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BOOK OF EXTENDED ABSTRACTS

PSG

POLISH GEOTHERMAL SOCIETY

28–30 IX 2021

7th Polish Geothermal Congress

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Dear Readers,

We are handing over the Book of Extended Abstracts of the 7th Polish Geothermal Congress, which took place on 28-30 September 2021. The Congress was addressed to a broad range of scientists, practitioners, government representatives and local government institutions, geological entities, companies, investors, service providers, students, and other individuals and companies interested in geothermal.

The Congress was co-organised by the Polish Geothermal Society and the Department of Fossil Fuels, Faculty of Geology, Geophysics and Environmental Protection, the AGH UST Faculty of Geology, Geophysics and Environmental Protection, Department of Fossil Fuels, Mineral and Energy Economy Research Institute of the Polish Academy of Sciences, and Geotermia Pyrzyce Sp. z o.o. The Congress Partners included G-Term Energy Sp. z o.o., Polish Geological Institute - National Research Institute, Association of Engineers and Technicians of the Oil and Gas Industry, Polish Organisation of Heat Pumps Technology Development, and GlobEnergia Editorial Office.

The Minister of Climate and Environment, the Ministry of Development and Technology, the National Fund for Environmental Protection and Water Management, the Marshal of the Malopolska Region, and the International Geothermal Association held honorary patronage over the Congress. They emphasised the Congress' high position and confirmed its significance as the main cyclical meeting of communities involved in research and use of geothermal energy in Poland. The media patrons of the Congress included the GlobEnergia quarterly and Wiadomości Naftowe i Gazownicze [Oil and Gas News].

The 7th Polish Geothermal Congress was inaugurated by a session attended by the representatives of the Ministry of Climate and Environment's Board involved in the development of geothermal energy in Poland. The representatives included Piotr Dziadzio - the Secretary of State, Chief State Geologist of the Country and plenipotentiary for the National Raw Materials Policy; Ireneusz Zyska - Secretary of State, a plenipotentiary for Renewable Energy Sources; and Artur Sz. Michalski - Vice President and management representative of the National Fund for Environmental Protection and Water Management. The presented information concerned the effects of previous governmental activities to boost geothermal energy development in Poland and the related plans and strategies. The sessions held in the three days of the Congress were devoted to the review of the state of geothermal uses in Poland and globally; sessions and discussion panels with geothermal companies and entrepreneurs (concerning, e.g. the current operation of the geothermal heating plants and other geothermal facilities in Poland and plans); geothermal heat pumps; a session with representatives of the oil and gas sector interested in broader involvement in the geothermal issues; sessions on some international projects implemented with Polish teams; technical and poster sessions presenting the state-of-the-art geothermal and related topics. Philippe Dumas, the Executive Director of the European Geothermal Energy Council, was invited to deliver a speech during the Congress. He discussed some aspects and direction of geothermal development in Europe, providing a broader context for our national projects, works and activities. A special session of the Polish Geothermal Society was organised as part of the Congress. Zbigniew Bociek was awarded the Diploma of the Polish Geothermal Society's Honorary Member and the Erazm Sykst Medal of Honor of the Polish Geothermal Society. An identical medal was granted to G-Term Energy Sp. z o.o., represented by Arkadiusz Biedulski, CEO. In addition, a summary speech was delivered, presenting the Society's operation during fifteen years of operation, since its establishment in 2006. Nearly six hundred participants registered for the Congress, which consisted of online streaming (28 September) and webinars (29-30 September). Almost fifty papers were presented during technical and poster sessions. Their extended abstracts are included in this Book.

The World Geothermal Congress 2020+1 was also held in 2021. Its closing session took place on 24-27 October. More than 2,000 papers were submitted, including reviews of the state of geothermal utilisation in ninety countries. Their summary revealed significant progress in many countries. Some key information was presented in the abstract and presentation in the 7th National Geothermal Congress.

The Polish Geothermal Congress has been popular since the first event held in 2007. Therefore, the organisers made every effort to hold it in 2021, although its form was modified. It was announced online on 22 September 2020 - the day the onsite Congress was initially scheduled for. The positive feedback shared by the Congress participants confirmed the event's success and high level of the presented content and organisation. In addition, up-to-date information and knowledge on geothermal development and its various aspects in Poland were presented, creating an opportunity to integrate people and milieus operating in the field. This was all the more valuable as in 2020 and 2021 the possibilities were very limited due to the pandemic.

The Board of the Polish Geothermal Society would like to thank all the Co-organisers, Partners, Sponsors, Honorary Patrons, Media Patrons and all members of the Organising Committee and Scientific Committee for their support, including financial support, and for several months of work devoted to the organisation of 7th Polish Geothermal Congress 2020+1 in the highly challenging new circumstances. We extend our thanks to the authors of papers presented during the Congress and collected in this Book of extended abstracts.

On behalf of the Board of the Polish Geothermal Society
Prof. Beata Kępińska
President

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THE STATE OF GEOTHERMAL ENERGY USES IN THE WORLD AND IN THE EUROPE IN 2020

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Keywords: geothermal energy, geothermal use, development prospects, world, Europe, years 2015–2020

Abstract

According to data presented at the World Geothermal Congress 2020+1 (Lund, Toth, 2020; Huttrer, 2020) and the European Geothermal Energy Council – EGEC market report (Garabetian et al., 2021), 2015–2020 a significant increase in the use of geothermal energy worldwide has been recorded. The number of countries reporting direct use of geothermal resources (including ground source heat pumps) has increased to 88 (34 in Europe), while the number of countries reporting geothermal electricity production to 29 (11 in Europe). The increase in the installed geothermal capacity for direct use in the last 5 years amounted to over 50%, to approx. 108 GW_t (thermal energy used slightly exceeds ca. 1 EJ/year), wherein ground source heat pumps (GSHP) possess the highest percentage share in the above increase. They are responsible for almost 60% of the energy produced. The world leaders in terms of direct use of geothermal energy, excluding ground source heat pumps, are in the following order: China, Turkey, Japan, Iceland, Hungary, and New Zealand. China, where the installed capacity of GSHP amounted to approx. 26 GW_t, holds the scepter of the world leader in this field. Three European countries: Sweden, Germany, and Finland, are on the “top five” list in the world in terms of installed capacity at GPC (Lund, Toth, 2020).

The total installed capacity of geothermal power plants in the world at the end of 2019 amounted to approx. 16 GWe (approx. 30% increase in 2015–2019), which allowed for the production of approx. 95 TWh/year of electricity. The world leader in terms of generating electricity from geothermal is the United States, with an installed capacity of approx. 3.7 GWe. The remaining countries with installed capacity exceeding 1 GWe are Indonesia, the Philippines, Turkey, Kenya, New Zealand, and Mexico.

A growing interest in generating electricity using binary systems, in particular in Europe has been noticed. In the period 2015–2019, three new binary installations in Croatia (16.5 MW_e), Hungary (3 MW_e), and Belgium (0.8 MW_e), were put into operation. In addition, in the 2020 year, 8 new geothermal power plants were commissioned in Turkey, which provides an additional capacity of approx. 165 MW_e.

In Europe, geothermal electricity is produced in 11 countries, and the installed capacity in 139 power plants has been estimated at around 3.5 GW_e (Garabetian et al., 2021).

In recent years, in the world, and especially in Europe, a significant increase in interest in the recovery of critical elements (CRMs) from geothermal waters, mainly lithium has been noticed. The initially identified potential indicates the possibility of covering up to approx. 25% of the EU countries' demand for Lithium from geothermal brines by 2030 (Garabetian, 2020).

In many countries, geothermal energy is one of the most promising sources of renewable energy, especially when it comes to environmental and economic considerations. In some countries of the world, geothermal energy is a key element of the economy, guaranteeing energy security and enabling the achievement of the goals of climate neutrality. In other, less developed countries, geothermal energy may constitute the basic source of energy, and sometimes a significant source of national income, conditioning economic development and increasing the country's economic and energy independence. The main directions of geothermal development in the world are presented in the figure below.

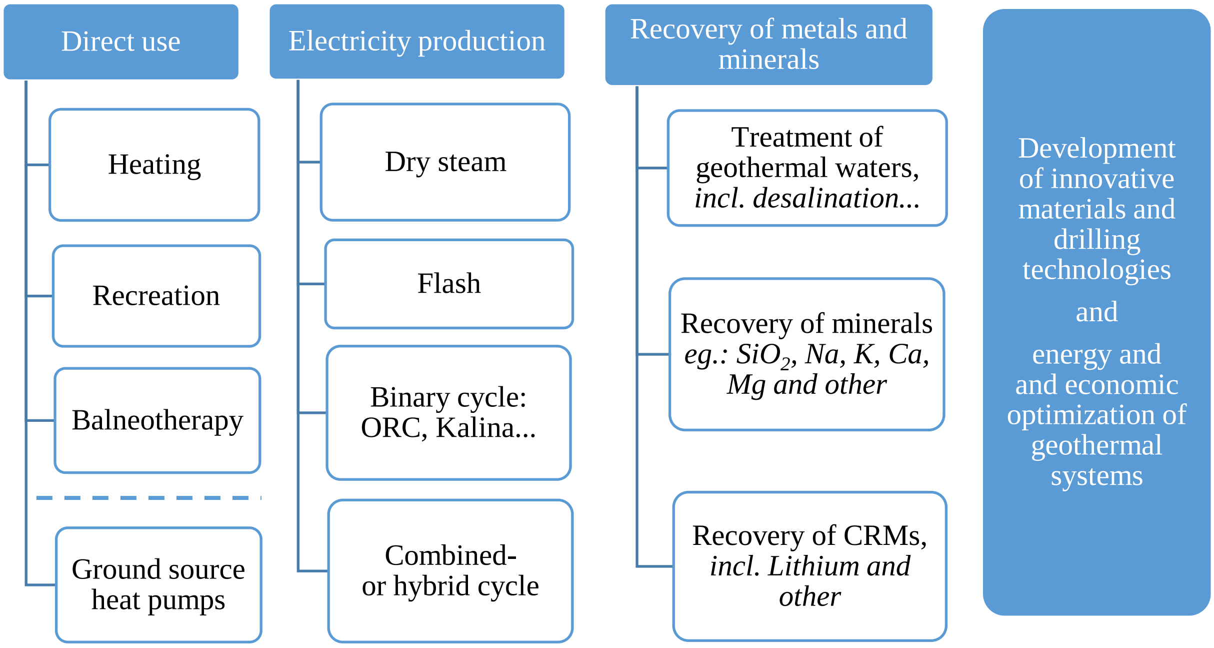

Figure 1. *The main directions of geothermal energy use in the world*

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AN OVERVIEW OF THE GEOTHERMAL ENERGY USE IN POLAND IN 2019-2021

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Keywords: geothermal energy, use, overview, Poland, 2019-2021

Abstract
The paper presents an overview of Poland's use of geothermal energy in 2019-2021, i.e. since the 6th Polish Geothermal Congress in 2018 (Kępińska, 2018). The periodic review of the state of geothermal energy use in Poland in 2015-2019, according to the International Geothermal Association methodology, was presented on the occasion of the 2020+1 World Geothermal Congress (Kępińska, 2020). The information on the state of use of geothermal energy in Poland in the last few years is also included in the publication by Kępińska et al. (2018).

The practical application of geothermal energy and waters in Poland includes but is not limited to district heating and balneotherapy, and recreation.

Six geothermal district heating systems have been operating in Poland: in Podhale (since 1993), Mszczonów (2000), Pyrzyce (1996), Uniejów (2000), Stargard (2006, after renovation in 2012) and Poddębice (2013). At the end of 2020, these systems' total installed geothermal thermal capacity was ca. 75 MW. The geothermal heat generation reached ca. 256 GWh (Table 1). The share of geothermal heat in the generation and sales of heat in each of the aforementioned heating plants ranged from 30 to 100%. For a few years, individual geothermal heating systems have been operating in several facilities in Kleszczów and Cudzynowice.

Table 1. *Geothermal heating plants in Poland, 2020 (based on information provided by the operators)*

Locality	Year of commissioning	Installed geothermal capacity [MW]	Total installed capacity [MW]	Geothermal heat generation [GWh]
Mszczonów	2000	3.7	8.3	4.49
Poddębice	2013	10.0	10	17.38
Podhale	1993	38.8	80,7	152.58
Pyrzyce	1996	6.0	22	21.15
Stargard	2006/2012	12.7	12.7	57.85
Uniejów	2006	3.4	7.4	2.50
Total		74.6	141,1	255.95

In Poland, ten health resorts use geothermal water. Their number has been constant since 2012 when Uniejów joined the group of localities with a formal legal status of a health resort.

In the leisure sector (meaning recreation, SPA and wellness), at least fifteen centres using geothermal waters, and heat in some cases, were operating in the reference period. The newest one was opened at the beginning of 2020 in Wręcza near Mszczonów. It is the largest centre of this type in Poland and a part of a multi-function complex. It should be noted that seven out of all Polish geothermal recreation centres are located in one area, i.e. in Podhale. Due to the COVID pandemic, the leisure sector had to reduce its activity

significantly throughout 2020 and at the beginning of 2021, but further development of the very attractive sector is expected in the upcoming years.
Other methods of geothermal water and energy management in Poland include:
- Atlantic salmon farming (on a large scale) in Janowo near Trzęsacz,
- wood drying - in the MEERI PAS facilities in Podhale (the system has been operating since (1993),
- football pitch and walking paths surface heating in Uniejów,
- selected pavements heating on the premises of the AGH University of Science and Technology in Krakow (shallow geothermal energy),
- production of cosmetics (based on geothermal waters from Iwonicz-Zdrój, Lądek-Zdrój, Poddębice, Podhale, Rabka-Zdrój, and Uniejów),
- pilot applications in agri-food processing in Pyrzyce and Uniejów,
- pilot use in algae cultivation (biotechnology) in Poddębice,
- geothermal water use as drinking water in Poddębice and Mszczonów,
- geothermal water use as domestic hot water in some residential buildings in Uniejów,
- extraction of mineral salts from geothermal waters in Ciechocinek and Iwonicz-Zdrój,
- extraction of carbon dioxide from geothermal water (cryptogeothermal at the outflow) in Duszniki-Zdrój.

More details about the operation of geothermal heating plants and other facilities in Poland and plans for the future will be shared by their representatives during the 7th Polish Geothermal Congress in September 2021.

The so-called shallow geothermal energy has been developing. In 2020, 5,260 geothermal (ground source) heat pumps were sold (6,190 units in 2019) according to the data provided by PORT PC (https://www.gramwzielone.pl/dom-energooszczedny/104926/w-polsce-rosnie-Sprzedaż-pomp-ciepla). The total number of geothermal heat pumps installed in Poland can be estimated as ca. 70,000, their total installed capacity in 2019 as at least 650 MW, and heat generation as 3,100 TJ. Poland was ranked eighth among the European Countries in 2020 for the number of heat pumps (2020 EGEC Geothermal Market Report) with such outcomes. The progressively increasing use of these devices is part of Poland's entire heat pump sector's development.

The geothermal energy share in the final energy consumption in the RES group and total energy in Poland was still very low, similar to previous years, and amounted to much less than 1% (deep geothermal energy and geothermal heat pumps). On the European scale, in 2020, Poland ranked fourteenth for the number of geothermal district heating systems (2020 EGEC Market Report). Geothermal heat is expected to be introduced to a few more district heating systems in the immediate future (mainly owing to the aforementioned support programmes); other applications are expected to develop as well. Poland's position behind many other countries may persist, as the progress in geothermal district heating is faster there than in Poland, as evidenced, e.g. by the information from the latest geothermal energy market review in Europe (2020 EGEC Market Report).

In 2015–2020, about twenty new geothermal wells were drilled in Poland, including around ten in 2018–2020. They will be used primarily for district heating purposes based on the existing district heating systems. Most of them were co-financed from the priority public support programmes introduced gradually since 2015/2016. Recently, the programmes have played an essential role in stimulating a more dynamic geothermal energy growth in Poland for energy purposes. Typically the programmes are executed as grants (up to 85% of eligible project costs) and loans. Some programme examples include:
- "Geology and mining, Part 1) Recognition of the geological structure of the country and management of mineral deposits and ground waters" – call for applications in 2016-2019,
- "Polska Geotermia Plus" – since 2019 (the next call is expected in mid-2021),
- "Providing access to geothermal waters in Poland" (2020-2025) – call for applications until 30 September 2020.

By mid-2021, these programmes already resulted in drilling about fifteen exploration, research and other well types. Most of them will then be used as geothermal heat-generating wells for several existing district heating networks, while others will serve as injection wells. Some new wells were made for the already operating geothermal heating plants (in Podhale, Pyrzyce, and Stargard). The implementation of projects aimed at constructing surface infrastructure to bring geothermal energy to the existing central heating networks and other related works have already begun. In March 2021, a call for applications under the "Construction of heat sources using geothermal energy (deep geothermal energy)" European Economic Area Financial Mechanism was closed. The Ministry of Climate and Environment (former Ministry of Environment) and the National Fund for Environmental Protection and Water Management are the programme operators. The support for geothermal heating investments was also offered under the EU Infrastructure and Environment Operational Programme (managed by the Ministry of Development Funds and Regional Policy).

Implementing projects co-financed from the aforementioned programmes is expected to result in the geothermal energy introduction into at least several already operating central heating networks in the next few years. It is also worth mentioning that geothermal funding opportunities are offered, e.g., the European Green Deal Fund, Reconstruction and Resilience Fund, National Recovery Plan, and programmes executed by the National Centre for Research and Development.

More details on the above-mentioned programmes and their effects so far will be included in a separate paper and presentation prepared for the 7th Polish Geothermal Congress.

Support programmes play an essential role in stimulating the geothermal energy development in Poland, especially in the initial stage. In the case of already operating heating plants and facilities, as well as various groups of potential investors, other types of support are also needed, including a risk insurance fund for geothermal projects. Owing to the MEERI PAS team's participation in an EU H2020 GEORISK project (www.georisk-project.eu), some proposals are under development.

In addition to investment projects, several research projects, feasibility studies, proposals for innovative solutions, applications for funding etc., concerning new projects (including drilling) were developed in the referenced period. It resulted from the potential investors' (local governments, other public and private entities) significant and constantly growing interest in deep and shallow geothermal energy, at a simultaneous possibility of obtaining funding.

Tests, research and development works, and educational and training activities financed from domestic funds (for statutory activities, NCR&D, NFEP&WM, etc.), and for the first time to a large extent from foreign sources (including H2020, Erasmus +, EEA FM, Norway Grants, POLNOR, POLTUR) were also developed. They are concerned with various aspects of geothermal energy. The activities mentioned above are broadly presented in the abstracts included in this volume and will be discussed during the 7th Polish Geothermal Congress. The geothermal milieus collaborated in some geothermal-related areas with the representatives of relevant ministries and institutions.

Summing up, it can be concluded that the 2019–2021 period saw the execution of subsequent wells and other investments oriented to the development of geothermal energy in Poland (including a few cogeneration cases). This was possible mainly due to priority public support programmes introduced since 2015/2016, including but not limited to Polska Geotermia Plus (since 2019). Therefore, a few more district heating networks in Poland can soon be expected to provide geothermal heat to their recipients (it has been expected for nearly ten years, since the launch of the geothermal district heating plant in Poddębice, being the "youngest" one in Poland).

