constructing transmission pipelines (commonly 10-20 km) from geothermal fields to towns, villages and individual farms. This change in the policy can be seen in the rapid increase in geothermal exploration loans provided by NEF from 1975 to 1983, see figure 5.12.2.3. This period included 66% of all loans it offered in the years 1964-1998 and the total amount was in total 48.8 million Euros (Fig. 5.12.2.4 – 5.12.2.6) or approximately 82% of the amount it offered over the total period. At this point, in 1983, the share of geothermal heating had increased from 40% in 1971 to 80%, i.e. it took only 12 years to double its share in regards of total space heating. This can also been put into another perspective. In the approximately 50 years before 1971 there had been 15 geothermal district heating companies established in Iceland but in the next 12 years, 22 new geothermal district heating companies were added to that number. That is increase of nearly 150%. However, over the time, many of these geothermal district heating companies have merged and today are 22 geothermal district heating companies operational.



Source: Orkustofnun

Fig. 5.12.2.3. Expansion of geoDH space heating by source 1970–2015

In the years after and until 1998, NEF provided 78 loans for a total amount of 5.4 million Euros. The market was saturated, in a way, since geothermal district heating systems had been installed in the most populated and geothermal potential locations all around Iceland.

Another reason, specifically in later years, is that the geothermal district heating companies got financially stronger and are able to finance the exploration or drilling costs without assistance from the state.

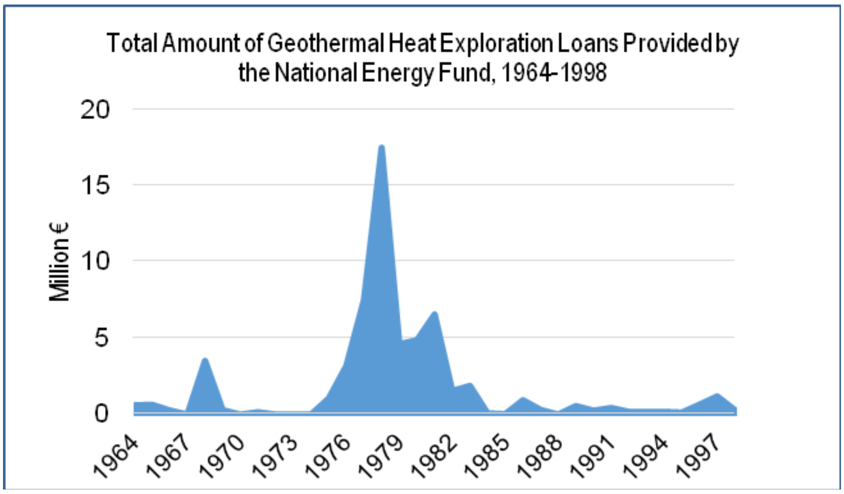


Fig. 5.12.2.4. Total amount of geothermal heat exploration loans provided by the National Energy Fund 1964–1998 (source: Orkustofnun)

The compilation of the NEF loans is currently a project in progress. All loans since 1998 are still to be assembled and therefore an unknown number. However, the number of loans is insignificant in context to the already collected information. The return rate of loans is unknown and the success behind each loan is to be evaluated. The loans are also to be categorized in regards to amount offered to exploration, establishment of geothermal district heating systems and other projects. Another aspect to look at is the fact some of the loans are additional loans, which were provided to support projects that had already received loans from NEF and needed further funding in order to meet increase in cost or to achieve positive results.

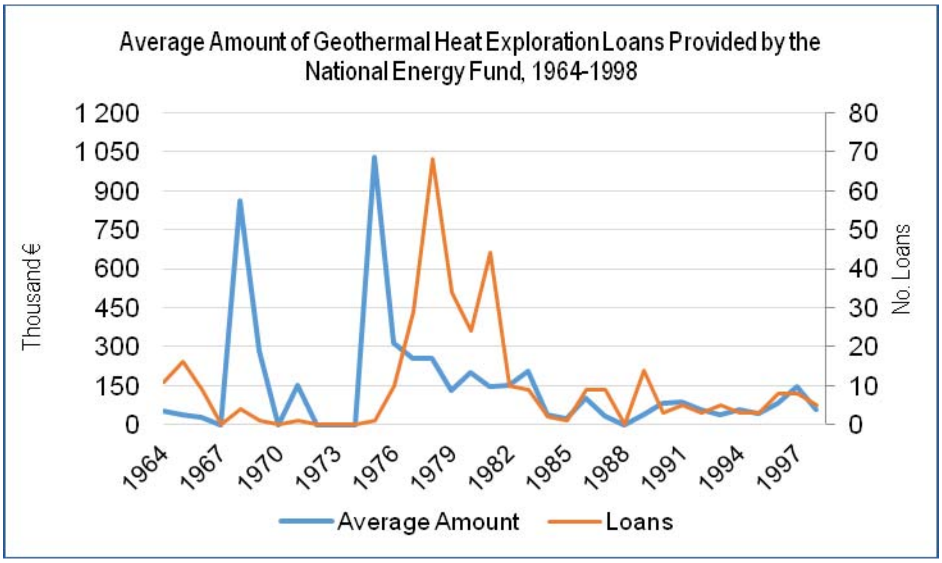


Fig. 5.12.2.5. Average amount of geothermal heat exploration loans provided by the National Energy Fund, 1964–1998 (source: Orkustofnun)

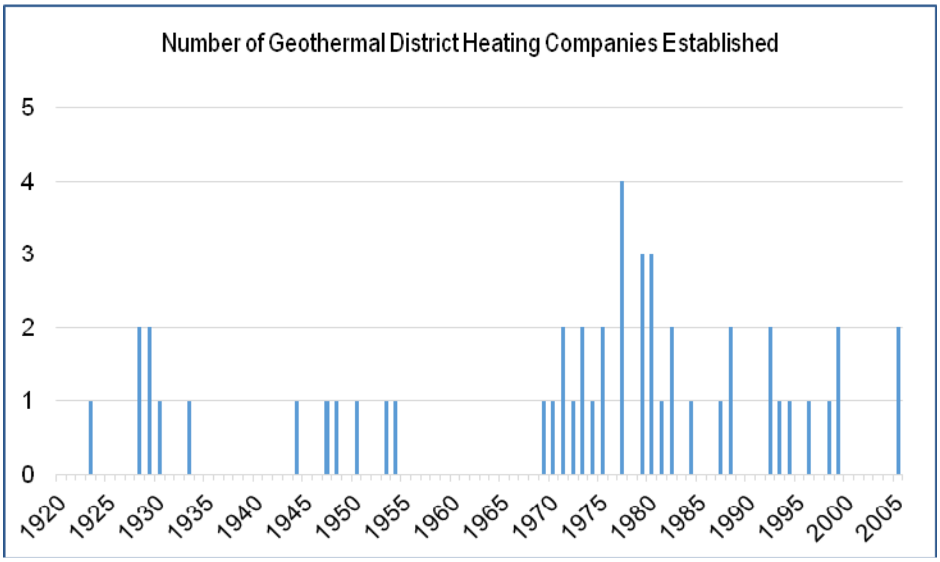


Fig. 5.12.2.6. Number of geothermal district heating companies established (source: Orkustofnun)

5.12.2.8. Economic impact

The economic benefits of the government's policy to increase the utilisation of geothermal energy can be seen when the total cost of hot water used for space heating is compared to consumer cost if oil would be used, as shown in figure 5.12.2.7-5.12.2.9. The stability in the hot water cost during strong variations in oil cost is noteworthy.

In the figure the line shows price for geothermal district heating, and the orange line the calculated price for heating by oil. Oil heating is 2-6 times more expensive than geothermal heating throughout most of the period but peaks to 17 times more expensive in the period 1973 to 1985 and rose again to a ratio of nine in the financial crisis.

In 2012, the difference in cost amounted to 61% of the state budget cost of health care in the same year.Evaluations of the estimated savings might vary somewhat as some might claim that sources other than oil could be used for heating. Heating energy could have been obtained through an increased generation of electricity with hydropower, as is done in Norway.

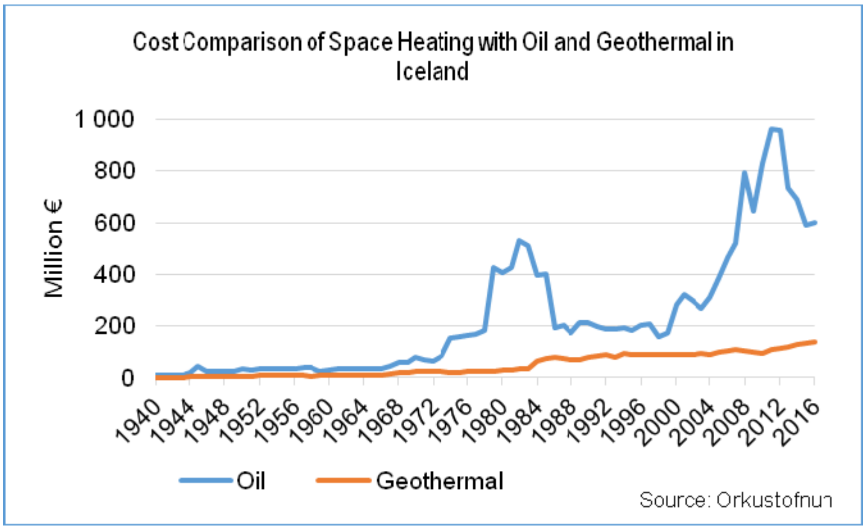


Fig. 5.12.2.7. Cost comparison of space heating with oil and geothermal in Iceland

Nevertheless, it is beyond dispute that the economic savings from using geothermal energy are substantial, have had a positive impact on the currency account and contributed significantly to Iceland's prosperity, especially in times of need. The average annual savings, in last 50 years, have been 2.6% of GDP and peaked at 7% in the period 1973 to 1985, and rose again up to 5.4% during the last years of the financial crisis, which started in 2008. In 2016, each savings percentile of GDP was equivalent to 551 € per capita and in accordance to the average it would be equal to 1.433 € per capita.

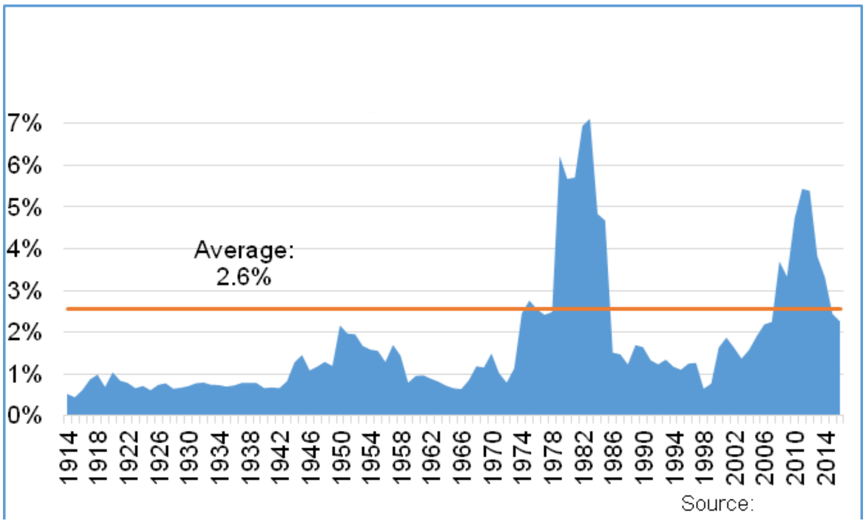


Fig. 5.12.2.8. National savings by geothermal district heating as % of GDP

In recent years, the utilisation of geothermal energy for space heating has increased mainly as a result of the population increase in the capital area, as people have been moving from rural areas to the capital area. Because of changing settlement patterns, and the discovery of geothermal sources in the so-called "cold" areas of Iceland, the share of geothermal energy in space heating is still rising. It is also possible to evaluate cumulative savings of geothermal district heating from 1914 – 2016, based on real price (fixed price 2016) and 2% annual interest rate. The estimated cumulative savings from 1914 – 2016 were 21.8 billion €.

From 1982 – 2016 the majority of savings has happened after the geothermal district heating implementation and is about 17.6 billion €. This is equal to 502.5 million € per year, or 6.290 € per family, or about 520 € per month per family, before taxes.

According to information from Registers Iceland, 21.8 billion €, is equal to 68% of the total value of all residential houses and apartments in Iceland which was estimated around 32.1 billion € in 2016.

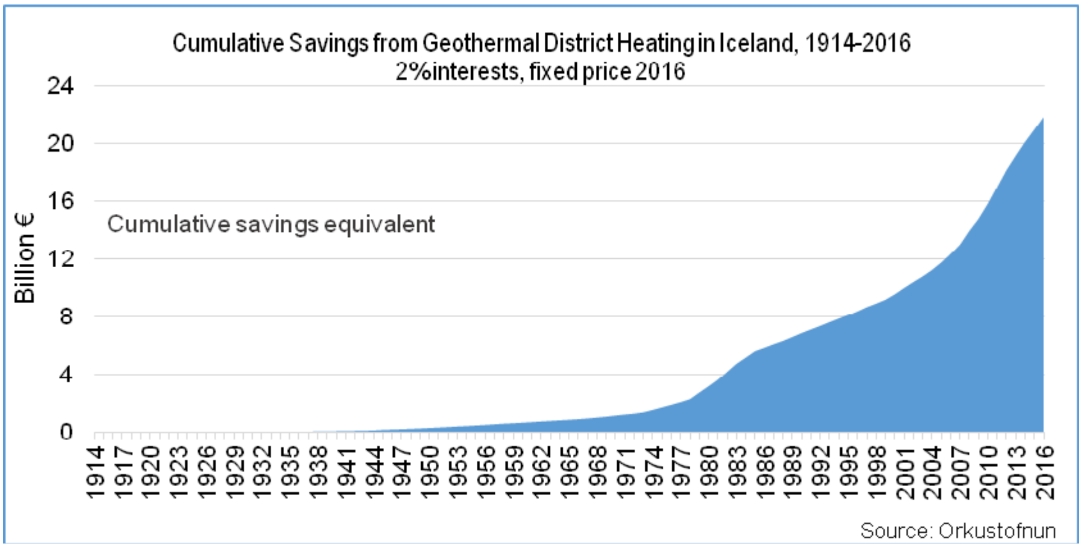


Fig. 5.12.2.9. Cumulative savings from geothermal district heating in Iceland, 1914–2016

5.12.2.9. Lessons Learned

- Important to recognize the importance of geothermal district heating for:
  a. economy (savings)
  b. energy security
  c. mitigate climate change
- Important to lower the risk of projects in the beginning, e.g. by supporting exploration and test drilling.
- Important for financial institutions to recognize opportunities within geothermal district heating.
- Successful exploration that leads to establishment of a geothermal district heating system quickly pays back its investment costs.
- Failed drillings do not exist. Unsuccessful drilling often provides more information on where to and/or where not to drill the next well.

5.12.2.10. Conclusion

Important element of a geothermal heating project is to have options and possibilities of support from public authorities towards the exploration and the drilling stages. Without the support from NEF, the geothermal energy sector in Iceland would not have developed as much it has, or at least not as quickly. New and effective exploration techniques have been developed to discover geothermal resources. This has led to the development of geothermal heating services in regions that were thought not to have suitable geothermal resources. Iceland's geothermal industry is now sufficiently developed for the government to play a smaller role than before. Successful energy companies now take the lead in the exploration for geothermal resources either in geothermal fields that are already being utilized, or by discovering new fields.

Besides the economic and environmental benefits, the development of geothermal resources has had a desirable impact on social life in Iceland. People prefer to live in areas where geothermal heat is available, in the capital area and in rural villages where thermal springs can be utilised for heating dwellings and greenhouses, schools, swimming centres and other sports facilities, tourism and smaller industry. Statistics show improved health of the inhabitants of these regions.

The total amount of the geothermal exploration loans offered by NEF in 1964-1998 is estimated to be close to 60 million €. Even though there would not have been any return from the loans, the economical savings have paid it back many times (21.8 billion € cumulative savings). In addition, the geothermal heating has had a huge and positive impact on the public health of the Icelandic citizens. It is easy to say that it is priceless since a good health is something that money cannot buy. The overall benefits from establishing geothermal heating are visible from different angles, such as economic, environmental, independent and health perspectives.

References:

Geothermal policy, options and instruments for Ukraine based on Icelandic and international geothermal experience. Orkustofnun, 2016.

5.13. General conditions for geothermal energy development in Poland and proposed actions

5.13.1. Introduction: geothermal energy today

When evaluating the conditions of the development of the use of geothermal energy in Poland, we should take into account the status of the development of geothermal district heating systems in the world, their financial and environmental effects, hazards, barriers, and chances for the development, as well as international and local experiences. In respect of the conditions of the development of Polish geothermal district heating systems, it is essential to chose the path of development, observing the needs and possibilities of implementation, and e.g. the resources, existing district heating networks in towns and the needs of local governments and investors. For that reason, the choice of an optimum method of the development of geothermal district heating in Poland should be defined in the Geothermal District Heating Development Strategy, being a result of the operation of an inter-ministerial team co-operating with the groups who participated e.g. in the National Geothermal Congresses.

For the geothermal energy resources to be used rationally, it is necessary to fulfil certain preconditions, e.g. good recognition of the resources, proper hot-water deposit parameters, motivated clients-recipients and investors, and proper local and national regulations. The use of geothermal energy in the world depends on e.g. the fulfilment of such conditions. Consequently, it is worth comparing the effects of the use of resources in the world and in Poland, for drawing correct evaluation conclusions.

5.13.1.1. Geothermal energy use in the world

Our further considerations concerning the status of geothermal district heating systems in Poland require comparison to the status of the same in Europe and in the world. The production of geothermal energy is one of the essential parameters which need to be evaluated.

The graph below (Fig.5.13.1) presents the capacities installed in the European countries.

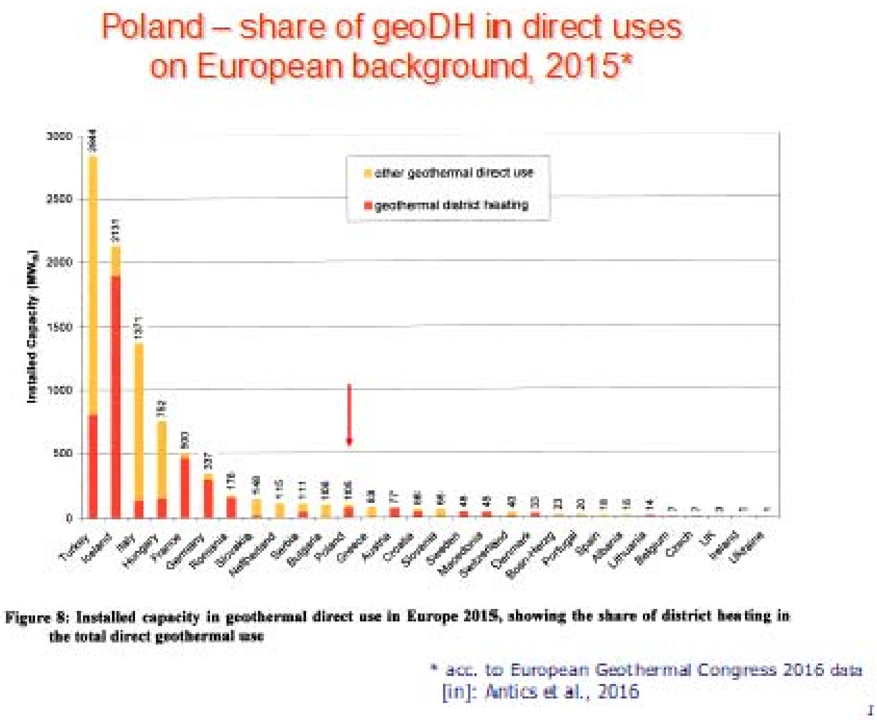


Fig. 5.13.1. Geothermal capacities for heating and other direct uses installed in Poland on the background of other European countries (acc. to Antics et al., 2016)

When evaluating the above presentation, we can conclude that the use of geothermal energy in Poland is very low in comparison to the country's resources and expectations regarding heat generation.

5.13.1.3. Geothermal energy use in Poland

The heat generation for district heating purposes amounted to 745 TJ in the Polish geothermal plants in 2013. However, according to the 2015 data, the total heat generation in Poland for the same purpose amounted to 560 PJ (data of the Office for Power Engineering Regulation). Comparing those data we can conclude that the proportion of national geothermal energy amounts to less than 1% in recent years.

When considering the geothermal energy resources in Poland, and the feasibility of its use, it is obvious that we are faced by a huge, harmonised effort of various circles responsible for environmental protection, energy security, and energy generation.

Figure 15.13.2 illustrates selected locations of some of the geothermal district heating plants and indicates the areas of geothermal energy availability in selected towns.

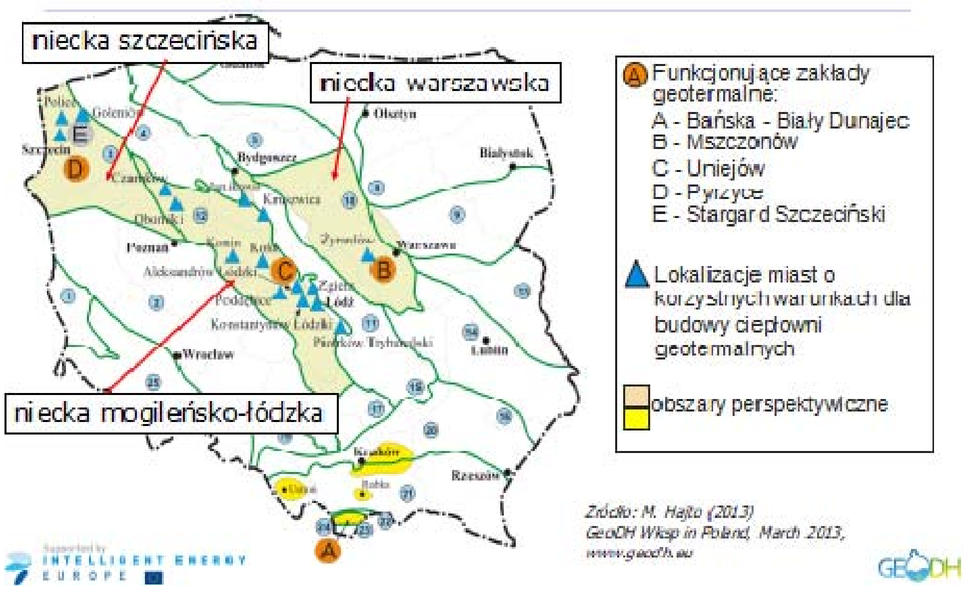


Fig. 5.13.2. Locations of selected geothermal district heating plants and of the areas of geothermal energy availability (www.geodh.eu)

Explanations to Fig. 5.13.2 Possibilities of construction of new geothermal installations: Polish Lowlands
A. Operating Plants. △ Towns with suitable conditions for geothermal plants ☐ Prospective areas

In the past several dozen years, thousands of exploratory boreholes were drilled in Poland, with temperature profiling, borehole floor temperature measurements, and profile documentation and processing. Such works were financed from public resources, similarly to a number of specialised geological, hydrogeological, and geothermal studies conducted on a regional scale, as well as the construction of geothermal installations. Consequently, we have a good recognition of the hydrogeothermal parameters in Poland. The total expenditures spent on such works are estimated at several hundred million Polish zlotys.

A considerable body of information on geothermal resources has been collected and large amounts are frozen in non-operated geothermal energy sources or the potential of limiting pollution generation. By finalising the work of several generations, the government can and should use such developed potentials for economic, ecological, and social benefits.

5.13.1.3. The condition of the environment: influence of the projects on the environment

Below, one can get acquainted with the statements made by Mr. Jan Szyszko, the Minister of the Environment, and Mr. Mateusz Kokoszkiewicz. The awareness of specific hazards for the Polish residents should be an essential argument for the construction of geothermal district heating plants, wherever the heating networks exist and there is potential access to geothermal resources. A full use of the geothermal potential in towns will fundamentally limit the level of pollution, especially on the areas of the towns mentioned above.

The suspended particulate matter (PM) and carcinogenic benzo(a)pyrene (read: benzo-alpha-pyrene) concentrations were exceeded on a large area of Poland in 2015, as we can conclude from the data presented by the Polish Minister of the Environment Jan Szyszko. According to the inspections conducted by the Environmental Protection Inspectorate in 2015, PM10 particulate matter concentrations were exceeded in 39 out of 46 zones of Poland. For PM2.5 particulate matter, the standards were exceeded in 23 zones. In the case of benzo(a)pyrene, the standards were exceeded in 44 zones. Out of the 27 EU countries, the standards were exceeded in 23 of them.

In respect of 16 countries, including Poland, the European Commission initiated the procedure that can be concluded before the European Court of Justice. The Polish Minister noticed that the problem of smog in Poland was caused by e.g. poor quality of coal burned in individual stoves. Beside the fuel, smog is also associated with car or industrial emissions, or weather conditions which may contribute to a long stay of pollution in the air. He added that smog was also typical for the towns located e.g. in valleys.

Suspended particulate matter (PM) that affects Polish towns contains dozens of harmful substances, from lead to carcinogenic benzopyrene. The particulate matter itself causes health deterioration. It can cause breathing problems and that will affect lung failure, leading to heart infarction or brain palsy. Particulate matter also permeates the blood circulation system causing blood vessel blocking and atherosclerosis. Later, the nervous system can be affected. Even a regular cold can be caused by particulate matter that irritates the respiratory tract. PM is harmful itself and it is also a medium of many other hazardous substances.

“Scientists have not fully established all the PM components. We know that soot particles "clean" air of hazardous substances. But when we breath it in, we also breath in heavy metals, mercury, lead, aromatic hydrocarbons, or sulphates,” said Mr. Łukasz Adamkiewicz from the Health and Environmental Alliance (HEAL) organisation involved in the study of the influence of pollution on our health. Benzo(a)pyrene is only one of the group of the so-called polycyclic aromatic hydrocarbons which develop e.g. as a result of coal burning.

If a high concentration of benzo(a)pyrene is recorded somewhere, it can mean that somebody is burning especially hazardous waste, e.g. PET containers. Once benzo(a)pyrene penetrates body cells, it can cause cancer. The benzopyrene indicators are much higher in Poland than in other countries.

Nitrogen dioxide (NO_2) is another important poisonous substance. It is generated mainly by car engines and power plants, and its safe levels have been exceeded in the largest Polish cities.

We do not meet the average annual standards (40 microgram per cubic metre) in Warsaw or Krakow. NO_2 causes lung irritation and reduces our immunity to respiratory tract infections. Frequent exposure to high nitrogen dioxide concentrations can lead to acute respiratory tract diseases in children, with asthmatic symptoms. Polish towns suffer the most polluted air in the European Union. That situation contributes to the occurrence of frequent diseases: asthma, cancer, and upper respiratory tract infections (Mateusz Kokoszkiewicz).

5.13.1.4. Geothermal resources in Poland

Long-term temperature measurements, e.g. for the geothermal degree classification, carried out in the majority of wells in Poland, made possible mapping of the Geothermal Atlases. The data collected in the Atlases cover the majority of the Polish territory and allow us to identify prospective basins and areas of usable geothermal waters (see the Fig. 5.13.3).

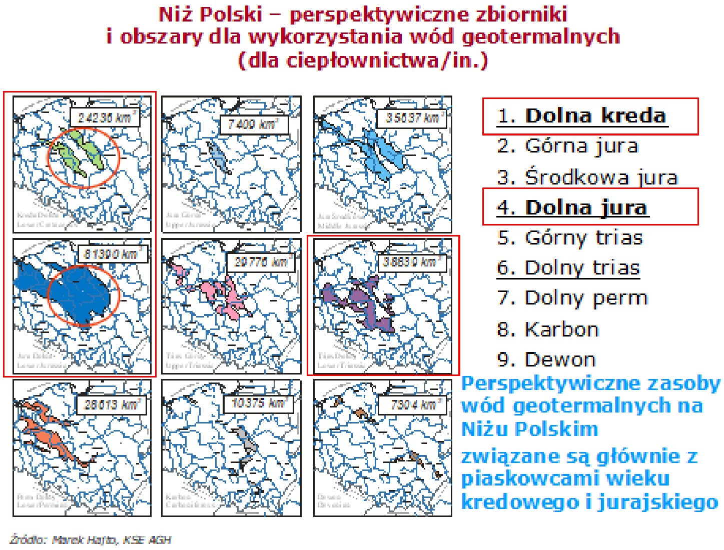


Fig. 5.13.3. Areas with the potential use of geothermal waters in the Polish Lowlands

1. Lower Cretaceous. 2. Upper Jurassic. 3. Middle Jurassic. 4. Lower Jurassic.
5. Upper Triassic. 6. Lower Triassic. 7. Lower Permian. 8. Carboniferous. 9. Devonian
Prospective resources of geothermal waters on the Polish Lowlands, associated mainly with Cretaceous and Jurassic sandstones

The resources determined in Poland allow us to assume the feasibility of the construction of up to one hundred installations feeding district heating networks in the specific towns.

5.13.1.5. Geothermal Atlases and the condition of the resources

Poland enjoys good geothermal conditions to be found in several areas of 3 geological districts: Central European, Fore-Carpathian, and Carpathians, in some places in Sudetes. Natural outflows occur quite rarely (Sudety Mountains: Cieplice and Lądek-Zdrój). About a dozen of Geothermal Water Atlases have been drafted (see the figure below) for Poland, under the supervision of Prof. Wojciech Górecki from the AGH University of Science and Technology, specifying the areas of geothermal water occurrence in Poland (Fig. 5.13.4). The first Polish Geothermal Plant of PAS was erected at Bańska-Biały Dunajec in 1989-1993. PEC Geotermia Podhalańska SA company has been operating the wells and installations since 2001.

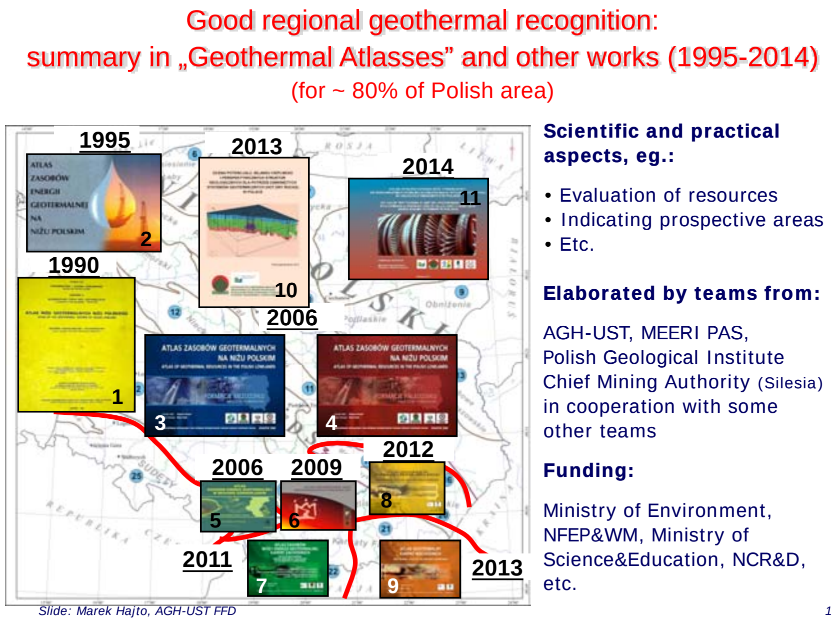


Fig. 5.13.4. Geothermal Atlases of Poland

26 geothermal water deposits have been documented on the Polish territory, as well as 30 deposits of waters displaying medicinal or thermal features. Common occurrence and renewability of geothermal energy, together with the lack of dependence on changing weather conditions, which is an essential problem of solar and wind power generation, give a possibility to use the geothermal potential in a number of installation, e.g. to heat buildings and prepare hot utility water, apply hot water in agriculture, balneotherapy, and recreational facilities. Presently, several geothermal district heating plants operate, using geothermal water sources, e.g. those at Bańska, Pyrzyce, Mszczonów, Uniejów, and Stargard. Geothermal waters are also used in Poland in recreational facilities, e.g. at Szaflary, Bukowina Tatrzańska, Białka Tatrzańska, Uniejów, or Mszczonów,

5.13.1.6. Possibilities of the use of geothermal waters

The Polish Geothermal Society (PSG) has proposed a solution for heat generation that would improve the use of the resources, taking into account the current status of the development of geothermal resources in Poland. The present rate of geothermal plant construction in Poland is not good enough for the development of geothermal district heating systems. For that reason, PSG took specific actions mentioned below, in response to the expectations of the circles represented at the Polish Geothermal Congresses.

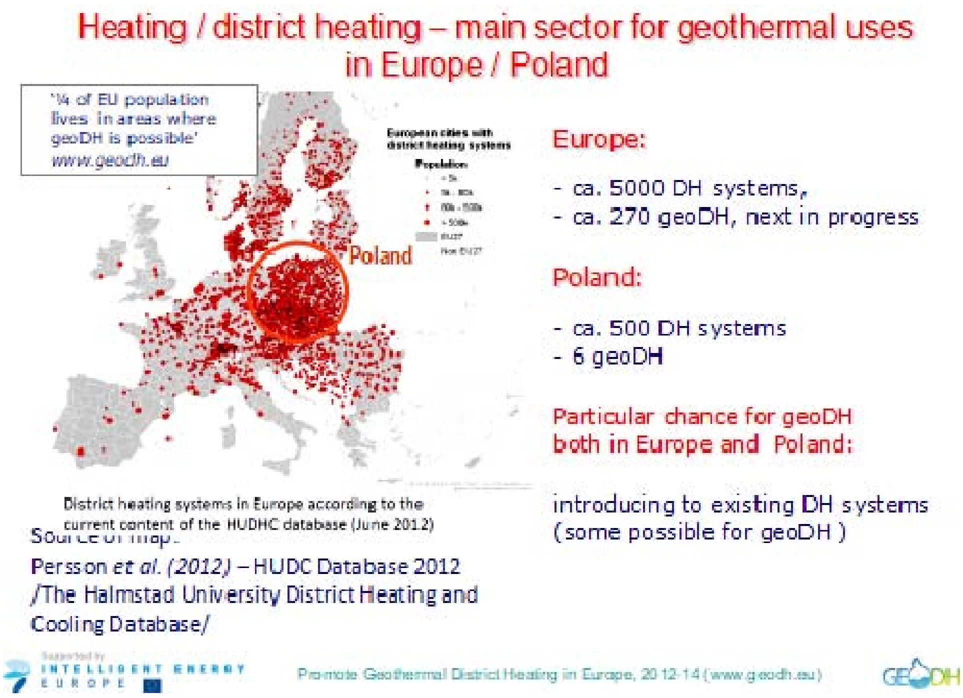


Fig. 5.13.5. Saturation with district heating plants in Europe (Beata Kępińska).

Considering the district heating networks in Poland (Fig. 5.13.5) and the map of most prospective areas for geothermal district heating (Fig. 5.13.6) one can conclude that we enjoy good conditions of the use of geothermal waters in district heating in Poland.

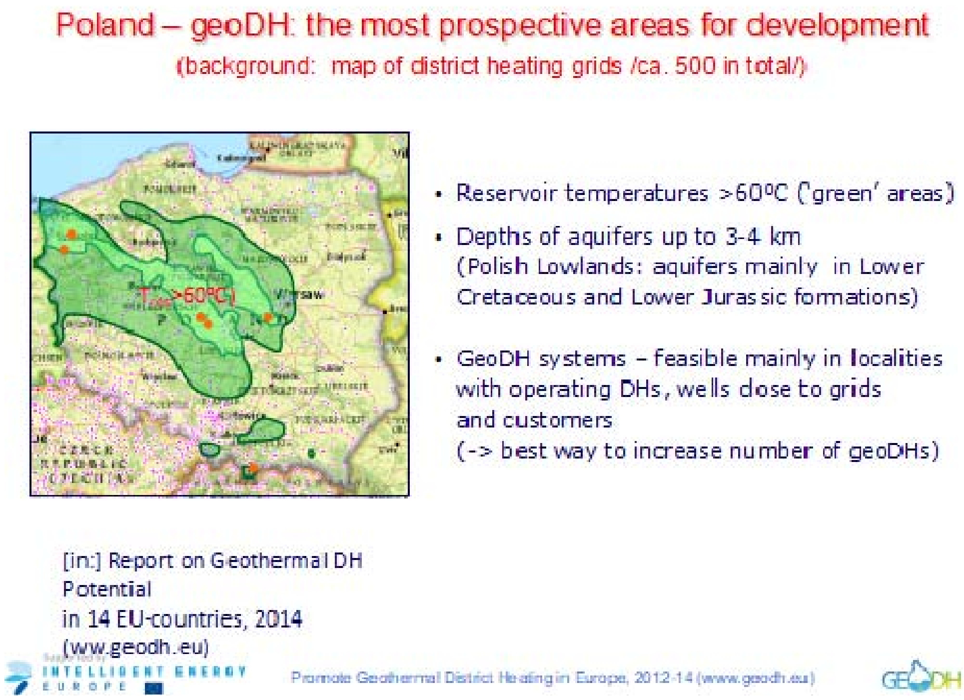


Fig. 5.13.6. Map of geothermal resources in Poland (www.geodh.eu)

5.13.1.7. Construction capabilities

In the past dozen of years, the designers and contractors of geothermal installations, together with system operators, gained large experience in making the geothermal resources available, mainly for heating and recreational needs in towns. The drilling and exploratory companies, the contractors executing heating pipelines, and other engineering and erection contractors specialising in geothermal plant building gained experience on the local and European markets. The operators of geothermal plants and local government activists can offer their experiences in the areas of legal issues, work organisation, or formulation of operating, technical, and process requirements.

Such a large national potential should be taken into account when drafting a Development Strategy for Geothermal District Heating in Poland.

5.13.1.8. Potential benefits

The delay in the development of geothermal district heating systems in Poland is surprising, in comparison to the same in Europe, especially in view of a very high level of social acceptance for the use of geothermal energy. Good conditions, specified in section 1.4.3 above, should favour the construction of geothermal district heating plants in many towns, not to mention installations in recreational and medical treatment facilities. The respective decisions relating to the use of the possibilities offered by the national geothermal water resources should result from a number of benefits to be obtained from:

- the improvement of environmental conditions,
- positive financial gains of the Polish geothermal facilities,
- possibility of job offers in relation to the plant construction and operation,
- increase of energy security.

What is definitely positive for making such decisions is the awareness of the need to use the huge potential of the capital frozen in the following:

- geothermal water resource atlases,
- international experience of researchers,
- international experience of construction companies.

5.13.2. Barriers and opportunities of the development of geothermal district heating systems in Poland

5.13.2.1. Barriers

Below there are presented several essential reasons for which the development of geothermal district heating systems in Poland has not attained the level resulting from the potentials existing in the country and the expected multiple benefits offered by such systems. There are four main barriers on the path of geothermal district heating system development.