The development of geothermal energy use in Poland is also favoured by the need to decarbonise the energy sector by replacing fossil fuels with clean energy sources, in line with the National Plan for Energy and Climate 2021–2030 and the assumptions of Poland's Energy Policy by 2040. They are essential determinants, and geothermal energy in Poland has the potential to (finally) take full advantage of them.

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RESEARCH AND EDUCATION ACTIVITIES OF DEPARTMENT OF FOSSIL FUELS, FACULTY OF GEOLOGY, GEOPHYSICS AND ENVIRONMENTAL PROTECTION AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY IN THE FIELD OF GEOTHERMAL ENERGY IN YEARS 2019-2021 AND FURTHER ACTION PLANS

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Key words: geothermal energy, research and education, geothermal heat pump, geothermal resources

Abstract

For many years, geothermal issues have been one of the basic research and teaching activities of the Department of Fossil Fuels of the Faculty of Geology, Geophysics and Environmental Protection of the AGH University of Science and Technology (KSE WGGiOŚ AGH). National and international research projects on the evaluation of the geothermal potential of Poland, innovative technologies for geothermal energy extraction, as well as effective management of water resources and geothermal energy are carried out. In recent years (2019 - 2021), scientific and research projects such as GeoPLASMA-CE, EnerGizerS, Geotherm, CA18219 Geothermal-DHC, Lajkonik, NiżPIG, concerning the issues of shallow and deep geothermal energy utilization, are implemented. As far as didactic activity is concerned, the AGH is developing Ecological Energy Sources, as well as petroleum geology and geothermal specialization at the Applied Geology. Doctoral theses in the field of geothermic are being carried out. Research works, including projects concerning the construction of heat pump prototypes, are carried out in the Centre for Sustainable Development and Energy Conservation of the AGH University of Science and Technology in Miękinia equipped with heat pump test stands. The Center is currently being expanded.

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GEOTHERMAL TOPICS IN THE CURRENT RESEARCH ACTIVITIES OF PAS MEERI IN 2017–2021 AND PLANS FOR THE FUTURE

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Keywords: geothermal energy, research projects, geothermal water, social environment, economy

Abstract

The Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (PAS MEERI) is celebrating its 35th anniversary this year. The Institute was established in 1986 on the initiative of Prof. Dr. Eng. Roman Ney, who was its first Director. Inspired by Professors Roman Ney and Julian Sokołowski, research on the recognition and use of geothermal energy in Poland was launched at the Institute. A measurable achievement of the research team established in 1993 was the launch of the first geothermal installation in the country, under the name of the Experimental Geothermal Plant Bańska - Biały Dunajec, located in the Podhale region. This prototype installation prompted the establishment of PEC Geotermia Podhalańska S.A. and inspiration for the construction of further geothermal plants in Poland.

Over the period of over 30 years, the team of scientists associated with the current Division of Renewable Energy Sources of the PAS MEERI has developed several hundred works on geothermal issues. These were, among others, documentation of new and reconstructed geothermal wells, resource documentation, pre-investment expertise, articles, monographs, atlases and various scientific presentations as well as information popularizing geothermal topics. In recent years (2017-2021), 42 research tasks of a utilitarian nature, 61 articles and scientific reports of national and international scope, and 9 research projects have been carried out in the Division of Renewable Energy Sources.

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INVESTMENTS MADE BY GEOTERMIA PYRZYCE IN THE YEARS 2018-2021

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Keywords: geothermal energy, Pyrzyce, wells, barriers and problems, postulates

Introduction

The Pyrzyce heating plant largely produces heat energy using a renewable energy source i.e. geothermal water. The geothermal system in the heating plant in Pyrzyce works based on one extraction well and four injection wells.

Construction of the GT-1 bis well

In 2017, the GT-1 bis well was commissioned and it is the only one with an extraction function, and the capacity regulated by the deep-well pump fluctuates as needed from 80 to 140 m3/h. The water extraction license gives the possibility of obtaining up to 200 m3/h, which will be possible after the installation of a new deep-well pump in September 2021 and will significantly improve the efficiency of renewable energy sources and minimize the volume of gas orders for production.

Modernization of the GT-2 and GT-3 wells.

In October 2020, a tender was announced for works related to the geothermal system, as part of the investment project entitled: *Modernization of geothermal wells in the geothermal system in Pyrzyce together with the construction of a photovoltaic installation,* in connection with obtaining funding in the form of a subsidy (40%) and a loan (60%) from the National Fund for Environmental Protection and Water Management in Warsaw, under the Polska Geotermia Plus program for the modernization of the GT-2 and GT-3 wells with photovoltaics with a capacity of 999.9 kWp as part of the project entitled “Modernization of geothermal wells in the geothermal system in Pyrzyce together with the construction of a photovoltaic installation”.

The project aims to maintain the achieved parameters for a long time while cleaning the injection wells and performing perforation, which is to be additionally guaranteed by acidifying the injected thermal water. Carbon dioxide (CO^2) will be used for this purpose. The treatment of acidification of the injected thermal water will take place twice, after perforation and cleaning of the injection wells. Work on the GT-2 well was completed in the first half of 2021.

At the beginning of February 2021, reconstruction work began on another well. When descending with the Ø 216 template to the GT-3, resistance was encountered which prevented further work. The template was replaced with Ø 130, which also stopped at the same depth. Due to this situation, on February 16, a decision was made to stop the works, due to the impossibility of reaching the zone intended for perforation.
It can be assumed that the cause of blockage of the access is the jamming of the well due to deformation of the casing and corrosion. During the operation of the system until November, there were no obvious symptoms that could indicate such a condition of the GT-3 well.

Part of the work has been completed as part of the project entitled “Modernization of geothermal wells in the geothermal system in Pyrzyce together with the construction of a photovoltaic installation”, co-financed under the priority program No. 5.18 Polska Geotermia Plus.
All the tasks included in the project will be possible after the work on the GT-3 well has been performed in safe mode.

Due to the need to re-install pipes in the well and obtain the possibility of injection into the originally used zones, it was necessary to: unblock a column of pipes 9 5/8”**,** place a new column of pipes 7" and cementing them in the well**,** placing a column of pipes with the possibility of using the existing injection layers**,** templating, geophysical measurements below 1450 m. It is planned to complete all works on the GT-3 by end of September.

All the following and planned works under the Polska Geotermia Plus program will then be completed in the GT-3 well, that is: unblocking the well with a drill string with an entrance to the filter 6 5/8” and rinsing

the deposit zone, perforation of intervals selected by geological supervision, acidizing of the filtered zone - preparation of acidifying fluid (15% HCL in the amount of 6m³), going down the drill string to the maximum possible depth and entering the filter, pumping acid into the filtered zone, cleaning the acidified zone, acidizing the perforated deposit zone - preparing the acidifying fluid (15% HCL in the amount of 9 m³), lowering the drill string to the maximum possible depth and gradual injection of the acidifying fluid with the simultaneous hoisting the drill string and using a brine, cleaning the acidified zone, rinsing the backfill in the well.
This scope of work guarantees the long-term, optimal operation of the wells.

Obstacles and problems in recent years.
After a few years, the known problem of clogging appears in injection wells. In addition to the high initial costs of investments in heating systems based on geothermal sources, during operation, necessary works are required to maintain the efficiency of the geothermal system (cleaning, acidizing, perforation of new absorbent layers).

Geotermia Pyrzyce sp. z o.o. postulated to take up the subject of addressing the Ministry of Climate and Environment and the National Fund for Environmental Protection and Water Management in Warsaw, in order to develop programs, addressed primarily to the existing heat plants, based on geothermal waters, which will enable obtaining funds for periodic modernization and works, maintaining the efficiency of the installation. Moreover, at present, there is no possibility of obtaining funds for connections for such heating plants as in Pyrzyce. The application submitted in 2018 to the National Fund for Environmental Protection and Water Management for the construction of connections to multi-family buildings, including the delivery and installation of individual exchangers, did not receive the required minimum number of points. In the area of 1 Maja Street, there is an old housing estate network that the Company leases from the Commune. In order to become independent and limit serious failures, which include several apartment blocks and cause downtime and losses, a concept was created to build new connections, switch off a group district heating substation, reduce network losses and install individual district heating substations. Unfortunately, the Housing Cooperatives did not agree to the supply of hot water, i.e. the installation of dual-function district heating substations in buildings, for fear of the scope of installation work in the apartments, the need to renovate bathrooms after installation of the DHW distribution system and due to the costs that individual owners would have to incur to install the distribution system inside. So far, it has not been possible for the Housing Cooperatives to obtain funds for the replacement of gas water heaters with a domestic hot water distribution system to receive water from the municipal network. The pilot program of the Provincial Fund for Environmental Protection and Water Management in Szczecin for 2021 does not provide for the replacement of gas installations with renewable energy sources. Again, the potential ecological effects demonstrated would not be met by Housing Cooperatives that use gas heaters to heat water. In cases of obtaining funds, it is necessary to demonstrate the achievement of the ecological effect (primary fuels replaced with renewable energy sources). Connections in place of gas-based systems would not have the desired effect.

From the beginning, the specificity of the investment process in Pyrzyce and the related costs was the lack of transmission networks and district heating substations. The need to add these fields to the construction of the heating plant itself increased its costs by about 40%. It was and still is the problem of creating a price fully acceptable by the community of Pyrzyce. Despite the undeniable advantages of renewable energy, such as geothermal energy, the price is one of the main obstacles to expanding the group of recipients.

In this situation, additional postulates should be taken into account:

- reduction of VAT (for individual recipients), which will improve the competitiveness of the price of energy from geothermal energy,
- another problem is the need to make substitute fees for the so-called white certificates. Geotermia Pyrzyce, as a heat energy company, is obliged by the provisions of the Energy Efficiency Act of May 20, 2016, to purchase white certificates if no modernization investments aimed at improving energy efficiency have been carried out in a given year. The company uses over 65% of geothermal water to produce thermal energy, so most of the production is based on a renewable source. Therefore, any enterprise whose production is based in more than 50% on RES should be exempt from the need to participate in this system.

Conclusions

The current conditions and possibilities of obtaining funds for the construction, then modernization and reconstruction of wells will not ensure the competitiveness of the price of geothermal heat in relation to others. In the future, the following preferences should apply:

- maintenance and development of aid programs focused on the construction of entire heating plants and their operation;
- changes to the regulations which prefer only the production of electricity in cogeneration with geothermal heat rather than the heat itself. The production of electricity with the current technical condition of the equipment and the low-temperature level of our deposits is the subject of the future;
- in the case of long-term mechanisms, introducing such changes in regulations that will encourage recipients to build low-temperature systems;
- reduction of VAT for heat energy consumers, which in the short term would improve the competitiveness of the price of energy from geothermal energy
- it is necessary to establish a risk insurance fund in geothermal projects and risk insurance in the further exploitation of geothermal resources in order to maintain the optimal operation of the installation and appropriate parameters.

Geotermia Pyrzyce sp. z o.o. postulated to take up the subject of addressing the Ministry of Climate and Environment and the National Fund for Environmental Protection and Water Management in Warsaw, in order to develop programs, addressed primarily to the existing heat plants, based on geothermal waters, which will enable obtaining funds for periodic modernization and works, maintaining the efficiency of the installation. Geothermal heat plants in Poland are a potential, source of knowledge and experience for newly built installations.

The abstract contains content developed within the GEORISK Project. The project received funding under the European Union's Horizon 2020 research and innovation program, grant agreement No. [818231 - GEORISK].

REALISED AND PLANNED INVESTMENT ACTIVITIES UNDERTAKEN BY PEC GEOTERMIA PODHALAŃSKA S.A. IN ORDER TO ENSURE THE OPTIMAL USE OF THE GEOTHERMAL SOURCE

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Key words: geothermal source, enterprise development, co-financing

Abstract

PEC Geotermia Podhalańska S.A. has been in business for over 27 years and is the oldest and the largest geothermal energy producer in Poland. The company operates 5 geothermal boreholes, 3 of which are production boreholes, and 2 injection ones. According to data from the end of 2020, the total length of heating networks and connections built by the Company totals 117 km, and the amount of extracted geothermal water totals 5.2 million m^3 per year. Over 95% of heat production came from the geothermal source (the rest was produced from gas and oil). The heating system based on the geothermal source makes it possible to supply 1770 facilities located within four communes – Szaflar, Biały Dunajec, Poronin and the Zakopane municipality – with heat. The average temperature of geothermal water is 86^{o}C. At the end of 2020, the ordered capacity totalled 75.65 MW, while heat sales totalled 454,000 GJ. In the years 1999-2020, thanks to geothermal energy in Podhale – one of the most frequented tourist regions in Poland, coal consumption decreased by over 333,000 tonnes of coal, and the CO_2 emission was reduced by 667,000 tonnes.

The heating system powered by the geothermal source is an innovative, Europe-wide high-tech solution. The project to use geothermal energy in Podhale ushered in the development of geothermal energy in Poland. It is especially environmentally friendly, and for heat consumers it is comfortable and safe. It is worth mentioning that the geothermal project not only is a modern solution for using hot water sources of great environmental importance, but also it is an economically viable enterprise. Heat prices have been stable for years, and the Company achieves good economic results.

The Company continues to develop by implementing investments in modernisation and expansion of heat sources, as well as the construction of new heating networks and connections. The sources of investment financing, apart from internal funds, include the subsidies from the National Fund for Environmental Protection and Water Management and the European Union.

In December 2017, the Company's Management Board signed an endowment agreement for the project entitled "Construction of heating networks and connections in the Zakopane municipality and the communes of Poronin, Biały Dunajec and Szaflary in order to increase the use of renewable energy sources and reduce the emission of pollutants into the air", under the Regional Operational Programme for the Małopolska Region 2014-2020, Sub-measure 4.4.2 low emissions level reduction, projects type B. development of district heating networks.

The project was implemented in the period from March 2017 to April 2020.

Total project value: PLN 9,324,856.21,

of which the value of eligible expenditure: PLN 7,495,764.07.

Endowment value: PLN 4,476,048.76, which equals 59.71% of the eligible expenditure.

The material scope of the project included:

- construction of a heating network and connections in the area of Kościeliska and Krzeptówki Streets in Zakopane,
- construction of a new pumping station in the area of Gładkie Street in Zakopane,
- modernisation of the existing pumping system at the Szymaszkowa pumping station in Zakopane,
- construction of individual heat connections within the existing networks in the municipality of Zakopane, the communes of Poronin, Biały Dunajec and Szaflary,
- construction of a heating network with connections in Poronin in the area of Tatrzańska and Piłsudskiego Streets, and in Biały Dunajec in the region of Piłsudskiego Street,
- construction of connections to existing and new facilities in the area of Zakopane town and the communes of Poronin, Biały Dunajec and Szaflary.

In 2019, the material scope of the project was completed. In 2020, the project was settled. Within the eligible expenditure, 123 heat connections were built. The total length of heat networks and connections built within the framework of eligible expenses of the project is 5.85 km. As a result of the project realisation, the planned environmental effect – reduced emissions of dust and greenhouse gases – was achieved.

In November 2017, the Company's Management Board entered into an endowment agreement with the National Fund for Environmental Protection and Water Management in Warsaw for the project entitled: "Expansion of the geothermal system in order to increase the capacity of the renewable source of thermal energy for PEC Geotermia Podhalańska S.A.", co-financed by the European Union under the European Fund for Infrastructure and Environment 2014-2020. The project was implemented in the period from 17 March 2017 to 31 December 2020. Total project value was PLN 20,689,266.85, of which the value of eligible expenditure: PLN 12,836,301.16. The endowment value was PLN 5,537,027.50, which equals 43.14% of the eligible expenditure.

Within the project, the following tasks were completed:

- Construction of a building (R1 and R3) on the premises of the Geothermal Heating Plant in Szaflary, together with internal installations and a transformer station (R3) – the cubature of the R1 and R2 buildings is 3100 m^3, the cubature of the R3 transformer and the electrical switchgear building is 900 m^3.
- Acidizing of the Bańska PGP-3 production borehole; thanks to the acidizing treatment the borehole productivity increased from 250 m^3/h to 400 m^3/h.
- Modernisation of booster pumps at the Geothermal Heating Plant, two pumps with the capacity of 425 m^3/h each was installed.
- Modernisation of injection pumps and filters at the geothermal pumping station, two pumps with filters with a capacity of 250 m^3/h each were installed.
- Modernisation of valves on PGP-2 and PAN-1 absorption borehole heads – two valves were installed on each head.
- Modernisation of geothermal pipelines – pipes were modernised along a section of approx. 420 m with diameters DN200-DN300.
- Acidizing treatment in the Biały Dunajec PGP-2 borehole – during works connected with the preparation of the Biały Dunajec PGP-2 borehole for an acidizing treatment, it turned out that the treatment could not be performed due to the poor technical condition of the borehole. It was necessary to carry out works aimed at unblocking the well. As a result of two-stage works, the well was partially unblocked, and its capacity increased from 400 m^3/h to 430 m^3/h.
- Two Sondex Type S-221-IS heat exchangers with the installed capacity of 7.8 MW each were installed in the new building at the Geothermal Heating Plant, and technological installations were installed and connected to the geothermal water installation and the mains water installation at the Geothermal Heating Plant. Control installation and the AKPiA [Polish: Aparatura Kontrolno-Pomiarowa i Automatyka, English: Control and Measurement Instruments and Automation] were installed, and the SCADA and control-and-warning systems were extended at the Geothermal Heating Plant.

  The geothermal exchangers were selected for the operating parameters of the geothermal system and the district heating network to increase the heat exchange surface after connection to a value that would enable the temperature difference reduction between the temperature of the return mains water and the thermal water by 1°C. This resulted in an increase in the utilisation of thermal energy from the thermal water.

As a result of the project implementation, the assumed objectives were achieved, i.e. increase in the efficiency of primary energy use and reduction of energy consumption of Przedsiębiorstwo Energetyki Cieplnej Geotermia Podhalańska S. A. by increasing energy generation from renewable sources.

All investment activities connected with the project realisation were aimed at ordering, rationalising and minimising the negative environmental impact of the heating system of PEC Geotermia Podhalańska S.A. Thanks to the project, the additional capacity to generate thermal energy from RES increased by 6.7 MWt.

The following result indicators have been defined for the project:

- thermal energy production from newly built/new capacity of RES installations: 9,593 MWht/year,
- estimated annual decrease in greenhouse gas emissions: 2,378.89 $MgCO_2$/year.

On 19 December 2018, the Company's Management Board entered into an endowment agreement with the National Fund for Environmental Protection and Water Management in Warsaw for the project entitled: "Construction of heat connections and networks in the Zakopane Municipality in order to increase the use of renewable energy sources and reduce air emissions" under the Operational Programme Infrastructure and Environment 2014-2020, measure 1.5 Efficient distribution of heat and cold, Priority Axis I Reducing the emissivity of the economy. The material scope of the project includes the construction of heating networks and connections with a total length of approximately 4.5 km in order to connect 150 individual customers.
The estimated total project value is PLN 14,458,533.19. The value of eligible expenditure is PLN 6,411,080.03. The endowment value is PLN 5,101,317.12, which equals 79.57% of the eligible expenditure. Project implementation period: from July 2018 to December 2021. The project is under implementation. From the beginning of the project until 30.07.2021, a total of 143 connections to new heat consumers were made.