Lack of objective methods of the evaluation of the effectiveness and security in power generation

We need to change the methods of making directional, strategic decisions in Poland, in the area of power generation, consisting in the departure from the present model, being in place for the past 27 years, and the adoption of a model based on objective criteria of the evaluation of energy effectiveness and security. This shortcoming causes that the parliamentary and government decisions taken in the past 27 years were dominated by the criteria not necessarily based on substantive issues. Lack of clear criteria allowing to conduct a comparative analysis in the area of energy generation often caused changes of decisions concerning either blocking or development of coal-based and nuclear power generation or search for oil and gas or wind and geothermal power generation. During the periods of the governments by such parties as AWS, SLD, PSL, and PO, the government and parliament decisions in the area of power generation were often made on the basis of suggestions offered by national and international lobbyists. Presently, the respective decisions have been made on the basis of national lobbyists only. Consequently, the losses borne by Poland in the areas of energy consumption, distribution, and production are estimated at billions of zlotys a year, with lack of optimisation for energy security. Introduction of objective procedures for decision-making in power generation is a method of changing that harmful situation in our country.

There is a need of a comprehensive, long-term consideration of the energy sector in Poland, taking into account e.g. its present condition, national and international aspects, trends, threats, needs, and capabilities. Of course, those considerations will also concern geothermal district heating systems.

5.13.2.2. “Formal pessimism”

A public conviction of the high costs of geothermal district heating systems has been formed for a long time. The representatives of the Polish Geothermal Society (PSG) often faced “formal pessimism” during official or unofficial meetings devoted to the development of geothermal district heating systems in Poland. All the PSG proposals were rather refused. The main argument justifying such a position was the common conviction of the high costs and unprofitability of geothermal plants.

That conviction was presented by government members and members of parliament. Those people could not accept our arguments justifying the incorrectness of the “formal pessimism” in that area. Without knowing the reasons of such a conviction, we used to present the facts specified in essence below.

Fact I.

The PEC Geotermia Podhalańska SA company was presented as an example of high capital investment expenditures, by adding, for the need of that premise, the costs of making the water deposit available, the costs of the construction of a pipeline from Bańska to Zakopane, the construction of the district heating plant and network in Zakopane (the town did not have one before). However, the capital investments for the construction of the geothermal plant, with a building, well-drilling and a peak-demand boiler house constituted only 34.7% of the total costs. The remaining costs referred rather to the network construction (52.2%). The conviction of the high costs of a geothermal district heating system was shaped on the basis of the principle: “if the facts are contradictory, too bad for the facts.”

Fact II.

For the needs of a presentation of the Geothermal District Heating Development Conception, we prepared a slide showing the capital investments that must be borne for water, wind, and geothermal installations (Fig. 5.13.7). Unfortunately, even that argument demonstrating a considerable benefit of investing in a geothermal system was rejected.

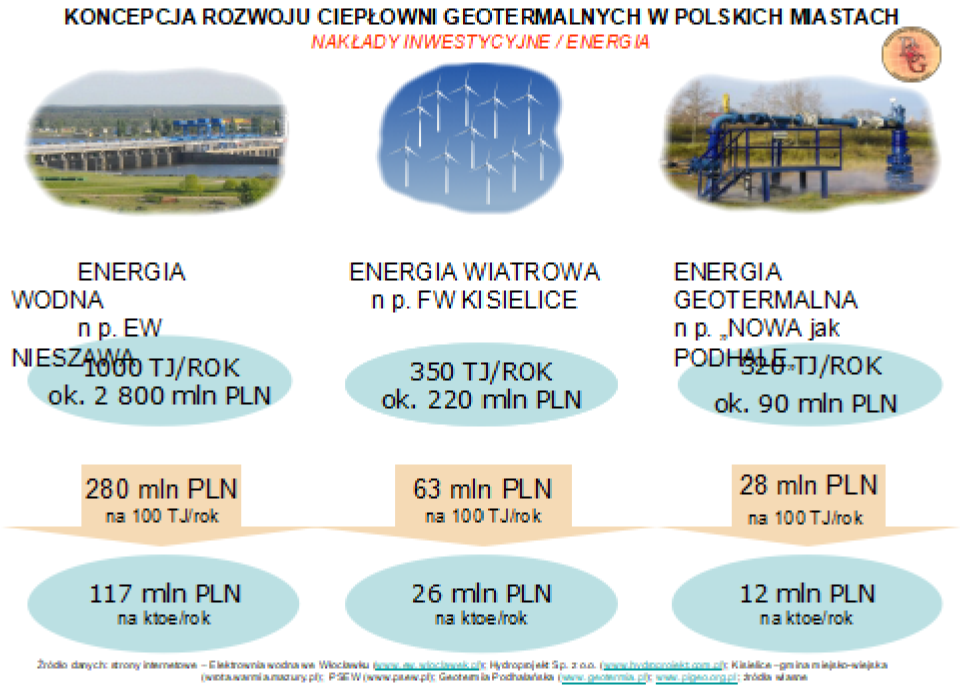


Fig. 5.13.7. A comparison of capital investments for obtaining energy from selected renewable sources (Z. Bociek)

5.13.2.3. “Radical optimism”

Below, we can read several quotations from independent public statements made by two researchers.

Quotation I - “Huge energy resources exceed several hundred times the annual needs of Poland, in view of our technical conditions.”

Quotation II - “Until 2050, we can and should erect in Poland about 300 geothermal power plants, and about 3,000 high-power plants to generate electricity at the level of 100-300 megawatt."

Voicing of radically optimistic but untrue statements among the parliamentary and government circles is detrimental to the development of geothermal district heating in Poland.

5.13.2.4. Lack of a Development Strategy for Geothermal District Heating in Poland

In the past years, geothermal district heating developed in Poland mainly owing to the enthusiasm and consistent actions on the part of local governments and investors. However, there is a shortage of a systemic solution that would facilitate decision making for the sake of investment in the construction of geothermal plants, in fact, similarly to the whole area of energy generation in Poland. The attitude of the investors and the persons responsible for supporting the respective projects was justified either by “formal pessimism” or “radical optimism.” It is time for a change. For the development of geothermal district heating to be shaped according to the best national and international models, guaranteeing the selection of optimum solutions, it is necessary to draft a Development Strategy for Geothermal District Heating in Polish Towns.

5.13.2.5. Unused possibilities: opportunities

There are many reasons that jointly create an opportunity for proper and efficient use of geothermal resources in Poland. Below, we present some of them. Our country is characterised by a high level of social acceptance for the production of energy from geothermal resources. The main reasons of such acceptance include good experiences of local communities, resulting from the effects of the operation of the existing geothermal plants. The residents of the towns in which geothermal plants operate feel a considerable air quality improvement. The local governments making decisions to implements a geothermal plant also refer to the increase of heat energy security. The construction of Aqua Parks supplied with thermal waters are equally well accepted. Besides, economic arguments are also important, and they result from the experiences of currently operating geothermal plants. The positive results and GJ sale prices (see the figure below), comparable to the prices offered for the same by coal-burning plants, constitute another argument for intense and systemic development of geothermal district heating plants in towns. The following present unused possibilities and developmental opportunities, e.g. knowledge of the geothermal energy resources, international experience of the researchers and engineering companies or the support for the development of geothermal district heating in Poland, offered by the Polish government. What is a fundamental and primary condition of using such opportunities is the necessity to draft a Development Strategy for Geothermal District Heating in Towns.

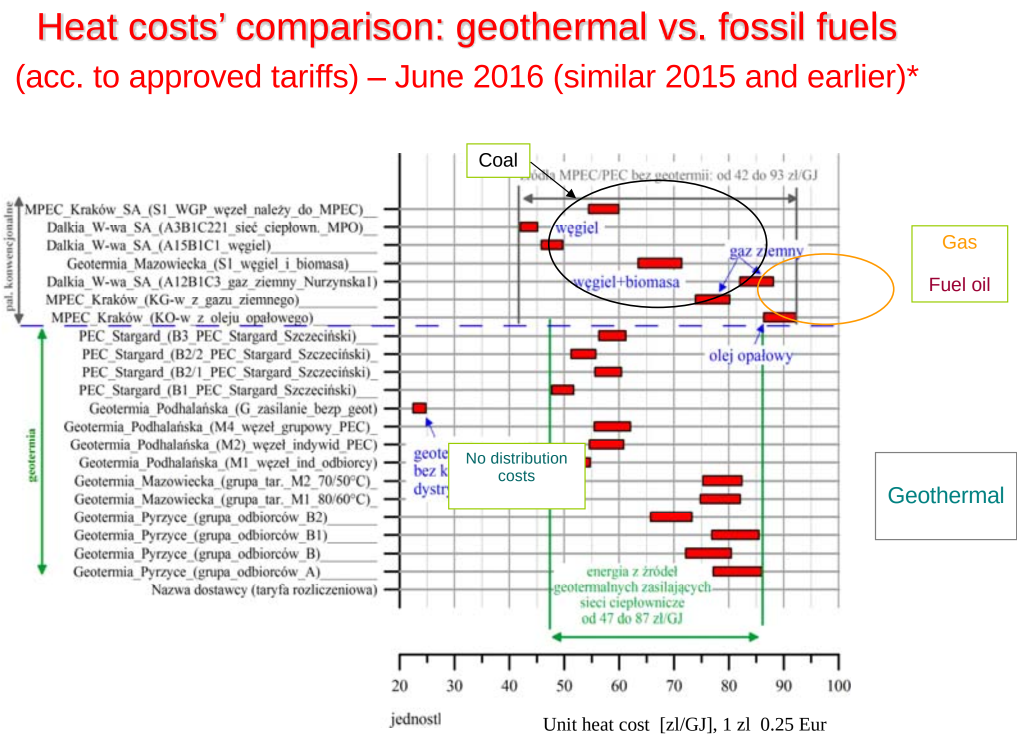


Fig. 5.13.8. A comparison of heat production costs (Pająk. L., Bujakowski W., 2016)

5.13.2.6. Establishment of Clean Energy Towns Association

The Association of Clean Energy Towns (ZMCE) was established in Włocławek in 2006. By consent of the Towns' Councils, the mayors of those towns defined the mission of the Association as follows: "The goal of the Association, in compliance with the conditions of accession to EU, is the optimum use of geothermal energy resources located in our towns to supply the existing district heating networks or for other uses, as needed by local communities."

The founding committee consisted of the following:

- town and municipality of Krotoszyn,
- town and municipality of Kępno,
- municipality of Ostrów Wielkopolski,
- town and municipality of Pyrzyce,
- municipality of Włocławek.

Unfortunately, the project was not supported or aided by the Ministry of the Environment or the Governors or Local Assembly Marshals in the respective regions. Consequently, the ZMCE initiative remained inactive.

5.13.2.7. Activities of the Polish Geothermal Society

The Polish Geothermal Society (PSG) is an interdisciplinary group. It gathers representatives of various fields of science, existing geothermal facilities, exploratory and drilling companies, as well as local government people. PSG organised five Polsih National Geothermal Congresses and its Management Board co-operated with e.g. the Polish Ministries of the Environment and Economy, The Energy Commission of the Polish Parliament, or the Association of Polish Towns (ZMP), Polish Oil and Gas Mining Company (PGNiG) and a number of interested municipalities.

The PSG Management Board acts in the spirit of the 2007 resolution and the Polish Geothermal Congress, with its main message reading:

„…it is especially essential to co-operate e.g. with the Association of Polish Towns and the Polish Government and Parliament. The Congress participants express their conviction that good, long-term and solid-base co-operation of various circles, including the Polish Government and Parliament, constitute fundamental condition for the development of geothermal district heating in Poland, as well as a condition for using national and EU funds for the development of that field in Poland."

Let us present a brief history of a dozen of years of PSG activities, their results, and conclusions for the future.

5.13.3. History of PSG activities

5.13.3.1. Polish Geothermal Congresses: resolutions

As we mentioned before, PSG organised five Polish Geothermal Congress as follows: Congress I in Radziejowice, II in Bukowina Tatrzańska, III in Lądek Zdrój, IV in Zakopane, and V in Mszczonów. The assemblies gathered representatives of the circles directly associated with geothermal district heating projects, leading science and research institutions, geological, geophysical, and drilling companies, and other entities associated with the geothermal sector, as well as invited representatives of the central and local government agencies.

Each of the Congresses was a forum of debate and presentation of experiences and solutions, favouring the development of geothermal district heating systems in Poland and in the world. All the Congresses ended with adoption of resolutions or conclusions, being collections of agreed proposals addressed to various entities in Poland, including the PSG Management Board.

We present below selected fragments of resolutions or conclusions adopted by the Congresses. The quotations illustrate the expectations of the Congress participants.

* I Polish Geothermal Congress, Radziejowice 2007

Resolution: „*…it is especially essential to co-operate e.g. with the Association of Polish Towns and the Polish Government and Parliament. The Congress participants express their conviction that good, long-term and solid-base co-operation of various circles, including the Polish Government and Parliament, constitute fundamental condition for the development of geothermal district heating in Poland, as well as a condition for using national and EU funds for the development of that field in Poland*."

* IV Polish Geothermal Congress, Zakopane 2013

<u>General conclusions</u>:

- The Congress participants were briefed on the establishment, by initiative of the Government and Parliament, of a special Energy Team. The representatives of the geothermal district heating sector were invited to join the Team. We express our hope of positive results for the development of geothermal district heating in Poland.
- The circles represented at the Congress expect that the Ministry of the Environment, the Ministry of the Economy and the managements of the NFEP&WM and VFEP&WM will adopt actions designed to limitation of the barriers to the development of geothermal district heating in Poland by creation of proper legal procedures and sources of financing to support the Renewable Energy Sources (RES) sector.

Detailed conclusions:

- The Congress participants support the continuation by the Polish Geothermal Society of the activities intended to expand the use of geothermal energy in Polish towns. That direction should become part of the National Development Strategy for Power Generation until 2030 and contained in the National Action Plan for supporting the use of Respondent until 2020.

- Lack of an ecological risk insurance system, at the stages of exploration and operation, constitutes a serious barrier to the development of geothermal district heating, especially deep systems.
- The circle of the entrepreneurs in the geothermal business emphasised the necessity to start close relationships with local governments, including especially the Local Assembly Marshals, in the area of placing geothermal projects in the Regonal Physical Plans and Regional Development Strategies, as well as strengthening the co-operation at the stage of handling new exploratory and operating projects.
- Conclusion regarding the flow of information to PSG: PSG should obtain information on the current works on geothermal district heating projects. That concerns in particular drilling works and hydrogeological research in boreholes.

  * V Polish Geothermal Congress, Mszczonów 2016

General conclusions:

- The fifth Congress requests the PSG Management Board to appeal to the Prime Minister to take into account the conclusions concerning the development of geothermal district heating in the work of the respective government Ministries and agencies (presented in a separate Appeal).

Detailed conclusions:

- The Congress participants support the continuation by the Polish Geothermal Society of the activities intended to develop geothermal energy projects in towns, including the existing central heating networks. The geothermal resources possessed by Poland in fact impose on us the necessity to adopt that direction of development, as part of the national Development Strategy for Power Generation, including e.g. the Strategy of Responsible Development, being drafted by the Polish government.
- The Congress participants request the PSG Management Board to send a letter to the Ministries of Energy and the Environment, as well as the President of the NFEP&WM, to propose the implementation of a programme or requirement intended to collect additional hydrogeological and geothermal data, including sampling of deep aquifers and thermal measurements in new boreholes produced by the corporations with a considerable share of the State Treasury (including PGNiG S.A., KGHM S.A. and others). Such data can constitute essential sources of information on the occurrence and parameters of potential geothermal waters in the locations that have not been recognised well.

5.13.4. A conception of the development of geothermal district heating in towns

Subsequent Congresses adopted a conception of the development of geothermal district heating in towns (Fig. 5.13.9).

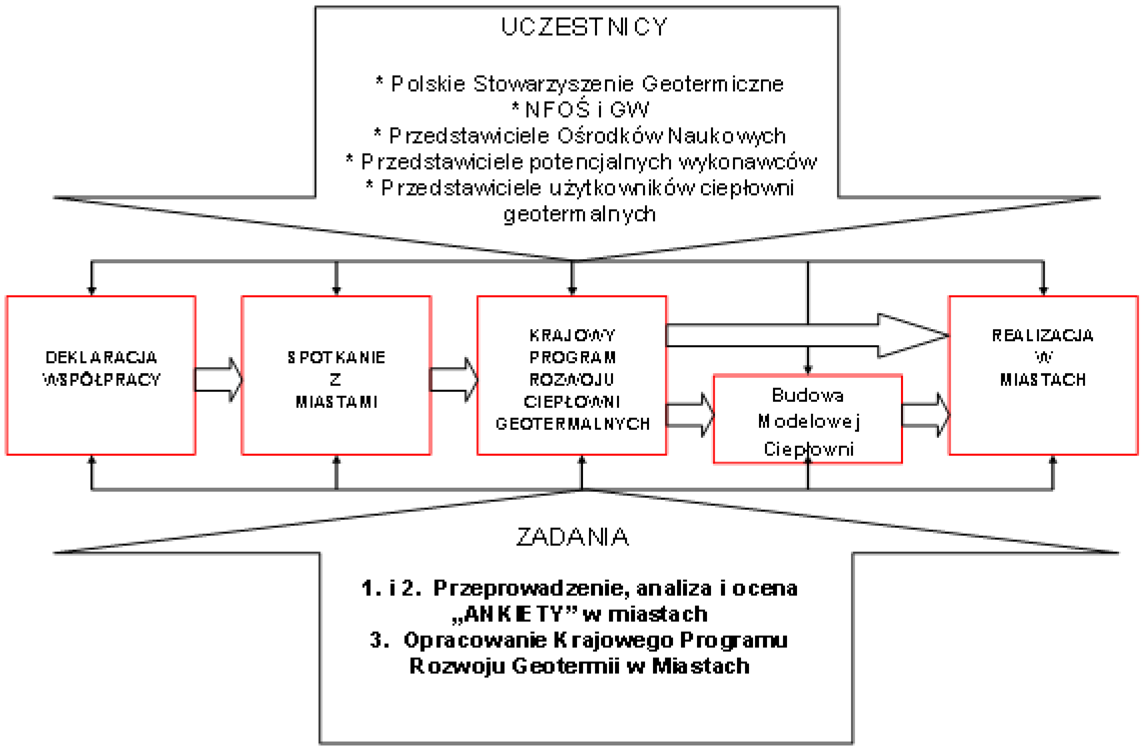


Fig. 5.13.9. A conception of the development of geothermal district heating in towns (Z. Bociek)

Fig. 5.13.9. Graph description:

PARTICIPANTS

Polish Geothermal Society

NFOŚ and GW Funds

Representatives of Research Centres

Representatives of potential contractors

Representatives of geothermal district heating plant operators

Declaration of Co-operation – Meeting with Town Authorities – National Programme of the Development of Geothermal Plants – Construction of a Model Geothermal Plant – Implementation in Towns

TASKS

1 and 2. Survey to be conducted in Towns, with evaluation

3. Drafting a National Programme of Geothermal District Heating in Towns

Below is a description of the proposed method to fulfil the three Stages of the conception of the development of geothermal district heating in towns.

Stage I – Survey preparation and distribution

A team appointed by the PSG Management Board prepared a preliminary set of questions regarding technical, organisational, and legal issues which should be presented to the town authorities and the owners of the existing district central heating plants and networks. The questions will be placed in a survey, or expert questionnaire, to be distributed among selected towns. Obtaining consent of the towns to participate in the survey will be a precondition of the success of that Stage of activity. We hope that such a consent will be obtained as a result of a joint invitation of the Mayors of towns and cities extended by the Minister of the Environment and the Presidents of PSG and ZMP.

Stage II – Survey analysis and evaluation

Detailed analysis will be applied to the data on e.g. the location and hydrogeological, geothermal, and technical facilities (e.g. the possibilities and methods of co-operation with the existing networks). Consequently, a list of towns will be established to select those which fulfil the criteria indicating the feasibility of building geothermal plants, co-operating with the existing district heating plants and central heating networks.

Stage III – Drafting the National Programme of the Development of Geothermal District Heating in Towns

The Programme will be prepared for the towns which have obtained positive evaluations in Stage II, with a collection of the solutions for the construction of a geothermal district heating plant, containing e.g. the following data:

- access to geothermal resources, with their parameters,
- borehole locations,
- geothermal installation designs, adopted to the local district heating systems in towns

And

- a preliminary feasibility study for particular installations,
- district heating models adopted to e.g. the number of customers, types of central heating networks and geothermal installations,
- preliminary feasibility studies for particular models,
- project implementation,
- determination of the methods of financing, execution, and access to national and EU sources,
- legislation tools favouring the development of geothermal district heating in towns.

KPRGwM will facilitate decision-making processes for the investors, and the project selection processes for the government agencies, in case such projects obtain public financial support.

The anticipated costs of Stages I and II are estimated at ca. PLN 500,000. The cost of the final Stage III is estimated at ca. PLN 1.5 million (depending on the number of towns interested and selected to that Stage).

5.13.3.3. Letters and contacts with the members of the Polish Parliament and Ministries

In 2010, the PSG members presented their Conception to the Energy Subcommittee of the Polish Parliament and the representatives of the Ministries of the Environment and Economy.

As a result of specific discussions, a Co-operation Declaration was formulated. It was signed on 8 March 2010. Unfortunately, without any consequences, despite a number of requests sent to the Ministries, meetings with the Ministers or Presidents of NFEP&WM and ERO (Energy Regulation Office).

PODKOMISJA STAŁA DS. ENERGETYKI KOMISJI GOSPODARKI SEJMU RP	MINISTER GOSPODARKI	MINISTER ŚRODOWISKA	POLSKIE STOWARZYSZENIE GEOTERMICZNE

Deklaracja współpracy na rzecz rozwoju wykorzystania energii geotermalnej w Polsce

Biorąc pod uwagę:

- pozytywny wpływ rozwoju wykorzystania odnawialnych źródeł energii zarówno na środowisko, jak również na stabilność gospodarki, poprzez zwiększenie bezpieczeństwa dostaw energii (w tym zmniejszenie uzależnienia od zagranicznych surowców energetycznych), poprawę krajowego bilansu towarowego i płatniczego (ograniczenie importu surowców energetycznych) oraz rozwój przemysłu związanego z energetyką odnawialną, co przekłada się bezpośrednio na zwiększenie ilości miejsc pracy oraz stwarza możliwość eksportu nowoczesnych technologii;
- ideę zrównoważonego rozwoju, która niesie ze sobą szczytne założenie postępu gospodarczego i społecznego – w pełni zharmonizowanego ze środowiskiem i bez ryzyka zmniejszenia możliwości zaspokajania potrzeb przyszłych pokoleń, w praktyce oznaczającą gospodarcze wykorzystywanie dóbr przyrody przy jednoczesnym ich poszanowaniu;
- potrzebę realizacji zobowiązań międzynarodowych w dziedzinie odnawialnych źródeł energii oraz ochrony klimatu;

deklarujemy partnerską współpracę w zakresie skutecznych działań zmierzających do rozwoju wykorzystania energii geotermalnej w Polsce.

Andrzej Czerwiński	Joanna Strzelec-Łobodzińska	Henryk Jacek Jezierski	Beata Kępińska
Przewodniczący Podkomisji Stałej ds. Energetyki Komisji Gospodarki Sejmu RP	Podsekretarz Stanu Ministerstwo Gospodarki	Podsekretarz Stanu Ministerstwo Środowiska	Prezes Polskiego Stowarzyszenia Geotermicznego

Warszawa dn. 08 marca 2010 r.

5.13.3.4. Meetings and conferences, national and international co-operation

In the past dozen of years, the representatives of the PSG Management Board participated in many national and international conferences and meetings on geothermal district heating. The President of PSG is a member of the EGEC authorities. PSG has access to the current data on the development of geothermal district heating in Europe and in the world.

5.13.4. Proposed activities

5.13.4.1. Conclusions

During the years, the development of geothermal district heating in Poland resulted from the activities based on enthusiasm and dedication of a small group of researchers, local governments people, and investors. The presently operating geothermal plants were developed owing to the determination of the representatives of such groups. The Polish government and parliament did not produce any systemic solution in recent 25 years to facilitate the use of geothermal resources available in Poland. No comprehensive evaluation of the effectiveness or security, at least in RES, has been provided. Such conduct was favourable for the creation of barriers on the way of the development of geothermal district heating in Poland. No geothermal resources or national and international experiences of Polish researchers or companies were used to that end. The same of the examples of good European practice in that area. Consequently, the development of RES in Poland was conducted on the basis of unclear criteria and with a considerable influence of lobbyists.

If that situation is supposed to change, and the development of geothermal district heating should be optimised, as a result of analysis, evaluation, and selection of proper solutions, it is necessary to start immediately to draft a Development Strategy for Geothermal District Heating in Poland.

We present below our suggestions regarding e.g. the objectives, and scope of work of the inter-ministerial team that will be in charge of drafting such a Strategy.

5.13.4.2. Proposals

An Appeal for elaboration the Geothermal Energy Strategy Development in Poland

It is a fundamental postulate, being a condition of drafting a consistent programme of developing geothermal district heating in Poland, to draft a Strategy of geothermal district heating, within the power generation sector, and for recreation and balneotherapy. The Management Board represented by the President of the Polish Geothermal Society formulated an Appeal to the Polish Prime Minister. One reads in in, among others:

> "Dear Prime Minister,
>
> Acting on behalf of the fifth Polish Geothermal Congress, taking place at Mszczonów on 11-13.10 2016, the Management Board of the Polish Geothermal Society requests you to support long-term activities of the circles meeting at the Congress, intended to attain a broad use of geothermal energy.
>
> We think that the development of geothermal district heating in Poland is much inadequate, considering our resources, potentials, and primarily extensive benefits. Only in 2007, the first Polish Geothermal Congress obligated the PSG Management Board to co-operate with the Polish Government and Parliament, for the sake of the development of geothermal district heating in Poland, with special attention paid to its use in towns that are privileged by having access to geothermal resources and the existing infrastructure (district heating networks).
>
> We gladly accepted the declaration of Minister Jan Szyszko regarding the development of geothermal district heating in Poland, expressed during the Climate Conference in Paris in December 2015.
>
> We further request your support, because despite the fact that a Declaration of Co-operation in the area of geothermal district heating was signed, with the representatives of the Polish Government and Parliament in 2010, or our long-term contacts with the Ministers and members of Parliament, or our participation in the consultations of bills and other activities, the majority of the essential postulates of the circles associated with the Polish Geothermal Society have not been fulfilled, regardless of the multiple benefits offered by geothermal district heating. Those have been proved by very positive national and international experiences.
>
> We request you to assist us in the fulfilment of the postulates addressed to:
>
> - The Ministry of the Environment, the Ministry of Energy, and the Ministry of Health – that geothermal resources should be taken into account in the respective bills based on benefits;
>
> - President of the NFEP&WM – that the implementation of a systemic solution be drafted and financed for Poland, in the form of a Conception for the Development of Geothermal District Heating in Towns. Such a Conception proposes a holistic solution, addressed to about a hundred of Polish towns, privileged to enjoy access to geothermal resources that

allow for use thereof for heating, recreational, or balneotherapeutic purposes. As a result of the Conception implementation, a study will be drafted to facilitate the decision-making process on the part of investors, local governments or state agencies responsible for financial support. We request that arrangements be made on financing the Conception from the NFEP&WM Fund.

- Ministry of Development – that the Strategy of Responsible Development should include the use of geothermal resources for power generation, recreation, and balneotherapeutic purposes, owing to the obvious and multiple economic, environmental, and health benefits, as well as the improvement of energy effectiveness and security. The draft Strategy of Responsible Development contains only one mention of "geothermal district heating" on page 34, in the chapter on "Natural environment." However, geothermal district heating should also be treated e.g. in chapter VI "Areas influencing the achievement of the Strategy's objectives," or "Energy and national security."

- President of Polish Oil & Gas Company (PGNiG SA) – that the Corporation's Strategy should include the possibilities of using the corporate capabilities to make the Polish geothermal resources available.

We request you to further recommend our proposals. We declare our readiness to co-operate on the above specified issues with the representatives of the Polish Government, NFEP&WM and PGNiG. Your reply will be highly appreciated."

The PSG Management Board received the answer from the Prime Minister's Office which shall open the door for ccoperation (and some has been ongoing).

Risk Guarantee Fund

Potential investors interested in making the geothermal energy resources available, e.g. for power generation, are aware that a large financial risk associated with siting of borehole is the basic threat to any project. That fact is one of the essential causes of a limited interest in investing in the use of geothermal energy projects in Poland. In many countries holding geothermal resources, tools were adopted to reduce financial risks on the part of an investor. Such risks are associated with the locations of borehole drilling necessary to make geothermal energy resources available. Investors are able to use such risk-reduction financial support.

There are quite a few models of funds applied in other countries, and we will be able to find an optimum solution for Polish geothermal projects. There are also examples of connections between such funds and the necessity to carry out e.g. seismic tests preceding drilling operations.

Fig. 5.13.10 illustrates the dependence of subsequent activities on correct borehole siting.

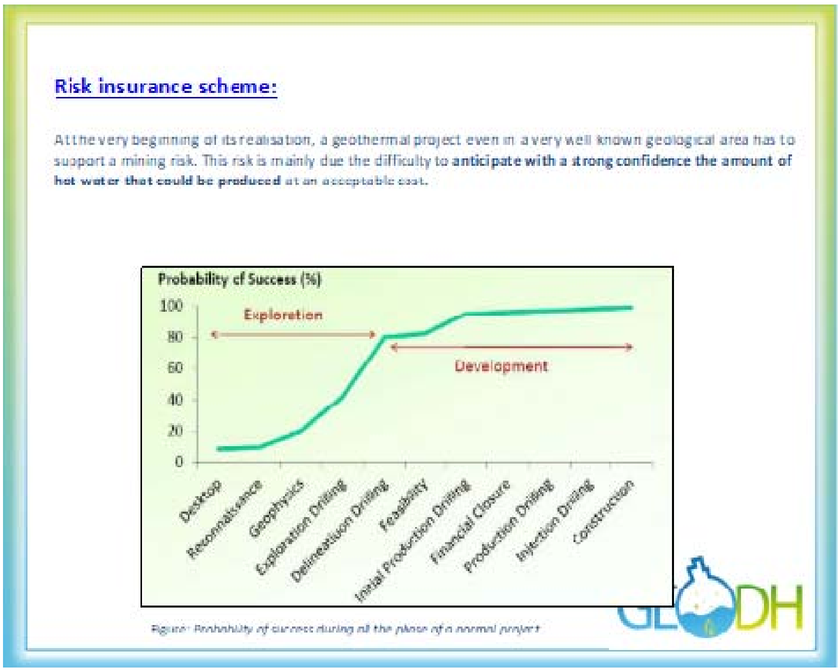


Fig. 5.13.10. A risk insurance scheme (www.geodh.eu)

3D seismic survey

Many countries apply 3D seismic testing before starting a drilling project to make geothermal resources available. The development of geophysical research influences the increase of the proper selection of sites for exploratory drilling. The implementation of the 3D seismic method instead of a 2D one resulted in the improvement of the success of exploration. The graph below shows that kind of dependence. Now, it becomes even more obvious that it is worthwhile connecting a Risk Fund with the necessity to carry out 3D seismic testing before drilling (Fig. 5.13.11).

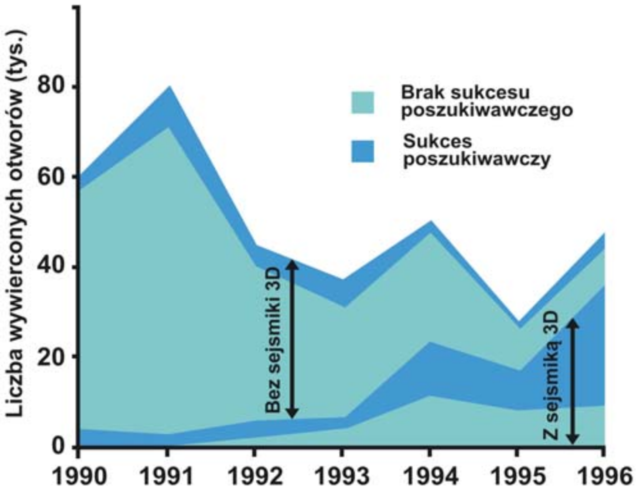


Fig. 5.13.11. The dependence of exploration success on geophysical research (data from the „Geofizyka Toruń")

Graph description:

Number of borehole drilled (in thousands) – No exploration success – Exploration success
Without 3D seismic testing – With 3D seismic testing

5.13.5. Final proposals

Considering the above-mentioned conclusions and proposals, and especially the Appeal and a reply of the Polish Prime Minister, we propose as follows:

To develop a Strategy and Programme of the Development of Geothermal District Heating in Poland by an inter-ministerial team. The representatives of the following entities should participate, e.g.

- Polish Geothermal Society,
- Convent on Geothermal District Heating,
- Local governments, with experience in geothermal district heating,
- Experienced contractors,
- Members of Parliament interested in the development geothermal district heating.

The Team should concentrate on the following, e.g.:

- Conception of the Development of Geothermal District Heating in Poland
- Survey assumptions
- Selection of optimum solutions of a Risk Fund
- Scope of study on the generation of heat and electricity, recreation and balneotherapy,
- Expectations of local governments and investors,
- Knowledge of the geothermal resources in Poland,
- Local and international experience of system contractors,
- resolutions and conlcusions of the Polish Geothermal Congresses,
- applications and proposals from the EEA Project – "Geothermal energy – a basis for low-emission heating, improving living conditions and sustainable development …"

The Strategy should entail legal, financial, organisational, technical, and process issues, e.g.:

- cogeneration,
- heat generation for municipal and other purposes,
- recreation,
- balneotherapy.
- agriculture
- model geothermal plant
- implementation recommendations

Elaboration of a Strategy of the Development of Geothermal District Heating in Poland is a fundamental condition of an optimum use of geothermal resources in Poland.

5.14. Proposals of pilot projects in Poland based on the Project results

The chapter contains the proposals of pilot geothermal projects for towns which were addressed by the reported Project, for several other localities and areas in Poland, and proposals of some geothermal research projects. Each partners' team presents its suggestions and point of view, however, in general all of them are interconnected, coherent as results of common activities, works and discussions during the Project duration.

The geothermal pilot project proposals are presented in a following order:

- Proposals for Project towns: Poddębice, Konstantynów Łódzki, Sochaczew, Lądek-Zdrój,
- Proposals for Project towns and other localities in Poland,
- Proposals of new localities within the Polish Lowlands prospective for geothermal space heating development,
- Proposals of research projects for Lądek-Zdrój area and Sudetes region – to facilitate optimal geothermal heating development,
- General proposals and recommendations for increased effectiveness and better operation of existing and planned geothermal district heating in Poland.

5.14.1. Proposals of geothermal pilot projects for selected towns: Poddębice, Konstantynów Łódzki, Sochaczew, Lądek-Zdrój

5.14.1.1. Proposals by MEERI PAS team and experts

Based on the initial pre-feasibility studies for Poddębice (Chapters 5.4.3 and 5.4.4), Sochaczew (Chapters 5.5.2 and 5.5.3), Konstantynów Łódzki (Chapters 5.6.2 and 5.6.3), as well as Lądek-Zdrój (Chapters 5.7.4 and 5.7.5), the best solutions, in the authors' opinion, were selected. Prioritisation, within particular locations, was performed on the basis of three groups of criteria: energy, economic and ecological criteria.

The measure of the energy criterion was the production of fully renewable geothermal energy, i.e. such energy which is produced directly, without heat pumps. If, in a given location, it was impossible to produce thermal energy directly, due to the lack of temperature coherence between the source and the consumer; such situation occurred e.g. in Sochaczew, so the criterion of the amount of geothermal energy acquired by means of heat pumps was followed. The higher the amount of geothermal energy, the better was the option under analysis.

The measures of the economic criterion were as follows: the level of the required investment expenditures, the level of variable costs and the total cost of producing net thermal energy. The lower the investment expenditures, variable costs and the total unit cost, the better was the option under analysis.

The measure of the ecological effects was local and global CO_2 emission. Although CO_2 as such does not pose any direct threat to the life of humans, animals or plants, it was assumed that the emission of the remaining polluting substances relates, in a way, to CO_2 emission: the higher the CO_2 emission, the higher the emission of other pollutants for the option being analysed. As mentioned before, the emissions of pollutants was analysed on a global and local scale. The local emissions related to direct proximity to the energy source, whereas the global emission, additionally, took into account the emission related to electricity used in the option. It was particularly important in case of compressor heat pumps – driven by grid electricity. Currently, electricity is generated in Poland based on hard coal and lignite; its share in the consumption structure of carriers used to generate electricity is estimated at ca. 90%.

Figs. 5.14.1 to 5.14.5 present, in the form of bar graphs, the scope of variability of parameters, selected for the classification and the selection of optimum options for the analysed locations. The graphs illustrate the best options, bearing in mind multi-criteria assessments. The scheme of marking of particular options included in the figures is analogous to the scheme used in the chapters, where options were described in detail.

The best options, selected as options for pilot project proposals for selected Project towns are given below.

Poddębice

The option suggesting the reduction of return temperature from the consumers' heating installations; it can be done by controlling return temperature, applying cascade system elements, wherever possible, and modernising consumers' heating installations (through increasing the heat exchange surface).

In the case of Poddębice, we propose the option relying on the reduction of the temperature of water returning from the customers' heating installations. That can be done by controlling the return water temperature through a cascaded system components, wherever possible, together with modernisation of the customers' heating installations (e.g. by increasing the radiator surface area). What is necessary to execute a pilot installation is to draft conceptual and process designs for particular components of the proposed energy management cascaded system. The facilities of the ZOO Safari (thermal energy recipient) constitute some of the most important system components. Those facilities should be subjected to a separate energy assessment (to establish heating demand and parameters), with the intention to reduce the return water temperature as much as possible, and to identify the technical solutions allowing to include the new installations in the distribution system. It is necessary to consider the delivery of thermal energy to the animal keeping facilities in a cascaded sequence (or series). In the case of that specific customer, it seems reasonable to provide also a heating system for roads and footpaths to obtain a maximum energy effect. The whole analysis will be subjected to a feasibility assessment, with cost estimation. A process design drafted on the respective data should take into account the staging of the whole system implementation.

The capacity demanded by the customers, after expanding the distribution system and inclusion of new facilities, as estimated at the present preliminary stage, will exceed 20 MW, with the energy consumption level of 177 TJ/y (the quantity of energy generated by the source must be higher as it is necessary to cover heat losses in the transmission system and the capacity will actually amount to ca. 207 TJ/y). If we are successful in attaining the assumed results, in the form of the reduction of the design parameters of the customers' heating installations, reaching the following parameters: 65/50/20/-20°C for central heating and 65/45°C for hot tap water, it will be possible to generate about 97% of the energy required in Poddębice (i.e. ca. 200 TJ/y), directly from geothermal energy (without using heat pumps). The total costs of using the energy source in such conditions is estimated at 3.5 million PLN/y (1.9 million PLN/y of fixed costs, mainly depreciation, and 1.6 million PLN/y of variable costs, or purchase of fuel). In total, the net unit price of energy purchase by the final customer is estimated at 20 PLN/GJ. That price level cannot be achieved even when coal is burnt (assuming that the net purchase price of coal, with the calorific value of 26 GJ/Mg amounts to 650 PLN/Mg and the boiler efficiency is 75%; energy generated from coal has the price of ca. 33 PLN/GJ, excluding fixed costs). The investment in the adjustment of the customers' heating installations to the source parameters will bring positive effects in Poddębice case in respect of all analysed aspects: economic, energy generation, and ecological. It is also important to reduce the flow rate of the exploited geothermal water which will improve the resource safety.

According to the experts and Geotermia Poddębice Ltd., recommendations designed for Poddębice, drafted under the present Project are congruent with the realistically updated proposals of the pilot projects to be implemented in town, as specified by the Project Partners, Geotermia Poddębice Ltd. and the Mayor of Poddębice, within the activities described below.

Connection of the ZOO Safari to receive heat from the geothermal plant, after the stream passes through a heat exchanger installed in the geothermal plant, for heating purposes and filling of the water tanks used by animals (with the temperature of ca. 50ºC). Presently, arrangements are being made with the distribution network and geothermal water pipeline designed to establish the piping routes (including a crossing under the river), pipe diameter selection, and determination of the heating demand and water temperature by the ZOO Safari.

Connection of the year-round geothermal swimming pool complex to receive heat from the geothermal plant, after the stream passes through a heat exchanger installed in the geothermal plant, for heating purposes and filling of pools, as well as for Spa treatment facilities (with the temperature of ca. 50ºC). The Poddębice Municipality signed an Agreement with the Marshall of the Łódź Region (Chairman of the Regional Assembly) in October 2017 to support the construction of a thermal swimming pool complex. The assumed construction execution period is 2018-2020. Consequently, it will be necessary to complete a connection to supply heat to the facilities included in the project.

Exchange of radiators or increase of their heating surface areas in a selected building to adjust them to reduced heating parameters. As a result of the review of the public utility buildings, conducted jointly with the Mayor, the Junior High School Building was selected for the pilot project. Although the building uses a large amount of heating energy, the required comfort is hard to maintain there. The school complex includes in particular a sports hall. Other facilities that could be thermally modernised are two kindergarten buildings and possibly the Town Office building.

Construction of an educational greenhouse to be erected close to the borehole where geothermal water will be used for farming and heating purposes.

Generally, a solution is needed which will allow us to reduce the return water temperature, and thus obtaining a higher Δt value, for the operation of a heating system in the Poddębice Geothermal Plant.

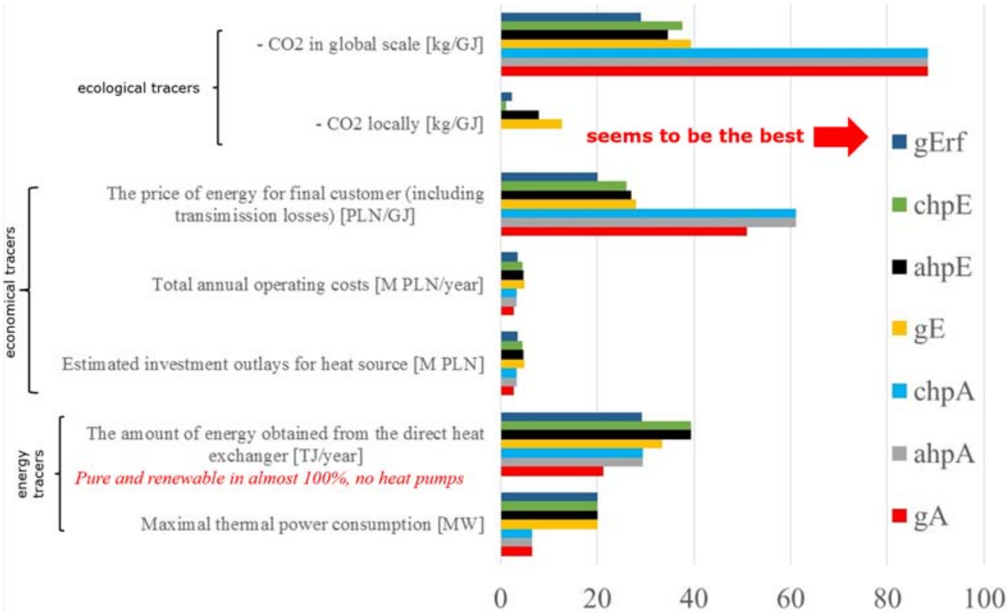


Fig. 5.14.1. Variability of selected groups of parameters for options analysed in Poddębice (options and their description in accordance with chapters 5.4.3 and 5.4.4)

Sochaczew

The option assuming the use of heat pumps, reducing of the required supply temperature and the achieved return temperature is also desired here.

In the case of Sochaczew, what seems to be the optimum option of the system development is the one which assumes the concurrent use and application of the following: heat pumps, with the reduction of the required water supply and return temperatures. Low temperature of the resource water (~40°C) will require the application of heat pumps to increase the water temperature up to the values required by the customers. The return water temperature has a large potential and, for that reason, the pilot installation should include the geothermal heat source (heat exchangers, heat pumps, peak demand boilers, accessories etc.). The customers should be divided into several sub-grids, with possibly low working temperature needs in their heating installations. The conception of a cascaded system application can be implemented there; the customers will be connected in a series, e.g. first the current customers (using the highest temperature parameters), followed by separated grids connecting the customers with lower temperature parameters required (with their heating systems adjusted to low supply parameters), and finally the swimming pool complex, possibly with road and footpath heating. The total customers' capacity, as anticipated presently within the geothermal heating network, is estimated at 15 MW. It seems to be realistic to expand the group of customers by inclusion of the swimming pool and recreation centre, and then the ordered heat demand will increase to ca. 17.6 MW. The energy sales will reach ca. 126-162 TJ/y. Our analyses indicate that better results can be expected by applying absorption heat pumps. However, at the stage of the feasibility study (especially at the stage of requests for quotation regarding the heat pump delivery), it seems to be reasonable to analyse the use of compression heat pumps, with large capacity and increased working temperatures on the lower and upper source sides. A bit lower resource temperature is partly compensated by the reduced working temperature on the customers' side (in comparison to the present standard value). Presently, the temperature parameters are 80/60/20/-20°C in winter (central heating and hot tap water) and 65/45°C in summer (hot tap water). The completion of the energy source facilities will require increased capital investment expenditures which are estimated at ca. PLN 30-35 million (including the costs of geothermal borehole drilling, heat pumps, and the surface facility building). The total costs of energy source operation are estimated at 6-7.5 million PLN/y (including ca. 1/3 of fixed costs, mainly depreciation, and 2/3 of variable costs, mainly the purchase of fuels). The net unit price of energy purchase by the final customer will be either similar to or slightly lower than that of the energy generated from the network natural gas (the value being estimated to obtain from the geothermal installation is 46-48 PLN/GJ, assuming that the purchase price of energy generated by a gas-burning heating plant is ~50 PLN/GJ). The increase of customer base using low-temperature radiators can reduce the costs of geothermal energy generation.

What distinguishes the borehole site is probably very low mineralisation of geothermal water, qualifying it to the category of potable water. That property should be taken into account in the pilot installation. Consequently, it will be necessary to consider the use of geothermal water in the existing municipal water supply network, and, based on the experience of the geothermal plant in Mszczonów, design an active water retention system to store geothermal water after cooling down, in natural Tertiary and Quaternary underground aquifers.

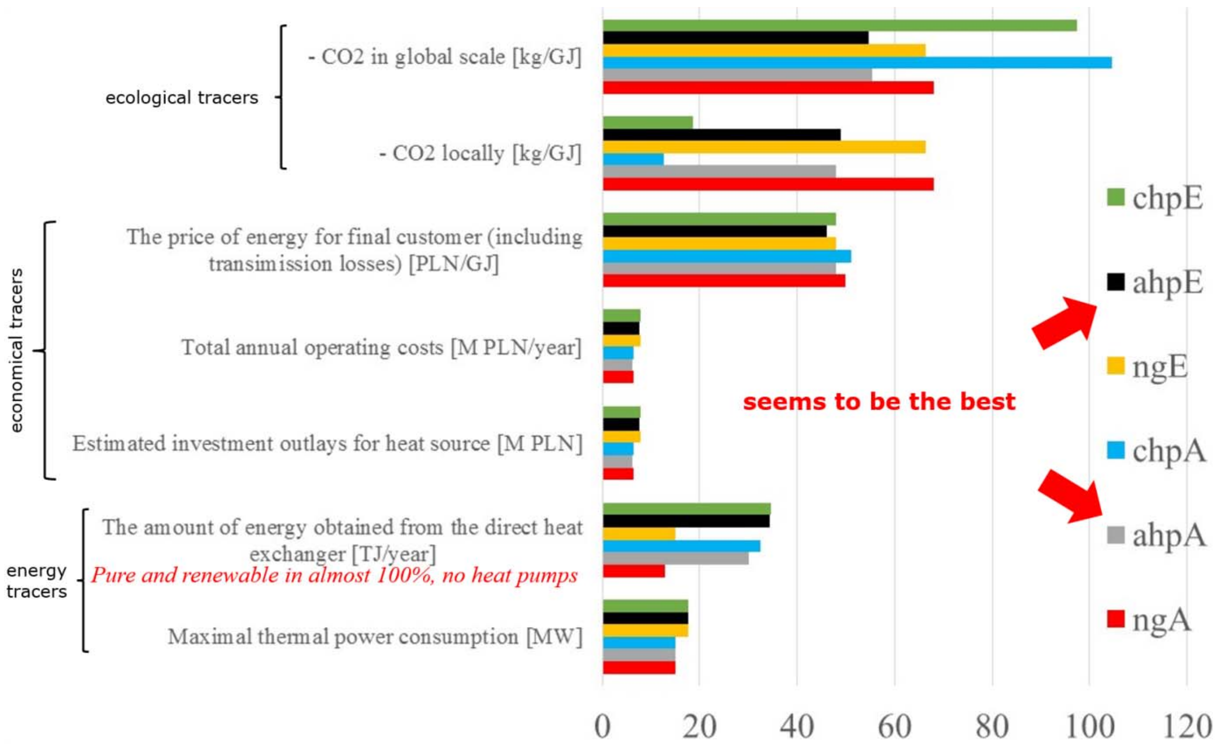


Fig. 5.14.2. Variability of selected groups of parameters for options analysed in Sochaczew (options and their description in accordance with chapters 5.5.2 and 5.5.3)

Konstantynów Łódzki

The optimum option assumes cooperation between a geothermal source in the summer with the district heating network in the City of Łódź (managed by Veolia Energia Łódź S.A.). Optimum cooperation covers the summer season, and the geothermal source satisfies, in this case, the needs of a significant number of consumers in the neighbourhood of Konstantynów. Reduction of the required working temperatures is very much desired.

In the case of Konstantynów Łódzki, the optimum option (based on the criteria specified above) assumes co-operation of the geothermal source during summer with the heating network of the city of Łódź (operated by the Energia Łódź S.A.). Optimum co-operation would be in summer and the geothermal source would meet the needs of a considerable proportion of the customers living in the neighbourhood of Konstantynów. The estimated capacity demand of the Konstantynów customers is ca. 7.8 MW, with the heat energy sales at the level of 60.5 TJ/y. At the same installed capacity and owing to co-operation with the system of the Veolia Energia Łódź, the energy sales can increase up to 108.6 TJ/y (with the same installed capacity), see Fig. 5.14.3. The forecast capital investment expenditures for the development of the energy source are estimated at ca. PLN 50 million (of which ca. PLN 42 million will be spent on geothermal borehole drilling). The total annual costs of energy source operation are estimated at ca. 4.2 million PLN/y (of which 3/4 are fixed costs, mainly depreciation). The total net cost of energy purchase by the final customer is estimated at ca. 35-36 PLN/GJ. That can be recognised as the cost corresponding to the that of energy generated from coal. The share of geothermal energy in the fuel consumption balance will be so high that the required installation will obtain positive ecological effects on both local and global scales.

The reduction of the required working temperatures is highly desirable. The pilot installation will include the execution of mainly the following: a dual geothermal borehole system to reach the Lower Jurassic geothermal aquifer level, geothermal heat exchangers, and the accessories of the district heating node. That kind of installation will benefit from the connection to the grid of the large city of Łódź, with a high number of customers, and will be operated long during the year, with the capacity close to the maximum value, which should allow the system to obtain very low costs of energy unit generation. In order to achieve the maximum possible return water temperature reduction, it will be necessary to consider the connection of existing or newly designed low-temperature customers into the pilot installation (e.g. swimming pools, with road, parking lot, and footpath heating). Additional quantities of thermal energy that can used effectively in the case of Konstantynów Łódzki are presented in Fig. 5.14.3.

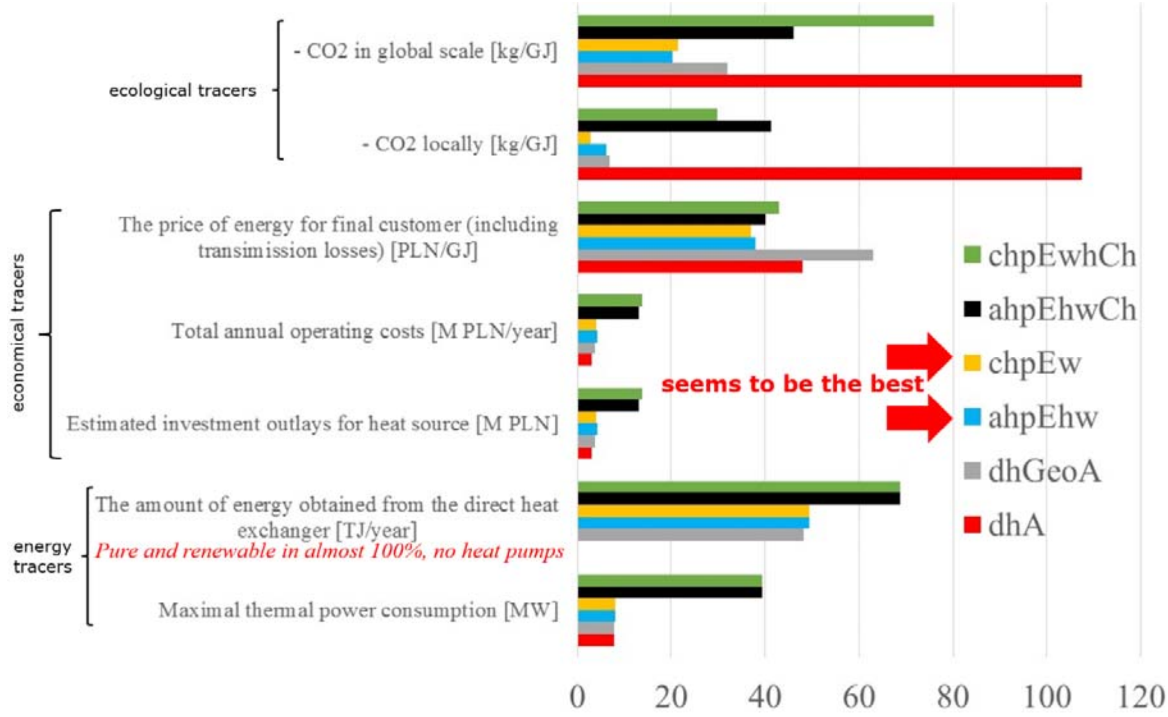
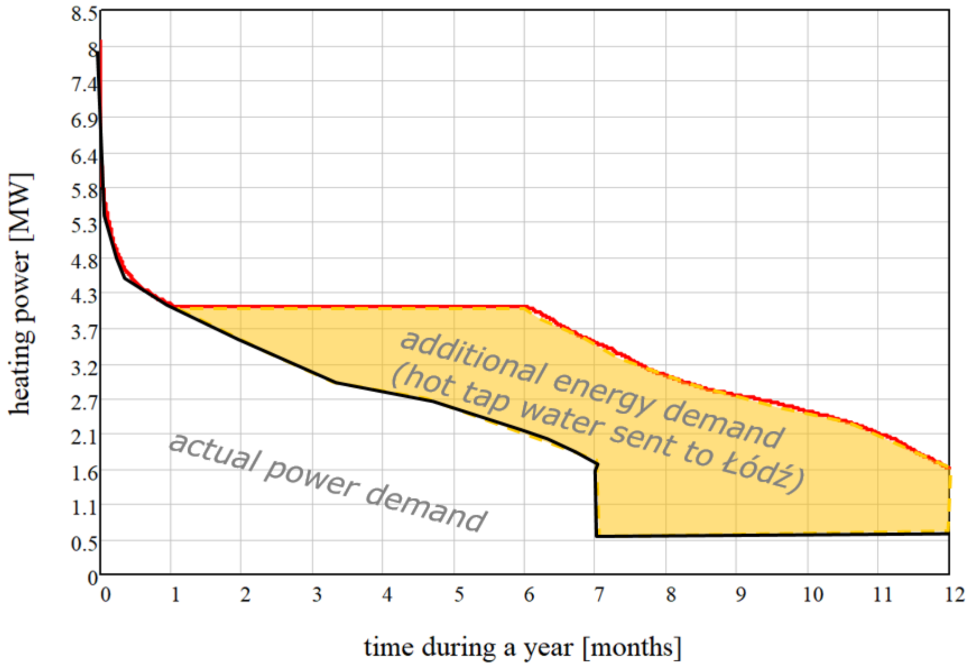


Fig. 5.14.3. Variability of selected groups of parameters for options analysed in Konstantynów Łódzki (options and their description in accordance with chapters 5.6.2 and 5.6.3)



5.14.4. An ordered thermal power and energy demand curve for Konstantynów Łódzki, the area filled with yellow color means the energy sold in addition to the Łódź heating system

Lądek-Zdrój – proposal by MEERI PAS, WUST teams and expert

The optimum option assumes connection of consumers from the town (the so-called "CITY" area) to the geothermal source. It is the outcome of quite a large quantity of geothermal energy possible to be generated and managed. It will be rather necessary to apply heat pumps. It is suggested to use compressor heat pumps. They will cause a decline in the local emission of pollutants and they will contribute to the improvement of the environmental condition on the local scale. Interesting and important solution is to apply heat of spent geothermal waters after their use for healing treatments – the temperatures are in the range 25–35 °C and can be successfully used for snow melting and de-icing of pavements and roads in part of that Town specially in hilly spa area) – this option is given in more details in this sub-chapter also by other partners teams (OS, CMR).

In the case of Lądek-Zdrój, the optimum option assumes the connection of some of the customers belonging to the municipal grid (the so-called "CITY" area in Fig. 5.7.4.1) to the geothermal source. That is possible because a large quantity of thermal energy can be generated and distributed from the geothermal source (ca. 31 TJ/y for general energy consumption on that area at the level of 85.5 TJ/y). It will rather be necessary to use heat pumps, with the installed heat capacity estimated at ca. 2.5 MW. High-temperature compression heat pumps are suggested to be used. That application will cause a reduction of local pollution emission and the environmental condition improvement on a local scale. The pilot installation should be executed on the basis of conceptions and process designs regarding the connection of the geothermal borehole (presently planned to be drilled) to the existing buildings and facilities, as well as to the road and footpath heating installations. That conception should be optimised in the energy (taking into account a cascaded system of energy management) and economic aspects (taking into account the spatial and infrastructural conditions). The forecast capital investment expenditures for the energy source development are estimated at ca. PLN 36 million (including the costs of the geothermal borehole of ca. PLN 18.3 million and of heat pumps at ca. PLN 4.2 million). The geothermal source should generate thermal energy at the total net annual cost of ca. 4.2 million PLN/y (of which more than half will be fixed costs, mainly fixed-asset depreciation). The final net energy purchase price that can be expected to be paid by the final customer will be a bit lower than that paid for energy generated by burning network natural gas, that is ca. 48-49 PLN/GJ (as compared to the price related to the high-methane gas burning of ~53 PLN/GJ).

The Wrocław University of Science and Technology team proposes the following to be included in the pilot project concerning the use of geothermal energy in Lądek-Zdrój:

- A more detailed exploration of the Lądek-Zdrój (LZ) geothermal system by developing a digital reservoir model, including its geological setting, on the basis of the previous and newly designed research works,
- Hydrodynamic, hydrochemical, and geothermal simulations. Such modelling should take into account the hydrodynamic test results obtained from the LZT-1 borehole and the necessary observations of the changes in the flow rates, temperature, and chemical composition of water, based on the water samples collected from all currently used geothermal sources in the local spa treatment clinics, as well as ordinary water samples collected from the L-1 borehole (such tests to be conducted concurrently with those relating to the samples collected from the LZT-1 borehole),
- Estimation of the available resources of the geothermal medicinal water reservoir of Lądek-Zdrój, on the basis of the proposed modelling research.

Once the relevant test results have been obtained, it will be possible to design comprehensive use of geothermal energy in the Lądek-Zdrój area. Such energy can be obtained from the currently available sources of the partially used geothermal medicinal water facilities of the Lądek-Długopole Spa, together with heat recuperation from the post-treatment water, supplemented with the supplies from the newly designed LZT-1 borehole.

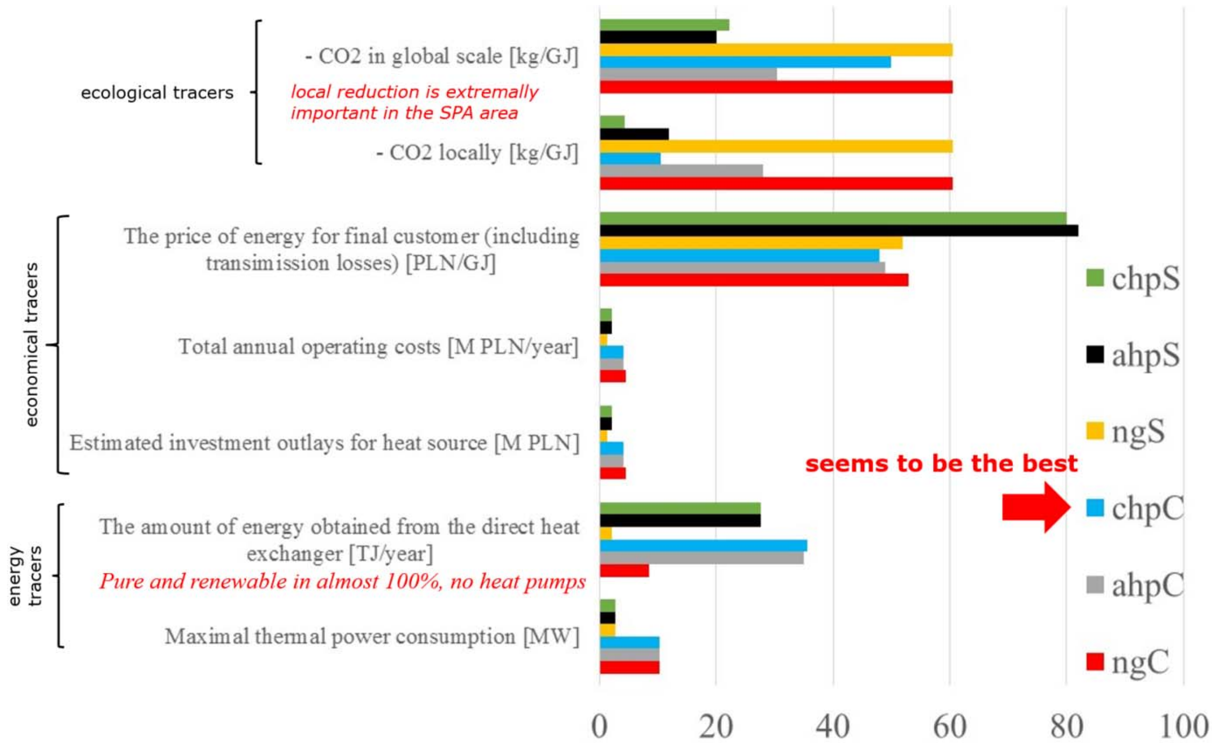


Fig. 5.14.5. Variability of selected groups of parameters for options analysed in Lądek-Zdrój (options and their description in accordance with chapters 5.7.4 and 5.7.5)

5.14.1.2. Proposals by National Energy Authority team

Poddębice large radiator pilot installation

One of the proposed operations in the district heating system is to increase the heating surface of radiators in selected buildings to reduce return temperature and water flow through the radiators in the building.

Earlier this year, a proposal was made to use return water in the distribution system in Poddębice, at a temperature of around 45–50°C, for floor heating. This would demonstrate cascade use of water at high and low temperature for heating.

However, now that the plan is to reduce the return temperature of both the geothermal return fluid and in the distribution system, maybe this floor heating suggestion may not be feasible. One important point: Even if the use of a heat pump will decrease the temperature of the geothermal return water to increase supply temperature in the district heating system, the return temperature in the district heating system will still remain high, as radiators in apartments are too small, resulting in water cooling only by 0–20°C.

It is therefore suggested that one or more apartments be fitted with a larger radiator area, to demonstrate how that change will reduce the return water temperature in buildings. Temperature drop may, in this way, be increased to over 30°C, therefore requiring 50% less water flow through each building. Supply temperature is still adequately high in the system for normal radiators, so floor heating is not needed.

A schematic diagram of the process is shown in Figure 5.14.6. The indicated supply temperature is shown as 64°C, which is the temperature in the heating network without added peak load. During the coldest days, the supply temperature is increased to 75°C.

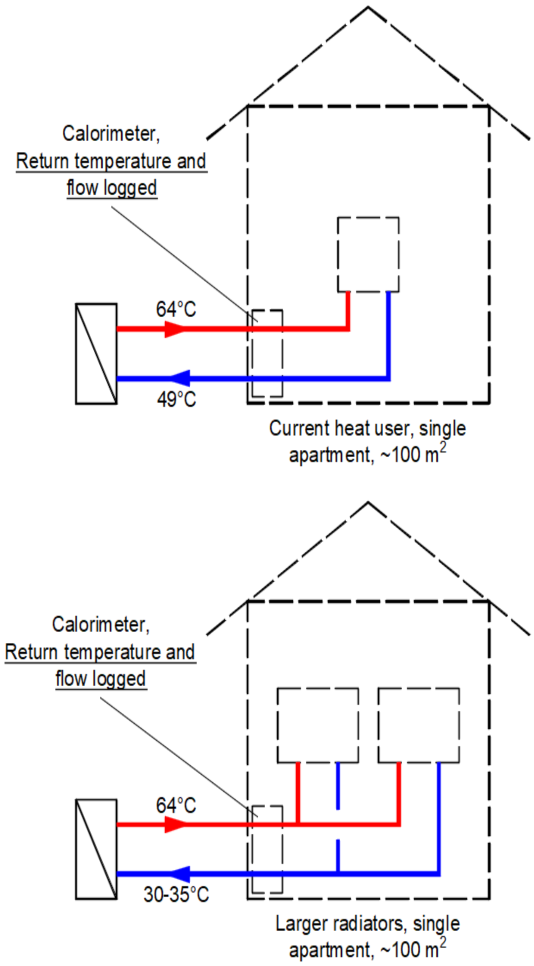


Fig. 5.14.6. Current radiator system and large radiator system in Poddębice, supply temperature without peak load

The proposed action is to install large radiators in an apartment of approximately 100 m², which corresponds to roughly 5,0 kWth heating peak load. Radiators should be selected for 75/30°C supply/return temperature during peak load and the number/size of radiators should then correspond to the estimated heat demand of the apartment.

These larger radiators are estimated to be around 60% larger than the more common 80/60°C to 90/70°C radiators that are more commonly used in Poland. This means that they will take up more wall space than usual and will require some more connection piping.

A calorimeter would be installed on the supply/return pipe in the house connection, measuring supply/return temperature and flow rate. This should be a logged calorimeter, which gathers average flow/temperature data at every hour. The behavior of the heating could thus be monitored over a whole year.

A similar calorimeter with data logging should be installed in a nearby apartment of the same size but using conventional high-temperature radiators, where data would also be collected over 1 whole year. The flow and supply/return temperature curve of an apartment with conventional heating could thus be compared to the same operational data from a house with larger low-temperature radiators during the same period. The end result will be lower flow rate and lower return temperature profile in the larger radiator building, demonstrating how more energy can be extracted from distribution system and thus, the geothermal fluid.

These 3 components would be required:

- A set of large, low-temperature radiators for 1 apartment, perhaps an extension to existing radiators would be sufficient,
- A calorimeter with data logging of flow and temperatures, collected over a 1 year period with at least 1 hour frequency,
- Same calorimeter as above, but installed in a house with conventional heating.

The cost of installing these components will be on the order of 10.000-12.000 PLN for the large radiator + calorimeter/logging in 1 apartment + around 5.000 PLN for the calorimeter/logger in another apartment with conventional heating.

Using larger radiators is therefore a simple suggestion for a pilot project in Poddębice, to demonstrate that return temperature in the district heating system can be lowered. Cost of such an installation would be minimal.

Konstantynów Łódzki geothermal make-up water de-aeration

One of the ideas proposed for this project is to use geothermal fluid to de-aerate cold water used for make-up water in the distribution system of both Łódź and Konstantynów Łódzki. Estimated water leakage is around 20 m³/hr, so the capacity of the geothermal well would be more then adequate.

Geothermal fluid at 70°C would be used to heat cold water at around 10°C through a heat exchanger, to 65°C. The return geothermal fluid would be around 15°C. The heated cold water would require de-aeration at 65°C, in a vacuum tank at 0,25 bar_{abs} (-0,75 barg) vacuum pressure.

A schematic diagram of the process is shown in Figure 5.14.7.

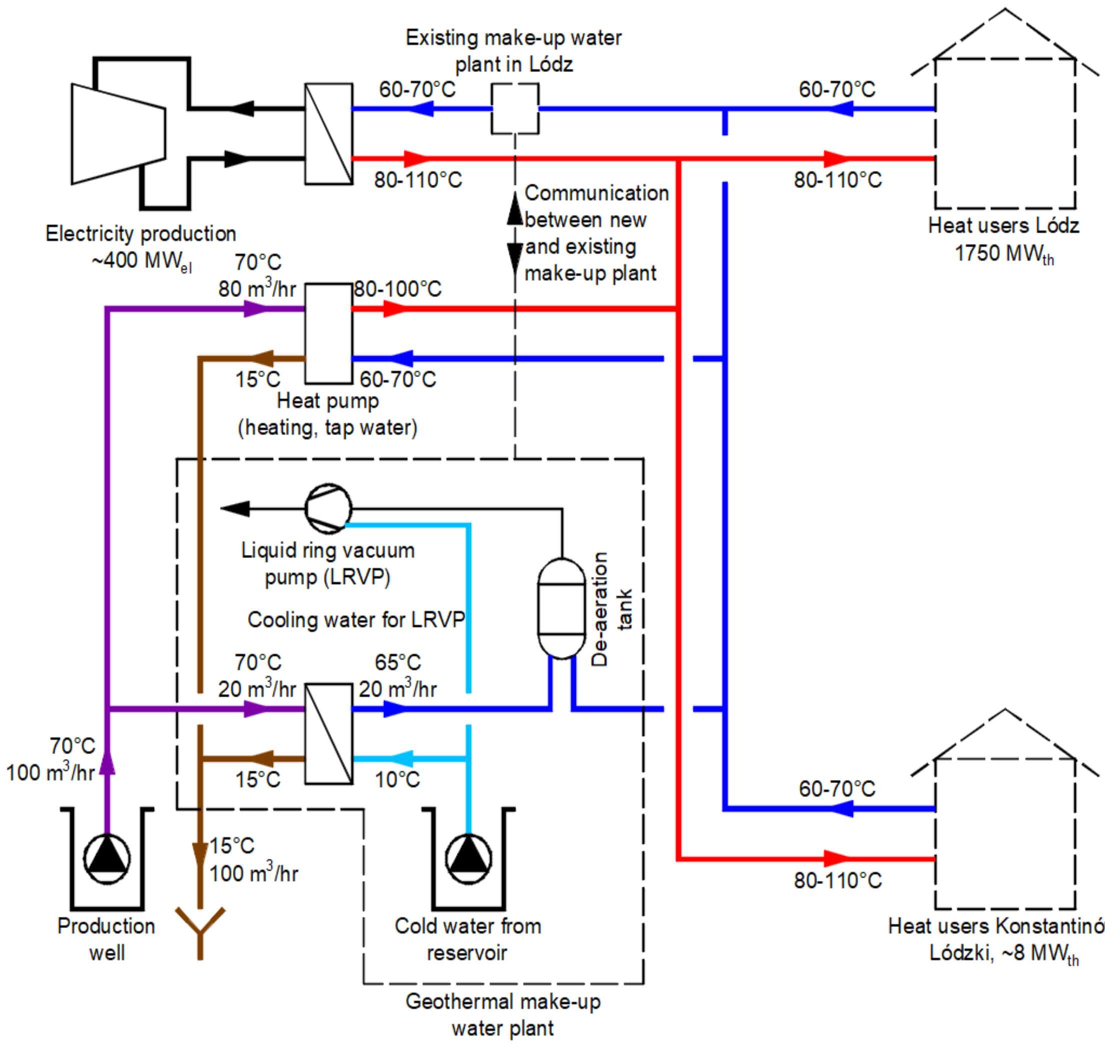


Fig. 5.14.7. Make-up water heating and de-aeration in Konstantynów Łódzki

The system of geothermal heating is shown within a dotted line in the lower half of the diagram. A heat exchanger with the geothermal fluid is used to heat cold water from the water reservoir to a temperature of 65°C. It is passed to a vertical vacuum tank, where vacuum pressure is maintained with a liquid ring vacuum pump (LRVP). Such a pump maintains vapour pressure of water at 65°C, around 0,25 bar_{abs}. The LRVP uses a small amount of water from the reservoir for maintaining the liquid ring and cooling the pump. The 65°C water boils at this pressure and oxygen is boiled from the water, before the water is pumped to the return water pipeline to Łódź.

There is already a make-up water plant in Łódź, at one of the Veolia heat centrals. The high temperature in the installation allows for de-aeration at atmospheric pressure. This existing plant will remain operational (stand-by) and needs to communicate with the geothermal de-aeration plant in Konstantynów Łódzki, demanding addition of make-up water into the system through the return water pipeline from Konstantynów to Łódź.

The heating power required to heat 20 m³/hr of water from 10°C to 65°C is close to 1,3 MWth. It can be assumed that water leakage is more or less constant throughout the year, as leakage rate only depends on the condition of the distribution system and water pressure, which is more or less constant. The energy required for heating the water is around 11200 MWh,th/year. If gas is used for heating the make-up water (at around 110 PLN/MWh,th), this amounts to around 1,2 million PLN/year.

It is therefore economically justified to install a de-aeration installation, using geothermal energy. The main pipeline for the system is only 65-80 mm. What is needed is the following components:

• A liquid ring vacuum pump, size approx. 1 kW.

• Heat exchanger between geothermal fluid, area 60-80 m².

• Vacuum tank, control valves, etc., needed for flow control in the de-aeration installation.

• Communication line between existing make-up water plant in Łódź and proposed system in Konstantynów Łódzki (where the proposed geothermal well is to be built).

• Connection to cold water supply, 20 m³/hr capacity.

• Other local electronic controls, using signal from Łódź that demands more make-up water

The cost of such an installation would probably be several hundred thousand PLN but will probably not exceed 1,0 MPLN. The economic savings alone from not using 11,2 GWh from gas would therefore be quite significant. The heated make-up water would be sent through the return water pipeline, from Konstantynów Łódzki to the pump substation in Western Łódź. No additional transmission pipelines would be needed for this installation. This make-up water installation is considered to be an addition to the geothermal heating system in Konstantynów Łódzki, which would still use around 80% of the energy from geothermal fluid for district heating.

Emissions from gas heating are close to 180 tonsCO_2/GWh,th, so the amount of CO_2 release avoided would be around 2000 tonsCO_2/year.

The key justificiations for implementing this pilot project are direct economical savings from not using gas for heating (which would repay the investment in the geothermal de-aeration in a short time) and reduction of greenhouse gas emission. In case of outage of this proposed system, there would always be access to make-up water production in the existing installation in Łódź, which would be operated as a stand-by system.

Sochaczew low temperature coil radiator pilot project proposal

There are quite a few radiator manufacturers that supply so-called “forced convection radiators”. These units are equipped with finned coils and a fan, that increases air flow and therefore convection in these units. These manufacturers are, for example, Licon (www.liconheat.com), Veneto (www.kinnan.se) and various others.

These forced convection units are somewhat thicker than normal wall-mounted radiators but the overall size. Noise levels from these units are very low (20-30 dBA) and they are able to heat houses from water as cold as 35-40°C.

Since the proposed geothermal heating system in Sochaczew is to use low mineralization geothermal fluid from upper cretaceous layers at 40°C (suitable as drinking water), it would be ideal to install this type of forced convection radiators in a couple of buildings near the proposed geothermal well. The cleanliness of the water would mean that no heat exchanger would be needed. Cooling of the geothermal water would also be within 10°C, so there would be negligible risk from scaling due to temperature change. Installing a filter on the low-temperature radiator inlet would be sufficient.

Typical peak heat load in a single 100 m² apartment is around 5 kW, so water flow to this type of radiator would be around 0,1 l/s for a single apartment, if the geothermal fluid cools from 40 down to 30°C. This would therefore require a standard 2x DN 20 mm (3/4") house connection pipe to/from the house.

A schematic diagram of the process is shown in Figure 5.14.8, where the connection to the low-temperature coil radiator is shown at the top of the picture. Using a small amount of the 40°C water from the geothermal well and re-injection 30°C return water will not affect the water temperature in the shallow water reservoir, as it is only a small fraction of the total flow.