On 3 July 2020, the Management Board signed a contract with the National Fund for Environmental Protection and Water Management in Warsaw for an endowment in the form of a grant and a loan for the project entitled: "Increasing the capacity of the renewable source of thermal energy of PEC Geotermia Podhalańska S.A. through the construction and reconstruction of absorption boreholes and the construction of accompanying infrastructure", as part of the National Fund for Environmental Protection and Water Management priority programme no. 5.18 "Interdisciplinary. Polish Geothermy Plus", co-financed from the national funds. The project aims to increase the absorptive capacity of the geothermal system for greater renewable heat production.
The material scope of the project includes:

- drilling a new absorption borehole Biały Dunajec PGP-5, to a depth of 3,523 m (±10 %),
- deepening and reconstruction of the Biały Dunajec PGP – 2 absorption borehole,
- construction of an injection pipeline from the geothermal pumping station to the PGP-5 wellhead,
- purchase and installation of further two heat exchangers at the Geothermal Heat Plant.

As a result of the project, the capacity of the geothermal renewable energy source will increase by a total of 2.671 MWt. The reconstruction of the PGP – 2 boreholes will ensure the energy security of the entire system (with the absorption capacity of this borehole of 450 m^3/h), which gives a capacity of 15,411 MWt. The total of the project is PLN 42,822,450.00, eligible expenditure: PLN 34,715,000.00, non-eligible expenditure: PLN 8,107,450.00. Amount of the endowment in the form of a grant: PLN 13,886,000.00 (40% of the eligible expenditure). Amount of the endowment in the form of a loan: PLN 20,829,000.00 (60% of the eligible expenditure). Project implementation date: from 01.01.2020 to 31.12.2021. The project is under implementation.

The functioning and growth of any enterprise require adequate capital expenditure, crucial for current and developmental activities. In order to function and develop, an enterprise must constantly obtain financial resources. Consequently, ensuring sufficient financial resources is important at every stage of the enterprise life cycle.

Investments related to the construction of infrastructure for heat generation and transmission based on a geothermal source were very capital intensive and required a constant capital supply, while its sources, both internal and external, were limited in the initial phase of the Company's development.
The main barrier to using external sources of financing was the risk, which is very high in the initial phase of enterprise development.

The Company's experience confirms that the development phase is characterised by a very high level of capital expenditure, the demand for capital in this phase is enormous and the risk is still high, which is why a bank loan is often unavailable and also very expensive.
In conclusion, since the availability of loans and grants is limited, and financial resources are necessary regardless of the stage of operation of a company, the use of alternative financial instruments such as a **geological risk insurance fund** should be given more consideration.

The Company's experience indicates that there are real long-term risks associated with resource deterioration (including reduced borehole productivity, reduced absorption, reduced thermal water temperature) during the exploitation of the wells. The geothermal market in Poland lacks financing mechanisms that would support the above-mentioned market’s development in the exploitation phase (in

a perspective of about 20 years). In order to finance treatments such as acidizing or the reconstruction of geothermal boreholes, large financial outlays are needed.
An insurance fund to mitigate the risk of long-term exploitation of geothermal boreholes related to the deterioration of resources would be a vital tool enabling the development of the geothermal market in Poland. Taking the life cycle of the company into consideration, currently, PEC Geotermia Podhalańska SA is at the stage of transition between the development phase and the maturity phase. At this point, investment financing is still largely based on direct subsidies, loans and grants, but as the company is moving into the next phase of the business life cycle, it seems necessary to create alternative financing options, such as insurance and guarantee system. In the phase of market maturity, tools such as a geological risk insurance fund appear to be a tool that can effectively mitigate the long-term risks of the business.

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GEOTERMIA PODDĘBICE UNDER DEVELOPMENT

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Keywords: thermal water, organization of heat supply, enterprise development, co-financing

Abstract

Geothermal system at Geotermia Poddębice Sp. z o.o. operates on one geothermal well Poddębice GT-2, which initially served research purposes, but after preparing hydrogeological documentation and obtaining a license, became a production well. Thermal water with low mineralization, not exceeding 0.5 g/l, is transported from the well to the heat exchanger, where two APV plate heat exchangers with a total capacity of 10 MW have been installed. Thermal water, on the secondary side, after the heat is transferred to the process water, which carries heat to the consumers, is used in thermal pools, in the thermal water pump room, and for rehabilitation in the district hospital.

The heat contained in the hot mains water is transferred through district heating networks made in modern pre-insulated pipe technology, taking its origin in geothermal exchangers. The circulation of water in the district heating system is forced by a pump unit consisting of 3 circulation pumps. Maintaining the required available pressure is realized by smooth regulation of the capacity of each pump. The installation is secured by a pump-controlled DHA REFLEX pressure maintaining system.

The geothermal heating plant works in conjunction with three boiler houses that act as peak load and reserve sources. Unused thermal water goes to water cooling tanks and, after cooling to a temperature below 35°C, is discharged into the Ner River. During the summer, the artesian flow of thermal water is used. With a self-outflow capacity of up to 50 m³/h, the system can provide domestic hot water in the city in multi-family and public buildings. During the transitional periods of spring and autumn the intake range from 100 to 140 m³/h, the thermal water is extracted by a surface pump with a 15 kW motor. The pump is controlled by an inverter and an electric gate valve. During the winter, a pumping unit consisting of a 110 kW motor and a pump suspended at a depth of 90 m below ground level is used to extract thermal water from the well. For energy security, Geotermia has two complete pumping units: one in the well and one as a backup.

Geotermia Poddębice Sp. z o.o. operates in the district heating sector based on a geothermal source with a maximum capacity of 252 m³ / h, defined by the license issued by the Minister of the Environment, with a temperature depending on the volume of water withdrawn from the intake. Throughout the year, the temperature ranges from 63.2 to 68.4 °C depending on the amount of water extracted. The heat collected from the thermal water in the heat exchangers is supplied to the consumers. Recipients located near the geothermal heat plant at 17A Mickiewicza St., connected in the first stage of construction of the geothermal heat installation are provided with the heat of the maximum temperature of 62°C, therefore they have their peak load and reserve sources to increase the temperature at times when the outside temperature in the winter period requires it. The fuel in these boiler plants is heating oil. Other heat consumers are connected via the district heating network to the boiler plants.

The district heating network in Poddębice consists of a two and four-wire preinsulated network with a total length (including connections) of over 13 km, which is powered by a geothermal heating plant with a total installed power of 10.00 MW. The district heating network is supported by three peak load and reserve boiler houses with a total installed capacity of 7,375 MW, fuelled by heating oil and biomass. The boiler houses are used in winter when the outside temperature drops to about minus 20°C. The heat carrier is hot water with parameters T max 75ºC/50ºC and P max 6 bar.

In order to make even more use of the advantages of thermal water from Poddębice and the existing installation, Geotermia is carrying out a large investment project, the aim of which is to obtain by Geotermia Poddębice Sp. z o. o. the technical possibilities of connecting new heat energy recipients by expanding the existing heat source and district heating network while maintaining optimal production and heat distribution costs. The objective will be achieved by expanding the currently operating geothermal heat source with

a cogeneration module with an electrical capacity of 999 kWe and a thermal capacity of 1,133 kWt. In order to install the cogeneration engine and the heat pump, it is necessary to extend the administration and technical building and perform the necessary installation works. This also requires a change in the development of the existing site.

An additional element of the project is a photovoltaic installation that will be located along the south elevation of the existing and new building. The heat produced in the high-efficiency cogeneration process will be used to power the swimming pool complex and the district heating network, while electricity will be used for the swimming pool and the Geotermia complex, with surplus electricity being exported to the DNO network. Taking into account the existing consumers, the total demand for heat power for the extended district heating system will be 7778 kW, including 1320 kW for DHW purposes. A serial hydraulic interconnection system of the geothermal exchanger unit and the cogeneration module is planned to be used for the power supply. The network water will be preheated in the geothermal exchangers, and then it will reach the appropriate parameters in the cogeneration module. If the heat demand in the heating system exceeds the production capacity of the geothermal source and the cogeneration module, peak load and reserve heat boiler units will be activated.

Once the source and the distribution system are expanded with a II stage heat recovery (heat pump), the peak load and reserve resources will be able to be successively removed from the system. The expanded district heating system will be suitable for both summer and winter operations. In summer, the heat produced by the geothermal source and the cogeneration module will completely satisfy the energy needs for heating pools and hot water in the city. The cogeneration system will also provide an emergency source of heat for the swimming pool facility located in the vicinity in case of failure of the submersible pump in the geothermal well.

An additional objective of the project is to ensure the possibility of using water from the geothermal intake by treating it and introducing it into the district water supply system, which will reduce water consumption in the process of heat production. Physicochemical composition and quality of thermal water, extracted from sandstone formations of the Lower Cretaceous through GT-2 well in Poddębice, and low mineralization below 0,5 g/l cause that by using standard treatment methods (iron and manganese reduction) it can be introduced to district water supply system.

A necessary step for the utilization of thermal water for drinking water purposes is the installation of a cooling system since the water leaving the exchanger station has a temperature of about 47-50 °C. Introducing water to the water treatment station is possible when the temperature does not exceed 30-35 °C.

The cheapest and most effective way to cool water is to use an open evaporative cooling tower. The construction of the thermal water treatment station will make it possible to manage a large part of the water discharged and not currently utilized at the moment, up to 50 m³/h, of which 35 m³/h can go to the district water supply system and up to 15 m³/h to the swimming pool facility. In this way, the amount of the quaternary water usage at the Poddębice water supply intake will be reduced. In the summer season, Geotermia Poddębice extracts on average about 50 m³/h and in the winter season up to 252 m³/h of thermal water, so the use of 50 m³/h of water mass for drinking and municipal purposes represents respectively 100% in summer and 25% in winter of the total exploitation.

Assuming that the water after passing through the water treatment plant will have a temperature below 30°C and there will be no need for its further cooling, it is possible to cover up to 100% of the water demand of swimming pool facilities for refreshing, filter cleaning, and water exchange in swimming pools.

With an annual water production of 35 m³/h for drinking water, there is a possibility to use 306.600 m³/year of thermal water, which is on average 75,7% of the production from the Poddębice water supply network, and the use of thermal water for the needs of the currently revitalized swimming pool facility in the amount of 15 m³/h will allow replacing 131.400 m³/year of quaternary water with cooled thermal water, which gives 32,4% of natural resources savings. It is especially important in the aspect of recent years, where precipitation was sporadic, and during the winter season, there was no snowfall in most of Poland.

The proposed savings will have a positive impact on the improvement of water conditions, especially that the thermal water for heating purposes is already extracted and can be used in a cascade manner, among others, for drinking and household purposes after minor treatment and cooling.

Geotermia Poddębice Sp. z o.o. has obtained funds for the above-mentioned project in the amount of nearly 15 million PLN from the National Fund for Environmental Protection and Water Management in Warsaw in the form of a grant of 30% of eligible costs and almost 70% of a loan. Own funds constitute a small percentage. In addition, the company must secure funds for VAT, allowing for smooth payment for construction works. The planned completion date is December 31, 2022.

From the 1st of June this year Geotermia Poddębice has become an operator of the revitalized complex of thermal pools, which includes a facility of Water Treatment and Recreation Centre (complex of thermal pools and saunas, fitness, massage, and bathing rooms) and an Integration and Meeting of Disabled People facility. Unfortunately, due to the COVID-19 pandemic, the Water Treatment and Recreation Centre facility has not been operational. The opening has been scheduled for April 1, 2022, if pandemic conditions allow.

The Integration and Meeting of Disabled People facility have been opened, where recreational and physical activities, as well as massages, are performed and hotel rooms are rented. There are 32 hotel beds located in 15 rooms with bathrooms for 2-3 people. Thermal water will be the main source of heat and water for the Water Treatment and Recreation Centre facility after it has been used for heating purposes.

The participation of Geotermia Poddębice in the two projects GEORISK and User4GeoEnergy allowed us to participate in the testing, development and evaluation of a risk assessment tool for geothermal projects. It also enabled us to take a closer look at the existing installation in our facilities and to benefit from the experience of other geothermal companies. From the assumptions developed in the GEORISK project, it can be concluded that a long-term risk fund is necessary for the projects. This would be the safest approach for investors. As the experience of other operating geothermal plants shows, in each case, various risks are appearing at different stages: exploration, drilling, and exploitation. The risks are related to socio-economic, operational, geological, technical, and human aspects. All of them ultimately boil down to financial risk or seeking financial resources to mitigate some of the risks. The National Fund for Environmental Protection and Water Management, which has been subsidizing the drilling of geothermal wells under various programs over the years, has the best knowledge of the problems investors have to face. Therefore, we believe that a tool could be created within the NFEPWM for geothermal projects to mitigate risk, e.g. through a risk insurance fund.

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We would like to express our gratitude to the management board of the Polish Geothermal Association and the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences for the continuous efforts to promote the vast possibilities of geothermal energy in science, engineering, and everyday use.

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Data comes from own studies of Geotermia Poddębice Sp. z o.o.

ACTIVITIES OF GEOTERMIA MAZOWIECKA S.A. – PRESENT AND FUTURE

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Keywords: geothermal water, heating installations, investment risk

Abstract

Under the name of Geotermia Mazowiecka S.A. is not only the Geothermal Plant in Mszczonów is operating. In 1998, Geotermia Mazowiecka S.A. A conventional district heating system has also entered, supplying heat to one of the districts of Sochaczew Chodaków. In 2003. the city of Błonie joined the production structure of the Company, and in 2008/2009 Ożarów Mazowiecki joined its heating system. At the same time, the Company built another heating plant in Sochaczew, thus enabling the supply of heat to about 40 inhabitants of the city.

The final stage of the development of Geotermia Mazowiecka S.A. was to build a gas heating plant in Żyrardów. Geotermia Mazowiecka S.A. has been licensed to generate heat since 1998. The subject of the activity covered by this license is an economic activity consisting of the production of heat from six sources:

1. Geothermal Plant in Mszczonów, with a total installed capacity of 8.5 MW, equipped with three water boilers and two absorption heat pumps, using natural gas as fuel.
2. "Chodaków" heating plant in Sochaczew, with a total installed capacity of 6.8 MW, equipped with two water boilers with an installed capacity of 2.9 MW each, using fine coal as fuel, and two water boilers with an installed capacity of 0.5 MW each, adapted to the combustion of biomass.
3. "Trojanów" heat plant with a total capacity of 3.5 MW equipped with two boilers with a capacity of 2.5 MW and 1.0 MW, using fine coal as fuel,
4. Boiler room in Błonie, with a total installed capacity of 9.9 MW, equipped with three water boilers using natural gas as fuel.
5. Boilerhouse in Ożarów Mazowiecki, with a total installed capacity of 14.0 MW, equipped with three water boilers using natural gas as fuel.
6. Boilerhouse in Żyrardów, with a total installed capacity of 10.0 MW, equipped with one water boiler, using natural gas as fuel

When thinking about Geotermia Mazowiecka S.A., we primarily think about the flagship project, which was the construction of the ZG-1 geothermal plant in Mszczonów. In place of the old coal-fired boiler house, a modern geothermal heating plant was built, fed with water from the Mszczonów IG-1 well. The heating plant replaced three water boiler houses powered by fine coal, which contributed significantly to the reduction of harmful pollutants in the form of sulfur dioxide, nitrogen oxides, carbon monoxide and dioxide, as well as soot and dust. The reconstruction of the Mszczonów IG-1 borehole enabled the commissioning of geothermal water. Thanks to investments related to geothermal energy, we mean the city's new district heating system, the construction of the Mszczonow Thermal Baths, and the Deepspot complex, the city received funds from external subsidies. In the mid-nineties, investing in geothermal energy, which was then considered a complete novelty, was associated with considerable risk. Nobody was able to guarantee that the investment would be profitable and bring tangible benefits to the city. However, as shown by the present times, it has paid off and has had an excellent impact on many aspects of life, both in the economic, social and environmental dimensions.

The best solution is to base the development of technology and business on energy from renewable sources. Geotermia Mazowiecka S.A. is a business partner that has been extracting environmentally friendly energy for a quarter of a century by cooperating with many companies, local governments and universities. Our knowledge and experience help us to constantly improve the technology of obtaining energy from the inside of the earth.

The company participated in a project aimed at the widest possible use of geothermal water for drinking purposes, by congestion after treatment, cooling and energetic use of geothermal water to Quaternary structures. In cooperation with partners from the Institute of Mineral and Energy Economy of the Polish Academy of Sciences, Warsaw University of Technology, responsible for the scientific side of the project, we drilled a borehole to a depth of 100 m and technical infrastructure allowing for the injection of geothermal

waters into the Quaternary formations. We are currently able to pump geothermal water underground in order to enrich drinking water resources. The water meets all drinking water requirements and standards. The installation equipped with automation also provides for the supply of geothermal water to the municipal water supply, which in today's times of water shortage is a very important and priority thing.

We are facing challenges such as further improvement of the efficiency of geothermal water use through:

1. 100% modernization of the ZG-1 geothermal plant in Mszczonów, including replacement of an absorption heat pump with a built-in gas burner,
2. Reconstruction of the IG-1 geothermal well,
3. Drilling a new geothermal borehole ensuring stable work and the possibility of further exploitation of geothermal waters,
4. Cooperation with local government units in the development of concepts and projects for the extraction and use of geothermal waters in individual municipalities, e.g. Błonie.

The promotion of renewable energy in the form of energy from geothermal resources will be possible thanks to the extensive cooperation of local government units with the central units. The local government is responsible for the energy used to heat houses, service institutions, industry, etc., on the other hand, the support of the government that will support the initiative of wider use of geothermal energy, which results from various international obligations, is indispensable. The geothermal support system must exist and remain maintained at the design, construction and subsequent operational stages. Loans, subsidies (eg Geotermia Plus), green certificates for heating and substantive support for communes are very important. Examples of other countries show that it is possible. The GeoRisk project led by the Institute of Mineral and Energy Economy of the Polish Academy of Sciences in which Geotermia Mazowiecka S.A. participates and the establishment of the geological risk insurance system, both short-term and long-term, perfectly fits the idea of promoting good practices which may facilitate or enable a positive view of green energy, which is geothermal energy. The situation in which Poland found itself, but also the whole world, related to the coronavirus pandemic, in the absence of establishing a geological risk insurance fund, may lead to a complete suspension of geothermal investments. We could observe a slowdown in the economy and the suspension or limitation of investments, which in a sense is understandable as potential investors are afraid of taking risks, and even more so, the risks that are already huge at the very beginning of the decision. We hope, however, that the enormous potential of geothermal energy and the continuation of geothermal investment support programs, perhaps with the possibility or chances of insuring, for example, Polska Geotermia Plus, will enable us to obtain funds for the construction of a second geothermal well in Mszczonów.

To sum up, the waters exploited in Mszczonów, apart from being used for heating purposes, are now also used as drinking water and supply the Termy Mszczonowskie recreation complex, as well as the deepest diving pool in the Deepspot complex. Cascade use is possible due to low mineralization. Particularly important in this aspect is the enrichment of the balance of ordinary waters in the city. Therefore, while the acquisition of geothermal waters in order to obtain clean heat energy is the first reason for their exploitation, the extension of their development creates the possibility of developing other areas of the economy in individual regions. Share of Geotermia Mazowiecka S.A. in research and development projects, related, for example, to monitoring microbial corrosion, acquiring drinking water, storing energetically used geothermal water, it allows assessing that these waters can constitute the basis for innovative activities and continuous development of even small towns. The most important thing in all this, however, seems to be the positive ecological effect, which was contributed to by the construction and operation of the Geothermal Plant.

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ASSESSMENT OF THE SHALLOW GROUNDWATERS POTENTIAL OF THE " KOŚCIERZYNA MORAINIC ISLAND" IN TERMS OF COLD AND HEAT SEASONAL STORAGE ATES

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Keywords: Aquifer Thermal Energy Storage, Ground-Water Heat Pump, cooling power raw value, Kościerzyna (PL)

Introduction

Low Temperature Aquifere Energy Storage (LT-ATES) which was recognized as the cheapest method of inter-seasonal thermal energy storage (Schmidt and Miedaner, 2012) could find applications in Poland. 6 years ago, a team from the University of Technology in Delft (NL) proved that the Polish Lowland is a very promising area for this kind of application (Bloemendal et al., 2015). Recently, based on the geostatistical analysis of data from the groundwater observation and research network, geologists from IGSMiE PAN in Kraków came to the same conclusions (Skrzypczak and Miecznik, 2019).

This paper presents the most important conclusions of an unsolicited study with the above-mentioned title (Lemoine, 2020). The study was sent to the archives of the Polish Geothermal Society at the beginning of June 2020. As in two previous studies (Lemoine, 2016, 2018), in this third one the focus was on the possibility of using the method LT-ATES in the young-glacial areas of the northern part of the Polish Lowlands, where the complex structure of shallow geological formations is usually, but perhaps excessively, perceived as unfavourable. In this case, the "Kościerzyna Morainic Island" was selected as the research area.

Samples and methods

Hydrogeological map of Poland on a scale of 1: 50,000 together with explanations (Kreczko A., Kozerski B., 2007) constitute the main source of data. The energy potential of shallow aquifers refers to the potential of LT-ATES Unitary Cyclic Module (JMC) as defined in the basic doublet LT-ATES hydraulic component operating in seasonal cyclic (bi-directional) mode (Lemoine, 2016, 2018). Computer simulation of the thermal stimulation of the JMC storages was performed with a simple spreadsheet following the recommendations of the French geological survey BRGM (Gringarten et al. 1979; Ausseur and Sauty, 1982). The concepts of raw cooling potential and raw cooling power were introduced here based on the JMC module The first value means the amount of cold that can be transferred to the cold zone over a thermodynamic half-cycle lasting 6 months, based on the 20 K temperature difference between the hot and cold side of the storage. The second value is calculated from the raw potential.

Results

Regarding the hydrogeological units occurring in the "Kościerzyna Morainic Island", the raw potential and raw cooling power of JMC LT-ATES were approximated in the range respectively of 2.5 ÷ 25 TJ and 0.15 ÷ 1.50 MW. With the hypothesis of the thermal energy recovery ratio of 0.5 and in the case of the western part of this moraine, which is the most promising area, the effective JMC-ATES cooling potential was estimated to be 5 TJ and the effective cooling power to 0.6 MW.

Conclusions

The location of small, for example, six-hole LT-ATES systems with several-MW cooling power looks technically possible in the "Kościerzyna Morainic Island". The western districts of Kościerzyna city are promising in this sense for two reasons. First, in this area, the characteristics of shallow groundwater make it possible to design typical LT-ATES systems with a cyclic hydraulic system as the most effective mode. Secondly, the presence of a large specialist hospital as the main potential consumer of cooled water would give an economic rationale for this type of investment. Apart from the western districts, the LT-ATES method could additionally be combined with groundwater remediation in the degraded areas of the city. Considering that the combination of these two technologies is currently not mastered but only understudy in Poland by hydrogeologists from AGH (Malina and Bujak, 2017), it could be specifically tested here only in a pilot project.

The results of these investigations show, first of all, that even in the lake district mesoregions of the Polish Lowlands, where the Quaternary cover is characterized by high structural complexity, favourable conditions may occur locally, not only hydrogeological but also economic, for low-temperature and inter-seasonal thermal energy storage using the ATES method.

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DETERMINATION OF EFFECTIVE THERMAL CONDUCTIVITY IN THERMAL RESPONSE TESTS - COMPUTATIONAL MODEL

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Keywords: effective thermal conductivity, hole heat exchanger, geothermal heat pumps, thermal reaction test TRT

Abstract

The easiest way to determine the parameters of the borehole heat exchanger is to use the literature values of the thermal conductivity of the rocks of the drilled profile. On this basis, it is possible to calculate the effective thermal conductivity in the hole heat exchanger, which is the same as the weighted average thermal conductivity of rocks. The importance, in this case, is the thickness of individual lithological formations.

Based on the data obtained from the thermal reaction tests (TRT) carried out in the hole heat exchangers, the results can be interpreted using 3 methods. The classical method (cm) is based on the determination of the slope coefficient of the line k, the dependence of temperature on time in a semi-logarithmic system. Using the point method (pm) assuming averaging of the temperature rise and the method of constant resistivity of the well (cbrm), i.e. determination of the value of the effective thermal conductivity coefficient λ_{eff} based on the graph $R_b = f(t)$.

1. Stages of interpretation of TRT results

After receiving the data from the thermal reaction test, the first stage is the determination of 6 characteristic points, which were determined as follows (Śliwa 2012):

– t_0 - the start of the heating phase of the test,
– t_1 - curve breakpoint,
– t_2 - time corresponding to $t=5\cdot r^2\alpha^{-1}$,
– t_3 - time corresponding to $t=20\cdot r^2\alpha^{-1}$,
– t_4 - half the duration of the heating phase of the test,
– t_5 - end of the heating phase of the test.

t_0 - the beginning of the heating phase of the test - this is the point of the sudden increase in temperature (Figure 1) when performing the thermal reaction test (as a result of switching on the heating power).

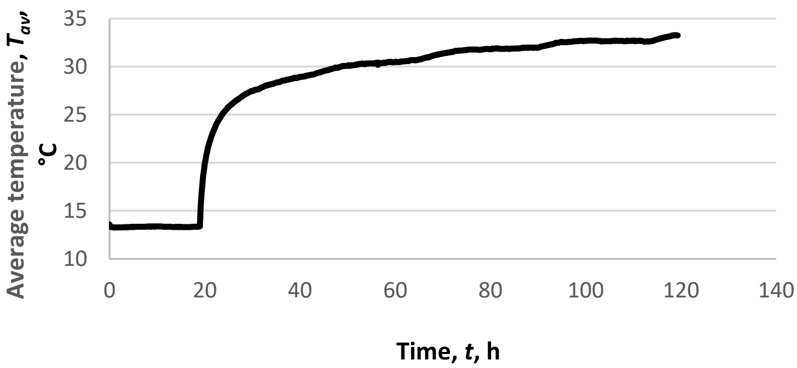

Figure 1. *Graph of the dependence of the mean temperature (T avg.) At the time of the thermal reaction test.*

t_1 - the breaking point of the curve - determined based on the graph of temperature dependence on the log of time (Figure 2).

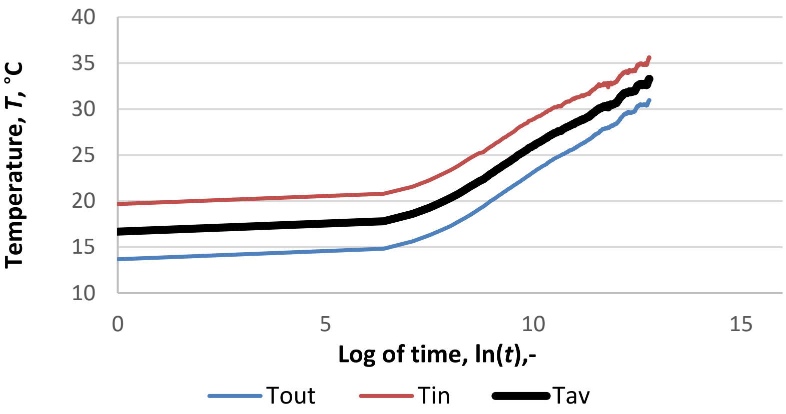

Figure 2. *Graph of the dependence of the mean temperature (Tav) on the log of time (ln (t)) of the thermal response test.*

The next step is to determine the value of the average heating power *P*. Average heating power *P* is the arithmetic mean of the instantaneous powers, calculated based on the results of the TRT test in the range from t_0 to t_5. It is defined by the following formula:

$$P = \sum_{i=1}^{n} \frac{Pchi}{n} \tag{1}$$

n - number of records recorded in the heating phase of the test,
P_{chi} - instantaneous heating power for the record i, W.

The calculations are performed for the following time intervals:

- t_0-t_5,
- t_1-t_5,
- t_2-t_5,
- t_3-t_5.

2. Characteristics of the methods of interpretation of TRT results

There are three methods for interpreting the results of a thermal response test. They are characterized below.

2.1. Classic method (cm)

In the classical method, to calculate the thermal conductivity of the profile rocks, the key is to know the k coefficient, which can be read from the diagram (Figure 3) for the appropriate time interval.

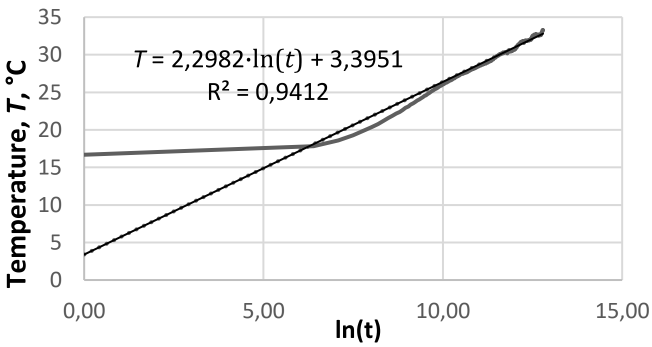

Figure 3. *Graph of the dependence of the mean temperature (T avg.) On the log time (ln (t)) of the thermal reaction test, interval (t_0-t_5).*

According to the equation (Gonet et al. 2011):

$$T = k \cdot \ln(t) + b \tag{2}$$

k - slope coefficient of the regression line,
b - the point of intersection of the regression line with the Y axis.
The thermal conductivity of the profile rocks is calculated from the following formula (Gehlin and Hellström 2003, Sanner et al. 2005):

$$\lambda_{eff} = \frac{P}{4 \cdot \pi \cdot H \cdot k} \tag{3}$$

P - average heating power calculated based on TRT results (arithmetic mean of instantaneous powers), W,
k - a slope of simple regression,
H - hole depth, m.

2.2. Point method (pm)

In this method, the thermal conductivity of the profile rocks is calculated based on the following formula (Gonet et al. 2011):

$$\lambda_{eff} = \frac{\frac{q}{4 \cdot \pi} \cdot \left[\ln\frac{t_{end}}{t_{beg}} + \frac{r_0^2 (t_{end} - t_{beg})}{4 \cdot \alpha \cdot t_{beg} \cdot t_{end}} \right]}{T(t_{end}) - T(t_{beg})} \tag{4}$$

t_{end} - final time, s,
t_{beg} - initial time, s,
$T(t_{end})$ - the average temperature of the heat carrier at the time t_{end}, ° C,
$T(t_{beg})$ - the average temperature of the heat carrier at t_{beg}, ° C,
α - thermal diffusivity (temperature conductivity coefficient), $m^2 \cdot s^{-1}$,
r_o - borehole radius, m,
q - heat loss per depth unit, W · m-1, calculated from the formula:

$$q = \frac{P}{H} \tag{5}$$

P - average heating power during the test, W,
H - hole depth, m.

2.3. Constant borehole resistivity method (cbrm)

The method of constant resistivity of the well (Śliwa 2012) consists in determining the value of the effective coefficient of thermal conductivity λ_{eff} in such a way that the linear regression of the equation (6) on the thermal resistance R_b as a function of time takes the form of the function $R_b = kt + b$, and the slope k has the value equal to or very close to zero (Figure 4). It is assumed that the value of λ can be considered correct if the condition is satisfied:

$$k < 10^{-9}$$

$$R_b = \frac{1}{q}(T_{av} - T_0) - \frac{1}{4 \cdot \pi \cdot \lambda}\left[ln\left(\frac{4\alpha t}{r_o^2}\right) + \frac{r_o^2}{4\alpha t} - \gamma \right] \tag{6}$$

t- time, s,
T_{av} - average temperature of the heat carrier in time (t), ° C
T_0 - average natural temperature of the profile, ° C
α - thermal diffusivity (temperature conductivity coefficient), m2 · s-1,
r_o - borehole radius, m,
q - heat loss per depth unit, W · m-1,
Υ- Euler's constant

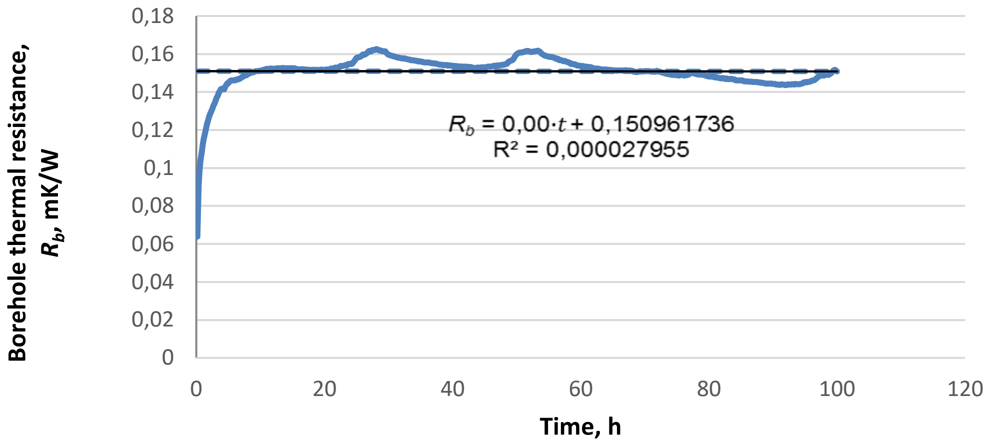

Figure 4. *Graph of the dependence of the temperature resistance R_b on the test time of the thermal reaction.*

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THERMAL CONDUCTIVITY RESEARCH BASED ON THERMAL RESPONSE TESTS

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Keywords: Thermal response test, borehole heat exchanger, thermal conductivity test

Introduction

In 2019, the European Union imposed the European Green Deal on its member countries, i.e. the energy transformation involving the fuel and energy sector modernization. The Polish Sejm has adopted an act on a new energy strategy and transformation. As a country, we have committed ourselves to becoming a zero- or low-emission (in the field of heating) country by 2040. Consequently, we will move away from fossil fuels and replace them with renewable heat sources (Energy Policy of Poland until 2040", the so-called EPP2040, described in the Annex to Resolution No. 22/2021 of the Council of Ministers of 2nd February 2021). The main issue will be the departure from hard coal and lignite, as Polish homes are supplied with hot water and electricity from power plants powered by those fuels every year. Using the heat of the rock mass to heat buildings is not a common method of utilizing renewable energy, but the development of low-temperature energy exploitation via borehole heat exchangers may change that. At the initial stage, a thermal response test (TRT) is required for the most efficient use of a borehole heat exchanger. Such a test enables the characterization of the borehole's thermal conductivity and thermal resistance. A classic test lasts from 40 to 140 hours with a constant heating power of 50 W/m (Gonet 2010). This solution does not provide real possibilities for optimizing and designing the heat exchanger field. To describe the thermal phenomena occurring in the borehole heat exchanger as accurately as possible, and to more precisely design the number and arrangement of heat exchangers for larger investments, a thermal conductivity test is performed on one borehole (Śliwa 2012). Based on the tests of one borehole heat exchanger at different heating powers and heat carrier flow rates, the dependence of thermal conductivity on TRT parameters was found (Gonet et al. 2012).

Samples and methods

To perform a thermal conductivity test on one borehole, 4 TRT tests with two different heat carrier flow rates and two different heating powers are conducted. A more extensive and precise method of performing the test is presented in the work of Gonet et al. (2012). In the full version of the test, it is required to conduct five thermal response tests on one borehole heat exchanger with three different heating powers and three different heat carrier flow rates (Figure 1). The time required to perform the test is about 500 hours (100 hours for one TRT), but the interval between individual tests should be 30 days. The thermal conductivity test has a big disadvantage - it takes a long time. To shorten the test time, simulations can be carried out, as the choice of computer analysis is justified by economic aspects. Conducting research on real objects would be a very costly endeavour, and due to advanced modern modelling techniques, it can be done at a relatively low cost. In the simulation, the mesh created for one exchanger can be used to test three different powers and flow rates, and the program calculation will take several hours. As a result, the temperature values on the inflow and outflow from the borehole heat exchanger, and thus the data needed for further calculations of the effective thermal conductivity λ_{ef} and the borehole's thermal resistance R_b, are obtained. The thermal conductivity test allows for a more accurate specification of the basic operating parameters influence on the parameters of a single borehole exchanger.

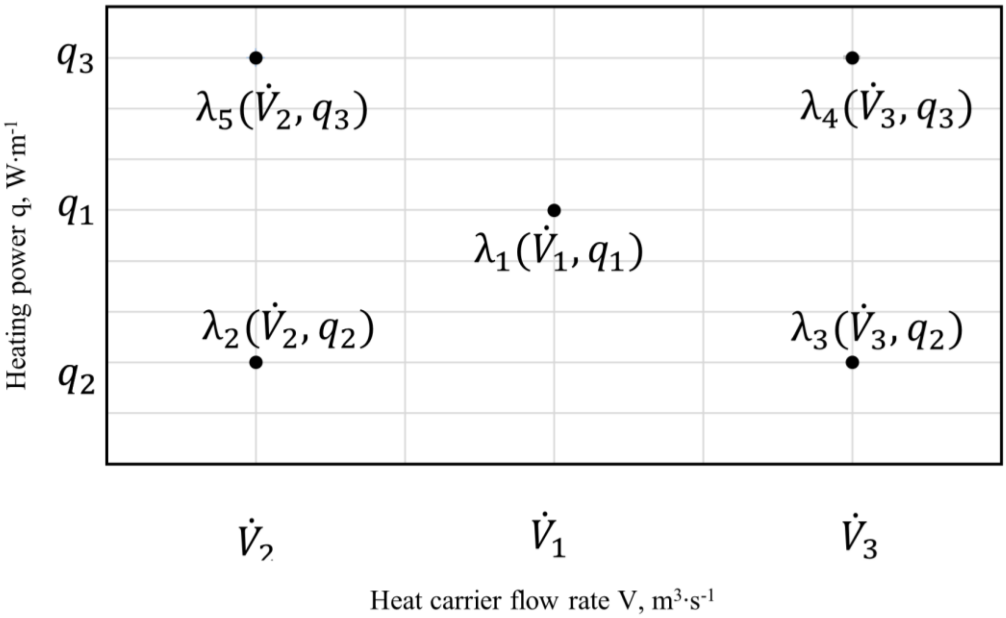

Figure 1. *Heat carrier flow rate and heating power in full thermal conductivity test.*

Results

The thermal conductivity value can be determined using the exponential function:

$$\lambda = c \cdot q^a \cdot \dot{V}^b$$

where:

λ – thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$

q – heating power, $W \cdot m^{-1}$

$\dot{V}$ – heat carrier flow rate, $m^3 \cdot s^{-1}$

c – a coefficient characterizing the system: rock mass - borehole exchanger,

a – a coefficient characterizing the effect of power on the thermal conductivity λ,

b – a coefficient characterizing the effect of the heat carrier flow rate on the thermal conductivity λ.