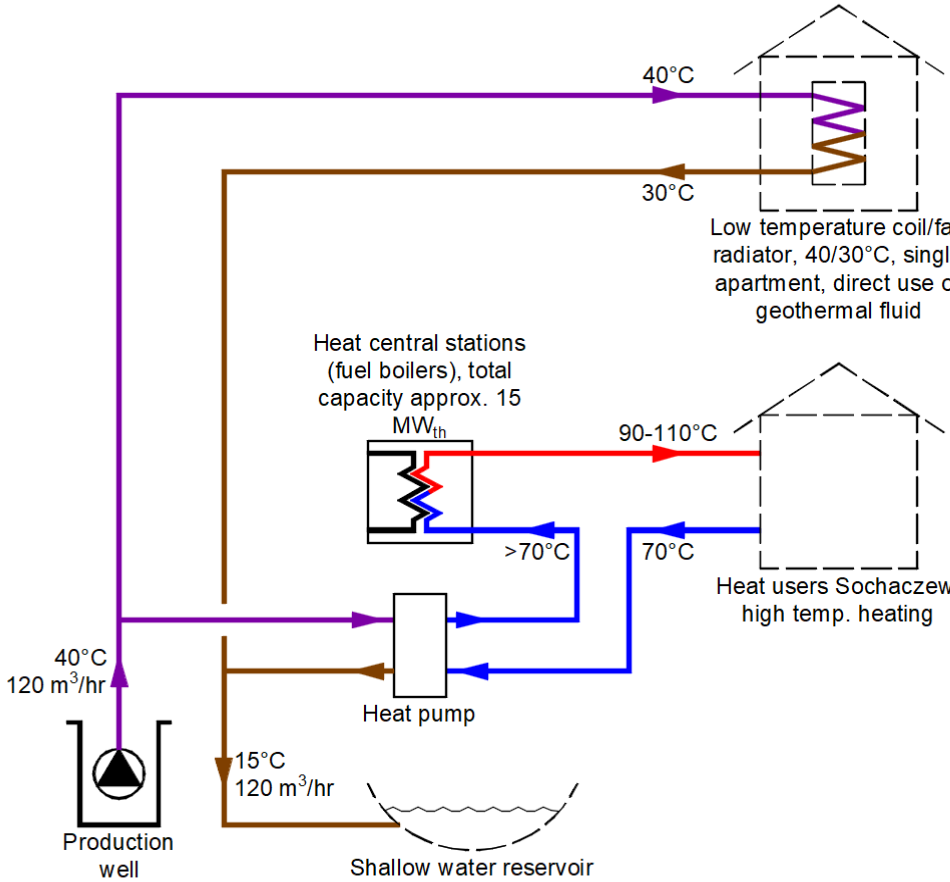


Fig. 5.14.8. Low-temperature coil radiator pilot project in Sochaczew

The rest of the heating system from geothermal fluid would still be through a heat pump, where return fluid from the 90/70°C distribution system is heated through a heat pump, from the 40°C geothermal resource.

The proposed pilot project is to install one of these radiators in an apartment near the proposed geothermal well. The 30°C return geothermal fluid would be collected and combined with the 40°C fluid from the production well, with negligible cooling of the geothermal fluid to the heat pump.

The following needs to be installed for this pilot project:

• Supply/return pipeline to/from a single apartment near the proposed geothermal well, a few dozen meters

• Fan/coil radiator(s), connected though 2xDN20 house connection

• Electric supply for the radiator fan, 24 or 240 V, power consumption typically several hundred watts

Typically, only one unit may need to be installed but it depends on the size of the proposed apartment, as well as the quality of insulation in the area. Cost of this radiator installation would be minimal, at several thousand PLN for the radiator and connection.

What this pilot project would demonstrate is that low-temperature fluid can be used in radiators, as has been done successfully in Norway. The radiator unit should be selected based on manufacturer's recommendations, where indoor temperature and heat load are first established and a suitably sized radiator then selected.

Lądek-Zdrój snow melting pilot project

Although direct use of geothermal fluid for snow melting is a fairly standard procedure in Icelandic district heating systems, this would definitely be a new idea in Polish geothermal heating systems.

The mineralization of the geothermal fluid is not known at this point but based on mineral content in thermal spa water in the town, it is not expected to be very high. Chlorine content in the spa in Lądek-Zdrój, for example, is only around 5 ppm (mg/L), which is negligible.

The question is whether cooling water down from 70°C down to 30-35°C from heating and eventually down to 10°C from snow melting would result in mineral scaling. The experience from Iceland is that scaling in district heating only occurs if two fluids with different chemical composition (e.g. one from geothermal reservoir, the other from heated cold water in power co-generation) are mixed. Cooling geothermal fluid, that starts at over 90-120°C down to 10°C in snow melting has not presented any problems in scaling, where geothermal fluid is used directly. Also, all piping used in snow melting tubes is plastic piping, where scaling does not form as easily as on metallic surfaces. Needless to say, plastic piping is corrosion proof and fully capable of operating at high pressures (up to 10 bar) for geothermal fluid well over 35°C.

It is therefore proposed that the pilot project for the town is the installation of snow melting that uses return geothermal fluid directly, at a temperature of up to 35°C. Depending on the location of the geothermal well, heat central (where a heat pump/peak load may be installed) and the steep parts of streets where snow melting is needed, there would be need for a transmission pipeline from the heat central to the snow melting station.

The snow melting pilot project could be implemented so that it uses all of the geothermal return water from the proposed production well in Lądek-Zdrój. The flow rate from the well is estimated to be rather low, around 14 l/s (50 m³/hr). The function of the snow melting system would be two-fold: It would serve as snow melting during winter time, when roads become slippery and also, would cool down return geothermal fluid to a temperature of 30°C or lower. It would have similar function as a typical direct use snow melting system that is used in the Reykjavik area, where it is possible to control the supply temperature to the snow melting loop via mixing of hot water (from geothermal well) and cold return water from the snow melting loop.

A schematic diagram of the proposed system is shown in Figure 5.14.9.

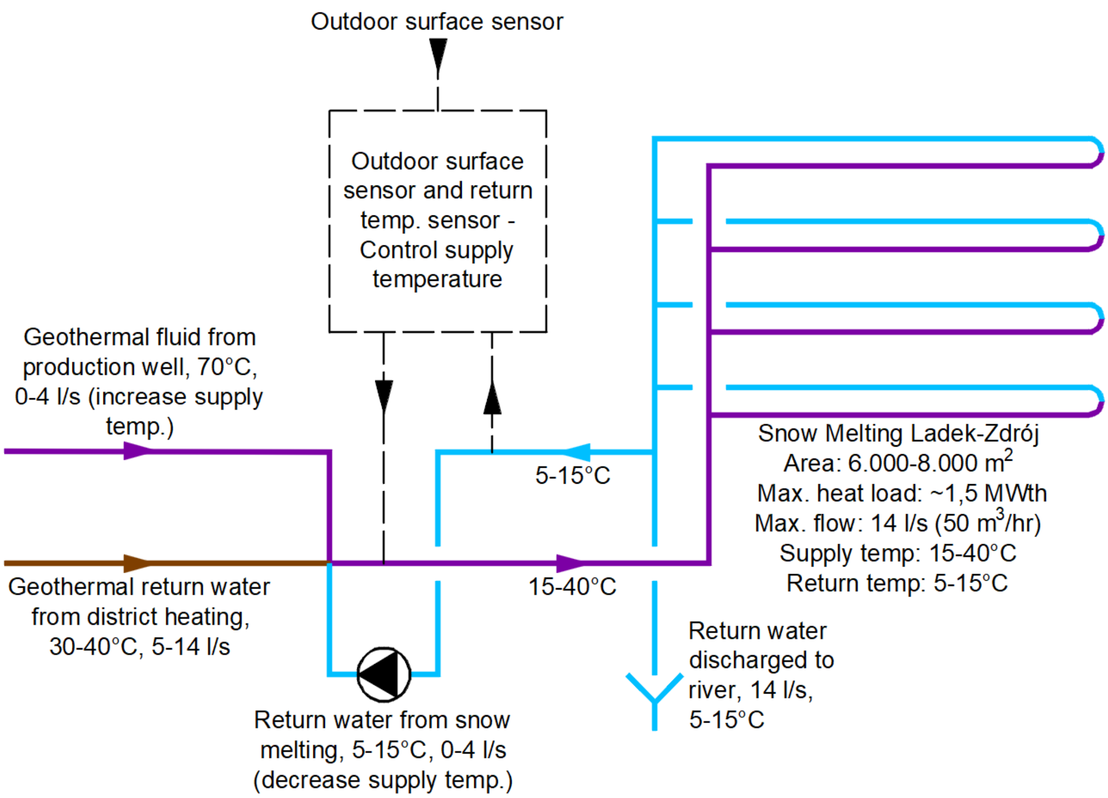


Fig. 5.14.9. Snow melting system in Lądek-Zdrój, schematic diagram

This diagram indicates the main piping connection in the snow melting heat control station, which is typically a very small building, with a few m² floor area. The above proposal applies to a system where all of the geothermal return water is used, with a possibility of hot water injection. The supply pipeline to the snow melting would typically be a DN 125 pipe (or a ø140 plastic pipe), while the hot water connection pipe would only need to be DN 50-65 mm (ø63 plastic pipe). Not shown in the diagram are flow sensors, control valves, safety valves and other piping equipment.

The return water pump from snow melting (bottom of diagram) recirculates return water if supply temperature to snow melting needs to be lowered. Supply pressure to the snow melting station is typically low, around 2-3 bar. The return water pipeline to the river needs to be DN 125-150 mm (ø140-ø160 plastic pipe). This station has very similar heating capacity as a snow melting station in Traðarkot, Reykjavik, which was visited in October 2017 by the Polish delegation.

The control of the supply temperature is based on both the signal from the surface sensor in the street where snow melting is installed, outdoor temperature and the temperature of return water from the snow melting. The controller monitors the combination of these temperatures and modulates the supply temperature accordingly, by mixing 70°C geothermal hot water (increase supply temperature) or mixing cold return water from snow melting (decrease supply temperature). The assumption is that the town heating system is implemented so that return water is at a suitable temperature. This is acheived through using heat pumps, that extract more energy from the geothermal return fluid and/or installing suitably large radiators in buildings.

The snow melting heating area is not certain at this point but has the potential to be up to 8.000 m², based on the available geothermal return water during the coldest days of the year. Such an area would require 3-4 snow melting loops, laid in a spiral-shaped grid under cobblestone streets and possibly also sidewalks. If it is decided to heat a smaller area or, alternatively, to build two or more smaller snow melting stations, the above figures would be scaled down.

This pilot project is one of the largest ones in the four towns and therefore one of the most expensive. The following main components are needed for this installation based on 100% utilization of geothermal return water:

• Supply pipeline, geothermal return water from heat central to snow melting station, DN125 or ø140PE pipe, length 300-500 m

• Supply pipeline, geothermal water for increasing supply temperature, from heat central to snow melting station, DN 50-65 or ø63 PE pipe, length 300-500 m

• Snow melting station, with piping, pump, control valves and temperature control system (incl. snow sensor on surface)

• Return pipeline from snow melting station to river, DN 125-150 (ø140-160 PE), length 300-500 m

• Snow melting installation in street/sidewalks, size up to 8.000 m²

The cost of the snow melting installation in streets could be as high as 2,5 MPLN. Cost of the snow melting station and equipment could range between 0,8-1,0 MPLN and the cost of the supply pipelines (hot and cold geothermal water to snow melting station) and return water pipeline to river could be around 1,0 MPLN. The total cost of a full snow melting system, using all geothermal return water is thus estimated to be between 4-5 million PLN.

This is then a rather ambitious pilot project and would demonstrate both low-temperature cascaded use of geothermal energy and a smart way to cool down geothermal return water so that it is not too hot to be discharged into the environment.

It should be noted, however, that this project cannot be implemented unless a geothermal district heating system (with a functional production well, transmission/distribution pipelines, heat central and radiator system) has been built the town of Lądek-Zdrój. A smaller-scale version of the snow melting is also possible, with smaller heated area, smaller piping and lower initial cost but then the discarding/cooling of excess return geothermal fluid (which may be at temperatures exceeding 30-40°C) has to be implemented via cooling ponds, re-injection or other methods.

5.14.1.3. Proposals by Christian Michelsen Research AS team

Poddębice – analysis and proposal for heat pump in geothermal district heating

Poddębice geothermal heating plant supplies heat to about 100 buildings (6000 people) and is designed for about 10 MW thermal capacity. Total length of the DHN is approx. 12 km. Further connections to geoD are planned (Figs. 5.14.10 – 5.14.12). Feasible output of the borehole lies at 190 m³/h with an outlet temperature of ca. 70°C. Heat from the ground water is utilized in the district heating using a heat exchanger and depending on return temperature from heat exchanger rejected to the river. As per Polish requirements, temperature of water rejected to the river should not exceed 35°C. However, the system has problems reaching such low return temperatures and cooling ponds are being used to reject the excess heat to atmosphere before the water could be rejected to the river. But unfortunately, the pond is not large enough and allowable temperature limits exceeds from time to time. Additionally, pond solution is not optimal or desired solution from environmental point of view. Heating company wants therefore evaluation of viable alternatives to meet the authority's requirement and optimal use of the available heat from the borehole.

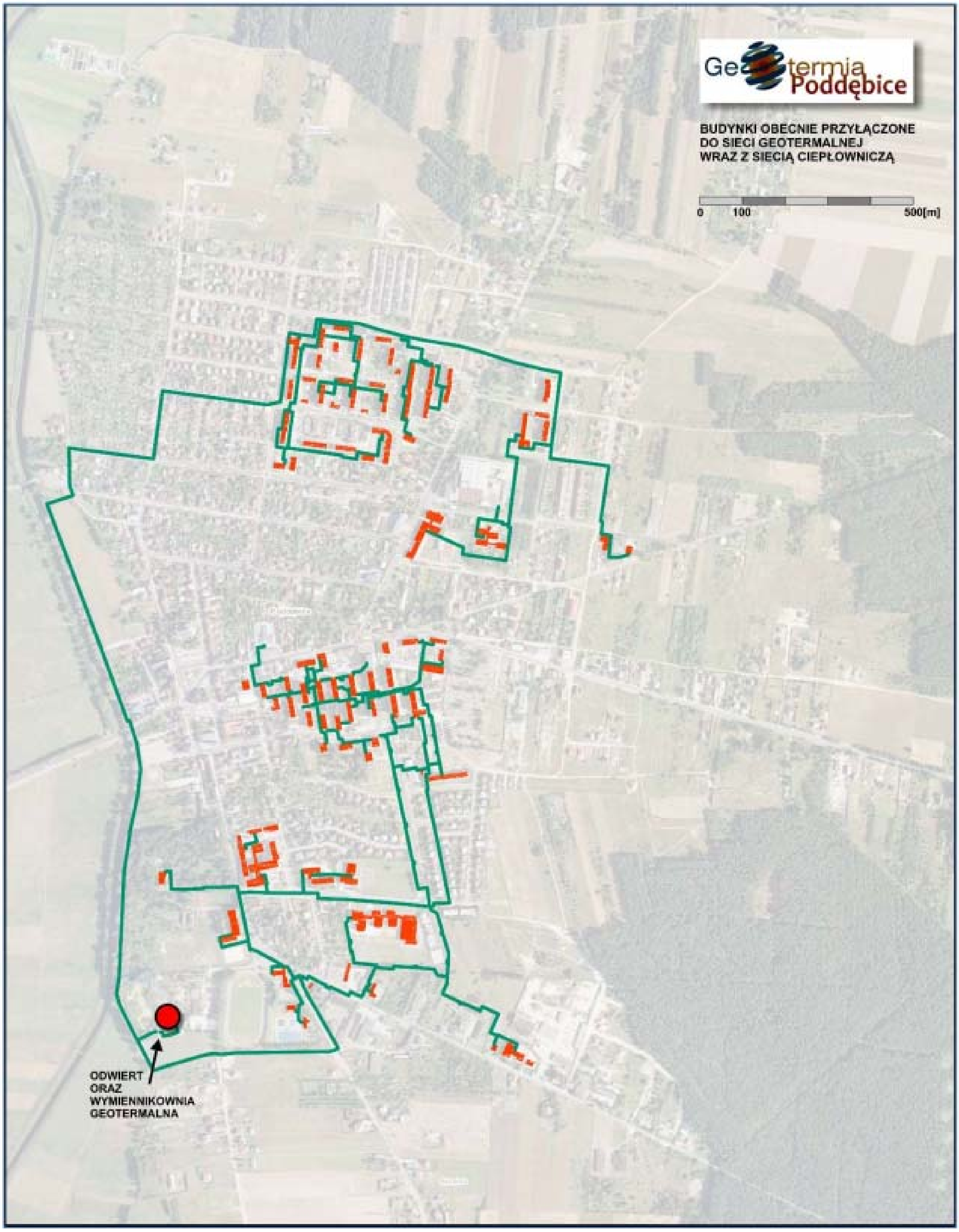


Fig. 5.14.10. Geothermal heating network in Poddebice, 2016. DHN supplies around 100 buildings (6000 inhabitants)

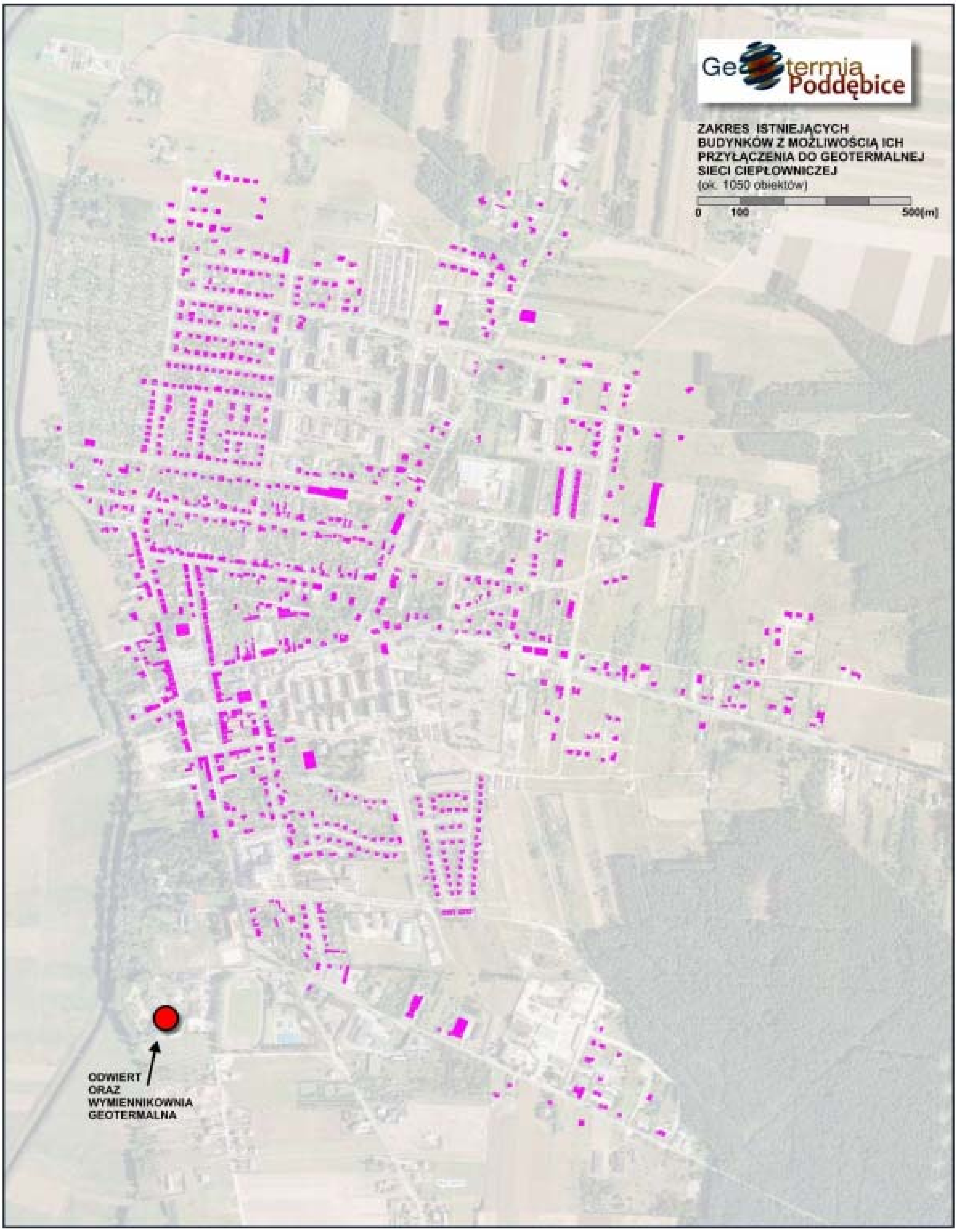


Fig. 5.14.11. Target building planned to connect into geothermal network in Poddębice

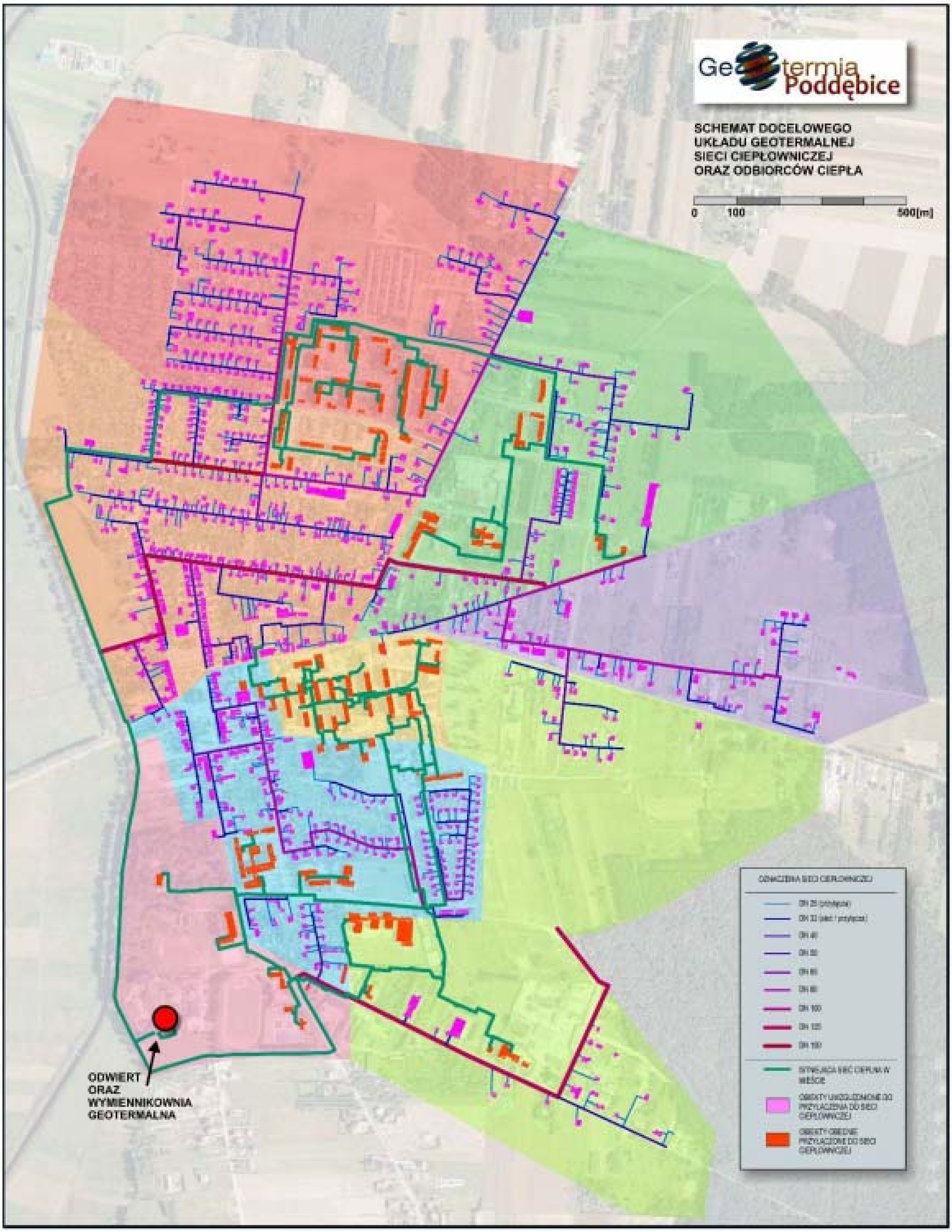


Fig. 5.14.12. Target district of geothermal network in Poddębice. Existing building as potential customers

General recommendations for Poddębice

Figure 5.14.13 shows supply and return temperature of the groundwater. Measurement shows that return temperature of the ground water is most of the times about 45°C and often exceed 55 °C. This reveals that the temperatures supplied to the DHN are not sufficient to meet the temperature requirements of heating systems installed in housing stock. The heating system in the housings therefore often run on high mass flow rates and cause high return temperatures to the DHN.

This problem can be solved in two ways:

1) By increasing the supply temperature from 70°C to e.g. 85°C in the DHN that would result in reduced return temperature near to 40–35°C,

2) By improved heating system in connected buildings so that the heating surface area is increased/improved that would result in reduced return temperature.

Based on this assessment, the solutions are divided in three categories A, B, C as given below.

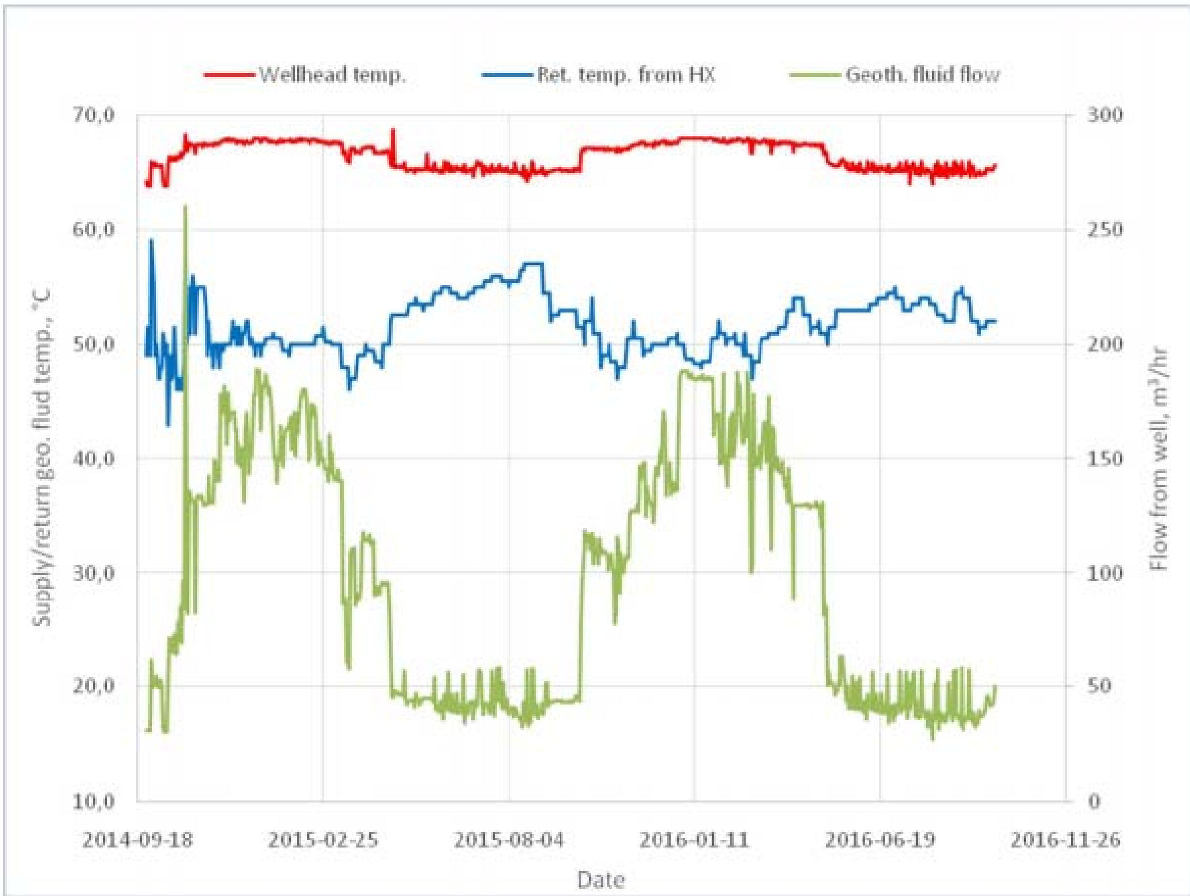


Fig. 5.14.13. Supply and return temperature of the geothermal water, Poddębice (in: Geothermal energy utilization potential in Poland. Town Poddębice. Study Visit Report /www.eeagrants.agh.edu.p/)

A. Short term solution by cooling pond or available customers for low graded (temperature) heat

Solution for lowering the temperature of the discharged water: Increase the cooling capacity by enlarge the cooling ponds. The easiest and probably cheapest way to lower the discharge temperature is to enlarge the cooling ponds. Similar solution could be finding customer where low temperature heat could be rejected. As already identified, such customers are open door swimming pools or connection to the Zoo Safari Borysew. However, the timeline might be decisive factor for the project.

B. Long term solutions by Improving operational temperature of district heating network

First alternative is easier as it can be implemented locally instead of 100 buildings. Solution can be realized by raising the supply temperature of the district heating system. Principally, this would reduce the water flow rate in the district heating to supply same amount of heat the housing. Similarly, radiator based heating system will deliver lower return temperatures and thus lower return temperature at ground water heat exchanger. Increase in temperature spread will result will enable the network to supply heat to large number of buildings. For exisiting heating demands that lies at around 4 MW, the flow rate requirement in the district heating network will reduce from 190 m³/h to about 80 m³/h. The requirement of peak load in existing system is estimated to be 1,4 MW. Rest of 2,6 MW will be supplied from borehole with reduced flow of about 80 m³/h. Solution will increase redundancy in capacity for existing borehole such that the increase in number of customers for DHN will not require to bore another borehole but only increase in peak load capacity.

The peak load solution might use gas or coal based boiler to raise the supply temperature. As obvious from the Figure 5.14.16, the return temperature is above 45°C almost throughout the year and hence such boiler should be operated throughout the year to eliminate the need of cooling ponds and problem with return temperatures higher than 35°C. Such solution will however drastically increase use of the gas or coal fired boiler and not recommended one both due to climate effects and local pollution. Another alternative to this is to use biomass based boiler that will lead to lower climate effects however will not solve problem with local pollution completely. Third solution is to limit the use of gas/coal fired boiler by combined the solution with cooling pond. The cooling pond is used still as main cooling solution for return temperature and boiler is activated only during limited periods when cooling pond cooling is not sufficient. Such solution will only solve return temperature problem but still lead to wastage of large amounts of energy.

The peak load can also be designed for the system using VCC or thermal driven heat pump. Thermally driver heat pump requires gas and therefore, not recommended of similar grounds mentioned earlier. VCC heat pump is considered as potential alternative for such installation. In this case, heat pump will take the heat from the return side of the geothermal water, upgrade the quality of this heat and deliver it to the supply side of district heating side. Heat pump will this cool down the return water of the geothermal water and at the same time raise the supply temperature to district heating. As already pointed out that system would need to deliver high supply temperature for dominant part of the year and would ensure improvement in supply capacity of the DHN. Thermal design capacity of such heat pump for existing system is estimated at around 1.4 MW.

Assuming cost of heat pump inclusive support equipment at around (2500 zl/kW), such installation would cost approximately 3.5 million zl. A requirement of payback time of 10 years, and distributing cost over whole heat supply to Poddebice (i.e. 15 TJ), such installation would add about 80-90 zl/MWh. An additional cost due to electrical consumption would amount to about 50 zl/MWh (here again distributing the electricity cost over whole supply). Total increase in cost of heat would be around 130-140 zl/MWh or ~35-40 zl/GJ. According to (Buńczyk, 2016), the average net heat prices for this area in Poland are approximately 52 zl/GJ. Further investigation is needed to identify the feasibility of a heat pump installation. Any support programs for energy efficient installations such as heat pumps, should be considered.

C. Strategic development of the GeoDH

District heating network at Poddebice is growing and estimated to have total capacity at around 18 MW compared to existing 4 MW. Heating system at the building level has large influence on specification of district heating network. The town has unique opportunity to move towards fourth generation district heating network with lower supply and return temperature. Several possible solutions for building level integration are shown in the report for city of Konstantynów in this project. It is highly recommended that Poddebice review these solutions and find ways to collaborate with building owner so that heating system in buildings could be transformed or designed for low temperatures.

Konstantynów Łódzki

Low temperature heating systems

Both the district heating system (DH) and heating system in buildings are designed for relatively high supply/return temperatures. Future district heating networks are moving towards lower design temperatures, such that these can be successfully integrated to renewable energy supplies. The same applies to the geothermal heating in district heating networks.

However, the challenges exist in form of higher investment costs and lower return investments for the heating system, on both the building and the heat supplier side. On one hand, cost of establishing low temperature heating system in buildings is high and can almost be linearly related with the surface area increase due to lowering of average temperature of the surface. Building owners wants to limit the increase in front-end capital investment. On the other hand, cost of establishing geothermal boreholes is high. Lower utilization of energy from these boreholes due to temperature limitation makes these investments unattractive for energy companies. Energy companies want to maximize the return on their investment. Such situation often leads to limited integration of renewable energy supplied into existing infrastructure.

Although, the problems seems difficult in beginning, a collaborative approach in this regard might be a key to solve such challenge at smaller scale. The district heating networks in both cities is getting larger each year and the heating company in Konstantynów Łódzki identified several projects of rehabilitation of existing buildings as well as new housing schemes as potential customers in coming years. The district heating company should collaborate with these housing projects and find common investment solutions alongside governmental support programs and subsidies. The investment solutions must look into total cost of both the heating system in houses alongside geothermal heat supplies to make offers to the building owners who are interested in choosing lower temperature heating systems along with connection the district heating network.

Covering the total heating demand of the building

According to the heating company Veolia, currently district heating network is mainly supplying space heating and ventilation heating and hot tap water is covered mostly by local electrically heated storage tanks. Such approach is seen as highly non-optimal both in term of technical as well as economical grounds. It should be find ways to promote district heating to deliver both space heating, ventilation heating and hot tap water from district heating.

This can be justified of both the technical and economical grounds. In older buildings, the share of space and ventilation heating has been rather significant compared to hot tap water. Trends in increasing insulation and air tightness has however lead to significant decrease in space and ventilation heating needs and thus share of hot tap water becomes now significant in heating needs for new buildings. Although, this phenomenon is specifically studied in Norway and has not been looked into for Poland, same can be assumed true for Poland. At the same time, changes n premises for heating needs has lead to questions regarding use of expensive radiator based heating system in buildings. Significant effort has therefore been made to find cost-optimal heating system for building and several new example of cost-effective heating system for energy efficient systems are proposed. Figure 5.14.14 shows some example of such successful implementation in Norwegian high energy-efficient buildings. The solution suggest that due to reduced heat losses from the building envelop, it is no longer required to install radiator in each room in apartments. This typology of heating system makes it possible to reduce the five-pipe system (supply and return pipe for heating, hot tap water, recirculation pipe and cold water) to three-pipe system (supply and return pipe for heating and cold water). Another cost effective optimal has emerged that employs the hot tap water and recirculation pipe to deliver both the hot tap water and heating to the apartment using local heating exchanger and a small circulation pump. The solution has been tested and proven in Norway with relatively cold climate having design temperatures down to -20 °C.

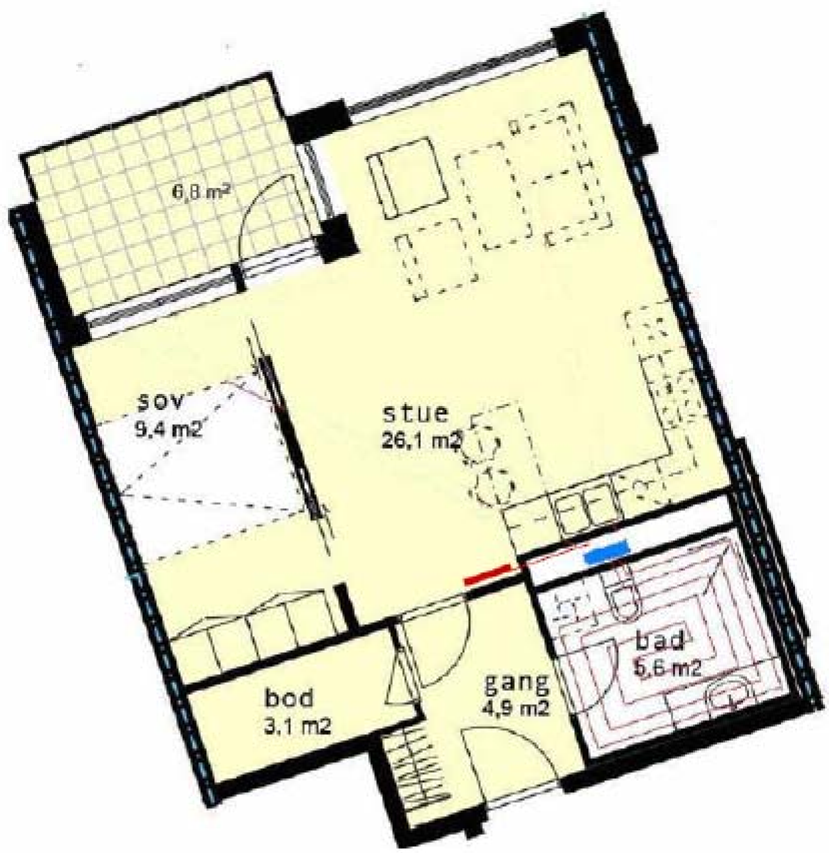


Fig. 5.14.14. Example of two-room apartment with just one radiators for Norwegian passive house (Wigenstad, 2009)

Sochaczew

Low-temperature heating systems

The geothermal source is located in an area that is not currently urbanized, but there are plans for development. This is an very good case for a low-temperature DH network, which can utilize geothermal heat in the temperature range 40°C (source for planned test well at 1400 m depth) to 70 °C (deeper source at 2500 m depth, could be an option for future utilization) more efficiently than existing DH networks in Sochaczew which have design temperatures of 80/60°C. A low-temperature DH network will also make it more efficient to utilize other lower temperature renewable heat sources, such as solar thermal, biomass and waste heat from processes.

Utilization of a low-temperature DH is in line with development scenarios towards low-temperature DH suggested by (Walnum & Fredriksen 2017), Thermal Energy Systems in ZEN, 2017). The consumer substation should be designed with focus on lowering the return temperature to provide the DH network with a high temperature difference for supply and return. (Walnum & Fredriksen, 2017) suggest several examples of varying complexity that will help produce the low return temperature needed in a low-temperature DH network (see **Błąd! Nie można odnaleźć źródła odwołania.**).

A low-temperature DH network should therefore be considered for the Sochaczew case. This should, however, be balanced with respect to the number of buildings to be covered with low-temperature heating system. Even for a low-temperature heating system there will be need for heat pumps, at least with the 40 °C source (see discussions in section **Błąd! Nie można odnaleźć źródła odwołania.**), but a higher COP and lower usage of other energy sources can be achieved for the renewable heat sources with a low-temperature DH network.