Table 1 contains the formulas for calculating the parameters in formula (1)

Table 1. *Methods for determining the coefficients of the equation (1).*

Coefficient	**3×TRT**	**4×TRT**	**5×TRT**
a	$a = \frac{ln\frac{\lambda_3}{\lambda_1}}{ln\frac{q_2}{q_1}}$	$a = \frac{ln\frac{\lambda_3.\lambda_4}{\lambda_1 \cdot \lambda_2}}{2ln\frac{q_2}{q_1}}$	$a = \frac{ln\frac{\lambda_4 \cdot \lambda_5}{\lambda_2 \cdot \lambda_3}}{4ln\frac{q_3}{q_2}} + \frac{ln\frac{\lambda_1}{c \cdot \dot{V}_1^b}}{2 * lnq_1}$
b	$b = \frac{ln\frac{\lambda_2}{\lambda_1}}{ln\frac{\dot{V}_2}{\dot{V}_1}}$	$b = \frac{ln\frac{\lambda_2 \cdot \lambda_3}{\lambda_1 \cdot \lambda_4}}{2ln\frac{\dot{V}_2}{\dot{V}_1}}$	$b = \frac{ln\frac{\lambda_3 \cdot \lambda_4}{\lambda_2 \cdot \lambda_5}}{2ln\frac{\dot{V}_3}{\dot{V}_2}} + \frac{ln\frac{\lambda_1}{c \cdot q_1^b}}{2 \cdot ln\dot{V}_1}$
c	$c = \frac{c_1+c_2+c_3}{3}$, where: $c_1 = \frac{\lambda_1}{q_1^a \cdot \dot{V}_1^b}$ $c_2 = \frac{\lambda_2}{q_1^a \cdot \dot{V}_2^b}$ $c_3 = \frac{\lambda_3}{q_2^a \cdot \dot{V}_1^b}$	$c = \frac{c_1+c_2+c_3+c_4}{4}$, where: $c_1 = \frac{\lambda_1}{q_1^a \cdot \dot{V}_1^b}$, $c_2 = \frac{\lambda_2}{q_1^a \cdot \dot{V}_2^b}$, $c_3 = \frac{\lambda_3}{q_2^a \cdot \dot{V}_2^b}$, $c_4 = \frac{\lambda_4}{q_2^a \cdot \dot{V}_1^b}$	$c = \frac{c_1+c_2+c_3+c_4+c_5}{5}$ where: $c_1 = \frac{\lambda_1}{q_1^a \cdot \dot{V}_1^b}$, $c_2 = \frac{\lambda_2}{q_1^a \cdot \dot{V}_2^b}$, $c_3 = \frac{\lambda_3}{q_2^a \cdot \dot{V}_2^b}$, $c_4 = \frac{\lambda_4}{q_2^a \cdot \dot{V}_1^b}$ $c_5 = \frac{\lambda_5}{q_3^a \cdot \dot{V}_2^b}$

Table 2 presents the calculation results for the OWC LG-1a well (coaxial borehole exchanger). The test parameters were

a) TRT-1, $q_1 = 54{,}7945\frac{W}{m}$, $\dot{V}_1 = 0{,}00034\frac{m^3}{s}$, [$Q_1$ = 4000W, $\dot{V}_1$= 20$\frac{l}{min}$, λ_{ef1} = 1.85$\frac{W}{m\cdot K}$]

b) TRT-2, $q_2 = 38{,}3562\ \frac{W}{m}$, $\dot{V}_2$=0,0002 $\frac{m^3}{s}$, [Q_2 = 4000W, $\dot{V}_2$= 20$\frac{l}{min}$, λ_{ef2} = 1.93$\frac{W}{m\cdot K}$],

c) TRT-3, $q_3 = 38{,}3562\ \frac{W}{m}$, $\dot{V}_3$=0,0004667$\frac{m^3}{s}$, [Q_3 = 4000W, $\dot{V}_3$= 20$\frac{l}{min}$, λ_{ef3} = 2.08$\frac{W}{m\cdot K}$],

d) TRT-4, $q_4 = 71{,}2329\frac{W}{m}$, $\dot{V}_4$=0,004667$\frac{m^3}{s}$, [Q_4 = 4000W, $\dot{V}_4$= 20$\frac{l}{min}$, λ_{ef4} = 2.11$\frac{W}{m\cdot K}$]

e) TRT-5, $q_5 = 71{,}2329\frac{W}{m}$, $\dot{V}_5$=0,0002 $\frac{m^3}{s}$, [Q_5 = 4000W, $\dot{V}_5$= 20$\frac{l}{min}$, λ_{ef5} = 1.98$\frac{W}{m\cdot K}$].

The tests were performed using a numerical simulations method on the BoHEx model (Gonet et al. 2011).

Table 2. *The results of the coefficients of the equation (1).*

Coefficient	3×TRT	4×TRT	5×TRT
a	$a = 0.039547$	$a = 0.03047887$	$a = -0.079$
b	$b = 0.091061$	$b = 0.08443579$	$b = 0.022$
c	$c = 3.635916$, where: $c_1 = 3.635916$ $c_2 = 3.635916$ $c_3 = 3.635916$	$c = 3.56197581$, where: $c_1 = 3.55197872$, $c_2 = 3.57197289$, $c_3 = 3.55197872$, $c_4 = 3.57197289$	$c = 3{,}189$ where: $c_1 = 2.62$, $c_2 = 3.11$, c_3=3.299, $c_4 = 3.51$, $c_5 = 3.348$

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EVALUATION OF THE APPLICABILITY OF SEISMIC AND MAGNETOTELLURIC DATA TO THE DESIGNING PROCESS OF GEOTHERMAL INSTALLATIONS

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Introduction

As a contribution to the need to increase the participation of geothermal energy in the state energy balance, the applicability was analyzed of comprehensive interpretation of independent geophysical and geological datasets to the recognition of the geothermal potential of the selected Obrzycko region in the Polish Lowlands. The principal aim of the project was to recognize the geological setting of that region for the purpose of geothermal investment. Another task was to present the relevant research methodology, which may be applied to similar studies run in the future, in other parts of the Polish Lowlands. However, the research did not include the analysis of the local energy market suitable for the planning of potential geothermal installation.

Samples and methods

The applicability of seismic and magnetotelluric methodologies to exploration for and recognition of the geothermal potential of a given area has been confirmed by the results of studies and analyses, which have been run in the last decades, both in Poland and worldwide. In order to reveal the opportunities provided by comprehensive interpretation of various geophysical data to indicate the zones of higher probability of the occurrence of geothermal waters deposits, the geological analysis of seismic, electromagnetic and gravimetric data was carried on for the Obrzycko region in the Polish Lowlands, located in the vicinity of the Szamotuły Graben. Initially, both the seismic and the magnetotelluric projects were focused on petroleum exploration and identification of structures surrounding the salt diapir, which might have been the hydrocarbon traps. The interpreted datasets originated from 5 magnetotelluric profiles numbered OZ1 – OZ5 and were recorded using the AMT and the MT bands as well as from the southern fragment of No. AGH-2 (AGH28511) seismic profile. Interpretation of seismic and magnetotelluric data required the acquisition of various geological and geophysical information including the literature concerning the geological setting of the study area. Moreover, the feasibility analysis of that installation was included, as well. All these datasets and information were integrated and used for the construction of a spatial structural model of the study area, which contained the crucial stratigraphic boundaries within the Mesozoic overburden. From this model, the zones of potential geothermal deposits were determined.

Conclusions

The results were presented in the form of magnetotelluric models, spatial maps and analyses of seismic attributes, which were used to estimate the deposit parameters. Interpretation of the results of archival geophysical surveys run in the study area, enabled us to identify the resistivity anomalies, which resulted from varied physical and petrophysical parameters controlled by lithological changes of rock formations. The main purpose of data analysis was to identify potential zones of favourable geothermal parameters.

Funding

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EDUCATION MOOC AS A KEY TOOL IN ACHIEVING SUSTAINABLE DEVELOPMENT. EXPERIENCE OF THE ERASMUS + PROJECT

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Keywords: MOOCs, sustainable development, education, Erasmus+ Project

Introduction

At present, because of climate change, increasing environmental pollution, and scarcity of natural resources, it is necessary to educate, raise awareness and qualification in these topics. Education is a powerful and key tool for achieving sustainable development, promotes the development of the knowledge and skills that ensure environmental protection. It is also in line with the demands of the UNESCO Agenda for Sustainable Development.

Online education has become an easily accessible learning tool to all, offering everyone equal opportunities to access the knowledge and instructors. To reach adults in all life stages, UNESCO gives high priority to Open Distance Learning tools. One of the platforms offering e-learning is Massive Open Online Courses which provide mass learners open education services. MOOCs are changing the way of learning and teaching as well with the help of electronic resources. The proper use of MOOCs can ensure that students can gain knowledge more efficiently and practically, which in the long-term view can make more benefits for students and teachers, as well as leads to more sustainable development. The joint German – Hungarian – Polish – Romanian Project "MOOC4all" in the Erasmus+ Founding Scheme develops a European educational concept as a MOOC. Elaborated under the Project courses will familiarize the recipients with the fundamental knowledge of geothermal energy, solar energy, and themes related to waste management and environmental protection.

Project overview

Under the international cooperation with five partners from four countries: Germany, Hungary, Poland, Romania in European educational concept as a Massive Open Online Course (MOOC) is designed. Through the concept of digital learning, MOOC4ALL will provide opportunities to people around the world to further their education and widen their knowledge of environmental and technical topics. With the freedom to do the courses from anywhere in the world and at their own pace, you as a learner will be empowered to educate yourself regardless of your current financial, professional, or personal situation. The end goal of the MOOC4ALL Project is to promote the construction of more green networks in remote regions while simultaneously improving international cooperation and adult learning quality. Along with those goals, MOOC4ALL is also hoping to increase cross-border knowledge, population mobility, reduce European expert shortage, and increase European competitiveness.

To achieve this, the consortium will create digital learning (MOOCs) in partners' national languages (German, Hungarian, Polish, and Romanian), and English. Chosen theory and practical topics are close together to participating students could participate in the diverse seminars in the Field of Natural Sciences in their four national languages plus English and gain extra knowledge for their future career. The MOOC seminars offer a wide range of theoretical backgrounds paired with practical instructions that can relatively easily be put into practice.

The expected results are a finished MOOC server with courses and participant network platform, the Innovative Training Handbook, the Train-the-Trainer Handbook, the Blended Learning Handbook, and the newsletters. The MOOC4ALL Project will enhance expertise, mutual learning, and knowledge transfer in an international environment. Through interaction with the local, regional, and national public through multiplier events, for example, MOOC4ALL seeks to create a synergy between the participating organizations and the respective regions.

MOOC4all for sustainable development

Elaborated within the MOOC4all Project curricula cover a wide range of topics related to energy and the environment. The education concept has been based on research about existing furthering education programs, experiences, needs, and requirements elaborated under the UEUBILD-UNAKLIM Project (Tomaszewska et al. 2018, Rahner et al. 2018). The thematic scope of the platform is presented in Figure 1. Two of the Project MOOCs are related to clean energy sources and the potential of their use: Geothermal Energy and Solar Energy.

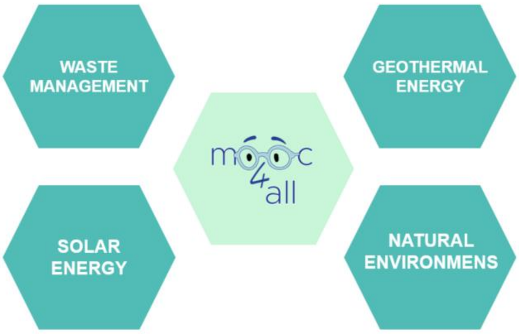

Figure 1. *Thematic areas of the MOOC4all courses.*

The geothermal energy course will familiarize students with the fundamental knowledge of geothermal resources. It covers the natural conditions, production, and utilization, as well as the economic and environmental impact of geothermal energy. The purpose of the course is to provide a broad understanding of geothermal energy utilization which will prove useful in practice. The course materials will familiarize students with the possibilities of rational use of these waters.

The Solar Energy module will give an overview of technologies and use in the field of solar and photovoltaic facilities as well as the use of these technologies in the building and power industry. Its advantages and challenges for energy suppliers are discussed. This module will familiarize the participants with specific fundamental knowledge and understanding of solar energy and its potential use in thermal applications. In particular the awareness for the interdependencies between technological, economic, and ecological aspects.

The Waste Management course covers topics related to the theoretical and practical foundations of waste management and their negative impact on the environment. Students will learn about various waste management strategies and legal aspects related to waste. In addition, students learn the basics of soil physics about pollution.

The last Natural Environments course will introduce students to our planetary natural environment. The course presents the general concepts and principles of climatology, hydrology, geomorphology, soils, and terrestrial ecosystems. The course will also introduce students to the human dimensions of environmental change with an emphasis on climate change and environmental governance.

Funding

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Iceland Liechtenstein Norway grants

CAPACITY BUILDING OF THE KEY STAKEHOLDERS IN THE AREA OF GEOTHERMAL ENERGY APPLICATIONS IN POLAND – POLISH-ICELANDIC COOPERATION (THE EEA PROJECT, 2020-2024)

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Keywords: EEA grants, capacity building, geothermal energy, Polish-Icelandic cooperation

Abstract
The "Capacity Building of the key stakeholders in the area of geothermal energy" Project is one of three predefined projects agreed between the parties at the negotiation stage of the "Environment, Energy and Climate Change" Programme, the European Economic Area Financial Mechanism for 2014–2021 in Poland. The Project is among the elements of activities aimed at geothermal energy uses a development in Poland. The Project's objective is to build the knowledge of key stakeholders in Poland in the field of optimal use of geothermal energy and management of its resources, particularly for the needs of low-emission heating and mitigating climate change. It includes but is not limited to:

- Building the knowledge of key stakeholders in Poland regarding optimal use of geothermal energy and management of its resources, especially for the needs of low-emission heating.
- Enhancing capacity building and knowledge-based methods rooted in many years of experience in geothermal energy in Iceland - through sharing good methods, practices, and technologies, supported by government initiatives, financial mechanisms and management strategies.
- Contribution to energy security, developing low-emission heating and raising social and economic equality by providing clean energy and reducing heating costs. The Project helps decrease pollution and CO_2 emissions and mitigate climate changes.

The Project is addressed to key stakeholders in Poland from the public and private sector in geothermal energy. They include the representatives of different administration levels, local governments, operators of existing and investors of future geothermal heating plants, beneficiaries of government support programmes, geological administration, research institutions, service providers, consultants, NGOs, and other entities from the geothermal sector.

Owing to the Project, Polish stakeholders gain professional knowledge and learn from many years of practical experience of the Icelandic partner in using geothermal energy through optimal methods and technologies, with the support of appropriate government initiatives, financial mechanisms and management strategies. It is a contribution aimed at increasing energy security, the development of low-emission heating, an opportunity to improve social and economic equality by providing clean energy and lowering heating costs.

The Project's main activities include training in Poland (2021–2023), study visits to Iceland (2022–2023), expert study visits to selected localities in Poland perspective for the geothermal uses (2022–2023), and report on these visits, information and communication activities regarding the Project and the EEA Funds (2020–2024).

The Mineral and Energy Economy Institute of the Polish Academy of Sciences (MEERI PAS) – the leader and the National Energy Authority (NEA / Orkustofnun) in Iceland are the Project partners. The Project was launched in October 2020 and will last until April 2024.

The Project partners represent leading geothermal energy sector institutions in their countries. They bring together experts with extensive practice and achievements in research, practice and training activities related to geothermal energy. The Icelandic partner has many years of experience in implementing international geothermal projects, training and qualifications. The Polish partner, MEERI PAS, is experienced in implementing geothermal projects in Poland and transferring expertise in geothermal energy to various national key stakeholder groups.

More information about the Project and the possibility of participating in the planned activities (training, study visits) is available on the Project website: keygeothermal.pl

The Financial Mechanism of the European Economic Area and the Norway Financial Mechanism (EEA and Norway Grants) for 2014–2021 finance the projects in 15 EU countries. The objective of these Funds is to contribute to reducing economic and social disparities within the EEA and strengthening bilateral relations between the donor and beneficiary states. The agreement between the donor states and the EU on the 3rd edition of the EEA Financial Mechanism and Norway Financial Mechanism for 2014–2021 was signed on 3 May 2016. Poland signed intergovernmental agreements on the 3rd edition of Norway Grants and EEA funds on 20 December 2017. Under the agreements, Poland received EUR 809.3 million (out of a total amount of over EUR 2.8 billion). These funds are intended for the implementation of 11 programmes managed by domestic operators. The “Environment, Energy and Climate Change” Programme, operated by the Ministry of Climate and Environment with the National Fund for Environment Protection and Water Management, is among them. The Programme partners include the Norwegian Water Resources and Energy Directorate, the Norwegian Environment Agency and the Icelandic National Energy Authority. The “Capacity building among key stakeholders in the area of geothermal energy” Project” is executed under the Programme, in the “Renewable Energy, Energy Efficiency and Energy Security” area. The Ministry of Investment and Development coordinates the implementation of the EEA and Norway Grants in Poland. The Programmes under the 3rd edition of EEA and Norway Grants will last until 2024.
More information on EEA and Norway Grants: https://www.eog.gov.pl

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Together we work for green, competitive and inclusive Europe

GEOTHERMAL DEVELOPMENT IN POLAND SUPPORTED BY PGI-NRI

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Keywords: thermal waters, geothermal energy, economic utilization, geothermal potential, geological information

Introduction

Thermal water is a geothermal energy carrier, which is one of the cleanest renewable energy sources. Due to escalating world ecological problems and the necessity to reduce the emission of greenhouse gases to the atmosphere, interest in thermal waters management has significantly increased in recent years. Geothermal investments, which use the energy potential of thermal waters, are an important impulse for the economic development of the country. Moreover, that investments are in line with the assumptions of the national energy policy, which projects among others, at least 23% share of renewable energy in gross final energy consumption in 2030 (Announcement of the Minister of Climate and Environment of March 2, 2021, on the national energy policy until 2040; National Energy and Climate Plan 2021-2030). In this regard, there is a need to collect and share geological and hydrogeological data to undertake investments related to thermal waters. Polish Geological Survey, which tasks are fulfilled by the Polish Geological Institute – National Research Institute (PGI-NRI), actively participates in promoting activities related to the management of thermal waters and promotes knowledge in the field of geothermal energy.

Sharing geological and hydrogeological data

Undertaking projects related to thermal waters management is burdened with geological risk. Its most important elements are actual depositional and hydrogeological conditions. Their recognition is possible after drilling a borehole and carrying out relevant analyses. Test results are a base for effective thermal water management. This data is collected and shared by Polish Geological Institute – National Research Institute in Mineral Groundwater Data Bank, operated by the web MINERAL application. As of July 2021, the database has contained information on 2371 hydrogeological objects (boreholes, springs, adits, deep exploratory well), including 62 thermal water intakes in 35 thermal water deposits. Temperature equal to or above 20°C has been identified in 283 intakes. Other intakes have contained mineralized and specific waters with lower temperatures (1311 objects), therapeutic waters (710 objects) and brines (5 objects). The sources of input and updated data are geological and hydrogeological documentation collected in the National Geological Archives, documents issued by geological administration and projects results realised by the polish geological survey.

The Mineral Groundwater Data Bank collects basic data on the objects – their location, lithostratigraphic profile, intake construction data, as well as measured and calculated hydrogeological data, laboratory analyses results (physico-chemical water determinations, dissolved gases determinations, isotopic composition) and water temperature measurements. Moreover, the database stores descriptive and spatial information on resource areas, spa protection zones, mining areas and mining countries.

Geological and hydrogeological information collected in the Mineral Groundwater Data Bank is shared on request in compliance with the Act of June 9, 2011, *Geological and Mining Law* (Journal of Laws 2021, item 1420, consolidated text), Regulation of the Minister of the Environment of October 30, 2017, *on the collection and disclosure of geological information* (Journal of Laws 2017, item 2075), Regulation of the Minister of the Environment of December 20, 2011, *on the use of geological information for remuneration* (Journal of Laws 2011, No. 292, item 1724), as well as procedures applied in Polish Geological Institute – National Research

Institute and available on the National Geological Archives website. Data is shared as sets of borehole cards and profiles, tables with any defined attributes, predefined reports and in spatial form as shapefiles.

The geological and hydrogeological information collected in the Mineral Groundwater Data Bank is basic data for conducting exploration work among others in the field of thermal waters. They are consistent with data presented in *Mineral resources in Poland* (Szuflicki et al., ed, 2021), which is released every year by Polish Geological Institute – National Research Institute.

Mineral resources in Poland presents current information on mineral deposits, their resources, management and mineral extraction in a given year. The publication includes all types of minerals documented in Poland, also thermal waters in compliance with the Act of June 9, 2011, *Geological and Mining Law* (Journal of Laws 2021, item 1420, consolidated text). The primary sources of presented data are hydrogeological documentation and annual reports based on the registration survey and prepared by the deposits users.

As of December 31, 2020, thermal waters in Poland have been documented in 35 deposits (Sokołowski, Skrzypczyk, 2021). Thermal waters with therapeutic properties occur in another 28 deposits. Exploitable resources of thermal waters, including therapeutic thermal waters, constitute the majority of the total resources of water deposits recognised as minerals. Their value amounts to 84.95%, while a number of their deposits accounts for only 43% of all documented deposits recognised as minerals. The size of exploitable resources of thermal waters has been increasing every year. Their growth in the years 2000-2020 has amounted to 4153.05 m^3/h (Skrzypczyk, Sokołowski, 2011; Sokołowski, Skrzypczyk, 2021). The upward tendency is conducted to the national energy policy and growing social awareness of climate protection and using a renewable energy source, e.g. for heating purposes. Undertaking costly investments related to the extraction of thermal waters has been facilitated by the government financial support programme, which is implemented by National Found for Environmental Protection and Water Management. A similar trend has occurred in the case of the extraction of thermal and therapeutic thermal waters. In the years 2000-2020 the increase of their extraction has amounted to 10 381 014 m^3/year (Skrzypczyk, Sokołowski, 2011; Sokołowski, Skrzypczyk, 2021). Despite the increase of thermal waters resources, new geothermal heat plants have not been built and several recreational centres using thermal waters have slightly changed over the years. The extraction of thermal and therapeutic thermal waters has still accounted for about 22% of the total approved resources of this type of water. It leaves large reserves of exploitable resources.

Recognition of geological structure and hydrogeological conditions is necessary to minimalize geological risk in investment realisation related to the exploration of thermal and therapeutic thermal waters deposits. This knowledge enables the identification of prospective areas for deposits occurrence as well as determination of the size of their resources including their rational economy. These activities have been taken by Polish Geological Institute – National Research Institute, which compiled *The balance of prospective mineral resources in Poland as of December 31, 2018* (Szamałek et al., ed., 2020). The publication describes prospective areas for the occurrence of thermal water (Socha, ed., 2020).

Prospective areas have been delineated by assuming suitable parameters in the context of thermal waters management for heating purposes. The minimal value of discharge was determined to be 60 m^3/h and minimal temperature – not less than 40ºC at the top of the aquifer. In this case, mineralization should not exceed 80 g/dm^3. These parameters were not applied in the Podhale basin, Sudetes and Fore-Sudetic Block. These areas are classified as prospective areas whole for thermal waters exploitation (Socha, ed., 2020b). Assumed values of parameters have resulted from the internal experience of functioning geothermal heat plants and are justified for economic and technological reasons. However, they are not a permanent and inviolate criterion.

Prospective areas for exploration and exploitation of thermal waters have been delineated in the Polish Lowlands in formations of the Lower Cretaceous and the Lower Jurassic, in the area of the Carpathian Foredeep in Neogene, Mesozoic and Palaeozoic reservoirs and the Outer Carpathians in zones of tectonic overthrusts. Despite the low level of recognition, Sudetes and Fore-Sudetic Block are wholly considered as a prospective for thermal waters occurrence. Within these areas, the zones particularly predisposed to thermal waters exploration are deep tectonic faults in crystalline rocks and early Paleozoic and Cretaceous rocks. They create privileged pathways for the migration of waters deeply into the rock mass and enable their underground flow (Socha, Ed., 2020b; Felter et al., 2021).

Popularisation activity

A wide compendium of knowledge on geothermal potential and management of thermal waters is *Map of economic use of groundwaters considered as minerals in Poland*, which has been published periodically by Polish Geological Institute – National Research Institute since 2015.

Map of economic use of groundwaters considered as minerals in Poland is an annual publication and presents a state of exploration and management of groundwaters classified as minerals. The presented information is consistent with *Mineral resources in Poland* (Szuflicki et al., ed., 2021) and *The balance of prospective mineral resources in Poland as of December 31, 2018* (Szamałek et al., ed., 2020). It also includes mineralized and specific waters, which are part of Mineral Groundwater Data Bank, but are defined as potentially therapeutic waters due to insufficient exploration and documenting. The map also presents the utilization of groundwater resources recognized as minerals.

For study purposes, data related to concessions for waters exploitation from deposits are updated every year. As of December 31, 2020, there were in force 23 concessions for thermal waters and 13 concessions for therapeutic thermal waters in Poland.

Due to steady interest in exploitation and management of thermal and therapeutic thermal waters and dynamic increase of investments related to exploration activities, *Map of economic use of groundwaters considered as minerals in Poland* has also presented projects connected with drilling a new exploratory borehole (in the works and progress). Their realization is possible on the basis of the project of geological works, which has to be approved by the marshal of the voivodeship. In 2020, there were 94 projects in force, including 97 new investments for thermal waters utilization in Poland.

The map is complemented by textual study, which describes basic issues related to thermal and therapeutic waters and brines. This publication along with the map are important positions intended for government and local administration bodies, schools and universities as well as potential investors interested in the utilization of groundwaters considered as minerals.

Due to interest in geothermal energy as one of the cleanest energy sources, Polish Geological Institute – National Research Institute has realized projects, which would conduce to increase of energy efficiency of heating systems by energy potential of thermal waters utilization. These activities are primarily destined for local administration bodies and business entities. Until 2020, the Polish Geological Institute – National Research Institute along with the University of Science and Technology has carried out a multivariate analysis of geological, environmental and infrastructural conditions (in terms of availability of district heating network) in communes of Polish Lowlands. This study states the 11 best locations for geothermal investments. The analysis included localities with low emission problems and populations below 50 000 as well as population density above 123 inhabitants per square kilometre. For the definite location, the list of estimated parameters was compiled. Moreover, the study includes optimum technical solutions and their economic assessment. As a result of the analysis, potential prospective locations for building geothermal heat plants in the Polish Lowlands are: Kutno, Lesznowola, Mogilno, Murowana Goślina, Oborniki, Piaseczno, Police, Strzelno, Ślesin, Września, Zgierz (Socha, ed., 2020a).

Polish Geological Institute – National Research Institute has been participating in the debate on geothermal energy in Poland for a few years, presenting its knowledge on the state of exploration and the possibility of management of thermal water resources. One of the forms of this activity is an organization of cyclic events under the name of Forum of polish geological survey. The third of them was related to the potential and prospects of geothermal resources utilization in Poland and was held in June 2021. The Forum presented issues concerning documented deposits of thermal waters – their resources, possibility of management and prospects of their utilization. What is more, legal regulations related to the exploration and management of thermal waters as well as geological risk connected with investing in the extraction of thermal waters were discussed. The Forum presented ways of risk minimization and the factors influencing the profitability of geothermal resources utilization. The functionality of the Mineral Groundwater Data Bank was also shown.

Polish Geological Institute – National Research Institute organizes training and workshops for local administration bodies, heating companies and private investors in order to popularize the knowledge on geothermal energy and state the best directions for the development of geothermal investments.

Since the Internet has been the most common and the most popular source of information, the Polish Geological Institute – National Research Institute runs a website related to groundwaters considered as minerals. The website www.mineralne.pgi.gov.pl contains among others information on thermal waters, which is intended for various groups of readers – both Earth's heat enthusiasts as well as potential investors. One can find there general information on thermal waters, therapeutic waters and brines as well as "Investors guide", which describes consecutive steps of the investment process.

Summary

Due to escalating world ecological problems and assumptions of the national energy policy, investors are encouraged to undertake activities related to the utilization of thermal water potential as an energy carrier. In relation to the above, the activities of the Polish Geological Institute – National Research Institute are very important. Institute has collected, updated and shared geological and hydrogeological data in a special database for many years. Moreover, it conducted research projects related to the recognition of geothermal potential and the risk associated with its management in various regions of Poland. The results of these activities provide input data for thermal waters exploration and aid utilization of thermal waters potential. Polish Geological Institute – National Research Institute prepares studies such as *Map of economic use of groundwaters considered as minerals in Poland*, which are a valuable source of information on thermal waters, therapeutic waters and brines. What is more, there are activities undertaken to support local administration bodies in geothermal investments and to educate the public on geothermal energy, encouraging the management of thermal waters as a clean source of heat.

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ON RESULTS OF THE PROJECT „YOUNG TECTONIC FRACTURES AND GEOTHERMAL CONDITIONS IN THE SUDETES...” (PGI-NRI, 2014-2020) THAT PRIMED ELABORATING OF A GEOTHERMAL ATLAS FOR THE AREA OF LOWER SILESIA

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Keywords: geophysical survey, structural-geological investigations, thermal rock parameters, basement thermic conditions, thermal groundwaters

Introduction

The research project „Young tectonic fractures and geothermal conditions in the Sudetes in the light of geochronological, structural and thermometric studies” was carried out between 2014 and 2017 as a statutory task of the Polish Geological Survey. Its principal goal was to collect new data and materials for the “Geothermal Atlas of the Sudetes and their foreland”, which is currently being prepared within a 4-year long project started this year. Apart from single geothermal drill holes and intakes of therapeutic mineral groundwaters of elevated temperature, the area of the Sudetes and its foreland, on several premises considered as particularly prospective for the occurrences of such waters, has not been yet surveyed at a regional scale. This is in contrast compared with the state of knowledge of the geothermal resources in other parts of Poland, for which such atlases has been prepared much earlier. The delay is due to the specificity of the geology of Lower Silesia (the Sudetes being a part of it) which is different in this respect from the rest of Poland and characterized by the dominance of crystalline rocks of minimum porosity and permeability in the deeper basement. As a result, the deep thermal groundwaters in the Sudetic region can circulate mostly along structural discontinuities, whereas in the other parts of Poland, they reside in extensive strata-bound collectors, typical of sedimentary terrains. The geology of Lower Silesia makes, thus, its area methodically difficult to search for thermal groundwaters.

Location and methods

The studies were carried out in several dozens of selected areas distributed in almost the whole area defined geologically as the Sudety Mts. i.e. both in their mountainous part situated to the south-east from the Sudetic Boundary Fault and in the Fore-Sudetic Block - on the north-eastern side of that fault and geographically representing the Sudetic Foothills and partly also Silesian-Lusatian Lowland. The investigations areas were selected on the basis of several criteria, including the probable or obvious occurrence of major deep tectonic discontinuities (zones) in their basement, represented by faults, fault zones or zones of considerable concentration of rock fractures active in recent geological past, in which thermal groundwaters may potentially circulate. The selection of the studied areas also took into account the proposals included in the officially approved geological work programmes made previously for the preparation of the regional geothermal atlas.

The areas selected for studies are situated in the Żytawa Trough, Izera Mountains, Jelenia Góra Valley, Kaczawskie, Wałbrzyskie and Sowie Mountains and their foothills, Fore-Sudetic Depression, Kłodzko Valley and its mountainous surroundings, Niemczańsko-Strzelińskie Hills and, also, on the Niemodlin Plain and south-western part of the Silesian-Lusatian Lowlands.

The studies comprised in location and fragmentary (i.e. along single profile lines) recognition of structural-geometrical and geophysical characteristics of several pre-selected major structural discontinuities (faults and fault or fracture zones) with geological-geophysical methods in order to assess their potential collector capacity for deep groundwater circulation. Field studies were carried out using the methods of shallow refraction and reflection seismic and electrical resistivity tomography, electromagnetic method (VLF), gamma-spectrometric surface profiling, deep magnetotelluric profiling and detailed structural mapping of surface occurrences of tectonic zones. Thermometric studies were also carried out by determining temperature profiles in existing boreholes. Moreover, petrophysical measurement data of thermal parameters of rocks (including the capability of radiogenic heat production by granite massifs) were made and analysed and, subsequently, used for modelling of temperature field and heat flux in the upper crust (using the Karkonosze granitoid massif as an example). Geochronological study of several Cenozoic basalt occurrences was also made in order to assess the possibilities of influence of remnants of young volcanism on thermal conditions of the Sudetes, using numerical modelling methods. Additionally, archival seismic survey data from two Sudetic Permo-Mesozoic basins were reprocessed using modern software and on this basis, the deep fault network in the surveyed areas was identified.

It should be stressed that the conducted studies were not aimed at direct prospecting for deep circulation thermal groundwaters, nor did they offer a possibility to determine whether thermal waters were present or not in a given location with the use of tools available for the task. In order to unequivocally establish the presence of such waters, they have to be drilled, and such tools were not available during the execution of the task and, moreover, their use for the purposes which were to be achieved by the planned research would not be economically justified. The aim of the studies carried out in particular local areas was to assess whether the geological-structural conditions, especially within the selected large discontinuous structures ("tectonic zones"), represented by complex fault zones of fracture corridors will - because of the geometrical characteristics and extent of the latter - favour deep circulation of waters, which due to infiltration to considerable depths, have a chance to show increased temperature.

Results

Within the two stages of the project, 46 local areas hosting large tectonic zones were covered by different types of geophysical and geological studies. The studies also comprised absolute dating of a number of Cenozoic basaltoid occurrences to verify the previously obtained determinations and to collect new data. Geological and hydrogeological analyses allowed us to better constrain the internal structure of the studied tectonic zones and estimate their capacity of accumulating deep groundwater.

We have also validated the approaches typically applied in sedimentary basins for prospecting underground thermal waters in the crystalline rocks of the Sudetic regions. The method of continuous magnetotelluric profiling (CPMT) was found to be the most useful for this purpose. The CPMT method allows for the detection of zones characterized by decreased electrical resistivity, down to the depth of several kilometres, that may be indicative of water-bearing fractures. The CMPT method was deployed for conducting measurements on 16 profile lines of a total length of 49 km, in cooperation with the Geophysical Research Company and the Geopartner Company from Cracow. Based on the CMPT results, potential sites with favourable conditions for groundwater circulation were recognized along deep-seated tectonic discontinuities in nine study areas, including the Nysa Kłodzka Graben, Kudowa Depression, Wleń Graben, Wierzchosławice Depression near Bolków, Sudetic Boundary Fault (Modliszów and Srebrna Góra areas), Niemcza Shear Zone and the eastern part of the Fore-Sudetic Block (Niemodlin area). In most cases, the outcrop zones of faults related to the deep zones of decreased electro resistivity are situated in topographic depressions directly neighbouring elevated areas, where probably increased infiltration of meteoric waters takes place due to topographically driven gravitational collapse of rock bodies.

We have compiled and discussed literature data on the thermal state of deep bedrock in the Sudety Mts, in particular the divergent estimates of geothermal gradient and heat flux density. Our preliminary numerical studies demonstrated a generally negligible thermal effect of a cooling magmatic body placed in the lower crust or at the Moho boundary in the Lower Silesian area several million years ago. Our studies also allowed for significant progress in recognition of key thermal parameters of the Lower Silesian bedrock, especially the thermal conductivity and radiogenic heat production. The newly gathered data and archival thermal profiles of several existing boreholes were used for modelling of temperature field and heat flux in the upper crust, using the granitoid massif of the Karkonosze Mts as an example. Temperature profiles from seven boreholes in the area were analysed. Four temperature profiles were excluded due to unstabilized conditions or too shallow borehole depth to obtain a reliable determination of the thermal gradient. In the remaining boreholes, the thermal gradient was estimated based on the bottom-hole temperature and an assumed annual average land surface temperature. Consistent thermal gradient values of about 25 ^{o}C/km for three holes and about 30 ^{o}C/km for one of them were obtained. From the point of view of the thermal state analysis of the Karkonosze massif, it would be valuable to repeat temperature profiling in deep boreholes Staniszów ST-1 and Karpniki KT-1 under more stabilized conditions.

The surface heat flux density was estimated based on the reconstructed values of the thermal gradient in the Karkonosze Massif. Our tests and analyses showed that the thermal conductivity of the Karkonosze granites at room temperature may be at a level between 3.0 and 3.5 $Wm^{-1}K^{-1}$, which is higher than the previously obtained estimates. Thus, the surface heat flux density in the area of the Karkonosze Massif may be estimated in the range between 75 and 105 mWm^{-2}. The heat flux values proposed so far for this area are close to the lower limit of our estimate. The results of thermal modelling take into account the temperature dependence of thermal conductivity and the radiogenic heat production observed in the granitoid massifs of the Sudety Mts.

Our results show a significant impact of these parameters on the thermal state of the lithosphere and thus on the geothermal potential of the region. The influence of the radiogenic heat on temperature distribution with depth was analysed and the resulting non-linear shaping of the thermal profile was described. Further detailed studies on the distribution of radiogenic heat in the rocks of the Karkonosze Massif and other massifs of the Sudety Mts are undoubtedly needed for the proper evaluation of the representative values of radiogenic heat production. The modelling showed that with increasing depth the temperature effect related to radiogenic heat increases strongly. Depending on the adopted averaged value of heat generation in the profile, temperature differences at a depth of 4-5 km may reach several tens of ^{o}C relative to simplified linear geotherms extrapolated on the basis of the near-surface thermal gradient. However, our modelling also showed that this effect is partially compensated for by a decrease in the thermal conductivity of granites with increasing temperature.