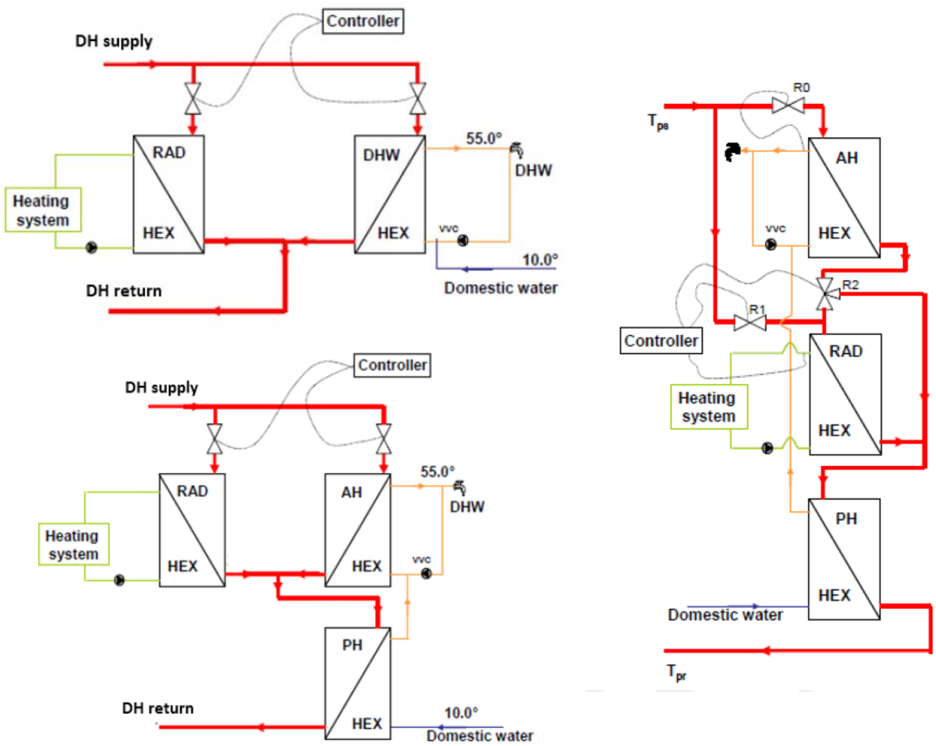


Fig. 5.14.15. Three different schemes for low return temperature in DHN, (Walnum & Fredriksen, 2017)

Possible application of aquifer thermal energy storage (ATES) in the energy system

There are two scenarios for which an ATES would be a preferable solution for Sochaczew:

- If there is a cooling need, either comfort cooling or industrial cooling (including e.g. shopping malls and data centers, drying processes). In this case the upper aquifer should be used as a reservoir.
- If there is excess waste heat available with temperature above 40 °C. In this case the temperature in the 40°C aquifer can be increased, making it possible to run the heat pumps more efficiently, increasing the efficiency of the system.

Neither of these scenarios have not been specified as a requirement at this stage, This recommendation should be further followed up and reevaluated in the future development of the energy system. If one of these scenarios should be implemented, there is a need for simulations and investigations of the reservoir regarding temperature and water quality. Also, monitoring and follow-up with respect to reservoir temperature and water quality is important.

Successful implementation of geothermal heating

The temperature from the geothermal sources in Sochaczew is too low for direct implementation in a high temperature (80/60°C or 90/70°C) DH network. Using a heat pump installation, the temperature can be raised to adequate levels – 80-90°C. Note that the water quality should be analysed in more detail before final planning of the energy system.

Scenario 1

The local DH officials have suggested using a gas fueled absorption heat pump (GAHP) as 1st stage (estimated COP of 1.4) and a vapor compression cycle heat pump (VCCHP) as 2nd stage. The 1st stage will likely produce a hot side temperature in the range of 45-60°C depending on capacity and solution, whereas the 2nd stage will lift the temperature to approx. 80°C when needed. This would likely give a combined COP of around 1.0-1.1.

An alternative would be to use a VCCHP for both stages. A rough calculation indicate that a VCCHP would have to deliver heat at a COP of 3.75 or higher for the same conditions[1]. A VCCHP using conditions with 40/20°C and 45/50°C can maintain a COP higher than 4.5. If the hot side temperature is increased by 5°C, the COP would drop significantly to approx. 4.0 - 4.5, depending on choice of heat pump design. The combined COP of two VCCHP stages to a temperature of approx. 80°C is therefore likely to be around 3 - 3.5. These numbers depend on a large number of design choices, but can are easily obtained using commercial solutions.

As a VCCHP will outperform a GAHP, a VCCHP for the 1st heat pump stage is recommended as well. The preliminary calculations indicate that a two-stage solution based on a VCCHP design can achieve the needed temperature for the DH network. Further evaluation should consider an economic optimization of the heat pump installation. A solution using a boiler for peak load demand and heat pump energy coverage of 80-90% will likely be a feasible scenario.

Scenario 2

For the 40°C source, one option current high temperature DH network would be to concentrate on heating the return water from the distribution system, which is normally around 70°C. Since there is no electricity generation in the system, there is no cold end temperature to worry about, so heating of the return water from 70°C to perhaps 75-80°C would only lower the heat load of the fuel boilers. These fuel boilers operate at hundreds of degrees, so it makes no difference if water into the boilers is 70 or 80°C. The simple representation of such a system is shown in **Błąd! Nie można odnaleźć źródła odwołania.**, where all the geothermal water goes through a heat pump, which heats the return water in the distribution system and lowers the heat load on the boilers.

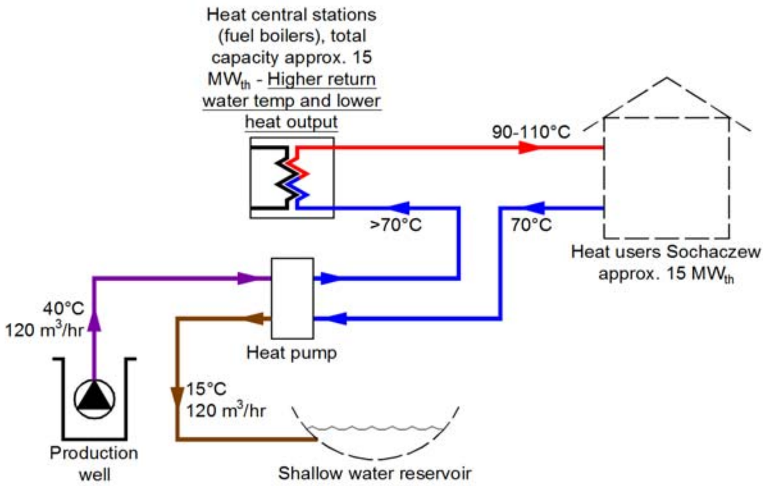


Fig. 5.14.16. Sochaczew low-temperature geothermal well and heat pump, schematic diagram

References:

Walnum & Fredriksen 2017: Thermal Energy Systems in ZEN, ZEN Report

[1] Using the energy prices of 100 PLN/MWh for gas and 300 PLN/MWh for electricity.

Lądek-Zdrój

Low temperature heating systems

The heating system in buildings is designed for relatively high supply/return temperatures. Future district heating networks are moving towards lower design temperatures, such that these can be successfully integrated to renewable energy supplies. This would require that the heating system in buildings are planned accordingly.

Choice of low temperature heating system require higher investment costs and offer lower return investments. However, this choice enable easy integration and increased utilization of geothermal heat in the district heating networks.

Lądek-Zdrój is an old town. Several anticipated customers for the future district heating network will be old buildings where renovation of heating system is coming in near future. It is recommended that district heating network should base its design on choice of supply temperatures closer to 60°C. This choice will open possibilities for integration of renewable energy in longer future. A district heating network can then of practical reasons be operated at higher supply temperatures to enable the transitions of older high temperature heating systems to low temperature heating systems.

The district heating network should then define requirements for the customers such that they are obliged to or prefer to choose lower temperature heating system in their buildings. One solution could be that the district heating company collaborate with the building owners and find common investment solutions alongside governmental support programs and subsidies. The investment solutions must look into total cost of both the heating system in houses alongside geothermal heat supplies to make offers to the building owners who are interested in choosing lower temperature heating systems along with connection the district heating network.

Implementation of district heating network

One of the key parameters for success of a district heating network lies in reaching higher density of heat sales per unit pipe length. Sparsely distributed areas often lead to slow penetration of district heating and offers low return on investments. Improvement in energy efficiency of building envelops should be important consideration in this regard. Although, it might look attractive to sell large amount of heat to few buildings, refurbishment of these buildings might change the scenario. District heating network are investments for at least next 60 years. It is therefore important to evaluate if the district heating network could reach such sales density in Lądek-Zdrój. Alternative solution can be to evaluate application of local energy supply solutions that is limited to heat supply to building in close vicinity to limit the investments scale.

Successful implementation of geothermal heating

Thermal waters have remained large attraction and resource for Lądek-Zdrój. It of therefore important to ensure that deep geothermal extraction of waters does not interfere with curative water resources. In case of positive results, the borehole will be supply around 2-4 MW of heat at 70°C. As the system will be connected to existing buildings with design temperatures (most probably) 90/70°C or 80/60°C, a certain amount of heat will still be supplied by peak load boilers. The system typology in such case might be such that heating from a district heating network (DHN) covers only base load, while the existing boilers cover the peak loads. Alternatively, the peak loads may be covered by centrally located boiler based on either gas or biomass. To avoid excessive use of peak boilers, it is strongly recommended to choose design temperatures for DHN closer to, or above, the design temperature in buildings.

Another alternative for the town of less risk of affecting existing sources and well, will be to utilize shallow geothermal boreholes with close loop heat exchangers. In this case, the heat will be taken from shallow geothermal boreholes at temperature between 10 -20°C and upgraded to required temperatures using heat pump technology. Shallow borehole with close loop heat exchangers are already installed in at least one kindergarden in Lądek-Zdrój with success and therefore greatly reduce the risk involved in the project. Such solution can be implemented with great success at individual or cluster of buildings. Moreover, a large amount of waste water from treatment facilities that is rejected at moderate temperatures of about 30°C can be combined with heat pump technology to upgrade available waste heat to required temperatures.

A heat source temperature of approx. 20°C is adequate for using a vapor compression heat pump (VCCHP) to raise the available temperature to 80-95°C. A total COP in the range of 3.0-4.0 can be expected from commercially available solutions. A three stage VCCHP installation may be needed, depending on design. Should the design temperature be closer to a low-temperature solution, around 60-70°C, commercial solutions should produce COPs in a range closer to 3.5-4.5. These figures are very sensitive to the choice of components in the heat pump, such as refrigerant, compressor and system design.

Snow melting of pavements is highly energy intensive. Heating load for snow melting varies as function of outdoor temperature, air velocity and amount and temperature of precipitation. Typical design load for de-icing lies at around 200-300 W/m². It is therefore recommended to limit the application of snow melting to only streets with high utilization factor. Snow melting should be limited to only pavement on one side of the street/road and identified with color coding or similar solution. The energy can be supplied to the deicing system using return side of the district heating network. Waste heat from curative thermal waters might also be used for the purpose depending on distances, amount and quality of required heat. Experience in Norway shows that need for snow melting often occurs in temperature zones near 0 to -6 °C and probability of precipitation at very lower temperatures is seldom. Typical energy use with optimal control strategies lies near between 100 – 150 kWh/m² but might soon go up to 400 kWh/m² with badly design and controlled system. It is therefore, recommended that these considerations are made in the design phase so that snow melting in the town does not become contrast to the original ambition of finding climate friendly energy solutions.

5.14.2. Proposals for Project towns and other localities an areas in Poland – by AGH UST, Drilling, Oil and Gas Faculty team

Proposals of projects related to geothermal energy in Poland, created at the Faculty of Drilling, Oil and Gas of AGH UST team are divided into two groups, i.e.:

A. Projects regarding geothermal and ground waters, used also by means of (absorption and compressor) heat pumps – hereinafter referred to as "*Geothermal waters;*"
B. Projects regarding heat acquisition from the Earth's crust without mass exploitation, possible to be used mainly by means of compressor (geothermal) heat pumps – hereinafter referred to as "*geothermal heat pumps.*"

Under the term "project" both *soft projects* (analyses, studies, opinions, research works, development works, changes to regulations, etc.) and *hard projects* (investment activities, performance of drilling, borehole reconstructions, trial pumping, construction/extension of heating networks, connections, heat exchange stations, etc.) were proposed.

The pilot project proposals are related both to the Towns embraced by the reported project and to several other localities within Poland.

A. Geothermal waters

1. In case of obtaining positive drilling results in Lądek-Zdrój, Sochaczew and Konstantynów Łódzki, it is necessary to continue works leading to the use of geothermal waters and energy. After drillings, research and measurement works have to be carried out, which will provide an answer regarding the quantity of geothermal water and its temperature (reservoir/head pressure). Together, those two parameters enable determining the quantity of energy (heating power) possible to obtain. Another basic parameter, which will be obtained in case of geothermal water production, is water mineralisation. Further works leading to commencing generally understood exploitation should take into account the acquired results and use the most recent available expertise (from abroad [including Iceland and Norway] and from Poland – covering 25 years of operation of the oldest installations of that kind in Poland) so that target installations become models for other municipalities.
2. The performance of next geothermal drillings should be recommended in towns, which have the best recognised and the best geological and reservoir conditions, as well as (!) an extended surface heating network (particularly low parameters). The human factor is obviously essential, i.e. involvement of local authorities and a favourable attitude of the residents. Thus, it is necessary to activate the local community in towns with good geological conditions and surface infrastructure. Such activity should have a priority over the performance of the first geothermal works in locations with poorer geology or infrastructure, but a favourable human factor. The human factor is changeable, while geology is not!
3. Geothermal works (based on geothermal and ground waters with different temperatures) should commence in Łódź and Szczecin (mainly Mesozoic formations) and in Warsaw (e.g. Oligocene waters).
4. The existing drilling wells should be used. It there are documented geothermal waters in the existing or shutdown wells, it is better to adapt such wells and reconstruct them, rather than make new ones. Usually, it is less expensive to buy land in order to have access to a well and be able to reconstruct it than drilling of a new one.
5. Geothermal locations outside towns, particularly on the basis of the existing wells (or possible to bring back after shutdown/partial shutdown) should be analysed in the selected place for the needs of recreation and agriculture (heating of greenhouses and soil, drying industry).
6. After obtaining positive results of test pumping in the well in Sochaczew, it is necessary to undertake activities leading to acquiring the existing wells after the initial analysis on the basis of drilling and test documentations, as well as shutdown protocols.

7. It seems appropriate to make pressure, temperature and hydrogeochemical models of the area with a geothermal well in Poddębice (mineralisation: 490 mg/dm^3) and three boreholes used by Geotermia Uniejów (mineralisation: 8845, 7400 and 6790 mg/dm^3) against the background of regional filtration. It will be aimed at specifying possible changes in water pressure, temperature and mineralisation for both Poddębice and Uniejów, as well as at counteracting potential negative phenomena.
8. In case of negative results of drilling of a geothermal well in Lądek-Zdrój, it is necessary to conduct analysis of possibilities of making a "heating" arrangement of the HDR (hot dry rocks) type. Such installations are performed in the world in impermeable rocks after rock fracturing after producing heat from rock mass to produce electricity. In Lądek-Zdrój, such a system could operate, which would be used for heating purposes. After obtaining of drilling results, it is necessary to take such a possibility into account, once research and implementation works have been completed. Hydraulic fracturing methods have been developed owing to the "shale boom" in North America. The geology of Sudetes is the most suitable in Poland in this respect (apart from crystalline substrate under Mesozoic and Palaeozoic formations).
9. It is recommended to perform studies concerning a project of heat storage installation (especially with respect to waste heat) in rock mass. There are a number of possibilities to carry out such activities.
10. Zgierz – it is proposed to make an exploratory well to produce geothermal waters from the area of Rogoźno salt diapir. A salt diapir located several kilometres to the north of Zgierz enables heat flow of higher intensity. It is manifested by higher temperature of locally occurring formations in relation to a regional value of a geothermal gradient.

B. Geothermal heat pumps

11. Implementation of a replacement of a heat source from a coal source into a geothermal source in several selected buildings in the Old Town. To this end, activities leading to making a prototype modular drilling device (anti-smog drilling rig) should be performed. Such a device could be transported to courtyards, basements of buildings and installed on the spot. Owing to this, it will be possible to perform borehole heat exchangers to the depth of 100 m from places with limited space. In case of opening the source of low temperature heat in the form of rock mass, it will be necessary to adjust a heating system to supply by means of a heat pump. A heat pump based on borehole heat exchangers, apart from heating, will have a possibility to air condition indoor facilities in the summer. In case of Kraków, it may be one of alternative solutions in activities leading to smog reduction.
12. Nowy Sącz (Sądecka Valley) has the highest number of wind-free days in Poland. In winter, it causes exhaust fumes concentration, particularly in the area of the old town. Smog occurring in this way belongs to the largest ones in Poland. In this town and in neighbouring towns (e.g. in Stary Sącz), pilot installations should be built based on an "anti-smog drilling rig" and compressor geothermal heat pumps. In case of such pilot installations, it is necessary to perform drilling wells from the inside of several buildings (from basements) or from courtyards, equip them with heat exchange systems with rock mass and adapt an internal heating installation to cooperate with heat pumps.
13. Polish spas – application of geothermal heat pumps in towns, where it is especially important to take care of air quality. They include Lądek-Zdrój, where three buildings were burnt (outside a spa part). An innovative solution should be applied there with borehole exchangers and geothermal heat pumps (anti-smog drilling).
14. In spas and other places, there are significant streams of waste heat (e.g. from post-treatment waters, from ventilation, from ice rinks, etc.). It is necessary to take into account the application of such heat when designing geothermal heat intake systems.
15. "Wieliczka" salt mine produces significant quantities of geothermal heat, which is wasted by entering the atmosphere. "Kościuszko" shaft, playing the role of an exhaust duct for mine ventilation, produces air with permanent temperature during the year (14-16°C). The stream of that air is stable in time. Heating low temperature power is over 1 MW! At a small distance from that shaft, there is a large heat consumer, being "Solne Miasto" Education and Recreational Centre. The centre collects heat with relatively low parameters, such as e.g. a complex of swimming pools (maintenance of water temperature), floor heating, and heating of ventilation air. Using relatively low costs, it will be possible to reduce significantly CO_2 emissions to the atmosphere, and also to reduce, to some extent, operating costs in "Solne Miasto."
16. "Wieliczka" Salt Mine runs works aimed at shutting down a great number of underground workings in order to protect a historic part of the mine. Liquidations, in general, consist in filling voids with filling sand. A project of equipping workings in tubes playing the role of a heat exchanger before filling should be co-financed. Heat collected from liquidated mine areas will be used for heating of an underground sanatorium (by means of heat pumps). Presently, electricity is used for this purpose. The mine, visited by over one million tourists annually, apart from historic attractions, will be able to prove its innovativeness on a world scale. Before making a design, it is necessary to perform research and implementation works aimed at e.g. specifying of a stream of heat possible to obtain in the above-described way.

17. The Act: Building Law (or respective regulations) should include a provision about the necessity to introduce installations of heat exchange with rock mass if bearing piles are designed for the purposes of reinforcing the rock mass. Bearing piles with heat exchangers tubes, referred to as thermal piles, energy piles or energy pillars can constitute an additional source of heat for heating and cooling (air conditioning). The conditions where such way of energy acquisition can be used should be identified in advance, based on studies. Similar regulations are already in force in western countries.
18. Deep borehole heat exchangers, which can be implemented in numerous places in Poland, on the basis of the existing drilling wells (existing, designated for liquidation, liquidated or partially liquidated, e.g. depleted oil wells or negative exploratory wells) should be analysed in terms of geothermal energy after making of a pilot installation. In Podkarpacie and Małopolska regions, such wells can often be found in urban areas. There are different possibilities of recovering liquidated wells, depending on the method of liquidation.
19. New drilling, exploratory or production wells should be designed and made, taking into account possibilities of using them in the future for making earth's heat available. To this end, it is necessary to develop design guidelines and support research works on drilling fluids for drilling wells, which will have increased or decreased thermal conductivity (depending on the potential well use in the future).
20. Making use of pilot installations with borehole heat exchangers in several schools, where solar collectors have been installed. The biggest heat production from such collector falls on a holiday period, when it is not needed. Thus, no heat collection from solar collectors in the summer is often the reason of unsealing such installations. Heat storage in rock mass will make it possible to use it in the period of higher demand and/or it will contribute to the improvement of heat pumps effectiveness.

5.14.3. Proposals of new localities within the Polish Lowlands prospective for geothermal space heating development – by AGH UST, Faculty of Geology, Geophysics and Environmental Protection team

The area of Mogilno–Łódź Trough is, next to Podhale, one of the most prospective areas in Poland for effective management of geothermal resources. The use of geothermal energy in this region should be, first of all, related to Lower Jurassic and Lower Cretaceous reservoirs. Currently – in Poddębice and Uniejów – Lower Cretaceous reservoir waters are produced successfully. At different development stages are projects of using the energy potential of waters from the Lower Jurassic reservoir (Konin, Konstantynów Łódzki, Sieradz, Koło and the like).

In order to identify possibilities of building new geothermal installations in the area of Mogilno–Łódź Trough, the analysis of geological and hydrogeothermal parameters for a Lower Cretaceous and Lower Jurassic geothermal reservoir was conducted on the basis of the analysis of archival materials, research works, geological designs and inventory of operational parameters of geothermal installations in operation. Hydrogeological and geothermal parameters were evaluated, including estimation of water temperatures and mineralisation, as well as intake capacities in the area of geothermal reservoirs being analysed.

Construction of a 3D geological-parametric model of the study area, made in Petrel program, enabled spatial distribution of parameters being analysed, and next, the evaluation of geothermal resources in the Lower Cretaceous and Lower Jurassic reservoirs.

As a result of those activities, thermal power of geothermal installations was calculated and places prospective for further management of geothermal resources were indicated.

A larger energy potential relates to waters from the Lower Jurassic reservoir, however, if they are used, one should bear in mind high water mineralisation. It will be necessary to apply two-well water abstraction systems.

Locations prospective for the use of geothermal waters from the Lower Cretaceous level occur at a much smaller area than in case of the Lower Cretaceous reservoir. Waters of that reservoir are characterised by lower mineralisation, but also lower temperature.

The purpose of geothermal production is to obtain waters with the highest reservoir and operating temperature, maximum efficiency in artesian conditions, as well as the lowest mineralisation. Apart from hydrogeothermal conditions, in order for an investment to be successful it is crucial to have a proper installation design, ensuring maximised use of the geothermal potential. Experience of the foreign partners are extremely important within this respect.

Analysis of the results of geological-parametric modelling

Below there is the analysis of the result of geological-parametric modelling for the Lower Cretaceous reservoir and the Lower Jurassic reservoir, maps presenting prospective areas for managing geothermal waters (Fig. 5.14.17. and 5.14.18), as well as a list of hydrogeothermal parameters in prospective locations in the area of Mogilno–Łódź Trough, with regard to the reservoirs being analysed (Tab. 5.14.1. and 5.14.2). The analysis of the results of performed works enabled indicating proposals of pilot projects.

Lower Cretaceous Reservoir

Roof of the Lower Cretaceous formations is reported at variable depths ranging from several dozen m above sea level in Trough border zones, to over 2500 m under sea level in the area north-east of Konin.

Total thickness of Lower Cretaceous formations ranges from several up to ca. 600 m in the central and eastern part of Mogilno-Łódź Trough, locally exceeding even 600 m. In the south-western part, the thickness of Lower Cretaceous formations does not exceed 300 m.

General **distribution of the total thickness of aquifers** occurring in Lower Cretaceous formations is similar to the distribution of the total thickness of that age formations. The thickness of aquifers reported in the profile of Lower Cretaceous formations ranges from several m in the Trough edge zone to ca. 400 m in the north-eastern zone. Locally, in the eastern part of the Trough, one may expect the maximum aquifer thickness even up to over 600 m.

Temperature of groundwaters in the roof of the reservoir under analysis remains the function of the depth of aquifer occurrence. In edge zones, temperature rarely exceeds 40°C; it grows towards central deepening of the Trough structure up to ca. 75°C, and achieves maximum values north-east of Konin and south-west of Poddębice.

Mineralisation of Lower Cretaceous reservoir waters varies from over 0 to ca. 100 g/L. Waters with low mineralisation, i.e. below 2 g/L, occur on a very large area of the Trough, particularly in its southern part. The highest mineralisation (several dozen g/L, locally >100 g/L) can be observed in the eastern part of the Trough. These are zones of high depths of Lower Cretaceous formations deposition. Waters of that reservoir indicate the presence of components essential from the point of view of balneotherapeutic application, such as Fe, I and Br. These are waters of the Na-Ca-HCO_3, Na-Cl, Na-Cl-HCO3 and Ca-Na-HCO3 type.

A map of potential intake **rates** in the Lower Cretaceous reservoir indicates clearly that outputs over 50 m^3/h should be expected only in the southern and south-eastern part of the Trough. In the central and northern parts, the output drops below that value. The highest output values, even over 400 m^3/h, are expected in the area of Koło.

A strong impact of that parameter upon the anticipated geothermal installations parameters can be seen on the map of the **potential thermal power of geothermal installations** within the Lower Cretaceous reservoir in the area of Mogilno-Łódź Trough. In a vast part of the area under analysis potential geothermal installations will not exceed the power of 5 MW. Yet, the eastern part of the Trough should be paid attention to, where, in the zone extending from Poddębice to the north a possibility of building geothermal installations with thermal powers over 5 MW, and even over 20 MW, is contemplated.

Lower Jurassic Reservoir

The roof of Lower Jurassic formations is deposited the most deeply, in the axial part of the Trough (max ca. 3750 m under sea level) and it rises towards peripheral part of the Trough structure. The shallowest deposition of Lower Jurassic formations, of about 750 m under sea level, is visible along the south-western Trough edge. Locally – in the southern and eastern part of Mogilno-Łódź Trough – there are no Lower Jurassic formations.

The total thickness of Lower Jurassic formations on a major part of the area under analysis ranges from several up to ca. 200-250 m. Within Kujawy anticlinorium, the thickness of those formations was reported even up to 900 m. The lowest thickness, below 100 m, occurs in the central and southern part of the Trough.

Distribution of **aquifer formations thickness** for the Lower Jurassic reservoir is very similar to the distribution of the total thickness. Analogously – the lowest thickness of those formations (below 100 m) occurs in the central and southern part of Mogilno-Łódź Trough, whereas the highest effective thickness (max. up to ca. 850 m) is observed within the limits of Kujawy anticlinorium.

Temperature distribution in the roof of Lower Jurassic formations strictly depends on the depth of those formations deposition. The highest temperatures are recorded in the axial part of the Trough, where, locally, they exceed 100°C. On the other hand, in edge Trough zones, water temperatures are 30-40°C.

Values of **water mineralisation** in the Lower Jurassic reservoir are much higher than in case of waters in the Lower Cretaceous reservoir. Maximum mineralisation values occur in the northern and eastern part of the Trough, where locally they exceed 250 g/L. Towards the south, mineralisation values decrease, reaching up a dozen g/L. In the southern, edge part, mineralisation value is the lowest and it does not exceed several g/L. In majority, these are waters of the Na-Cl type, other types of waters are encountered rarely (Na-Mg-Cl, Ca-Na-Mg-Cl and the like). Those waters contain Fe, I and Br.

Potential discharge of wells for the Lower Jurassic reservoir is variable from several dozen up to even 500 m³/h. Considerable output growth is observed towards the east, where, in some places, it is over 150 m³/h. Locally, such high output values can be expected also in the northern part of the area, although the highest outputs can be expected in the eastern part of the stud area, particularly in the area of Koło (even over 400-500 m³/h).

The above-mentioned distribution of hydrogeothermal parameters of the Lower Jurassic reservoir is reflected in the values of geothermal resources and in the distribution of the expected thermal powers for geothermal installations in the study area.

Special attention should be drawn particularly to the eastern part of Mogilno-Łódź Trough, where, similarly to the Lower Cretaceous reservoir, a possibility of building geothermal installations with powers over 5 MW is anticipated. Locally, such zones can be found also in the northern and southern part of the Trough, although their range is much smaller than in the eastern part, and expected powers do not exceed 15 MW. In the most prospective eastern region, one can expect geothermal installations with powers ranging from 10-30 MW, and, locally, even over 40 MW.

Table 5.14.1 Hydrogeothermal parameters of the Lower Cretaceous reservoir in prospective locations (the values refer to centre of each locality)

No	Name of the municipality	Depth of the top surface [m n.p.m.]	Cumulative thickness of groundwater horizons in the reservoir [m]	TDS [g/L]	Temperature at the top surface of reservoir [°C]	Potential discharge of wells [m³/h]	Thermal power of geothermal installations [MW]
1	Grzegorzew	-2173,87	367,47	38,04	66,32	422,17	21,44
2	Olszówka	-2099,86	273,69	18,29	62,27	446,47	20,9
3	Poddębice	-1934,97	101,27	1,96*	72,81	181,18**	9,63
4	Koło	-2030,1	281,78	60,6	66,48	296,85	14,1
5	Dąbie	-1669,06	207,66	12,7	57,35	361,67	12,47
6	Świnice Warckie	-1532,88	174,22	10,29	53,97	345,17	10,45
7	Koło-miasto	-2390,81	333,07	71,8	72,65	147,93	8,97
8	Grabów	-1439,1	231,92	19,2	50,12	331,63	8,54
9	Wartkowice	-1352,64	136,76	7,73	51,62	448,15	12,47
10	Babiak	-2015,56	112,91	68,58	64,42	165,58	7,51
11	Osiek Mały	-2287,2	272,71	77,85	73,38	116,05	6,51
12	Uniejów	-1986,51	122,66	6,41	70,86	159,56	8,51
13	Łęczyca	-1324,21	275,57	13,87	42,96	249,72	6,01
14	Zadzim	-2162,99	122,47	0	76,55	89,82	5,26
15	Dalików	-1377,05	377,54	0	51,14	167,68	5,04
16	Wodzierady	-1946,51	143,3	0	59,64	105,47	5,42

* 0,4 g/L in case of water discharged by Podddębice GT-2 well, ** in case of Poddębice GT-2 well approved water reserves are 252 m³/h

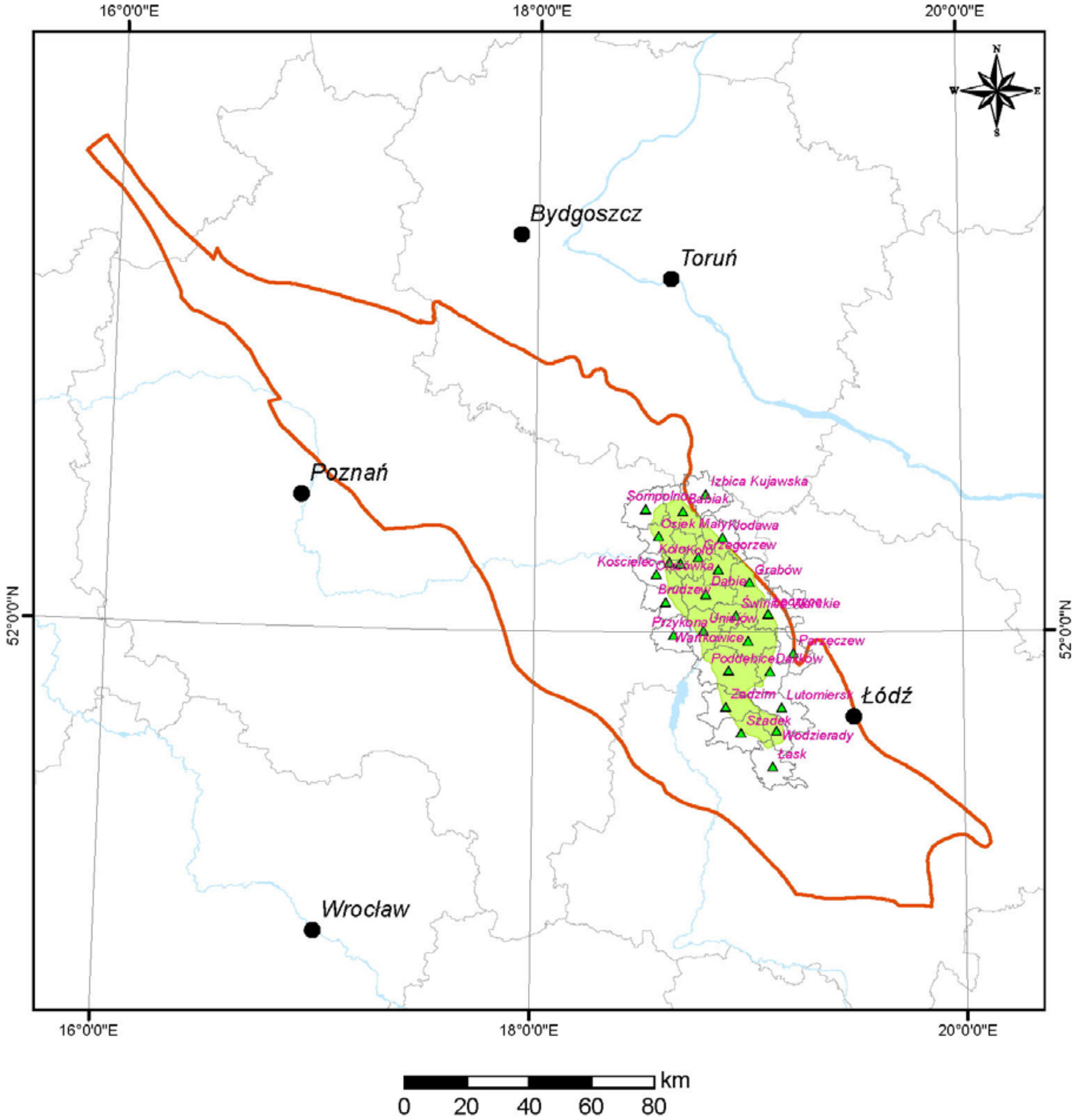


Fig. 5.14.17. Prospective areas (marked in green) for managing geothermal waters in the area of Mogilno–Łódź Trough within the Lower Cretaceous reservoir

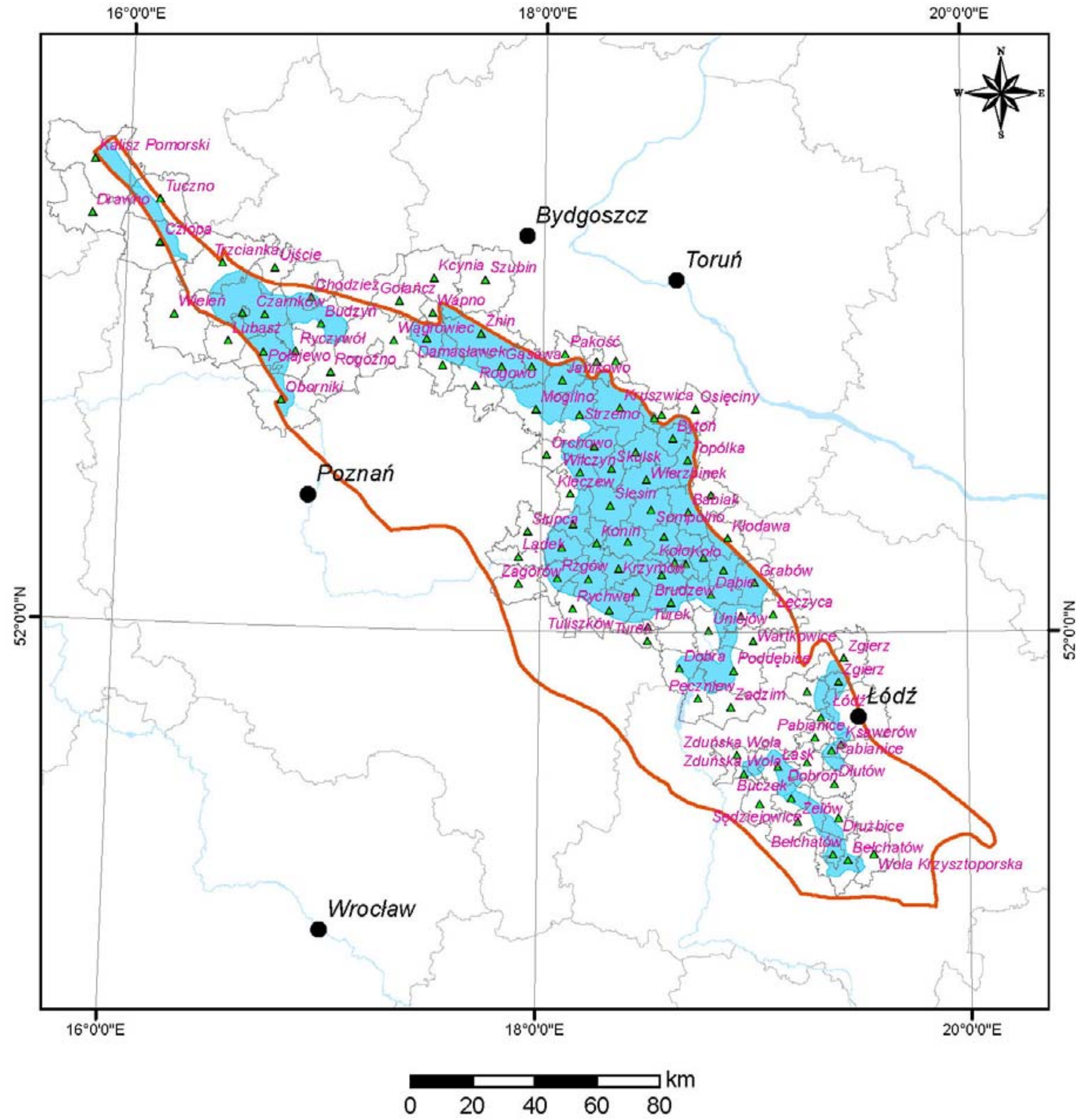


Fig. 5.14.19. Prospective areas (marked in blue) for managing geothermal waters in the area of Mogilno–Łódź Trough within the Lower Jurassic reservoir

Table 5.14.2. Hydrogeothermal parameters of the Lower Jurassic reservoir in prospective locations (the values refer to the centre of each locality)

No	Name of the municipality	Depth of the top surface [m b.s.l.]	Cumulative thickness of groundwater horizons in the reservoir [m]	TDS [g/L]	Temperature at the top surface of reservoir [°C]	Potential discharge of wells [m^3/h]	Thermal power of geothermal installations [MW]
1	Grzegorzew	-3271,16	230,7	237,64	94,47	540,11	49,56
2	Babiak	-2741,86	443,29	178,71	82,07	550	38,34
3	Olszówka	-3110,27	248,3	214,89	90,22	330,74	27,47
4	Skulsk	-3157	176,98	189,86	92,26	278,32	25,05
5	Osiek Mały	-2912,68	298,91	172,01	88,14	306,98	22,9
6	Koło	-3268,52	269,26	220,35	98,52	245,35	21,93
7	Sompolno	-3493,33	273,6	172,43	101,31	230,46	21,49
8	Topólka	-1716,92	758,4	133,03	59,01	508,08	20,86
9	Wierzbinek	-2517,49	536,48	183,38	77,51	307,73	20,82
10	Ślesin	-2928,48	292,87	185,54	97,43	220,25	19,08
11	Bytoń	-1637,68	771,75	136,54	57,62	493,6	19,01
12	Kościelec	-2974,82	176,52	197,5	98,23	202,83	18,24
13	Piotrków Kujawski	-2228,85	502,75	192,68	70,28	264,08	17,21
14	Kramsk	-2863,11	100,78	148,35	97,44	162,51	13,73
15	Konin	-2703,74	85,64	156,99	98,96	141,99	12,47
16	Grabów	-2894,45	716,62	123,27	84,73	153,04	11,11
17	Czarnków	-2102,65	308,76	227,17	73,35	189,01	11,09
18	Kruszwica	-1688,97	633,59	191,42	55,8	242,45	10,46
19	Połajewo	-1924,35	220,45	184,84	70,8	185,2	10,02
20	Władysławów	-2515,07	85,28	159,33	93,56	117,73	9,57
21	Golina	-2042,11	120,86	150,71	83,36	131,9	9,08
22	Czarnków	-1814,65	476,61	235,37	66,72	166,9	8,56
23	Kazimierz Biskupi	-2059,41	78,92	170,39	83,52	113,17	7,92
24	Dąbie	-2735,74	169,36	245,65	83,3	104,74	7,61
25	Wilczyn	-2398,47	246,32	224,16	86,68	95,86	7,27
26	Brudzew	-2524,03	126,3	215,11	89,09	87,08	7
27	Damasławek	-2230,64	506,01	238,17	74,77	113,1	6,96
28	Bełchatów	-1702,42	118	0	63,97	154,54	6,87
29	Rzgów	-2148,85	56,49	140,95	85,37	95,02	6,85
30	Stare Miasto	-2535,66	52,87	145,59	95,24	110,59	6,73
31	Strzelno	-2372,99	84,86	257,96	71,64	118,08	6,65
32	Krzymów	-2688,26	32,95	146,29	98,47	72,91	6,31
33	Zgierz	-2027,46	327,29	49,32	68,77	113,05	5,81
34	Tuliszków	-2278,72	216,13	148,54	88,83	74,52	5,6
35	Chodzież	-1542,83	361,78	181,62	58,45	138,89	5,5
36	Gąsawa	-2979,13	89,34	224,62	89,61	66,23	5,32
37	Pabianice	-2151,48	305,07	40,98	70,06	100,14	5,21
38	Budzyń	-2142,72	319,38	221,49	73,62	86,09	5,15
39	Zduńska Wola	-1618,12	101,55	127,92	64,45	108,35	5,14
40	Dobra	-2696,8	104,73	164,68	91,9	63,15	5,12

In summary, the following conclusions from the conducted studies are presented below, which lead to the indication of pilot project proposals in the area of Mogilno–Łódź Trough:

1. In the area of Mogilno–Łódź Trough there is still an unused geothermal potential.
2. Perspectives of buildilng new heating installations related to the Lower Cretaceous and Lower Jurassic reservoirs.
3. Analysis of hydrogeothermal parameters of the Lower Cretaceous reservoir has shown that there are perspectives for building new geothermal installations with power over 5 MW, based on waters of that reservoir on the area of **16** municipalities.
4. Analysis of hydrogeothermal parameters of the Lower Jurassic reservoir has shown that there are perspectives for building new geothermal installations with power over 5 MW, based on waters of that reservoir on the area of **40** municipalities.
5. The most favourable conditions for managing geothermal waters in the Lower Cretaceous reservoir in the area of Mogilno–Łódź Trough occur in municipalities: Grzegorzew, Olszówka, Poddębice, Koło, Dąbie, Świnice Warckie, Koło–town, Grabów, Wartkowice, Babiak, Osiek Mały, Uniejów, Łęczyca, Zadzim, Dalików, Wodzierady.
6. The most favourable conditions for managing geothermal waters in the Lower Jurassic reservoir in the area of Mogilno–Łódź Trough occur in municipalities: Grzegorzew, Babiak, Olszówka, Skulsk, Osiek Mały, Koło, Sompolno, Topólka, Wierzbinek, Ślesin, Bytoń, Kościelec, Piotrków Kujawski, Kramsk, Konin, Grabów, Czarnków, Kruszwica, Połajewo.
7. Higher energy potential relates to waters of the Lower Jurassic reservoir, however, when it comes to using them, one should bear in mind high water mineralisation, translated into the necessity of using two-well systems for water production.

5.14.4. Proposals of research projects for Lądek-Zdrój area and Sudetes region – to facilitate optimal geothermal heating development – by AGH UST, WUST teams

A. Evaluation of current state of recognition of geothermal reservoir's conditions

The geothermal water reservoir located in the Lądek-Zdrój area occurs in unique geological conditions that are fundamentally different from those of other areas of Poland. However, those conditions can be recognised to be representative for the Sudety Mountains. The reservoir is of fissured nature and it feeds crystalline waters of the Lądek-Śnieżnik Metamorphic Unit. The waters occur mainly within meso-metamorphic and poly-metamorphic sections of the Stronsk formation, composed mainly of crystalline schist shale, with marble and para-gneiss inserts. The deposit also partly entails infracrustal (probably kata-metamorphic and partly ultra-metamorphic) Gierałtów formation, composed mainly of gneiss in that area. The managed and operated aquifer horizons are pressurised which causes that the present exploitation of both surface springs and one borehole (with the depth of ca. 700 m under the ground level) relies on artesian outflows.

The fissured type of reservoir rocks raises some concern of the representatives of the Lądek Spa Management, using that reservoir as the only operator. The hydraulic connections of the parts of the reservoir through fissures causes a prompt reaction in the existing wells, which has been proven empirically in the operational history. The total water output of all wells (operating on the basis of artesian outflows) remains stable. Some people worry that the drilling of a new borehole and its future operation will affect the use of the existing wells operated by the Spa. It is hard to judge such remarks on the basis of currently available data. The existing surface water collection points (springs and wells), as well as the boreholes, reach down to the maximum depth of ca. 700 m, while the target depth of the newly planned borehole is 2.500 m. The logging data (magnetotelluric surveying) indicated the presence of two levels (or zones), both fissured and filled with mineral (geothermal) water. Unfortunately, one cannot declare whether the increased resistance layer separating the two aquifers is not cut through with cracks that would cause hydraulic connection between the aquifers, and the quantitative assessment of such a connection cannot be done. A modest magneto-telluric data set does not allow for the evaluation of the spatial distribution of aquifers or the potential aquifer insulation layer.

A set of geophysical research was conducted in the geothermal reservoir area of Lądek-Zdrój. The project was designed to recognise general geological conditions of the reservoir and its surroundings, starting with magnetic and geothermal tests to radon emission to VLF (Very Low Frequency) profiling to electrical resistance surveying and profiling to three short magnetotelluric profiles. Those tests allowed for providing an interpretation of rock fault zones, discovery of temperature anomalies and, to a limited degree, spatial recognition of fissured aquifers. Complex geological conditions and limited underground data did not allow for building a digital hydrogeothermal model of the Lądek reservoir and its surroundings, or conducting a simulation of the possible influence of the new borehole on the existing wells, and consequently, an assessment of the possible hydraulic connection between the respective hydrogeological levels. The initial magnetometric tests of ΔT on a semi-detailed and partly detailed scale, were completed by the end of the 1960's. The results of those magnetic tests were used for the recognition of the tectonic structure of the area. The results confirmed the occurrences and the courses of previously known faults and allowed for mapping the previously unknown fault distribution. The research project was supplemented later and reprocessed in 2005-2007 as part of semi-detailed magnetometric tests of the Sudety Mountains area. Gravimetric tests completed in that area were regional or semi-detailed in nature. The first round of research, not to mention the previous historical tests, was completed in 1966, followed by those in 1971 and 1973. Small concentration of the measurement sites does not allow to use the collected data for any detailed reservoir analysis. Under the present project, a review of the measurement data was completed, with the calculation of transformations allowing to separate the fields by distinguishing regional anomalies and a set of residual anomalies referring to the selected depth levels. Generally, we noticed the deviations among the distribution of the anomalies in the gravity field in respect of the maps showing the geological formation outcrops, being different in lithological composition and thus in rock density.

A special role in the geophysical area exploration, in the context of the occurrence of geothermal waters, is played by surface geothermal tests. Such tests were designed within two supplementary methodological options:

I. Shallow probes placed in boreholes of up to 2.5 m,

II. Test boreholes reaching up to 25 m.

The tests under Option I were conducted in 853 boreholes drilled by the vibrohammer technique in two periods: November 1970 (about 150 probes) and May-August 1971 (about 700 probes). Diverse geological conditions did not allow to obtain the assumed borehole depths (that was obtained only for about 10% of probes). Consequently, the measurements were taken at various depths and obviously depended on daily temperature and weather fluctuations. Therefore, the reliability of the test results for geothermal purposes was questionable.

The thermal tests under Option II were completed in 53 boreholes of 25-30 m each, including the radon content and hydrogeological research. The research works consisted in the determination of the geothermal degree (or temperature gradient). The tests resulted in drafting a map of thermal anomalies, allowing to indicate the zones representing increased temperatures, and those are the sites for potential geothermal borehole drilling. Geothermal anomalies were associated with the fault zones, and that confirmed previous assumptions regarding the geothermal water migrations through the fissured zones, within the fault areas. The distribution of geothermal parameters obtained as a result of the tests conducted under Option II (Stage II), which tests were completed on relatively regularly distributed benchmarks, seems to be fully reliable. The measurements were completed with the observation of the rules of stable thermal conditions around each borehole.

The initial geoelectrical tests, in the form of continued electrical resistance surveying (or geoelectrical electrical resistance surveying), supplementing the semi-detailed magnetic tests, were completed by the end of the 1960's and were intended to recognise tectonic features. Another series of electrical resistance surveying, supplemented with VLF (Very Low Frequency) electromagnetic profiling, was completed only in 2005, or about 30 years later. A new set of tests, being a supplement to and a consequence of the previous geoelectrical tests, were the tests using the method of continuous magnetotelluric profiling, completed in 2008. The VLF (radio wave) profiling results were used to verify the courses and determine the nature of tectonic zones, considered to be potential paths of streaming geothermal waters. Based on such works, the tectonic courses were verified, with the determination of the nature of the main faults presented in tectonic sketches of the tested area. It was found that all the tested faults running NW-SE were confirmed by measurement results, obtained by increased intensity of the registered anomalies. In addition, another anomaly was mapped. It can be associated with a previously unknown fault. From the viewpoint of geothermal water exploration, the most promising were the faults situated along the lines of Lądek–Gierałtów and Rasztowiec–Karpno, presented as tectonic zones made up of parallel and forking faults. The tests using the electrical resistance method were designed to recognise the subsidence of prospective fault zones down to the depth of 250-300 m.

The completion of tests with continuous magnetotelluric profiling in 2008 supplemented previous geoelectrical works by adding geophysical research at lower depths (down to 2-3 km). Besides, research was conducted along three profiles, with the total length of 1.9 km, located perpendicularly to the selected tectonic zone sections, within the locations showing good conditions for taking measurements. The results of that research project were presented in the form of pseudo-2D depth resistance cross-sections, developed by the inversion of 1D data. The resistance contrast existing in the geological conditions of Lądek-Zdrój were associated with the lithologically diverse rock series, high-resistance gneiss and low-resistance metamorphic shale, as well as tectonic phenomena. What is a typical symptom of tectonic phenomena is the lowering of electrical resistance values associated with the rock cracking and weathering processes, underground water circulation (including that of geothermal water) and a frequent occurrence of ore mineralisation. The cross-sections show the most essential element of geological interpretation: the determined axes of tectonic zones, with vertical subsidence, perpendicular faults, and the probable plane of overthrust associated with a Lądek-Zdrój fault/overthrust. The graphs show the sections with intense fissuring of fault zones, associated with irregularly reduced resistance values, with a high probability of the occurrence of geothermal water, especially at lower depths. The test results were used to determine two sites for deep drilling of the wells to extract geothermal water.

Under the present Project, the research team completed a reinterpretation of magnetotelluric data, with the inclusion of gravimetric data interpretation. The reinterpretation works also resulted in the review of measurements, verification of procedures, measurement data processing, and verification and expansion of probing curve interpretation. The previous 1D inversion of probing curves (selected in respect of the orientation of the measurement system) was expanded by an analysis of the dependence of the 1D magnetotelluric data inversion results on the measurement system orientation in respect of the courses of geological structures. Besides, the analysts completed multi-optional, inversional 2D modelling. Such analyses were intended to expand knowledge of the deep geological structures in the Lądek-Zdrój area and verify the previous test results and tectonic conceptions. One can infer from the 2D geoelectrical cross-sections that completely different rocks occur along Profile 3 than along Profiles 1 and 2. Cross-sections 1 and 2 are characterised by high resistance values, within which one can identify low-resistance anomalies. From the viewpoint of geothermal research, the anomalies of Profiles 1 and 2 and an area in Profile 3, with the domination of low-resistance rocks, seem to be interesting. However, one may not exclude that the anomalies described under Profiles 1 and 2 are the results of lateral reflections from the rocks with fairly low resistance that occur north of Profiles 1 and 2 and are marked in Profile 3.

In our opinion, the data obtained during the team's Study Visit and reinterpretation works allow us to formulate the following conclusions:

1. The recognition of the close-to-surface zone of the Lądek hydrogeothermal reservoir is good. However, the data on its deeper sections are incomplete and unreliable.
2. A digital model of the reservoir and its surroundings is not available and thus it is not possible to carry out simulations to explain the interaction of extraction operations in particular sections of the reservoir, with the determination of the nature of hydraulic connections, supply zone activity, the role of thermal convection (ascending and descending water) etc.

B. Proposed pilot projects

I. Improvement of the degree of recognition of the conditions relating to the occurrence of the hydrogeothermal reservoir in the Lądek-Zdrój area and its geological surroundings by geophysical research

The analysis of the geological conditions and the current status of reservoir recognition and development suggests the need to carry out supplementary prospecting works with the intention to improve the degree of recognition of the deep geological structures by geophysical methods. The design of geophysical tests will be preceded by drawing conclusions and a critical analysis of the presently available geophysical test results, obtained in part under the present Project. The contemplated tests will consist in the following:

– completion of a shallow geothermal description ("photograph"), based on present-day methodological and technical requirements, to provide a reliable recognition of the geothermal field anomalies in the close-to-surface area;

– conducting a broader scope of electromagnetic tests (mainly magnetotelluric ones) to determine the spatial distribution of aquifers and potential insulation layers;

– completion of a semi-detailed or detailed gravimetric description, with possible supplementing of a detailed magnetic description;

– drafting interpretation of comprehensive geophysical data, with the use of integrated interpretation procedures (joint inversion), geological interpretation (mainly tectonic one) and reservoir interpretation based on test results.

Magnetic tests allow to recognise the distribution of the magnetic values of the rock medium. In the case of the Lądek-Zdrój surroundings, the analysts will need mapping of the outcrops of various types of rocks buried by weathered formations, as well as determination of the courses of faults that are usually associated with the fissured zones and mineral and geothermal water migrations. It will be interesting for deepening foundation knowledge and practical applications (e.g. in geothermal projects) to recognise in detail all magnetic anomalies in the area of the basaltoid (basanite) outcrops that have been known to appear in at least three locations near Lądek-Zdrój. They are proofs of the existence of a fairly young Miocene-Pliocene volcanism in that area. The distribution of such anomalies, associated with the increased magnetite content in basaltoids, can be related to the geometry of intrusive bodies in the bedrock, which will be used for making decisions about the role of young intrusions and magma flows in shaping the local geothermal field.

The completion of a new detailed gravimetric description will allow to update the measurement data obtained nearly 50 years ago. The gravimetric anomalies reflect the density diversity of the geological medium. The distribution of anomalies and of the horizontal gradient of gravity forces in anomalies indicate the courses of tectonic zones, giving grounds for detailed recognition of the geological structure. The recognition of the vertical diversity in rock density has been limited owing to inadequate number of historical data collected in the area of the current works, i.e. from the territory of neighbouring Czech Republic. The necessity to use such data collected from the surroundings of the present site results from the requirements of the most recent software packages used for the interpretation and analysis of potential fields. The structural gravimetric and magnetometric tests will be planned to obtain geophysical and borehole data collected on the borderlands on the side of the Czech Republic, supplemented by the laboratory test results relating to the physical parameters of the site rocks.

The previous, methodologically correct, geothermal description covers only part of the area of interest, although its accuracy may turn out to be inadequate in the context of assuming the connection between the temperature anomalies with the ascending migrations of heated water along fault zones. It seems to be important from both scientific and practical viewpoints to expand the territorial scope of the geothermal surface description or adding details to the existing one. The completion of that project, with drilling of 25-30 m deep boreholes, will be fairly expensive. For that reason, it is recommended to use a combination of control measurements taken in deeper benchmark boreholes with dense measurements taken in shallow boreholes 3-4 m deep), with the application of modern techniques and measurement methodologies, taking into account the reduction of the influence of daily, weather-related, and seasonal temperature fluctuations. The results of such a description will allow to provide a detailed anomaly distribution within the Lądek-Zdrój area, as well as an assessment of anomaly propagation around the town. It will be probably possible to relate or exclude the relationship of thermal anomalies with the outcrops of the Neogene vulcanite occurring in the vicinity. New geothermal research will be extremely important for planning further development of the Spa and a wider use of geothermal energy. Besides, another important aspect of such research will consist in the recreation and implementation modern geothermal surface research that has been missing in Poland in the past thirty years.

Magnetotelluric research gives a chance to recognise the geological structure even several kilometres deep, including the recognition of the locations of the potential fissure zones which are the migration paths for mineral and geothermal waters. Explanation of the doubts relating to the spatial structure of the reservoir area will require the provision of magnetotelluric profiles, with the azimuth similar to that of Profile 3, although much longer ones, covering both areas of rocks with lower resistance, located north of the town, and high-resistance rocks occurring south of the town. Even a better solution will consist in the provision of a 3D magnetotelluric description.

II. Development of a digital model of the reservoir and its geological surroundings, as well as hydrodynamic simulations showing the consequences of the reservoir exploitation

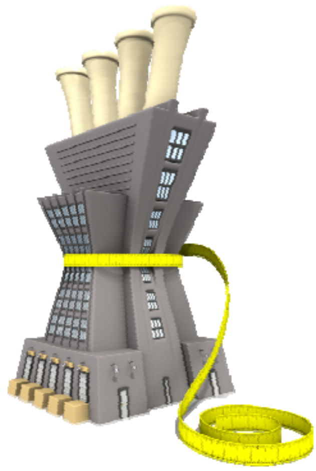
The list of currently available geological data is inadequate for the development of a reliable digital model of the reservoir and its geological surroundings. Drilling of the newly designed deep borehole and the completion of a set of geophysical tests should considerably improve the status of recognition of the geological medium. The first stage will include a 3D static model produced with the application of the Schlumberger Petrel software package. Later, hydrodynamic and geothermal modelling will be completed, including simulations designed to explain mutual interaction of water extraction from particular areas of the reservoir, and, consequently, to determine the nature of hydraulic connections, water supply zone activity, the role of thermal convection (ascending and descending water) etc. The reservoir model, improved and updated with the arrival of fresh data, will become the foundation of not only hydrogeothermal research but also verification of the geophysical strata interpretation, with the use of simple modelling methods. Owing to the similarity of the geological structure and hydrogeothermal conditions, the research to be conducted in the Lądek-Zdrój area can be treated as a pilot project for the whole Sudety Mountains.

5.14.5. General proposals and recommendations for increased effectiveness and better operation of existing and planned geothermal district heating in Poland – by National Energy Authority team, Iceland

1. Generally speaking, start immediately to design new buildings with low temperature heating systems as well as cooling facilities in mind. Also start converting existing heating systems to a low-temperature heating systems. This can be accomplished by using:
   A) Underfloor heating,
   B) Larger radiators,
   C) Fan Coils. Those are a key element in low-temp heating and cooling of buildings. One pce pr. house or a flat will normally do (for further info check www.sabiana.it or www.aermec.com),
   D) Any combination of the above.

The above actions are of outmost importance and shall be treated as a special topic within the entire projec because:
1. Elevated temperatures in district heating systems and individual buildings will result in elevated thermal losses and therefore:

Lower temperatures:
- Lower losses,
- Lower fuel consumption,
- Lower operational cost, Lower emission of CO_2!



So, lower system temperatures will inevitably imply:

- Greatly improved heating efficiency of geothermal water,
- Improved results of drilling operations and presumably lower drilling cost,
- Reduced need for heat pumps and peak-load boilers,
- Better indoor climate in residential houses and other buildings,
- Valuable work for Polish craftsmen in converting older house heating systems,
- Lower heating costs for Polish power companies,
- Reduction of CO_2 emission proportional to less energy consumption.

2. Think seriously of energy storage in aquifers or rock mass.
3. Consider hybrid solutions such as geothermal + solar + energy storage.
4. Set some guidelines referred to disposal of geothermal water. Unless reinjection is needed, avoid disposal to the environment until its enthalpy has been reduced to resonable limits. The guideline could perhaps be set at 5 to 10°C.
5. Water is amongst our most precious and important resources. Watch out for the dual purpose of the drilling, ie the production of hot water plus a wise use of the cold discharge from the heat pump. Cascade use in other words. One out of many possibilities is illustrated below (Fig. 5.14.19).
6. Finally a thougth by far outside the box. Now that the Lignite mining is soon over at present location in Belchatów, we wonder whether it would it make sense to use the facilities for building a reversible hydro-power plant. The meaning with a reversible power plant is to pump to a reservoir during low-load periods, but produce electricity at peak load hours.

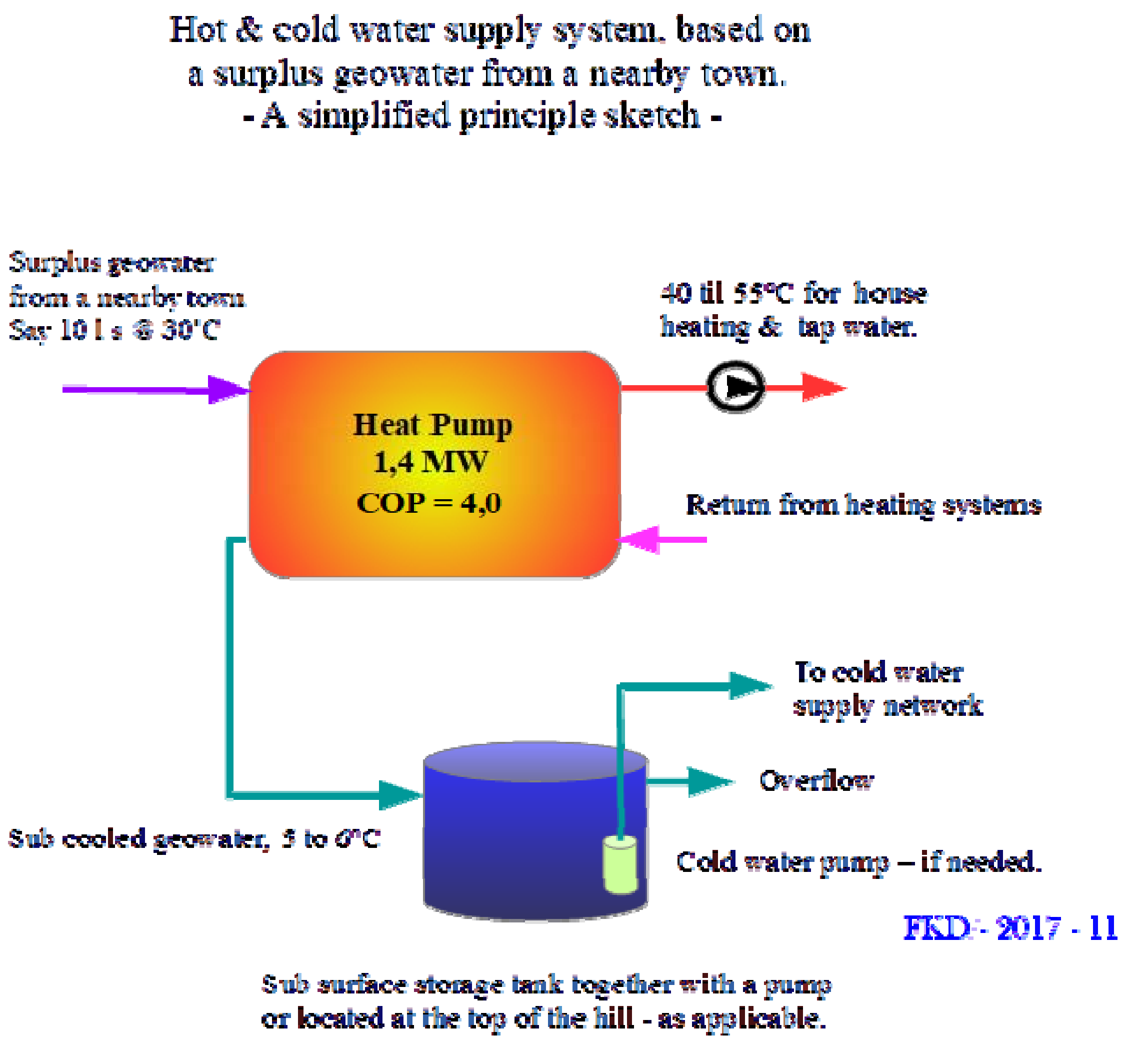


Fig. 5.14.19. One out of many possibilities of casscade uses' of geothermal water

Executive Summary

Geothermal Options, Opportunities and Benefits in Poland

The geothermal heat generation has several advantages, such as:

Resources and systems

- Geothermal resources are available in many places in Poland.
- Many and large district heating systems in Poland.
- Poland have the possibility to be leader in geothermal utilisation in Europe

Smarter and more efficient DH

- Increased feed-in of renewable energy to existing energy infrastructures.
- Improved energy efficiency in buildings.
- Develop geothermal and heat pumps - small and large grids - towards Smart Thermal Grids.

Cleaner and more secure system

- Renewable energy – reduce greenhouse gas emissions and mitigates climate change.
- Improvement of energy security.
- Reducing dependency on fossil fuels for energy use.

Economic development, finance and quality of life

- Awareness raising and capacity building in each locations and national.
- Promote financial support for early stage development and exploration – based on local payback.
- Promote Cluster Activities.
- Resource Parks – several industrial and services opportunity – fish farming, greenhouses, balneotherapy, etc.
- Develop low carbon and geothermal technology industry, and create employment opportunities.
- Improving quality of life based on economic and environmental / climate benefits.
-

Additional International Recommendations

International Framework Recommendations

Following recommendations are highlighted:

1. Simplify the administrative procedures to create market conditions to facilitate development.
    a. Separate law regarding geothermal resources and other fossil fuels resources.
    b. Improve access to geothermal data – to improve development of geothermal utilization.
2. Develop innovative financial models for geothermal district heating, including a risk insurance scheme, and the intensive use of structural funds.
3. Establish a level playing field, by liberalizing the gas price and taxing greenhouse gas emissions in the heat sector appropriately.
4. Train technicians and decision makers from regional and local authorities in order to provide the technical background necessary to approve and support projects.
5. Increase the awareness of regional and local decision-makers on geothermal potential and its advantages.

1. Modernize the district heating system – and harmonize national and EU law in the sector.
2. Improve the role of district heating companies – the role of independent regulators.
3. Consider additional elements of public authorities, energy efficiency etc.
4. Consider, what international financing institutions can do to help.
5. Support – regional and energy clusters – to speed up development and process.
6. Geothermal energy is economic, secure and a powerful tool to fight against global warming.

Geothermal Development and Lessons Learned in Iceland

The following elements of policy priority have been shown to be important regarding geothermal development:

1. Awareness raising among policymakers, stakeholders and municipalities.
2. Education and capacity building.
3. Evaluation of geothermal resources.
4. Promotion of geothermal power generation and district heating projects.
5. Development of legal and regulatory framework.
6. Financial support for early stage development and exploration.
7. International cooperation, geothermal and financial expertise.

Heating Houses in Norway, Lessons Learned

The following elements of policy priority have been shown to be important regarding geothermal development:

1. Awareness raising among policymakers, stakeholders and municipalities.
2. Education and capacity building.
3. District heating is key player in reaching climate goals.
4. Geothermal energy is key contributor to district heating in future.
5. Heat pump application in district heating increasing.
6. Geothermal heat pump applications dependent on temperatures.
7. Increasing trend for heat pump application in Norway .
8. Work in progress

Lessons Learned – from Europe (by EGEC)

The following elements of policy priority have been shown to be important regarding geothermal development:

1. Demand for comfort, energy / electricity will increase in Europe.
2. Costs of fossil fuel energy will rise.
3. Ensuring Access to Affordable Energy for All.
4. Towards an European Geothermal Risk Insurance Fund (EGRIF).
5. Well-designed support schemes.
6. Climate dimension.

PART III

GEOTHERMAL DISTRICT HEATING IN EUROPE
INTERNATIONAL LESSONS LEARNED

1. Geothermal district heating – cost structure

In most cases, geothermal district heating projects face the same issues as geothermal power plants. Furthermore, geothermal heat pumps can also be considered as a capital intensive technology in comparison with other small scale plications (EGEC, 2013) (Figs. 1.1, 1.2).

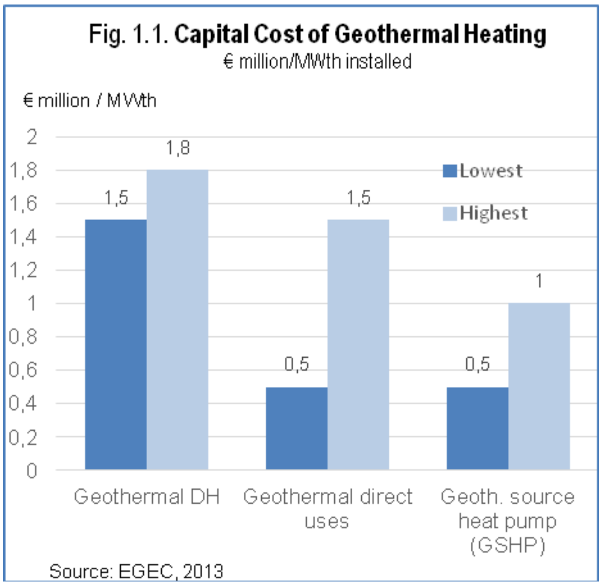


Fig. 1.1. **Capital Cost of Geothermal Heating**
€ million/MWth installed
Source: EGEC, 2013

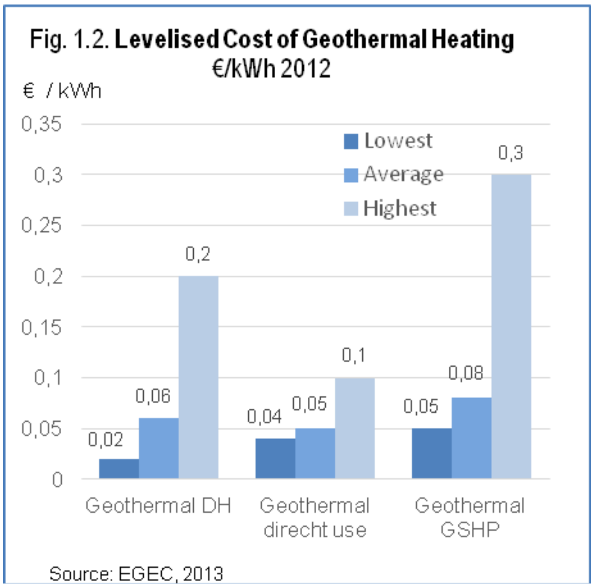


Fig. 1.2. **Levelised Cost of Geothermal Heating**
€/kWh 2012
Source: EGEC, 2013

Geothermal heat is also important and competitive for district heating, where a resource is available, especially where a district heating system is already in place. Geothermal heat can also be competitive for industrial and agriculture applications. Geothermal heat pumps can also be profitable, in comparison with fossil fuel heating systems.

Geothermal heat may be competitive for district heating where a resource with sufficiently high temperatures is available and an adaptable district heating system is in place. Geothermal heat may also be competitive for industrial and agriculture applications (greenhouses). As geothermal heat pumps can be considered a mature and competitive technology, a level playing field with the fossil fuel heating systems will allow phasing out any subsidies for shallow geothermal in the heating sector.

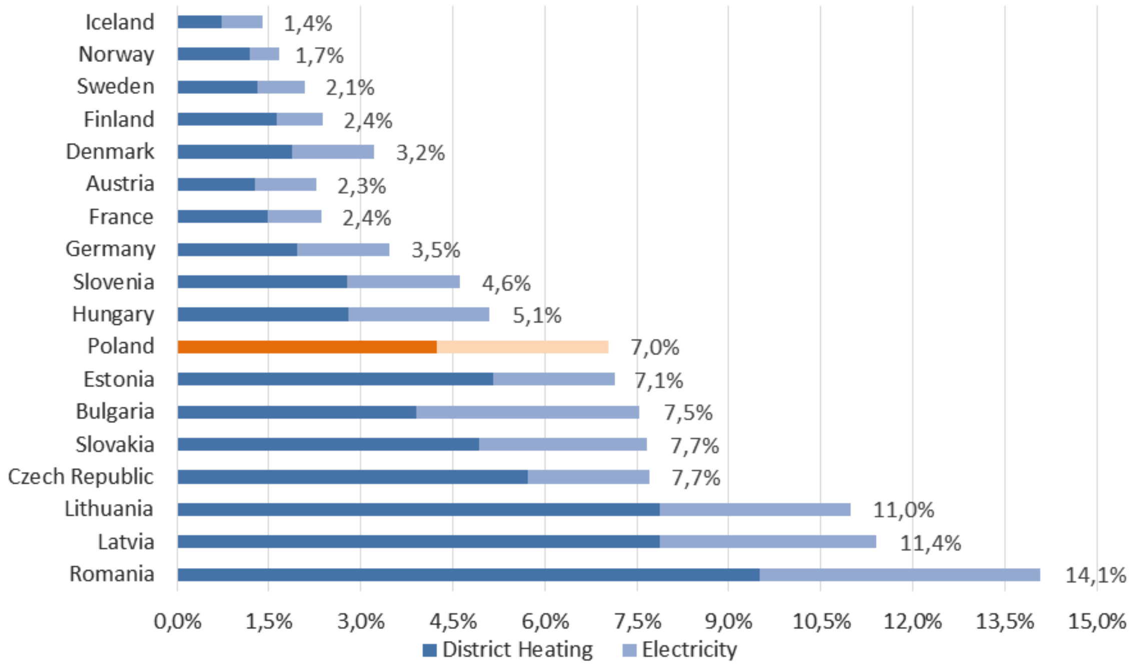
In many cases, geothermal district heating projects face the same issues as geothermal power plants, the need of capital and risk mitigation is therefore also valid for this technology. Moreover, notably because of the drilling, geothermal heat pumps can also be considered as a capital intensive technology in comparison with other small scale applications. Geothermal heating and cooling technologies are considered competitive in terms of costs, apart from the notable exception of EGS for heating.

In addition, an important barrier for both electricity and heating and cooling sectors is the unfair competition with gas, coal, nuclear and oil, which is the primary reason justifying the establishment of financial support schemes for geothermal.

If we look at the proportion of annual's salaries of people for buying district heating and electricity for 100 m^2 household in Europe, we can see that Iceland is paying the lowest proportion for both district heating and electricity, and Romania is paying the highest (Fig. 1.3).

The risk characteristics of a geothermal heating project are different depending on the three stages of the projects, which are: 1. Exploration, 2. Drilling, and 3. Building, which is less risky.

Fig. 1.3 **The Proportion of Annual's Salaries of people for buying District Heating and Electricity for 100m² Household in Europe**



Source: Orkustofnun Data Repository: OS-2016-T006-01

In a calculation presented in a GeoDH paper from 2014, it is estimated that, *"a private investor who would be given the opportunity to invest 20 million Euros in the building, and receives a feed-in tariff of 90-96 Euros/ MWh would earn around 9-10% per annum on the 20 million € invested. If that investor financed two-thirds of this investment with debt, as is common practice for such investments, the return on equity can rise to 20%. This observation leads us to the conclusion that a feed-in tariff, such as is already available in the wealthier member states of the European Union, is sufficient to attract investment for the building and operation stage of a geothermal electricity generating plant, if only the exploratory and drilling stages are completed"* (Christian Boissavy, 2014).

It is therefore an important element of a geothermal heating project that there are options and possibilities of support from public authorities towards the exploration and the drilling stage of such a project. In the above mentioned paper it is recommended that the support should cover 75%-80% of the exploration and drilling cost if the project fails. This is especially important due to the risk of test drilling.

In Iceland for example, the test drilling for such projects can be refunded by the Energy Fund if the test drilling is not successful.
Regarding heat generating geothermal plants, the benefits are greater when high temperature resources is used to generate both heat and electricity than when it is used for heat alone.

The geothermal heat production has several advantages, such as:

1. Economic opportunity and savings.
2. Improvement of energy security.
3. Reducing greenhouse gas emissions.
4. Harnessing local resources.
5. Reducing dependency on fossil fuels for energy use.
6. Local payback in exchange for local support for deep drilling.
7. They complement existing district-heating networks offering an alternative to other fuels.
8. They can be combined with smaller binary cycle (if reservoir and economics allow) electricity generating plants to bring the utilisation of the reservoir to the maximum.
9. May be a useful complement to regional and local economic development programmes with positive effect on employment and the viability of public infrastructure.
10. They raise public awareness for the geothermal energy to a broader section of the public
11. Improving quality of life based on economic and environmental / climate benefits.

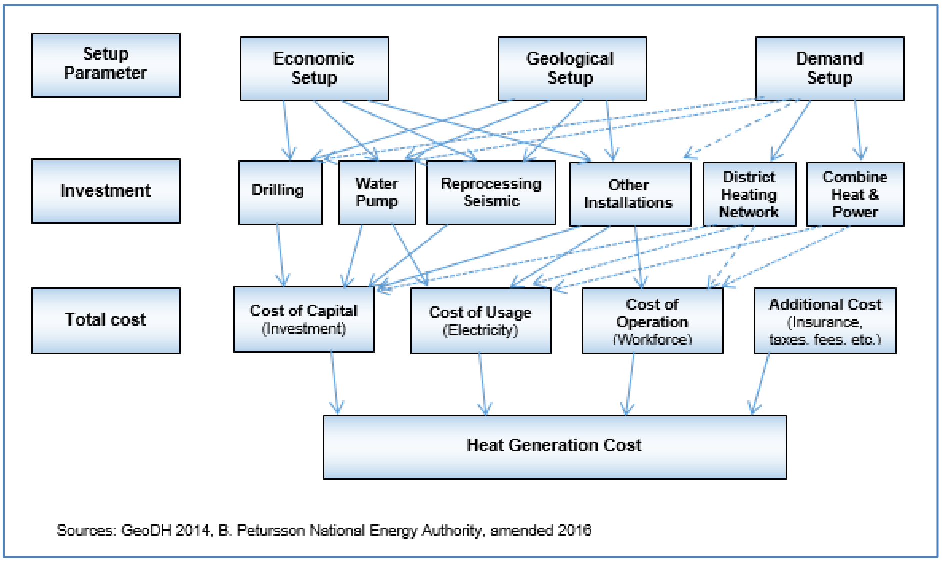
It is difficult or impossible to present standard costs of geothermal district heating projects, as the cost vary between regions and variable conditions. Nevertheless, the costs of such a project can be estimated, based on the most important parameters for the understanding of the individual projects, by:

- first defining the basic conditions affecting the heat generation cost,
- secondly by developing theoretical projects in order to explore economic viability.

Key factors for geothermal district heating projects are:

- geological framework,
- economic conditions and
- demand.