In addition to deep geothermal studies, temperature and some Physicochemical parameters of groundwaters (EC, pH and O2 concentration) were also profiled down to the depth of 200 m below the surface in 23 drilled wells and piezometers using KLL-Q2 multimeter equipped with MPS-D8 probe. Water with elevated temperature, in addition to the wells Pełczyn IVP–17.39 ^{O}C, Wałbrzych Stara Kopalnia – 15.45°C and Stary Waliszów 7R–15.08°C, was also recorded at the bottom of the KWB Turów opencast mine, where temperatures exceeding 20°C were measured in two cases. Some of these occurrences could be associated with ascending groundwater originating from fractured deep circulation systems in the crystalline basement through fault zones.

Deep seismic data from the 1970s and early 1990s, which were subjected to modern reprocessing, were also used to obtain information on deep-seated tectonic structures in the Sudety Mts. In this way, reliable information was obtained on faults penetrating deep into both Sudetic synclinoria – the northern and mid-Sudetic ones, which may be potential exploration targets for thermal waters of deep circulation. The seismic method shows, with better resolution and reliability than the magnetotelluric method, the structure of deep faults and fault zones but it bears little information about the state of their infiltration.

The results of detailed fracture mapping in selected quarries, using an especially elaborated classification scheme for tectonic discontinuities typical of Sudetic conditions, were an important contribution to the understanding of complexity and details of the internal structure of tectonic fracture zones studied by the "coarse" geophysical methods.

Measurement, computational and literature data gathered in the course of implementation of phases I and II of the project "Young tectonic zones and geothermal conditions in the Sudety Mts” supplied a significant contribution to the preparation of the Atlas of geothermal resources, however, the latter task still requires a considerable amount of new data, including results of magnetotelluric profiling for tens of new localities, to cover fairly evenly the whole area of interest. At least equally valuable in this respect will be also studies on thermal state of deep bedrock, concentrated on a few selected areas such as e.g. the granitoid massif of Karkonosze, where they may be of relatively detailed character.

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GEOTHERMAL INVESTMENTS AS AN ELEMENT OF DEVELOPMENT STRATEGY OF LOCAL GOVERNMENT UNITS – AN ATTEMPT TO IDENTIFY DEVELOPMENT BARRIERS OF GEOTHERMAL ENERGY IN POLAND

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Introduction

In Poland, local governments implement a significant part of administrative tasks of local importance. The process of social, economic and spatial development begins at the lowest level - in communes. The possibility of development of area depends on societies acceptance of new investments. The basic tasks to be carried out by local governments include meeting the needs of local residents, such as water, electricity, heat and gas supply while preserving the environment. These actions should fit into polish energy policy, which the main objective is to ensure the country's energy security. It can be done through access to fuels and energy sources. Both now and in the long-term perspective are taking into account the needs of future generations. Therefore, geothermal energy should be an important element in the effective implementation of national energy policy.

Development of usage of geothermal energy in Poland

In December 2019, the European Commission published a communication on the European Green Deal, with the overarching aim of making Europe climate neutral in 2050. The leaders of the EU confirmed a new target for reducing greenhouse gas emission in 2030 to at least 55% emission reduction at 2030 compared with 1990 levels.

In accordance with Directive 2009/28/WE of the European Parlament and of the Council of April 23, 2009, on the promotion of the use of energy from renewable sources, Poland as a member of EU has been committed to ensuring a 15% share of energy from renewable sources in gross final energy consumption in 2020 (National Renewable Energy Action Plan, Energy Policy until 2030). According to the data of the Central Statistical Office, in 2019 the share of energy from renewable sources in gross final energy consumption was 12.16%. The total share of energy from renewable sources in the production of primary energy amounted to 15.96% (396,498 TJ), including a 0.26% share of geothermal energy (Berent-Kowalska et al., 2020). These results show that Poland should strengthen work to increase usage of renewable energy sources (RES) in order to achieve the goals set by the EU in the field of a low-emission economy.

The level of geothermal energy development in Poland can be defined partly by the number of approved projects at geological work plans for drilling boreholes to capture thermal waters and approve their exploitation resources. As of the end of 2020, 94 such projects were approved, and the total of resources amounted to 6135.19 m3/h. Compared to the previous year, it was an increase in both the number of projects (by 15) and the documented resources (by over 460 m3/h). In the last decade, the volume of approved resources has almost doubled (Szuflicki et al., Ed. 2011, 2020, 2021, Felter et al., 2021; data obtained from marshal offices). Despite the apparent intensification of exploration works and increase thermal water resources, there are no new geothermal heating plants, while the number of new geothermal resorts has slightly increased. As shown by the geological works, the geothermal potential exists in Poland, but its use is limited by various obstacles preventing the transition from the project and documentation phase to the thermal water exploitation phase.

Identification of development barriers of geothermal energy

Deciding to invest in geothermal energy requires a careful, multifaceted analysis from local governments. These undertakings should also fit into assumptions of communes development strategy. It is a document that sets the direction of development to achieve adopted strategic goals. Although it is still optional, local governments very often undertake its creation, treating it as a plan for the development of the commune. This combines expectations of local residents and potential investors with the actions of local authorities. It can also promote assumptions of the strategy and the proposed pro-development actions. Development strategy as a document facilitates the acquisition of new partners and investors, as well as external financial resources to implement its assumptions (Hoinkis et al., 2021). Successes of a properly conducted development policy in local government units are proved by new investments. In the case of geothermal investments, there is a noticeable disproportion between local governments that have planned to use geothermal potential and those that have proceeded to its implementation.

To examine the level of interest of communes in the use of RES like thermal waters and identify development barriers, the Polish Geological Institute – National Research Institute as part of the activities of the Polish Geological Service has conducted survey research (Socha, ed., 2020).

Due to adopted assumptions, the research concentrated on the area of the Polish Lowlands. Results should therefore be interpreted relative to local governments only in this area. To get a broader view of acceptance of the use of geothermal potential in Poland, similar research should extend also the area of the Carpathians, the Carpathian Foredeep and the Sudetes, as well as other prospective areas in terms of thermal water management.

The survey showed that local governments mostly have a positive attitude towards the use of geothermal energy and they are looking for information on this subject. However, communes encounter various difficulties that make it impossible to undertake investments related to the development of the use of thermal water potential. Taking action to use geothermal energy is hampered by the lack of funding to create the necessary infrastructure, lack of suitable support from the government and insufficient knowledge about the geothermal potential in specific locations. Another obstacle is the legislation regarding the management of thermal waters (Figure 1).

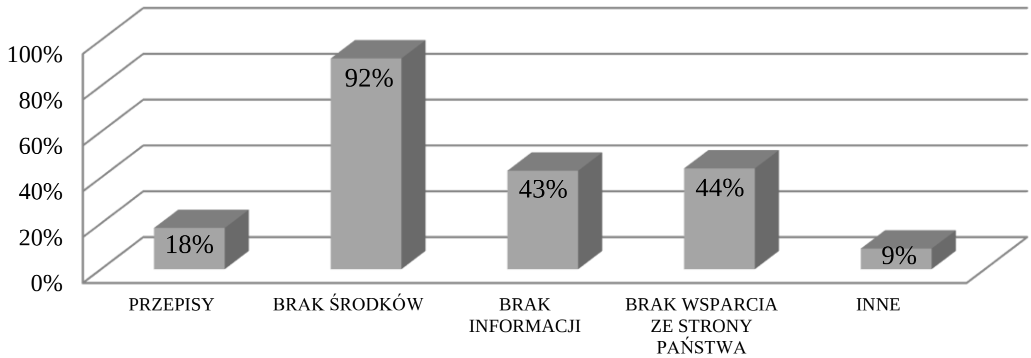

Figure 1. *Development barriers of using geothermal energy indicated in a survey by communes interested in geothermal energy (Socha et al., 2020)*

The lack of adequate financial resources for new investments is a problem for many local governments, especially when it concerns ventures with a significant risk of failure. Some communes directly indicate that it does not pay to invest in geothermal energy. This is associated with high initial costs, which include not only drilling but also the creation, often from scratch, of the necessary infrastructure. One of the issues indicated by local governments was the lack of government's support and difficulties in finding private investors. On the other hand, the vast majority of communes that are interested in geothermal energy do not assess the initial capital outlays and the costs necessary for their future functioning. Meanwhile, the government's financial support programs implemented through the National Fund for Environmental Protection and Water Management, such as *Providing thermal waters in Poland* and *Polish Geothermal Energy Plus*, effectively reduce geological risk and successfully support the use of geothermal energy in our country. Financial support such as subsidies and loans on preferential terms can effectively solve the problems signalled by local governments with obtaining funds for launching geothermal investments.

Also, a lack of knowledge on geothermal energy is an obstacle to development. Local governments indicated insufficient knowledge of actual geothermal potential in the areas they administrate, which is a serious problem in managing thermal waters. Although the information on the possibilities of using energy sources is included in the commune's development strategy, it is often incomplete or outdated, thus the geothermal potential may not be properly defined. Currently, it is not possible to impose on local governments the obligation to identify prospective areas of using geothermal energy in the commune's development strategy or the local zoning plan. Although the local zoning plan specifies the usage of communal land, it is often not developed at all or is not updated for many years. An attempt to persuade local governments to assess geothermal potential could be to extend the provisions of the act on spatial planning and development to include issues related to the identification and use of potential renewable energy sources.

The awareness of the possibility of using thermal waters in a given area is still too low. Communes usually do not assess geothermal energy resources, that is why they often see opportunities for its development when there is none. The problem is also selecting the wrong sources of information on geothermal energy in Poland. The first source is still the Internet. Unfortunately, apart from reliable content, there are also those unsupported with facts, causing disinformation among communes interested in geothermal energy. Therefore, it seems necessary to intensify cooperation between local government units and scientific institutions in charge of geothermal issues. Increased cooperation and interaction between those will contribute to a better understanding of the real geothermal potential of our country and define the possibilities of its effective use.

Barriers in the process of thermal waters management are also created as a result of the unsuitable legislation. The lack of appropriate regulations has been signalled many times (Kołakowski, 2015; Kępińska, 2016, 2018). Legal provisions regarding renewable energy sources have been changing and expanding. There is still no clear regulations for the usage of geothermal energy. In the act on renewable energy sources, there is no direct provision regarding the production of heat by using geothermal energy. The legislator focuses primarily on the production and distribution of electricity, which in the case of geothermal energy in Poland is unobtainable. References to geothermal energy are also missing in the *Energy Law*. Only the *Geological and Mining Law* speaks directly about thermal waters and their management, which, however, regulates only to process of searching and exploiting thermal waters, and not its use for energy production.

Conclusions

The use of geothermal energy is determined by several factors, such as geological and hydrogeological parameters of geothermal reservoirs, physical and chemical properties of thermal water, the efficiency of technical and technological solutions, structure of heat recipients, economic competitiveness of investments and many more. In the last dozen or so years an increase has been observed in the exploitation resources of thermal water. This is the result of the interest of local governments and entrepreneurs in geothermal energy. Therefore, diagnosis of major problems and finding solutions is crucial. This will enable action to be taken with aim of reducing barriers and allow for consistent strategic regulatory, organizational, legislative, institutional, procedural, technical, control and financial actions at national, regional and local levels.

In recent years, the Polish government has provided different forms of support for local governments, such as subsidies and loans on advantageous terms. Access to an efficient and ecologically clean source of energy, such as geothermal, ensures local governments a platform for economic development and guarantee energy security. It can also improve the quality of life of local residents. The added value of developing geothermal potential should be a stable source of income for budgets of local governments, entrepreneurs and local residents, related to tourism, trade and services. In the area of heating, the crucial thing is the optimal use of geothermal resources, especially in district heating networks of cities located in the areas where these resources occur. However, the use of the Earth's heat should take place in a comprehensive manner, also extending other socially and economically important areas, such as agriculture or balneotherapy. Such an approach, together with lowering the number of factors limiting the development of geothermal potential, comply with the pro-ecological policy of the county. It is also an answer to the goal of climatic neutrality. Geothermal energy should certainly be one of the essential elements that Poland shall contribute to the European Green Deal.

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RELATION BETWEEN WATER CONTENT AND EFFECTIVE THERMAL CONDUCTIVITY OF MINERAL SOILS BASED ON LABORATORY TESTING RESULTS

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Keywords: thermal properties of soil, effective thermal conductivity of soils, transient line source method, soil laboratory testing

Introduction

Determination of thermal parameters of soils is essential for the successful development of innovative projects using renewable energy sources (RES) including shallow geothermal energy. The recent trend to increase the use of RES and the necessity to decrease the use of fossil fuels have caused the rise of interest in thermal parameters of rocks and soils (Kłonowski et al., 2020). To properly design and implement shallow geothermal installations such as borehole heat exchangers (BHE) or thermoactive foundation elements (Baralis et al., 2018) it is necessary to correctly attribute subsoil rock and soil layers with thermal parameters. Such thermal parameterization is also essential in the evaluation of the soil and rock capacity for heat dispersion from underground high voltage electric cable lines and district heating pipes. It is also important for the evaluation of long term underground storage of nuclear waste influence on surrounding rock massif. In the presentation, the authors present the results of laboratory tests of effective thermal conductivity of mineral soils performed according to the procedure developed in Centre for Laboratory Testing of Rocks and Soils (CBGS) in Polish Geological Institute – National Research Institute (PGI-NRI) (Łukawska et al., 2020). All data acquired during laboratory measurements of thermal conductivity for rock and soil samples are gathered and stored in the PGI-NRI thermal parameters database. This database is then used to perform thermal parameterization of layers in 3D models used for the purpose of the development of shallow geothermal potential maps (Ryżyński et al., 2020).

Samples and methods

Measurements of effective thermal conductivity are performed on mineral soils samples with various water content and bulk density. Details of the testing procedure are described in the paper "Serial Laboratory Effective Thermal Conductivity Measurements of Cohesive and Non-cohesive Soils for the Purpose of Shallow Geothermal Potential Mapping and Databases — Methodology and Testing Procedure Recommendations" by Łukawska et al., 2020.

To perform measurements of effective thermal conductivity the KD2 Pro thermal properties analyser is used. The KD2 Pro is used with a set of various probes – thermal needles. To form the mineral soils samples the auxiliary equipment is used – the metal cylinders, hand rammer for compression of cohesive soils and a tapping fork to compact the non-cohesive (sandy) soils. To eliminate external environmental factors that decrease the stability of measurement, tested samples are stored in a thermal incubator (set for a constant temperature) for the whole time of measurements. All thermal conductivity measurements were performed in a temperature set of 10 ^{o}C. To measure effective thermal conductivity proper probe (thermal needle) in means of length and diameter is chosen accordingly to the material (soil) type of tested sample. On each sample, the test is performed three times (on three sub-samples).

Results

Results of laboratory measurements of effective thermal conductivity of mineral soils samples are presented in Tables 1 & 2 and charts. In total over 30 samples of each soil type (according to Tables 1 & 2) were tested. Thermal conductivity measurements were performed for 5 ranges of water content for non-cohesive soils and 5 ranges of liquidity index according to national soil classification standard PN-B-02480:1986. Each sample has been tested on three subsamples. In total over 5400 unique measurements of λ parameter were performed.

Table 1. *Values of effective thermal conductivity (λ) for cohesive soils samples according to liquidity index classes (I_L).*

Soil classification according to PN-B-02480:1986	Liquidity index I_L [-]														
	$I_L < 0$			$I_L \leq 0$			$0 < I_L \leq 0,25$			$0,25 < I_L \leq 0,50$			$0,50 < I_L \leq 1,00$		
	λ min	**λ max**	**x̄ λ**	**λ min**	**λ max**	**x̄ λ**	**λ min**	**λ max**	**x̄ λ**	**λ min**	**λ max**	**x̄ λ**	**λ min**	**λ max**	**x̄ λ**
Π Pył	0,605	1,404	1,253	1,102	1,906	1,705	1,804	2,305	2,103	1,602	2,102	1,902	1,410	1,905	1,708
Pg Piasek gliniasty	0,705	1,606	1,454	2,103	2,860	2,708	2,407	3,309	3,059	2,001	2,804	2,557	1,906	2,507	2,305
Gp Glina piaszczysta	1,008	2,103	1,903	2,008	2,606	2,459	2,409	2,904	2,759	2,003	2,607	2,306	1,707	2,307	1,801
G Glina	0,909	1,806	1,409	1,509	2,407	2,205	1,802	2,603	2,344	1,704	2,203	1,854	1,406	1,906	1,702
Gπ Glina pylasta	0,806	1,406	1,201	1,208	2,007	1,860	1,604	2,409	2,207	1,406	2,003	1,704	1,205	1,601	1,457
I Ił	0,608	1,006	0,857	0,609	1,255	1,110	1,108	1,502	1,356	0,904	1,306	1,102	0,754	1,157	1,005

Symbol description: λ min – lowest measured effective thermal conductivity value [W/m·K]; λ max – highest measured effective thermal conductivity value [W/m·K]; x̄ λ – arithmetic mean value of effective thermal conductivity for certain soil type [W/m·K]. Soil classification based on particle size distribution according to PN-B-02480:1986:
Π *- 0,05 - 2,00 mm:* ***0 ÷ 30 %****; 0,002 – 0,05 mm:* ***60 ÷ 100 %****; <0,002 mm:* ***0 ÷ 10 %****;*
Pg *- 0,05 - 2,00 mm:* ***60 ÷ 98 %*** *0,002 – 0,05 mm:* ***0 ÷ 30 %****; <0,002 mm:* ***2 ÷ 10 %****;*
Gp *- 0,05 - 2,00 mm:* ***50 ÷ 90 %****; 0,002 – 0,05 mm:* ***0 ÷ 30 %****; <0,002 mm:* ***10 ÷ 20 %****;*
G *- 0,05 - 2,00 mm:* ***30 ÷ 60 %****; 0,002 – 0,05 mm:* ***30 ÷ 60 %****; <0,002 mm:* ***10 ÷ 20 %****;*
Gπ *- 0,05 - 2,00 mm:* ***0 ÷ 30 %****; 0,002 – 0,05 mm:* ***50 ÷ 90 %****; <0,002 mm:* ***10 ÷ 20 %****;*
I *- 0,05 - 2,00 mm:* ***0 ÷ 50 %****; 0,002 – 0,05 mm:* ***0 ÷ 50 %****; <0,002 mm:* ***30 ÷ 100 %****.*

The measured values of effective thermal conductivity for cohesive soils are initially increasing as the water content (saturation) increases, but in the later phase, the λ values are decreasing (see Table 1). For all types of tested cohesive soils highest values of thermal conductivity are for the liquidity index range $0 < I_L \leq 0,25$. From the scope of analysed cohesive soil types the highest thermal conductivity values were measured for sandy clays (***Pg***) – up to 3,309 W/m·K for the liquidity index range $0 < I_L \leq 0,25$. Lowest values were measured for clays (***I***) – from 0,6 W/m·K in $I_L < 0$ range to 1,5 W/m·K for the liquidity index range $0 < I_L \leq 0,25$. All cohesive soil types show a decrease in effective thermal conductivity values in I_L ranges exceeding 0,25.