Fig. 1.4. Cost structure of geothermal heat generation project



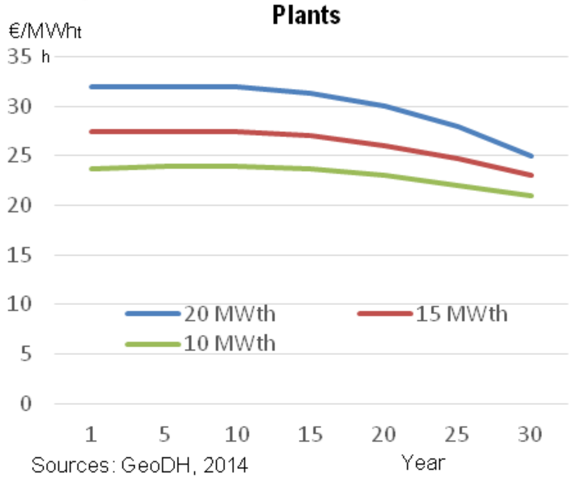
Although it is difficult to estimate profitability of such projects, the cost for each project can be based on the demand structure, geological conditions, the costs of capital and the existing geological data, as is shown in figure 1.4.

The demand aspect plays an important role in defining the project and the investments e.g. drilling, size of the water pump, buildings, district heating network and a power plant's mechanisms. In addition, the evaluation of heat production costs depends on the geothermal energy resource. It should also be noted that many of these cost elements are the same as for a standard heat production installation.

However, due to the fact that every location has different demand conditions, it is not possible to incorporate these factors in a general heat production cost calculation. Moreover, many costs are equal to those of a conventional heat generation installation. A paper for GeoDH from 2014 presented a calculation estimating the cost of a geothermal heat production project. The calculation was based on the following costs elements:

- capital cost (investments for drilling, water pump, substation, depreciation),
- operational cost (electricity for pumping & equipment, maintenance).

Fig. 1.5. **Heat Generation Cost of three Different Plants**



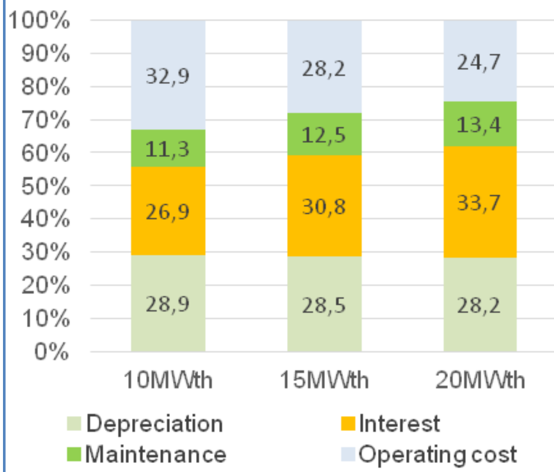
However, in addition to these costs, geothermal heat generation plants have to be connected to a network of plants using other energy sources, like a gas-fired or coal-fired power plant to be able to cope with peak loads. That kind of cost is not included in the project example that will be described in figure 1.5.[1]

[1] The geothermal generation heat project provides the base load energy for district heating, which will be delivered to the district heating network, total hours of the plant will be 8.000 hours/year. The focus will be on generation cost so no revenues will be calculated. Life time of the project is estimated 30 years of operation; repayment of loans is 30 years, depreciation off the drilling is 50 years, depreciation of the substation is 30 years, depreciation of the pump is 3 years and interest rate will be 7,5%. The costs for a district heating network and special installations, as well as taxes and fees, are not included.

Calculations on geothermal heat generation cost carried out for GeoDH in 2014, involved three projects 10, 15 and 20 MW_{th} as shown in figure 1.5. It is interesting that the figure illustrates that the generation cost is stable for a period of 30 years, (due to lower costs of capital over time), which is opposite to the trend for forecasted prices for fossil fuels. Higher cost for 15 and 20 MWth projects than 10 MWth, is due to a higher capital cost in form of interests due to more expensive drilling.

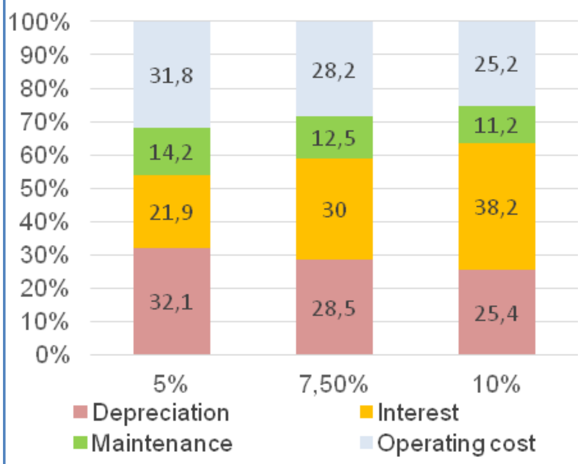
As can be seen from figure 1.6, the cost structure is different depending on size of project, but for all projects the capital cost (depreciation and interests) is the biggest part of the overall cost, as this is a capital intensive sector. For the 10 MW_{th} case, the biggest single cost factor is operation coming from electricity cost to run the water pump.

Fig. 1.6. **Cost Structure of Generation Project Depending on Size**



Source: GeoDH, 2014

Fig. 1.7. **Cost Structure of a 15 MWth Project and Sensitivity Analysis of Interest**

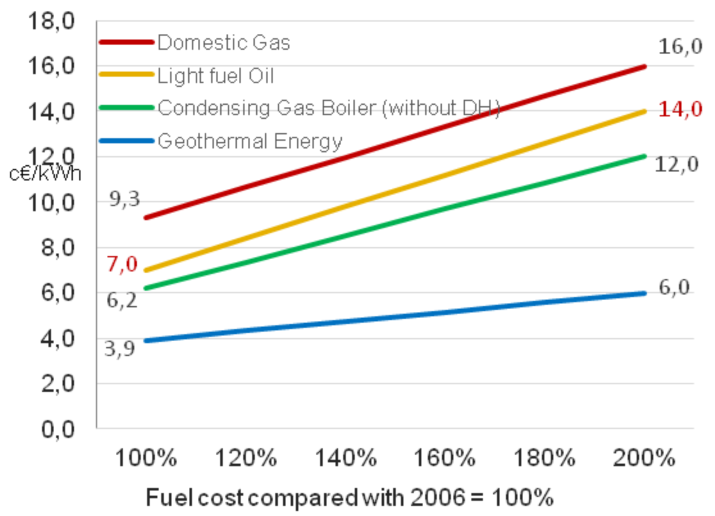


Source: GeoDH, 2014

For the biggest project the largest cost factor is capital cost - interest. As these projects are capital intensive, interest plays a major role regarding profitability, as can be seen for the sensitivity analysis in figure 1.7, where the 5% interests cost go from 21,9% up to 38,2% if the interests are 10%. Rates of interest are therefore one of the biggest risk factors.

Fraunhofer Institute for Environmental, Safety and Energy Technology carried out a study for Germany, comparing the heat generation costs between fossil fuels and geothermal heat plants delivering heat to district heating networks, (2006 prices). The study shows, that cost structure of generating heat from fossil has higher operating costs than geothermal which has higher fixed costs. Total heat generation costs of geothermal energy are low in absolute terms due to the high utilisation rate and low variable cost. During increase of primary energy prices, the total costs of generating heat from fossil fuels are rising more rapidly due to high variable cost, than from geothermal, as can be seen on figure 1.8.

Fig. 1.8. **Heat Generation Cost for District Heating Network by Fuel**



Source: GeoDH 2014.

Business Model for Geothermal District Heating and Gas

Cost Comparison – kWh Produced by Natural Gas and Geothermal Heat

Following business model is based on comparison between a district heating network using natural gas and a geothermal district heating network, in the Paris area, described in GeoDH paper from 2014. The project (geothermal doublet) has been running for 31 years. However, the geothermal water flow rate is decreasing (GeoDH, 2014).

The key findings of this demonstrative example in France is that the actual production cost of the heat produced using 100% gas is about 5,6 c€/kWh for a final selling price to the consumer at 70 c€/kWh, all inclusive.

However, the same kWh produced with a mix of natural gas (24,82%) and geothermal (75,18%) is 3.27 c€/kWh. The benefits and difference, which is 2,33 c€/MWh, will allow to finance the construction of the doublet. The annual production of the project is 81.980 kWh/ year with a turnover of 5,739 k€. The annual profit using geothermal is 1.918 K€.

This profit will pay back the investment cost in 7,45 years, meaning that after 8 years the community will start to gain about 2 million euros per year, or it would be possible to lower the price of 2,33 c€/kWh and keep the profit as before (GeoDH, 2014). This demo example, shows the opportunities and economic benefit that may be gained from geothermal resources in combination with other energy resources in district heating.

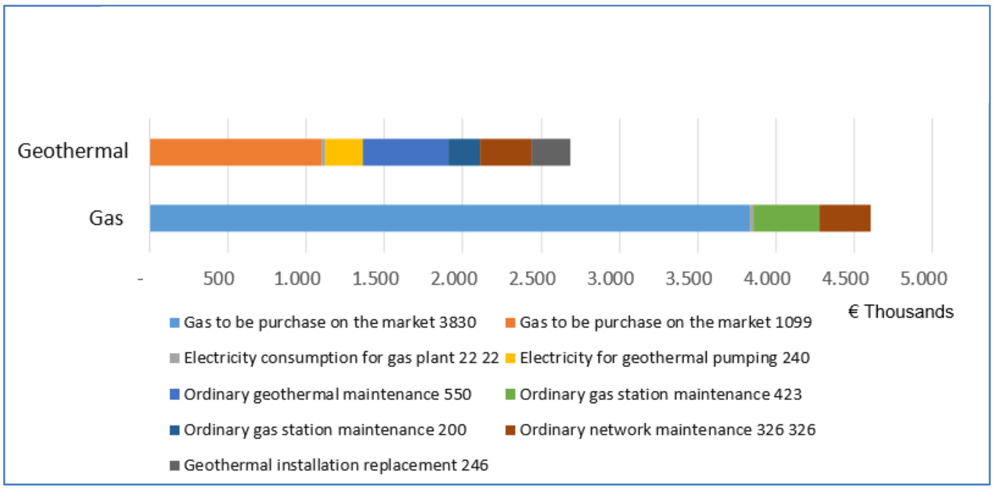


Fig. 1.9. Annual operational cost comparison of district heating powered by gas (100%), geothermal (75%) and gas (25%) in France

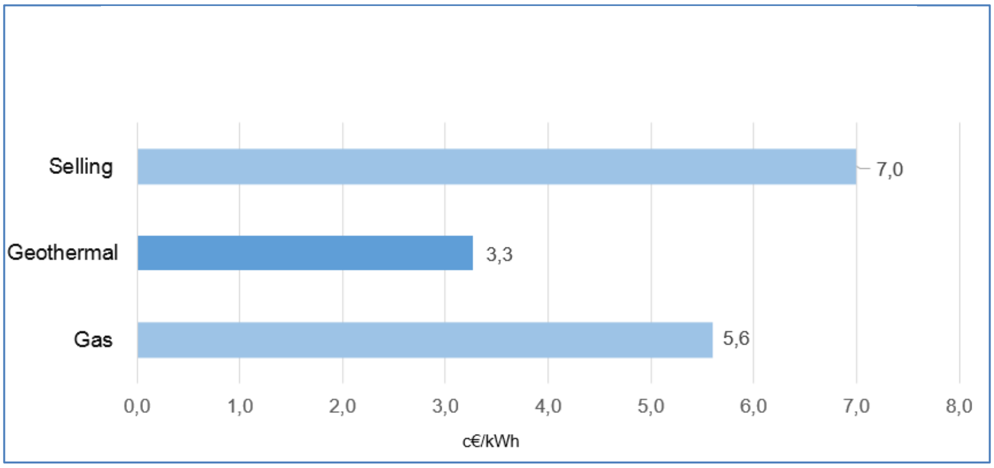


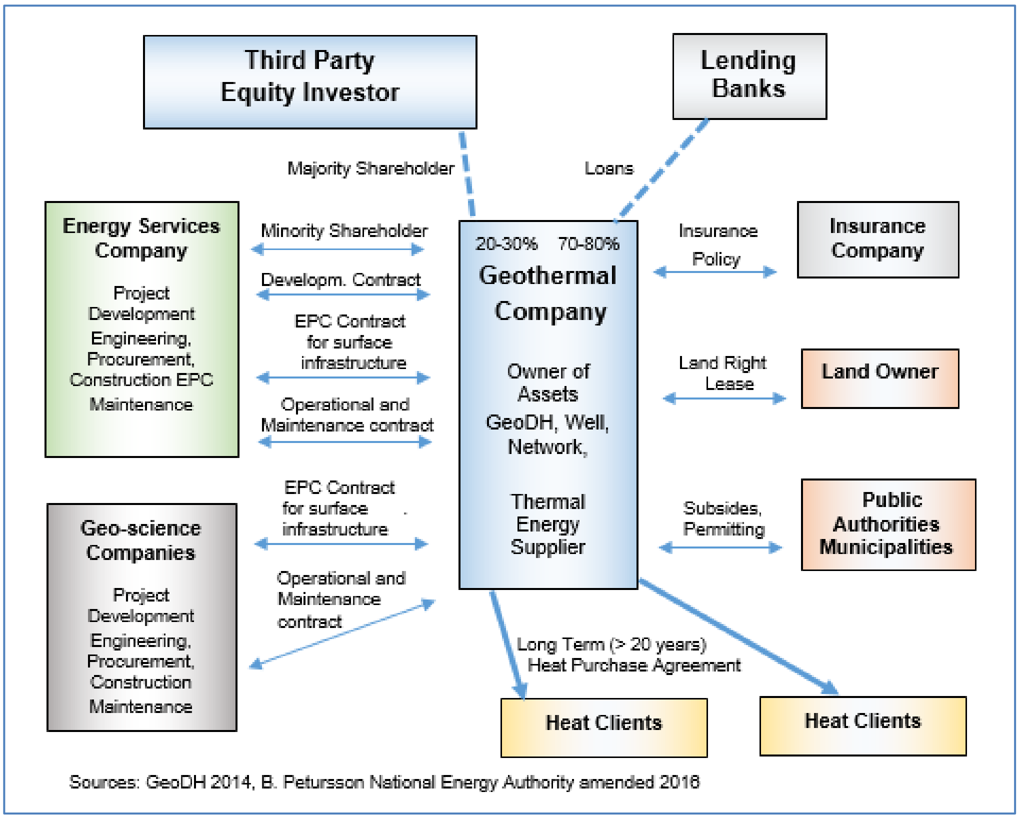
Fig. 1.10. An example of economic benefit that may be gained from geothermal resources in combination with other energy resources in district heating

As can be seen from the case in France, the actual annual operational / production cost of the heat generated using 100% gas is about 4,6 M€ (5.6 c€/kWh) – but only 2,7 M€ (3,27 c€/kWh) with a combination of geothermal (75%) and gas (25%).

The benefits and difference which is 2,33 c€/MWh will allow to finance the construction of the doublet – and the profit will pay back the investment cost in 7,45 years – meaning that after 8 years the community will start to gain about 2 million euros per year – or it would be possible to lower the price of 2,33 c€/kWh and keep the profit as before.

2. Geothermal district heating – legal structure

Fig. 2.1. Legal and financial framework for geothermal district heating



Legal and financial structure and planning are main elements of geothermal district heating planning and risk assessment. However, risk assessments depend on each type of project which can be different based on location, regulation, technology, management, finance etc. Nevertheless, there are also general similarities for such projects regarding legal and financial frameworks for geothermal district heating – as can be seen in enclosed figure 2.1.

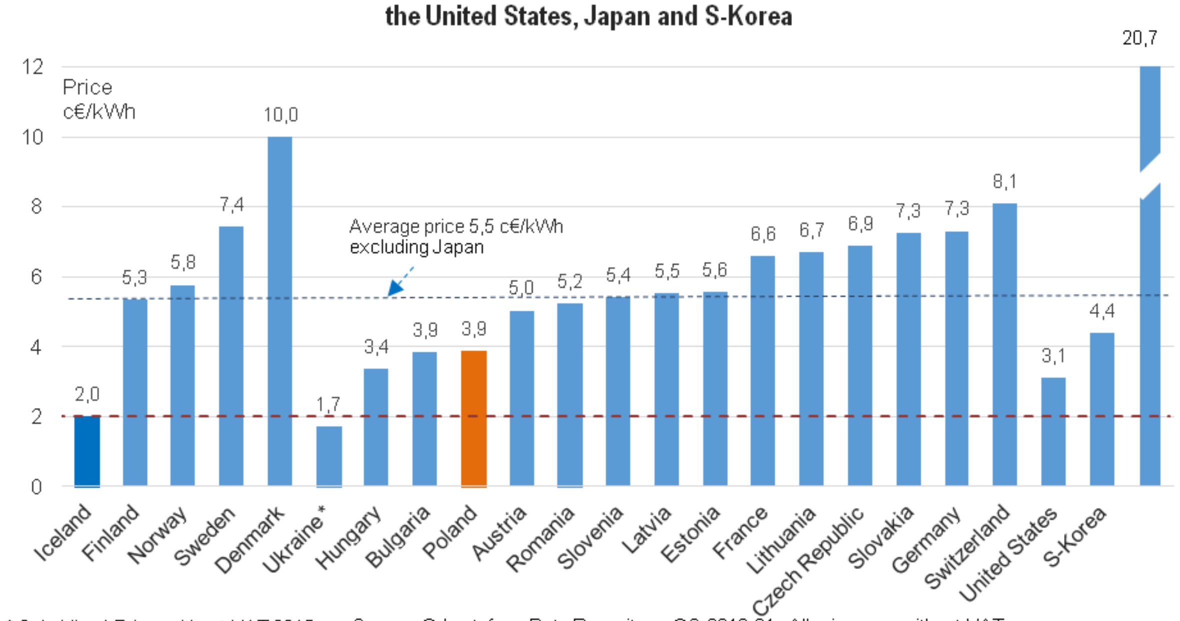
A Geothermal Company (GC) financed by the equity investor (20-30%) and by bank by loans (70-80%), is established to centralise the assets, rights and operational agreements. This company signs long term (>20 years), heat purchase agreements with end users with a fixed charge (capacity charge) linked to kW of capacity subscribed, and a variable charge ("consumption charge") proportional to kWh supplied.

The company should also sign key contracts regarding engineering, procurement and construction and operating and maintenance, for both the geothermal well and the district heating network. The company also has to have insurance policies (civil liability, damage, geothermal resource risk if possible, etc.). Finally, the company has to secure land rights, permitting and subsidies with the land owners and public authorities or municipalities. (GeoDH, 2014).

3. Global price comparison of geothermal district heating

Due to its diffusive nature, there are economic limits to the geographic transport of heat. As a result, the utilization of geothermal resources for direct applications is quite localized, as demonstrated by the fact that the longest geothermal heat transmission pipeline in the world, found in Iceland, is 64 km in total (Georgsson et al., 2010). In contrast, electricity can be transmitted thousands of kilometres and oil can be shipped around the globe. In Europe, gas is a common source of heat that can be transported in pipelines over thousands of kilometres.

Fig. 3.1. **Average District Heating Prices in Europe, the United States, Japan and S-Korea**



* Subsidised Price, without VAT 2015. Source: Orkustofnun Data Repository: OS-2016-01. All prices are without VAT

Nevertheless, local resources are commonly used where possible, which results in substantial differences in the energy mix between countries. Figure 3.1. shows this variation for heating in the Nordic countries. District heating systems are in many of the regions, with the exception of Norway, where electricity covers 70-80% of heating demand, with the remainder primarily met by bioenergy (7%), oil (7%) and district heating (4%) (NVE, 2013).

Out of all countries surveyed by Euroheat & Power, Iceland has the lowest unsubsidised, district heating price of 2,0 €¢/kWh compared with an average value of 5,5 ¢€/kWh, and a maximum value of 20,7 ¢€/kWh. The great variation in prices within the Nordic countries, which all have cold climates and therefore a considerable need for heating, is of particular interest.

Out of the 20 surveyed countries, the highest price is encountered in Denmark (except Japan) and the second highest in Sweden. It is probable that the reasons are not only economic, but also political. In general, taxes tend to be high in the Nordic countries and countries with limited domestic energy options, such as Denmark, have been supporting and subsidising renewable energy such as wind, which have resulted to higher price to customer.

The fortune of Icelandic consumers is therefore the abundance of low-price, environmentally friendly geothermal heat that translates to the lowest average district heating price on record in Europe and possibly the wider world. In the United Kingdom, one of Iceland's neighbouring countries, the main source of energy for heating is gas (Association for the Conservation of Energy, 2013). In 2009, the average gas price in the UK was 11.84 EUR/GJ, including all taxes and levies (Eurostat, 2014). Assuming 80% efficiency (Association for the Conservation of Energy, 2013), brings the price up to 14.80 EUR per GJ of usable heat.

This translates to 5.33 EUR¢/kWh, or 7.12 USD¢/kWh, which is slightly above the average price for district heating in Europe, and substantially higher than the price in Iceland. From these comparisons, it is evident that Icelandic geothermal district heating prices are very competitive.

However, it is important to be aware of differences in climatic conditions between countries that lead to differences in the length of the heating season. Shorter heating seasons may lead to higher unit prices, as district heating companies must cover incurred costs based on sales over a limited time period each year. Other factors that influence heat demand, and thus consumers' wallets, include:

- **Ambient temperature:** The heat flow through a building wall is directly related to the temperature difference over the wall, indicating that year-to-year fluctuations in ambient temperature affect heat demand as was clearly observed in Norway in 2010 (NVE, 2013).
- **Indoor temperature,** which is influenced by personal comfort choices, habits, prices and other factors, and can therefore vary over the population of a country.
- **Insulation and airtightness of buildings,** which may vary between countries.
- **Ventilation,** preferences of home owners.
- **Heat metric and pricing system (HMPS).** The HMPS is a key element regarding the price and consumption. In some less developed countries there is no individual HMPS, and even confusing management and ownership of the GeoDH companies, damaging price, demand and efficiency.

4. Geothermal for industrial use

Geothermal resources can be used for various activities, as can be seen from the picture. In Iceland it has also been done, e.g. for greenhouses, fish farming, bathing, etc. (Fig. 4.1).

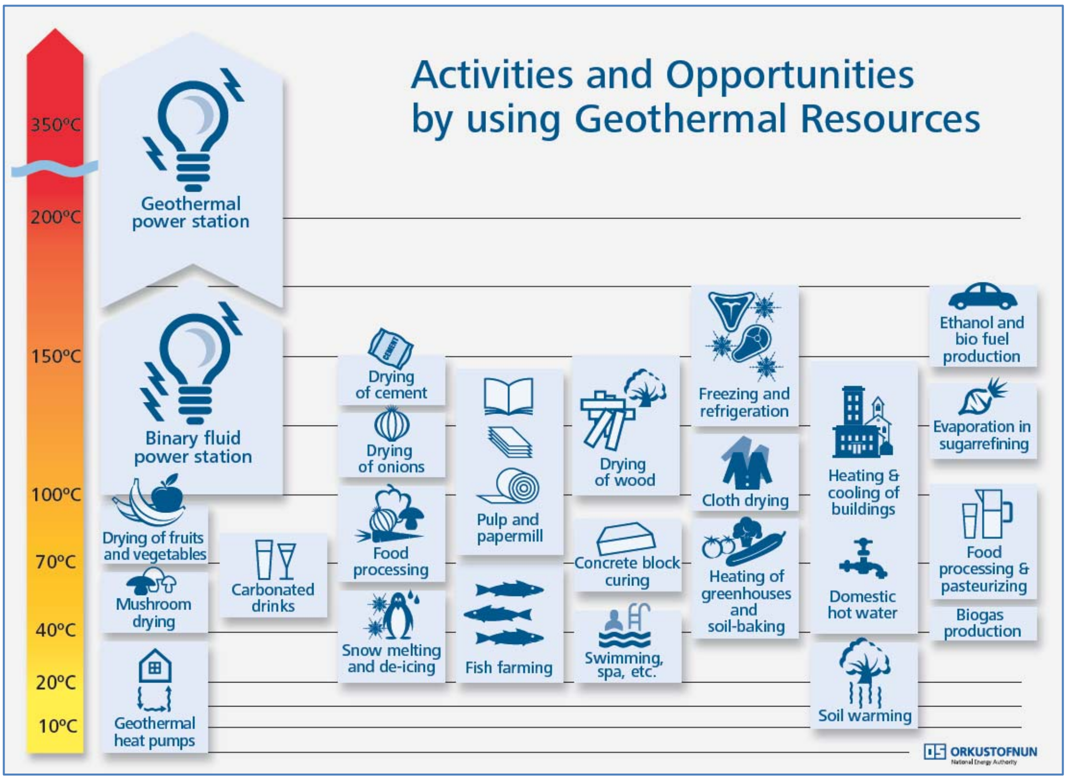


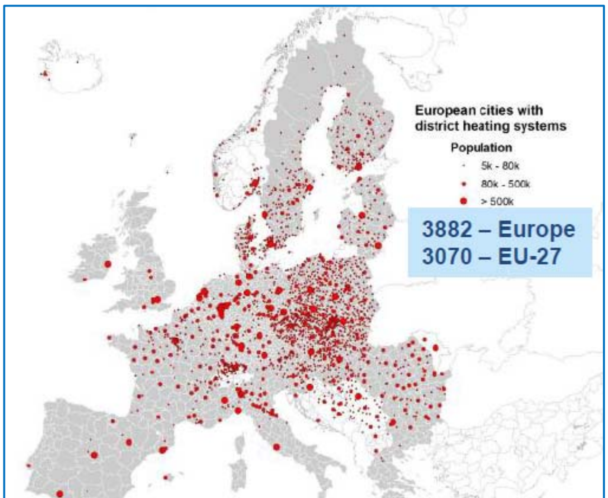
Fig. 4.1. Activities and opportunities by using geothermal resources

5. Policy towards geothermal district heating in Europe and Poland

5.1. Geothermal policy in Europe

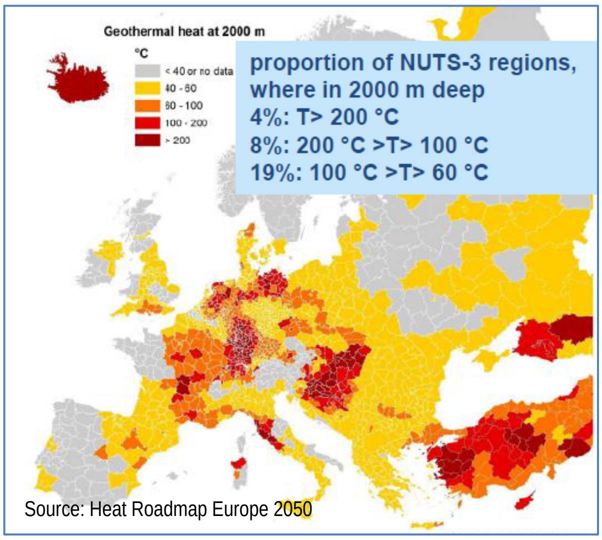
AEBIOM, EGEC and ESTIF, organizations representing the biomass, geothermal and solar thermal sectors respectively, addressed an open letter to the EU Heads of State and Government, 19th of March 2014. The letter states that "...Investing in renewables for heating and cooling will bring security of supply and more competitiveness, and could save EUR 11,5 billion per year, announces the industry. Over recent years, the lack of awareness and political support to renewables for heating and cooling has meant only modest market development in the sector. However, in view of the upcoming discussion of the European Council on EU climate and energy policies beyond 2020, there is a great opportunity to invert this trend." Dr. Guðni A. Jóhannesson Director General of the National Energy Authority of Iceland, also stated in the ERA NET Newsletter in May 2014 that, "It is important for policymakers and others to recognize the great opportunity regarding geothermal heating for savings for countries, as it is estimated that geothermal heating in Iceland is saving equal to 7% of GDP or 3000 US$ per capita or close to 1 billion US$ for the economy only for 2012.

Fig. 5.1. Localities with district heating systems in EU-28



Source: Heat Roadmap Europe 2050

Fig. 5.2. Geothermal heat at 2000 meters



Source: Heat Roadmap Europe 2050

Untapped geothermal resources could significantly contribute to the decarbonization

According to Heat Road Map Europe 2050, untapped geothermal resources in Europe could significantly contribute to the decarburization of the district heating market as it has been estimated that geothermal district heating would be available to 25% of the EU-27 population. It has been estimated that 12% of the communal heat demand is from district heating and heat supply to district heating systems is 17% from power plants, 7% from waste, 3% from industrial heat, 1% from biomass and only 0,001% is coming from geothermal resources.

According to Eurostat, about one third of the EU's total crude oil (34,5%) and natural gas (31,5%) in 2010 was imported and, 75% of that gas was used for heating (2/3 in households and 1/3 in the industry). Geothermal district heating therefore has potential possibilities to replace a significant part of imported oil and gas for heating households and industry. GeoDH consortium has proposed policy priorities towards such development which are (GeoDH, 2014):

1. Simplify the administrative procedures to create market conditions, to facilitate development;
2. Develop innovative financial models for geothermal district heating, including a risk insurance scheme, and the intensive use of structural funds.
3. Establish a level playing field, by liberalizing the gas price and taxing green-house gas emissions in the heat sector appropriately.
4. Train technicians and decision-makers from regional and local authorities in order to provide the technical background necessary to approve and support projects.
5. Increase the awareness of regional and local decision-makers on deep geothermal potential and its advantages.

5.2. Geothermal opportunities in Poland

According to Heat Road Map Europe 2050, untapped geothermal resources in Europe could significantly contribute to the decarbonization of the district heating market as it has been estimated that geothermal district heating would be available to 25% of the EU-27 population.

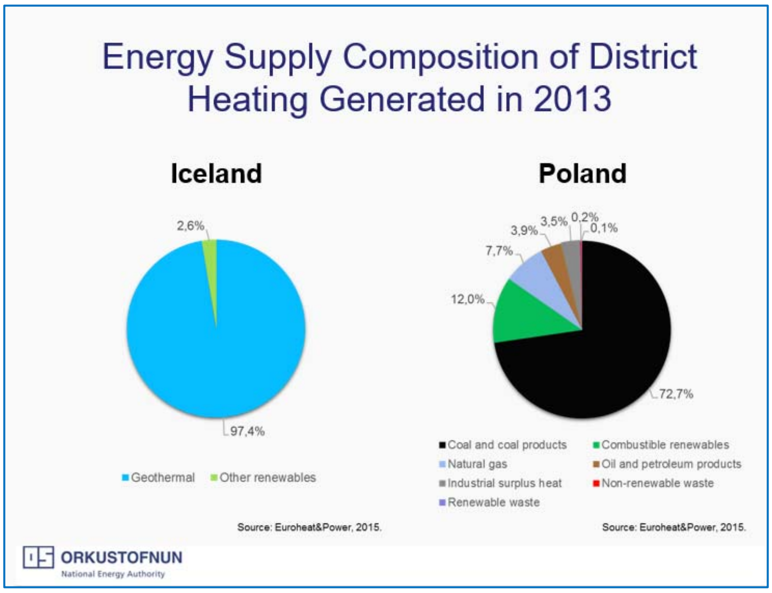


Fig. 5.3. Energy supply composition of district heating generated in 2013

Nearly 5000 cities in Europe have district heating systems and about 500 in Poland. In addition, in many of these areas and cities, there are geothermal resources that can be utilized for district heating.

In Poland there are relative high number of citizens that are served by district heating, or about 53%. In addition, Poland has one of the highest district heating sources coming from coal.

- Poland has therefore exceptional and great opportunities to increase use of geothermal resources for district heating that are available.
- Poland can also shift district heating resources from coal to geothermal – and at the same time reduce greatly CO2 for heating.

Therefore, Poland can play a key role for geothermal district heating development in Central Europe - and contribute to mitigate climate change and constantly increasing temperature in the world, due to climate changes.

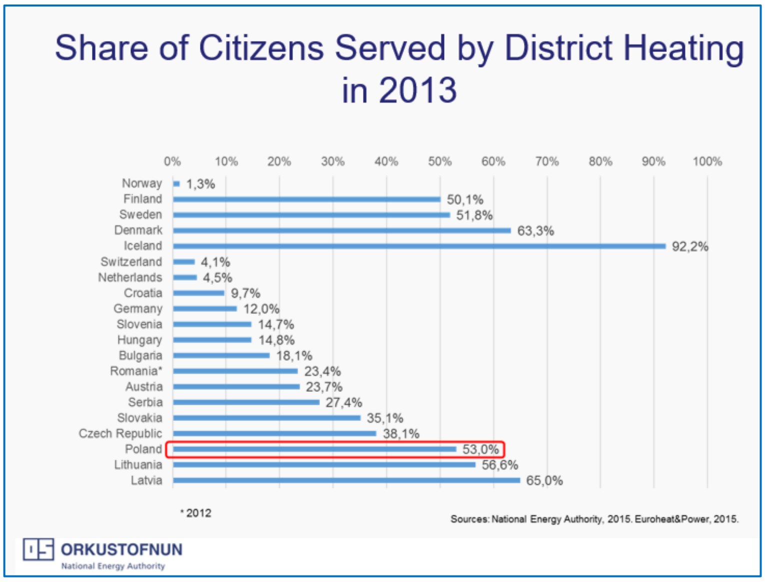


Fig. 5.4. Share of citizens served by district heating in 2013

5.3. Geothermal utilisation – international framework recommendation

In many countries in Europe, geothermal district heating has potential possibilities to replace a significant part of imported oil and gas for heating in households and industry. The following general recommendations are highlighted:

1. Simplify the administrative procedures to create market conditions that facilitate development;
    a. Separate law regarding geothermal resources and other fossil fuels resources.
    b. Improve access to geothermal data - to improve development of geothermal utilization.
2. Establish a level playing field, by liberalizing the gas price and taxing greenhouse gas emissions in the heat sector appropriately;
3. Increase the awareness of regional and local decision-makers on geothermal potential and its advantages.
4. Modernize the district heating system:
    a. Better quality of service.
    b. Lower cost.
    c. Improved transparency.
    d. Following improvements of financial viability of district heating companies.
    e. Reduce cost of supply.
    f. Increase revenue.
    g. Quality service should be affordable.
5. Improve the role of independent regulators.
6. Improve the role of district heating companies.
7. Additional elements of public authorities.
    a. Finance energy efficiency programs.
    b. Support public awareness campaigns for benefits of metering.
    c. Providing incentives for demand-side management.
    d. Providing target support to poor customers.
8. Harmonization with EU Law.
9. Train technicians and decision makers from regional and local authorities in order to provide the technical background necessary to approve and support projects.
10. Develop innovative financial models for geothermal district heating, including a risk insurance scheme, and the intensive use of structural funds;
    a. Grants / risk loans to geothermal district heating for exploration and test drilling to lower the risk.
    b. Grants to individuals (apartments) for changing to geothermal district heating.
    c. Grants to district heating companies for transformation to geothermal district heating.
    d. Loans to district heating companies' tor transformation to geothermal district heating.
11. What can international financing institutions do to help?
    a. Financing / Support district heating transformation towards geothermal district heating
    b. Financing and implementing heat metering and consumption based billing.
    c. Financing energy efficiency measures along the supply line.
    d. Technical assistance to newly established regulators.
    e. Technical assistance for the design of targeted social safety nets.
12. Access to International Geothermal Expertise, Markets and Services.

Geothermal Options, Opportunities and Benefits

The geothermal heat generation has several advantages, such as:

1. Economic opportunity and savings.
2. Improvement of energy security.
3. Reducing greenhouse gas emissions.
4. Harnessing local resources.
5. Reducing dependency on fossil fuels for energy use.
6. Improving industrial and economic activity.
7. Develop low carbon and geothermal technology industry, and create employment opportunities.
8. Local payback in exchange for local support for geothermal drilling.
9. Improving quality of life based on economic and environmental / climate benefits.

6. Geothermal utilisation – lessons learned – Iceland

6.1. Expansion of geothermal district heating 1970 – 2015

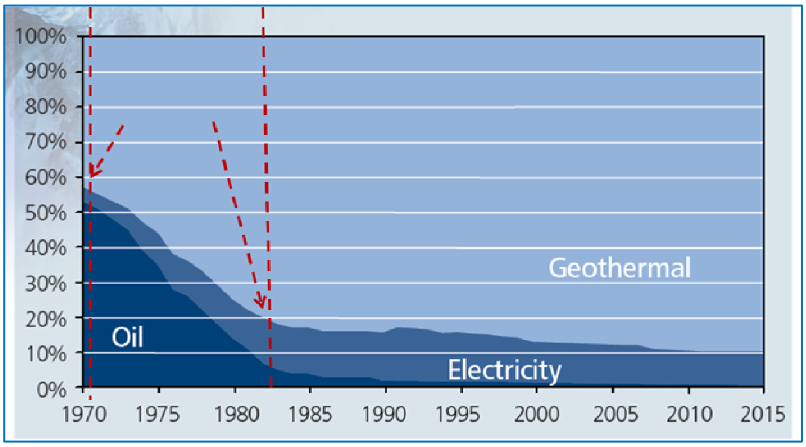


Fig. 6.1. Expansion of district heating by source 1970-2015

- **Biggest steps in GeoDH were taken during the oil & war crises 1970 – 1982**
- **External conditions – raised the need of evaluation and GeoDH Planning**
- **Policy goals to increase geothermal – both national and within main cities**
- **It took only 12 years to increase GeoDH from 40% to 80% of total space heating**

Expansion of geothermal district heating

When the oil crisis struck in the early 1970s, fuelled by the Arab-Israeli War, the world market price for crude oil rose by 70%. At the same time, close to 90.000 people enjoyed geothermal heating in Iceland, about 43% of the nation. Heat from oil served over 50% of the population, the remainder used electricity. In order to reduce the effect of rising oil prices, Iceland began subsidizing those who used oil for space heating. The oil crises in 1973 and 1979 (Iranian Revolution) caused Iceland to change its energy policy, reducing oil use and turning to domestic energy resources, hydropower and geothermal (Fig. 6.1).

This policy meant exploring new geothermal resources, and building new heating utilities across the country. It also meant constructing transmission pipelines (commonly 10-20 km) from geothermal fields to towns, villages and individual farms. This involved converting household heating systems from electricity or oil to geothermal heat. But despite the reduction in the use of oil for space heating from 53% to 7% from 1970 to 1982, the share of oil still remained about 50% to 60% of the total heating cost due to rising oil prices.

6.2. Economic benefits of using geothermal energy

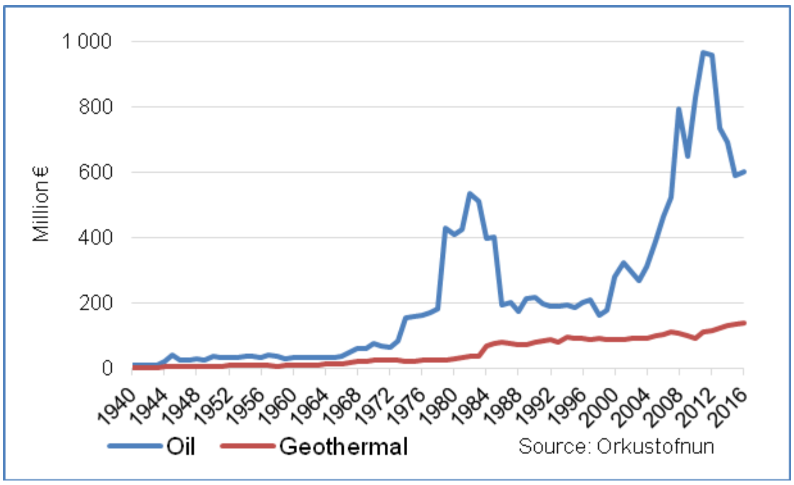


Fig. 6.2. Economic benefits of geothermal district heating
Price of a space heating by geothermal district heating and by oil 1914–2013

The economic benefits of the government's policy to increase the utilisation of geothermal energy can be seen when the total cost of hot water used for space heating is compared to consumer cost if oil would be used, as shown in Fig. 6.2. The stability in the hot water cost during strong variations in oil cost is noteworthy.

In Figure 6.2 the blue line shows price for geothermal district heating, and the red line the calculated price for heating by oil, (adjusted to the consumer price index 1 USD = 120 ISK).

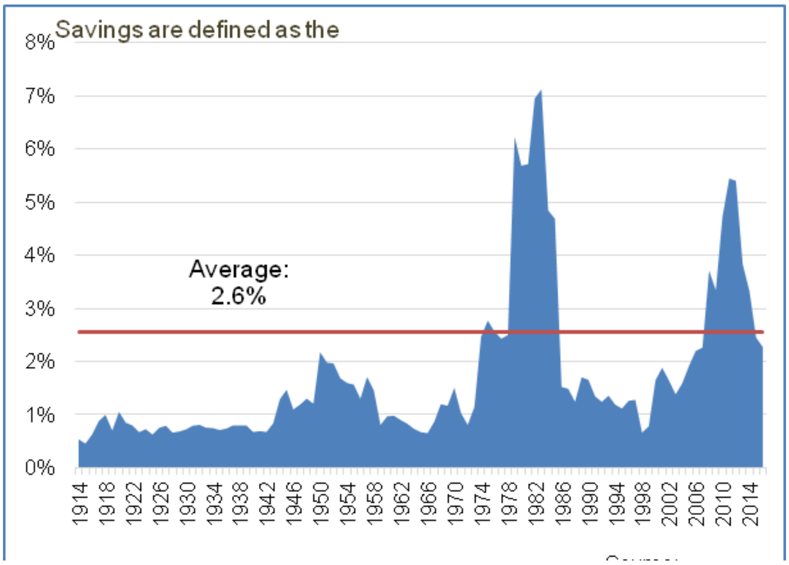


Fig. 6.3. Cumulative Savings from Geothermal District Heating in Iceland, 1914–2013
2% interests, fixed price 2013

Oil heating is 2-6 times more expensive than geothermal heating throughout most of the period but peaks to 16 times more expensive in the period 1973 to 1985 and has risen again since 2007 to a present ratio of 10. In 2012 the difference in cost amounted to 80% of the state budget cost of health care in the same year.

Evaluations of the estimated savings might vary somewhat as some might claim that sources other than oil could be used for heating. Heating energy could have been obtained through an increased generation of electricity with hydropower, as is done in Norway.

Nevertheless, it is beyond dispute that the economic savings from using geothermal energy are substantial, have had a positive impact on the currency account and contributed significantly to Iceland's prosperity, especially in times of need. The annual savings have been about 2,6% of GDP for most years but rise to 7% in the period 1973 to 1985, and have been nearing that peak again in recent years. The 7% of GDP is equivalent to 3.000 USD per capita and 2,6% is 1.115 USD.

Besides the economic and environmental benefits, the development of geothermal resources has had a desirable impact on social life in Iceland. People prefer to live in areas where geothermal heat is available, in the capital area and in rural villages where thermal springs can be utilised for heating dwellings and greenhouses, schools, swimming centres and other sports facilities, tourism and smaller industry. Statistics show improved health of the inhabitants of these regions.

In recent years, the utilisation of geothermal energy for space heating has increased mainly as a result of the population increase in the capital area (Fig. 6.4) as people have been moving from rural areas to the capital area. As a result of changing settlement patterns, and the discovery of geothermal sources in the so-called "cold" areas of Iceland, the share of geothermal energy in space heating is still rising. It is also possible to evaluate cumulative savings of geothermal district heating mainly from 1950 – 2013, based on real price (fixed price 2013) and 2% annual interest rate.

Fig. 6.4. Reykjavik

Based on these calculations, the overall cumulative savings is equal to 31 million ISK per family (€200.000), which is equal to the price of an apartment for a family (4 persons) in Iceland.

From 1982 – 2013 the majority of savings has happened after the geothermal district heating implementation and is about 2.000 billion ISK. This is equal to 64 billion ISK. (€412.000.000) per year, or 800.000 ISK (€5.160) per family, or about 70.000 ISK. (€450) per month per family, after taxes.

According to information from Statistics Iceland, 2.500 billion ISK, is equal to 80% of the total value of all residential houses and apartments in Iceland which was estimated around 3.200 billion ISK in 2013.

6.4. CO_2 savings by renewables in Iceland

The use of geothermal energy for space heating and electricity generation has also benefited the environment, as both geothermal energy and hydropower have been classified as renewable energy resources, unlike carbon fuels such as coal, oil and gas.

The benefit lies mainly in relatively low CO_2 emissions compared to the burning of fossil fuels. Since 1940 to 2014 the CO_2 savings by using geothermal district heating have been around 100 million tons, which is equal to saving of using 33 million tons of oil (Fig. 6.5, Fig. 6.6).

In 2014 the geothermal district heating savings of CO_2 in Iceland was about 3 million tons of CO_2, or equal to 1 million tons of oil, equal to CO_2 bindings in 1,5 billion trees and 7.150 km^2 of forest.

If we look at the accumulated savings of CO_2 by all renewables in Iceland 1914 – 2014, that savings is about 350 million tons, mostly since 1944. That is equal to CO_2 bindings in 175 billion trees, or 850 km^2 of forest and is equal to 120 million tons of oil. In 2014 the annual savings of CO_2 from renewables in Iceland was 18 million tons, equal to bindings of CO_2 in 9 billion trees, equal to 43.000 km^2 of forest. It is also equal to 6 million tons of oil.

These saved tons of CO_2 have been an important contribution for mitigation of climate change, not only in Iceland but on a global level as well, as climate change has no border between countries or regions. Geothermal district heating in Iceland and the use of other renewables, contributes towards economic savings, energy security and reduction of greenhouse gas emissions.

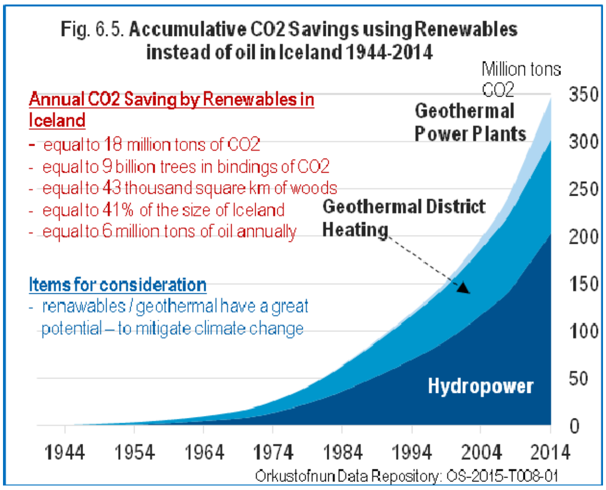
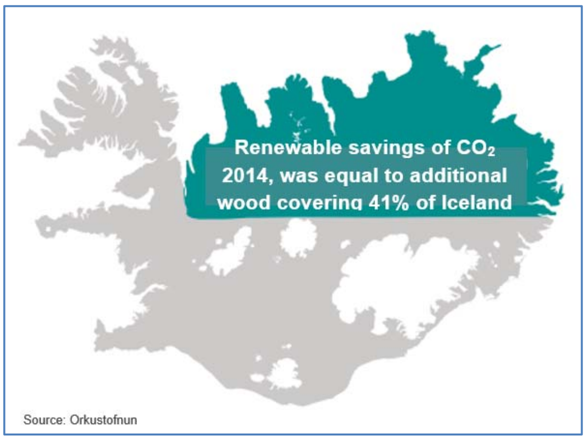


Fig. 6.6. The annual savings of CO_2 2014 from renewables in Iceland was equal to bindings of CO_2 in 9 billion trees, equal to 43.000 km^2 of forest or 41% of Iceland



7. International competitiveness of the geothermal sector

7.1. Cluster competitiveness

When recommending formulating policy recommendations for the geothermal sector, the enclosed model of 8 factors of geothermal competitiveness, challenges and opportunities, was used to highlight the key elements for policy recommendations and options in the concerning countries (Petursson, 2014, 2012).

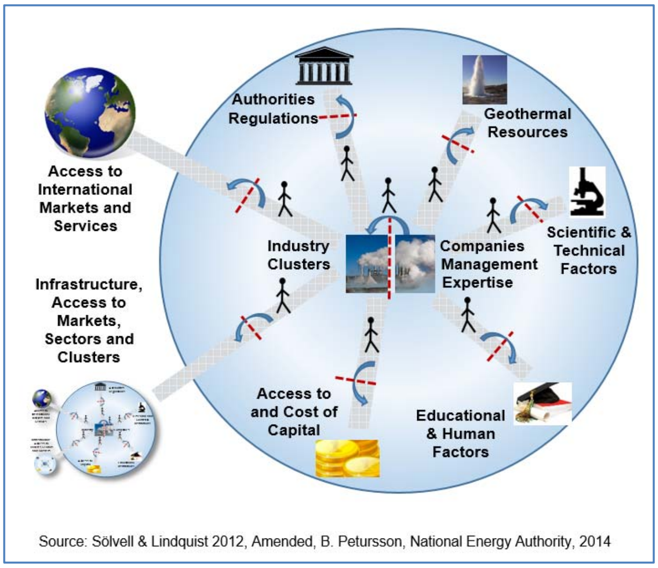


Fig. 7.1. Competitiveness of the geothermal sector

Success for the geothermal sector in the concerning countries is not only based on geothermal resources, but also on these factors for competitiveness (Fig. 7.1). The cluster competitiveness model can be used in many different ways to increase competitiveness and growth of companies.

One possibility is to use the enclosed model to analyse the seven main framework conditions in the geothermal sector:

1. Authorities and regulation.
2. Geothermal resources.
3. Scientific & technical factors.
4. Companies, management, expertise – industry, clusters assessment.
5. Education & human factors.
6. Access to capital.
7. Infrastructure and access to markets, sectors and other clusters.
8. Access to international markets and services.

By evaluating these seven factors of the geothermal competitiveness in the concerning country, it is possible to highlight the key weaknesses and strengths of the frameworks conditions as a base for the formulation of a better competitiveness policy for the geothermal sector; to increase competitiveness, growth, jobs, productivity and quality of life.

7.2. Opportunities and policy options

There are several options regarding geothermal possibilities and policy formulation, based on opportunities and by steps towards overcoming barriers and challenges already identified.

1. Authorities and Regulatory Factors
   - Simplify the administrative procedures to create market conditions that facilitate development;
   - Separate law regarding geothermal resources and other fossil fuels resources.
   - Improve access to geothermal data - to improve development of geothermal utilization.
   - Publicise the characteristics and benefits of geothermal energy for regional development
   - Design regulation specific to the promotion of direct uses of geothermal energy.
   - Promote cooperation with international organisations.

2. Geothermal Resources
   - Improvement of geothermal regulation.
   - Separate law on geothermal and fossil fuels – to speed up access to geothermal data and avoid hindering geothermal development, and problems due to secrecy of oil and gas information.
   - Improvements for data analysis of reservoirs in regions.

3. Scientific and Technical Factors
   - Promote relationships with industry.
   - Promote alliances with research centres and educational institutions for the formation of specialised human resources.

4. Companies, Management, Expertise – Industry Clusters
   - Promote alliances with research centres and educational institutions for the formation of specialised human resources.
   - Promote cooperation with IFI for financing, donor support and consulting.
   - Organize workshops and conferences to improve knowledge on geothermal energy.
   - Identify geothermal energy-related productive chains.

5. Educational and Human Factors
   - Support for the generation of the human resources needed for the geothermal industry.
   - Creating seminars and specialized courses on the different stages of a geothermal project and adding them to the existing engineering degrees.
   - Give the personnel technical training to participate in the different stages of a project.
   - Implement programs for scientific and technical development.

6. Access to, and Cost of Capital
   - Promote additional access to financing geothermal projects – domestic and international.
   - Increase access to capital by providing capital to exploration and test drilling and DH networks e.g. soft loans or donor grants, to lower the risks at the beginning of projects.
   - See also additional elements page 15.

7. Infrastructure, Access to Markets, Sectors and Clusters
   - Promote training in the banking system for the development of financial mechanisms specific to geothermal energy.
   - Awareness; organize workshops & conferences to improve knowledge of geothermal energy.
   - Increase the available knowledge about opportunities and benefits of geothermal resources.

8. Access to International Markets and Services
   - Support international cooperation in area of geothermal knowledge, training and service.
   - Promote international cooperation with IFI and donors on finance, grants and funding.
   - Support international consulting cooperation on various fields of geothermal expertise.

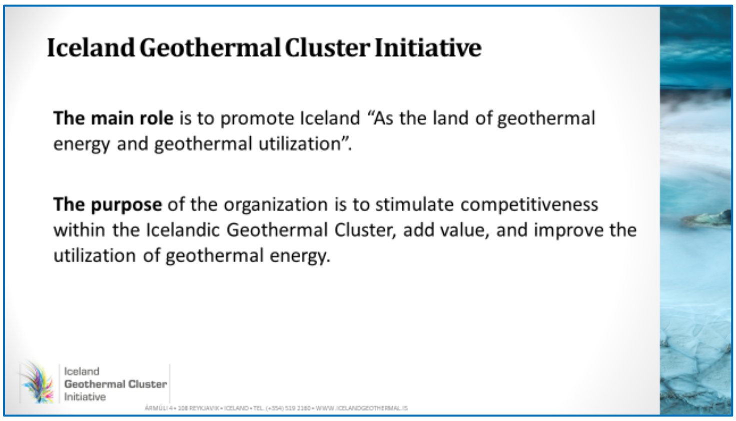
8. The Icelandic Geothermal Cluster

Iceland Geothermal Cluster has been taking part in organising the country's geothermal industry for almost a decade. The organisation has unique access to the Icelandic geothermal industry, facilitating Icelandic companies to harness high and low enthalpy geothermal sources. Iceland is a leader in designing, constructing and operating CHP geothermal power plants, generating renewable power (MWe) as well as thermal power (MWt), for district heating and industrial processes.

In this context around 50% of the energy demand in the EU is space heating and cooling, with district heating (MWt) representing the largest part of this load. Going from fossil fuels to renewable resources such as geothermal, gas/CO2 emissions could be cut significantly.

Other benefits from utilising geothermal resources include improved energy security, lower greenhouse gas emissions, improved quality of life, and lower heating costs. Iceland is known for its clean and renewable energy, and the Icelandic case is here presented as a potential blueprint for similar energy transitions throughout Europe.

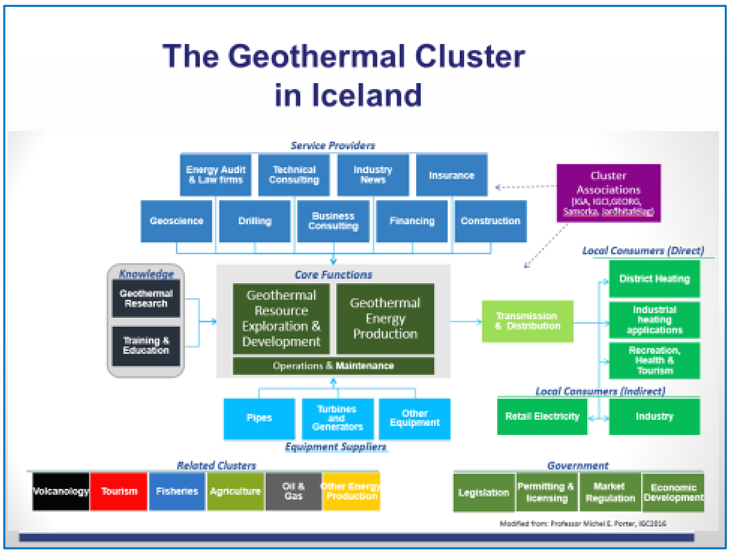
Introduction



The term cluster is defined as a geographically group of companies and associated institutions in a particular field, linked by commonalities and complementarities. In a cluster there is a system of interconnected firms and institution whose value as a whole is greater than the sum of its part. The cluster policy has been part of the structure of the Icelandic economy for two decades. So far, such work has mainly been formed by local conditions and initiated by the government.

In 2010, Dr. Michael Porter and Dr. Christian Ketels performed an analysis of the Icelandic geothermal cluster in cooperation with an Icelandic consulting firm. Nearly 60 different stakeholders within the cluster were involved in the project. According to the results Iceland is naturally uniquely situated in terms of access to a quality resource. The high percentage of geothermal energy as proportion of Iceland's total primary energy consumption is unique in the world.

Most of the development of geothermal utilization in Iceland has occurred for the last one hundred years or so, especially in the latter half of the 20th century. Iceland is a strong player in the global geothermal market, enjoying the benefits of a powerful geothermal cluster. The cluster's strength consists of a developed system for using geothermal energy in multiple ways, experienced specialists, and a strong international reputation and network. The cluster's weaknesses include poor access to capital, a lack of cri tical mass of companies, a complex domestic market environment, and fragmented educational activities.



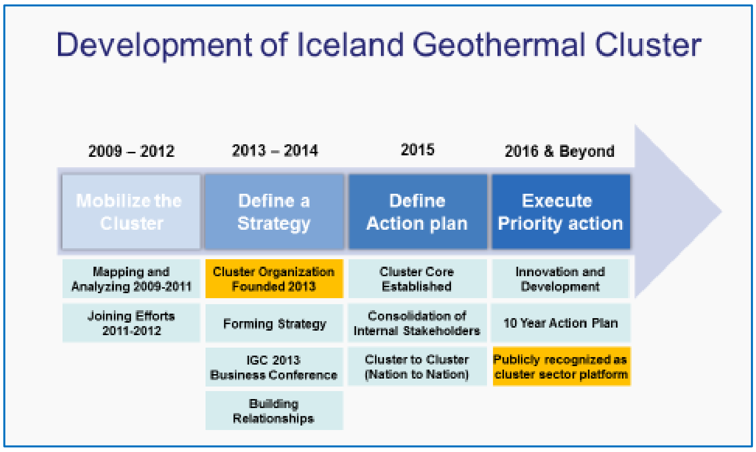
The Icelandic geothermal cluster is a resource cluster and the geothermal resource is such that it cannot be exported directly. The main growth opportunities for the cluster involve attracting energy-intensive activities to the country (both for direct and indirect use), the laying of a marine cable to Europe and the export of Icelandic geothermal expertise.

Stakeholders in the Icelandic geothermal cluster must develop a strategy and an action plan if they at all have the capacity and will to take advantage of unique opportunities in the global geothermal energy sector.

Following the analysis, work was started on creating a platform for collaboration within the Icelandic geothermal cluster. The work was led by a steering committee of leading experts within the cluster. An emphasis was placed on a value-adding cooperation on the terms of the industry. At the same time, it is important that the government lend the cluster good support by engaging in a dialogue and providing it with a good regulatory transparency and efficiency.

History

The geothermal sector in Iceland has been developing since the 18th Century. The development commenced when a hot spring area in Reykjavík was designated and constructed for open air laundering. At the same time, indirect utilisation took place by drilling in geothermal fields to mine sulphur. In 1900, experiments with drilling shallow geothermal wells and transferring hot water via pipelines for space heating began, and in 1908 a small-scale district heating system became operational. Later, other direct utilisation methods emerged and the first greenhouse in Iceland heated with geothermal heat commenced operation in 1924. The first steps towards eliminating Iceland's dependence on coal and oil for space heating were taken in 1928, when the city of Reykjavík initiated its drilling programme with the aim of gaining access to hot water.



In 1930, a district heating system was constructed in Laugardalur, Reykjavík. The system supplied a hospital, a swimming pool, a school and 60 homes with geothermal hot water, marking the beginning of the district heating revolution in Iceland. The next big step was harnessing geothermal steam for power generation, and the first turbine in Iceland powered by geothermal steam commenced operation in 1944. Today, more than 90% of all industrial facilities and residences in the country are heated by geothermal water and roughly 30% of all electricity generated in the country comes from geothermal power plants. The remaining electricity demand is supplied by hydropower plants, making Iceland's electricity 100% renewable.

Iceland Geothermal Cluster Initiative

In October 2009, steps were taken to establish a geothermal cluster in Iceland. The mapping of the cluster was supported by a diverse group of companies and conducted by Professor Michael Porter and his team at Harvard Business School, US, and co-ordinated by the consultancy company Gekon. The output of the mapping process was a recommendation for an optimal path to strengthen the infrastructure within the geothermal sector in Iceland by formalising a cluster initiative.

Main activities within Geothermal Clusters

1. Diverse Usage
2. Project Management
3. Drillings
4. Equipment: Develpment and Maintenancce
5. Recruitment/Education
6. Iceland Geothermal Conference
7. Operational Environment
8. Data Collection
9. Cluster Networking
10. Financing

Iceland Geothermal Cluster Initiative (IGCI) is a non-profit organisation that aims to promote geothermal energy as a competitive renewable energy solution for businesses and society. Utilisation of high and low temperature geothermal resources creates high-value jobs and improves the quality of life and social wellbeing. Investment in geothermal utilisation is a long-term investment that offers base load electricity and a diverse portfolio of other related revenue streams. It has turned out that harnessing geothermal resources opportunities reveals multiple utilisation methods among those harnessing the energy resource. Geothermal resources in general are renewable and ideally suited to supply baseload energy, improving energy security and encouraging growth.

The IGCI and its members participate in hosting events and workshops, receiving delegation, sharing knowledge and experience, and assist in promoting geothermal energy. The cluster takes an active part in defining best practice methodology for the sector and building international collaborations to map best practice methods across the world, as well as performing energy-related analyses and publishing reports and papers. IGCI is involved in international collaboration and is a member of the International Geothermal Association (IGA) and the Global Geothermal Alliance (GGA).

The previously mentioned mapping looked to the already mature energy sector in Iceland and its century of experience in utilising hydropower and geothermal resources. Within the sector, a unique set of skills and knowledge had accumulated, especially regarding geothermal utilisation. Icelandic experts have also been active in sharing their knowledge with equipment manufacturers, geothermal specialists, and other countries through delegation visits. However, what was missing was the focus of a unified platform on developing business and innovation opportunities. The Iceland Geothermal Cluster is business-driven and aims at sustaining the competitive advantage of the geothermal industry.

Iceland Geothermal Conference (IGC)

The aim of the IGC has been to raise awareness of geothermal energy as one of the main renewable energy solutions. More importantly, it aims to serve as a platform upon which world leaders and professionals can come together and address the urgent, business-related topics. Despite the opportunities for geothermal to contribute to energy transformation and to aid the international community in reaching climate change commitments, sector growth has been slow. The overall theme of the IGC is to share effective methods and to examine the best practices currently employed in geothermal projects, informing stakeholders on how to make the most out of a geothermal project, and to explore ways in which the value of a project can be increased.

Today, the IGC is an internationally recognised event that brings together industry leaders and policy makers. The quality of the conference and the experience of a visit to Iceland is carefully planned and monitored by the IGC committee. Lectures, exhibitions, field trips, and other recreational activities tailored to the themes of the conference are part of what is on offer at IGC. Few places in the world can provide access to six geothermal power plants with different installation and turbine setups, the geothermal fields, exciting new technology development, showcase various direct utilisation options, and also exhibit the interaction between geothermal and other industries such as fuel cell technologies.
IGC 2018 – breaking the barriers The Fourth IGC will be hosted in Iceland in April 2018. The conference offers an in-depth discussion of the barriers that hinder development in in the geothermal sector and how to overcome them. It also focuses on the business environment through three separate themes: vision, development, and operations.

Vision

A non-technical overview of how stakeholders and policy makers can pave the way for geothermal development. This theme is aimed at those who are participants at the top-level of decision and policy making processes, both in the public and private sectors.

Development

A comprehensive overview of effective solutions for project developers. During the development phase, there are multiple challenges to address that can vary depending on the country, the project itself, and the experience of the developer's team. This theme explores solutions to these challenges and focuses on financing strategies for geothermal projects for various parties to consider, including developers, development banks, and other financial institutions.

Operations

A business-oriented overview of how plant owners, investors, developers and financiers can plan and maintain long-term profitability and sustainability of the geothermal field. This theme explores real business cases related to geothermal projects. Operators will share their knowledge and experience, from which other conference guests can gain valuable insight into the business expansion opportunities surrounding waste heat utilisation and other disparate geothermal resource streams.

More about the conference

IGC 2018 offers field trips to nearby geothermal areas and easy access to Icelandic geothermal experts. IGC is known to offer quality lectures delivered by carefully selected speakers from around the world. As before, a networking event is hosted where buyers and sellers get the opportunity to establish new relationships that could lead to new business opportunities.

The founders of (IGC) recognise that networking is an integral part of any good conference. Therefore, we offer attendees the option of using an interactive app to become more visible. This conference provides a great opportunity to learn and network within the geothermal community.

Past IGC conferences have been a success, with roughly 700 participants on average. IGC is a non-profit event sponsored by IGCI. The conference was set up as an international platform for the geothermal industry and project developers to gather and share views on how to improve the business environment for geothermal projects. To learn more about this event visit http://www.igc.is/.[2]

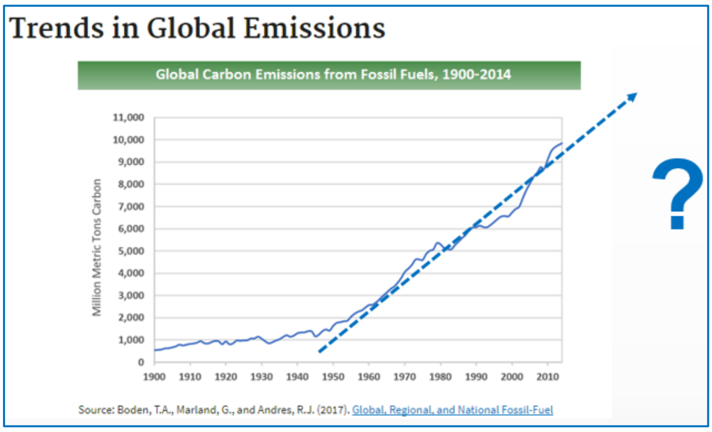
[2] Vidar Helgason, Iceland Geothermal Cluster +354 519 2160, vidar@icelandgeothermal.is http://www.icelandgeothermal.is/

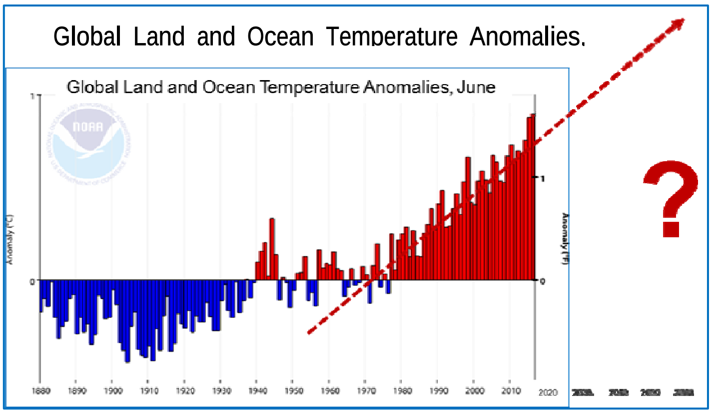
9. Geothermal is a powerful tool to mitigate climate changes

According to the Intergovernmental Panel on Climate following statement was made:

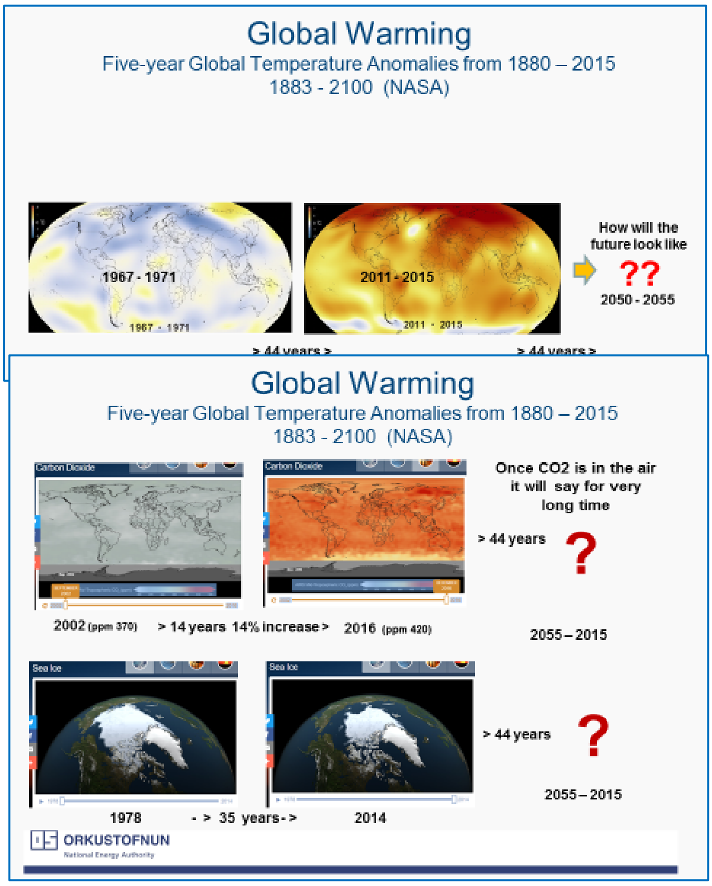
"From 1880 to 2012, average global temperature increased by 0.85°C. To put this into perspective, for each 1 degree of temperature increase, grain yields decline by about 5 per cent. Maize, wheat and major crops have experienced significant yield reductions at the global level of 40 megatons per year between 1981 and 2002 due to a warmer climate.

Oceans have warmed, the amounts of snow and ice have diminished and sea level has risen. From 1901 to 2010, the global average sea level rose by 19 cm as oceans expanded due to warming and ice melted. The Arctic's sea ice extent has shrunk in every successive decade since 1979, with 1.07 million km² of ice loss every decade.





Given current concentrations and on-going emissions of greenhouse gases, it is likely that by the end of this century, the increase in global temperature will exceed 1.5°C compared to 1850 to 1900 for all but one scenario. The world's oceans will warm and ice melt will continue. Average sea level rise is predicted as 24–30cm by 2065 and 40–63cm by 2100. Most aspects of climate change will persist for many centuries even if emissions are stopped.



Global emissions of carbon dioxide (CO_2) have increased by almost 50 per cent since 1990

Emissions grew more quickly between 2000 and 2010 than in each of the three previous decades.

It is still possible, using a wide array of technological measures and changes in behavior, to limit the increase in global mean temperature to two degrees Celsius above pre-industrial levels.

Major institutional and technological change will give a better than even chance that global warming will not exceed this threshold" [3]

[3] http://www.un.org/sustainabledevelopment/climate-change-2/, The UNU sustainable goals regarding climate change

"Climate change is now affecting every country on every continent. It is disrupting national economies and affecting lives, costing people, communities and countries dearly today and even more tomorrow.

People are experiencing the significant impacts of climate change, which include changing weather patterns, rising sea level, and more extreme weather events. The greenhouse gas emissions from human activities are driving climate change and continue to rise. They are now at their highest levels in history. Without action, the world's average surface temperature is projected to rise over the 21st century and is likely to surpass 3 degrees Celsius this century—with some areas of the world expected to warm even more. The poorest and most vulnerable people are being affected the most.

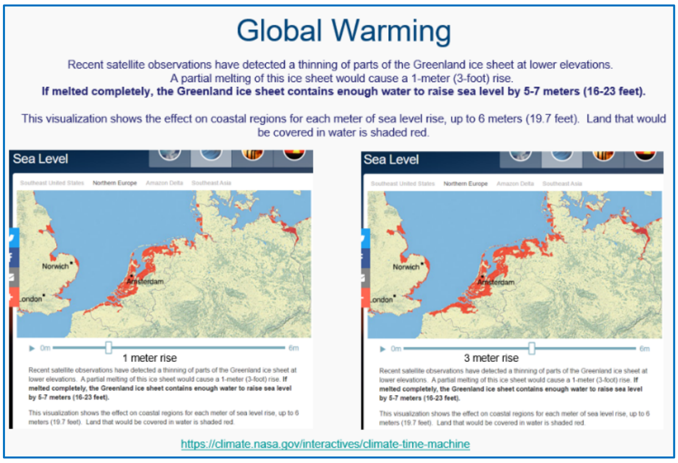
Affordable, scalable solutions are now available to enable countries to leapfrog to cleaner, more resilient economies. The pace of change is quickening as more people are turning to renewable energy and a range of other measures that will reduce emissions and increase adaptation efforts.

But climate change is a global challenge that does not respect national borders. Emissions anywhere affect people everywhere. It is an issue that requires solutions that need to be coordinated at the international level and it requires international cooperation to help developing countries move toward a low-carbon economy.

To address climate change, countries adopted the Paris Agreement at the COP21 in Paris on 12 December 2015." [4]

Implementation of the Paris Agreement is essential for the achievement of the Sustainable Development Goals, and provides a roadmap for climate actions that will reduce emissions and build climate resilience.

Renewables and geothermal district heating solutions area powerful tool to fight against global warming.

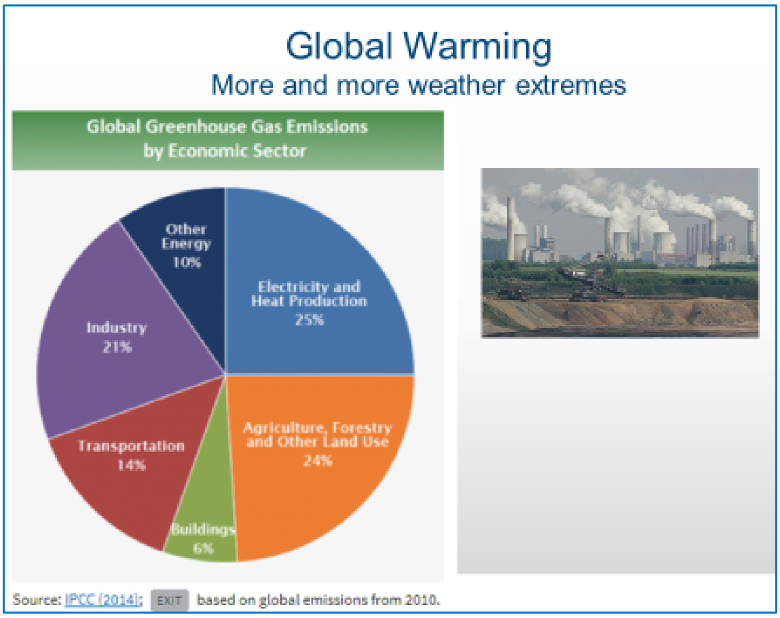


[4] http://www.un.org/sustainabledevelopment/climate-change-2/, The UNU sustainable goals regarding climate change

I seems that there is a slow reaction time since, there was 21 years from the Kyoto meeting 1994 on climate change, at the Paris climate conference 2015.

More awareness is needed, and link the need with available tools like geothermal contribution towards mitigating climate change. It is important to highlight the climate risk, and bring it closer to people – in time and space.

Last 24 months there have been heat record every month around the globe. In February 2016, the temperature was on average 1,35 degrees on Celsius, higher than 1951 – 1980.



In some areas like in N-America, Northern Europe and central Asia, the average monthly temperature increase was even 4–11,5o degrees C, far beyond the average 1,5 – 2 degrees Celsius.

Due to this trend more regional consequences are foreseen – and therefore more action is needed – including in the area of geothermal.

- Climate change trend are also moving faster than expected, with higher temperature of air and sea and greater ocean acidification.
- Increasing renewables are moving slowly – including utilisation of geothermal district heating.
- There are great possibilities in Europe regarding geothermal district heating – but things are moving too slowly.
- However, Geothermal projects con do more to fight the global CO2 / climate problem.

<u>Oil crisis</u>

–> very visible –> automatic awareness raising –> fast reaction time –> focus on economic issues –> economic balance fairly quickly –> no global environmental risk

-> geothermal contribution - did help many countries like Iceland to avoid economic problems of oil.

<u>Climate crisis</u>

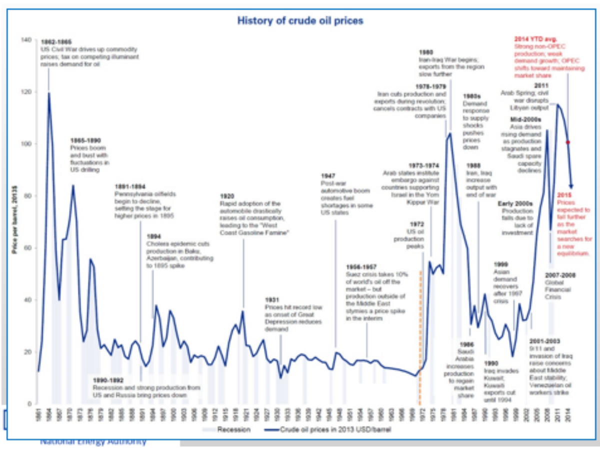
–> difficult to see climate changes –> therefore very slow reaction time (22 years from Kyoto)

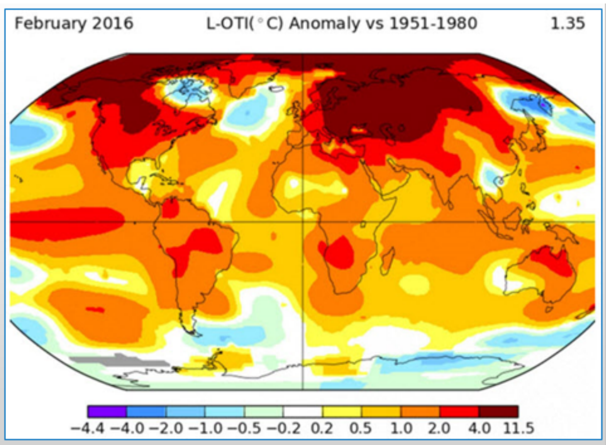
–> denial of problems –> very problematic and poorly managed awareness raising

–> globally very risky and urgent on all levels of societies (economic, social, environmental, etc.)

–> increasing risk of slow action and more damage and disaster than expected

-> geothermal contribution – can have valuable impact to mitigate climate change in many countries.





Global Warming

Ban Ki-moon: There is no plan B, because we have no planet B

Renewable Energy can mitigate Global Warming

Renewable Energy and Geothermal District Heating is a Powerful Tool to Fight Against Global Warming