In the case of all measured non-cohesive soil type samples, the rise of effective thermal conductivity values is observed as the water content is increasing. The most dynamic increase in thermal conductivity values occurs in the water content class between 0 to 5%. As the porous space of non-cohesive soils gradually saturates with water, the increase in effective thermal conductivity value becomes slower. The highest values of thermal conductivity are observed in non-cohesive soils that are fully saturated with water (2-phase media). From the scope of analysed non-cohesive soil types the lowest thermal conductivity values were measured for gravels (***Ż***) – from 0,216 W/m·K in water content range 0-5% to 2,803 W/m·K for water content >20%. The highest thermal conductivity values were measured for sandy gravels + cobble (***Po***) – from 0,415 W/m·K in water content range 0-5% to 3,205 W/m·K for water content >20%.

Table 2. *Values of effective thermal conductivity (λ) for non-cohesive soils samples according to water content.*

Soil classification according to PN-B-02480:1986	Water content [%]														
	0 - 5			5-10			10-15			15-20			> 20		
	λ min	λ max	x̄ λ	λ min	λ max	x̄ λ	λ min	λ max	x̄ λ	λ min	λ max	x̄ λ	λ min	λ max	x̄ λ
Pπ Piasek pylasty	0,275	1,796	1,060	1,658	2,107	1,859	1,822	2,248	2,135	2,230	2,673	2,542	2,598	2,880	2,761
Pd Piasek drobny	0,242	1,812	1,083	1,699	2,155	1,904	1,866	2,421	2,169	2,390	2,747	2,656	2,630	2,903	2,765
Ps Piasek średni	0,278	1,857	1,106	1,719	2,206	1,948	1,933	2,446	2,199	2,410	2,903	2,731	2,878	3,116	3,034
Pr Piasek gruby	0,248	1,885	1,120	1,740	2,253	2,003	1,977	2,460	2,273	2,390	2,830	2,700	2,712	3,006	2,854
Po Pospółka	0,415	2,007	1,262	1,820	2,305	2,187	2,102	2,559	2,331	2,551	2,920	2,615	2,814	3,205	3,050
Ż Żwir	0,216	1,755	1,034	1,611	2,001	1,838	1,951	2,370	2,152	2,269	2,609	2,304	2,538	2,803	2,667

Symbol description: λ min – lowest measured effective thermal conductivity value [W/m·K]; λ max – highest measured effective thermal conductivity value [W/m·K]; x̄ λ – arithmetic mean value of effective thermal conductivity for certain soil type [W/m·K]. Soil classification based on particle size distribution according to PN-B-02480:1986:
Pπ: *0,05 – 2,00 mm:* ***68 ÷ 90 %****; 0,002 – 0,05 mm:* ***10 ÷ 30 %****; <0,002 mm:* ***0 ÷ 2 %****;*
Pd: *> 2 mm:* ***< 10 %****; > 0,5 mm:* ***< 50 %****; >0,25 mm:* ***< 50 %****;*
Ps: *> 2 mm:* ***< 10 %****; > 0,5 mm:* ***< 50 %****; >0,25 mm:* ***> 50 %****;*
Pr: *> 2 mm:* ***< 10 %****; > 0,5 mm: >* ***50 %****;*
Po: *< 0,002 mm:* ***< 2 %;*** *> 2 mm****: 10 - 50 %****;*
Ż: *< 0,002 mm:* ***< 2 %;*** *> 2 mm:* ***> 50 %****.*

Conclusions

On the basis of performed thermal needle measurements, it was found, that the highest impact on effective thermal conductivity value of mineral soils has the medium (water) that saturates the pore space. In non-cohesive soils, the effective thermal conductivity increases gradually with the increasing water content up to the point of full saturation. In the case of cohesive soils the highest values of effective thermal conductivity are for the liquidity index in the range of $0 < I_L \leq 0{,}25$. All cohesive soil types show a decrease in effective thermal conductivity values in I_L ranges exceeding 0,25.

Variability of the grain size distribution for different types of tested mineral soils also has a significant impact on effective thermal conductivity values. The highest values in non-cohesive soils were obtained in soil types with the highest amount of finest fractions – clays. It is due to the ratio of clay minerals content vs quartz content and their contrasting values of thermal conductivity.

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MITIGATION OF RISK FACTORS IN GEOTHERMAL PROJECTS – PROPOSALS FOR POLAND (GEORISK, H2020)

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Keywords: geothermal projects, risk factors, mitigation, insurance fund, proposal

Abstract

The GEORISK project aims to develop proposals of financial schemes to mitigate the impact of the resource risk. It applies to situations when geothermal resources with the parameters designed on the design stage cannot be obtained. The risk should be spread fairly so that the geothermal project developers could accept it. Risk mitigation with financial instruments allows lowering the developer's financial exposure in case of failure to develop a geothermal reservoir whose parameters enable the resource use as assumed in the design.

In the framework of the GEORISK project, the proposals of geothermal risk mitigation schemes were elaborated in collaboration among teams from several countries. The activities included:

- Facilitating the transition of the existing insurance scheme in Europe (France, Germany, and Turkey),
- Presenting proposals of risk mitigation schemes for geothermal projects in Switzerland and the Netherlands – depending on the geothermal market's maturity,
- Using examples of good practices and proposing relevant insurance schemes for the target European countries (Greece, Poland, Hungary, Belgium, Croatia, Denmark, Slovenia, and Serbia),
- Adapting risk mitigation schemes for geothermal projects and presenting a proposal for the North, Central and Latin America (Chile, Mexico and Canada) and Africa (Kenya).

An online version (www.georisk-project.eu) is available of the risk register developed by GEORISK partners and their collaborating geothermal companies (e.g. from Poland). It contains a list of all plausible risks that developers of deep geothermal projects may encounter. Corresponding de-risking measures are presented for each risk. This is the starting point for developing a risk management framework adapted to the particular project's needs.

As part of the Project's activities, proposed assumptions were developed for establishing a public risk insurance fund in geothermal projects for the Project's three target countries: Greece, Poland and Hungary (based, e.g. on the positive experiences of the fund, which has been operating in France for nearly 30 years). Then, simulations of such funds' ten-year operation were carried out for each country.

The following assumptions were made for the fund's ten-year operation simulation in Poland (the most probable under the geological and economic conditions and considering the stage of the geothermal heat market development in Poland):

- the fund's initial capital amounting to 11.28 M EUR, which is three times the average cost of drilling a geothermal well, estimated based on the value of drilling projects eligible for public non-repayable grants and loans (average well depth of 2,606 m),
- number of insured wells: 20 and 30 in the ten-year perspective,
- well success rate (i.e. confirming the availability of geothermal resources with the assumed design parameters): 80% (16/4 and 24/6 successful/unsuccessful wells, respectively),
- insurance premium (one-off, paid by the well investor): 4, 6, 8 and 10% f the insured well's value,
- provision for risk: 70% and 75%,
- duration of a geothermal drilling project covered by the insurance: 3 calendar years,
- risk insurance fund overhead cost: 150,000 EUR/year.
- project expert cost: 10,000 EUR per ongoing project, annually.

Operation analysis of the proposed risk insurance fund for geothermal projects is presented in Figures 1 and 2 for 20 and 30 covered projects, respectively.

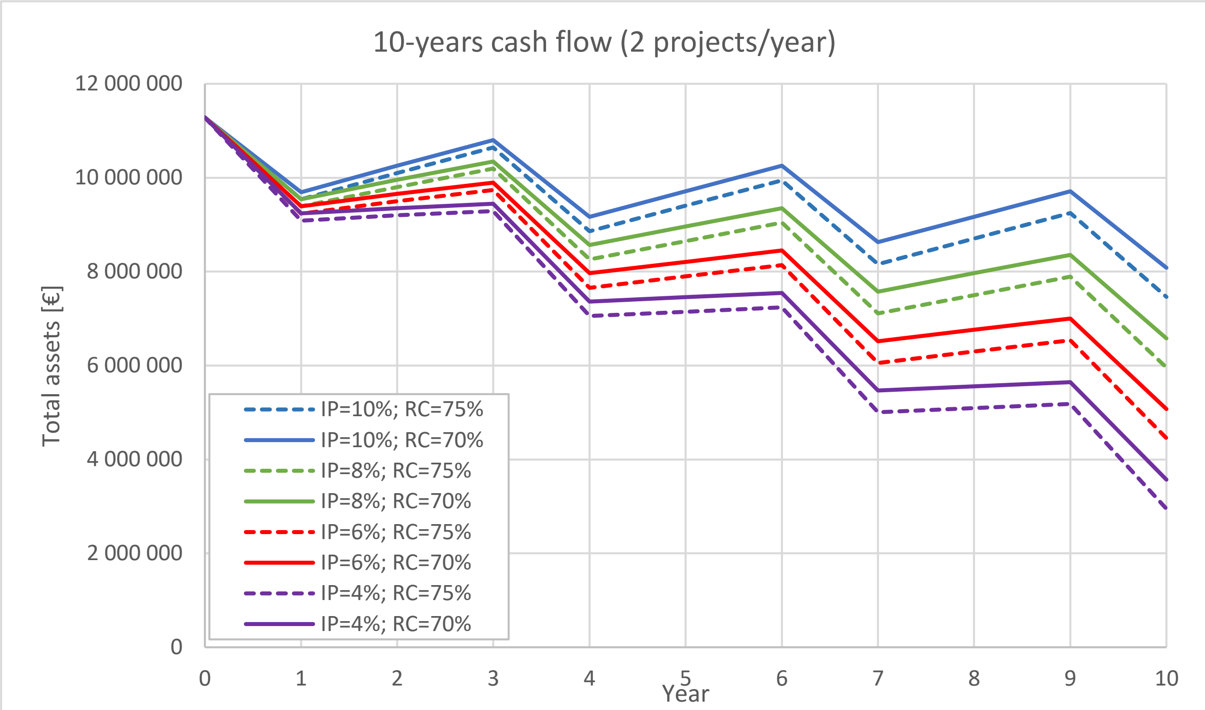

Figure 1. *Simulation for Poland: ten-year cash flow of the proposed risk insurance fund for geothermal projects: 2 projects/year with 80% success rate, 20 projects. IP – insurance premium, RC – risk cover (Kujbus et al., 2021).*

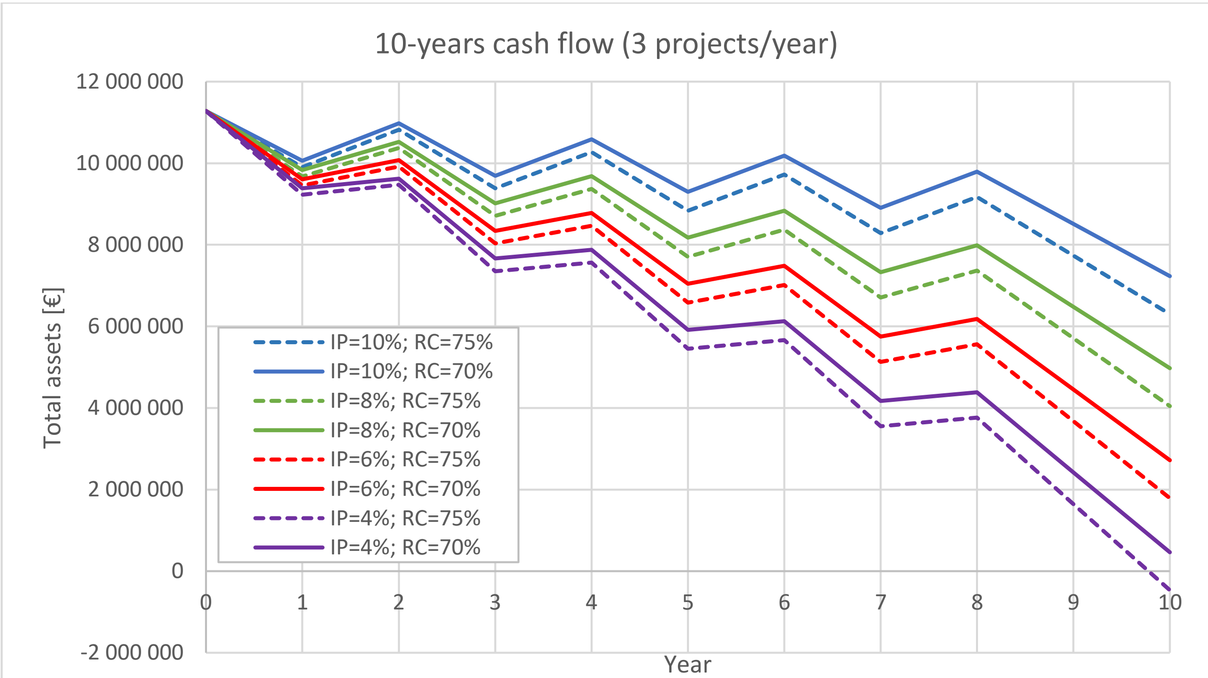

Figure 2. *Simulation for Poland: ten-year cash flow of the proposed risk insurance fund for geothermal projects: 3 projects/year with 80% success rate, 30 projects. IP – insurance premium, RC – risk cover (Kujbus et al., 2021)*

An analysis of the simulation results for Poland reveals that in almost every case, the initial capital (fund's base amount), supplemented by the geothermal developers' contributions (insurance premium), would allow an even 75% reimbursement of the incurred costs to unsuccessful projects (assuming 80% success rate). The fund assets would expire only in exceptional cases before the end of the ten-year perspective (4% premium, 75% risk coverage; 3 projects/year). Such a solution should encourage private and other investors (other than local governments) and state bodies to set up the fund due to the higher likelihood of developing more geothermal drilling projects and the reduced involvement of public funds. At this same time, these would bring significant leverage effects: 8.00 EUR from the investment / 1 EUR from the public funds in case of 24 positive projects and 5.33 EUR from the investment project / 1 EUR from the public funds in case of 16 positive projects (80% success rate).

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www.georisk-project.eu

GEORISK

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ENERGIZERS PROJECT – CO_2-ENHANCED GEOTHERMAL SYSTEMS FOR CLIMATE NEUTRAL ENERGY SUPPLY

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Keywords: unconventional geothermal systems, CO_2-EGS, hot dry rocks, CO_2 sequestration

Abstract
In the 21st century, research projects aimed at obtaining energy in a manner that is as neutral as possible to the natural environment are of particular importance, bearing in mind that the current combustion of fossil fuels, even in modernized installations, causes significant emissions of greenhouse gases into the atmosphere. Therefore, the great challenge of our time is their reduction, and especially the mitigation of anthropogenic carbon dioxide emissions. Hence, the growing interest in many countries around the world in the use of geothermal energy, which is a clean, independent of weather conditions, ecological source of energy. This issue is addressed in the currently implemented project entitled: CO_2-Enhanced Geothermal Systems for Climate Neutral Energy Supply, acronym EnerGizerS. This project received funding as part of the Polish-Norwegian research projects POLNOR 2019 financed by the Norwegian Financial Mechanism program and is implemented by an international consortium composed of: AGH University of Science and Technology in Kraków (Project promoter; Kraków, Poland), Institute of Mineral and Energy Economy of the Polish Academy of Sciences (Kraków, Poland), SINTEF Energi AS (Trondheim, Norway), Norwegian University of Science and Technology (Trondheim, Norway) and EXERGON LLC (Gliwice, Poland). The project will be implemented in 2020-2023.

The main goal of the project is to analyze the effectiveness of the operation of unconventional geothermal systems (EGS) using carbon dioxide (CO_2) as a working medium. This technology (CO_2-EGS) combines the aspects of obtaining clean energy from the Earth's interior and the reduction of carbon dioxide emissions from the combustion of fossil fuels by partially binding it permanently in the deposit rocks (Gładysz et al. 2020a, b).

An important element of the EGS system is the network of fractures created as a result of hydraulic fracturing and enabling heat exchange between the injected working fluid and the rock formation (Sowiżał et al., 2021). The temperature of reservoir rocks plays a key role in the system efficiency and should be at least 150 °C (Avanthi et al., 2019), therefore, wells providing rock formations at this temperature should be sufficiently deep. In Poland, such conditions occur at depths of at least 4 km (Sowiżdżał et al., 2021). In most EGS systems in the world, water is the working medium, although supercritical carbon dioxide is more and more often indicated as a medium with favourable thermophysical parameters (Aminu, 2017).

The CO_2-EGS technology is currently not widely used, therefore it is necessary to work on the possibilities of its effective application. One of the first such projects was the pilot project in Japan (Ogachi) carried out in 1989-2001. The petrothermal reservoir was a granodiorite with a temperature of over 230 °C at a depth of 1000 m (Kumari, 2019).

The research carried out under the EnerGizerS project aims to identify and characterize in detail potential geological structures for the location of CO_2-EGS systems in Poland and Norway, combining the requirements

of Enhanced Geothermal Systems (EGS) and Carbon Dioxide Sequestration (CCS) technologies. As a part of 6 work packages, comprehensive laboratory tests will be carried out on drill core samples taken from appropriate geological structures to assess petrophysical, thermal and mechanical characteristics. The obtained results will be the basis for advanced mathematical modelling, including the structural modelling of the deposit, modelling of the rock fracturing process and 3D modelling of the system operation along with forecasts of the deposit's behaviour over time. The project also involves the experimental determination of the properties and behaviour of working fluids (CO_2), as well as mathematical modelling of heat and energy production systems based on supercritical carbon dioxide. All the conducted tests and analyzes will constitute the basis for the proposed technology's technical, economic and environmental assessments. Project outcomes will help to determine the capability of combining two considered technologies: EGS and CCS to reduce carbon emissions and generate clean energy that can cover the baseload power. An important aspect of the EnerGizerS project is also the exchange of experiences and deepened cooperation between Polish and Norwegian partners to define the best framework for CO_2-EGS technology and reduce the risk for future geothermal investments.

The first stage of the work undertaken within the EnerGizerS project allowed for the identification of important parameters for the location of the CO_2-EGS system onshore (Poland) and offshore (Norway). The research was carried out applying the method of structural analysis, using impact-dependence matrices developed by experts from partner units. 49 parameters were assessed for the impact-dependence assessment, 8 of which were considered crucial for the determination of the CO_2-EGS system's location in any of the partner countries. The analysis of key parameters together with the study on geothermal conditions in both countries made it possible to identify geological structures suitable for the CO_2-EGS system. In Poland, the Gorzów Block and the Mogilno-Łódź Basin area were identified as the most promising areas for the implementation of this technology, while in Norway the Åre Formation in the Norwegian Sea, the Ula Formation and the Skagerrak Formation located in the North Sea were selected.

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WORLD EXPERIENCE IN THE USE OF THE ENERGY FROM HOT DRY ROCK

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Keywords: EGS (Enhanced Geothermal System), HDR (Hot Dry Rock), petrothermal energy

Abstract

Energy from hot dry rocks is used globally through EGS technology – Enhanced Geothermal System. Unlike conventional hydrogeothermal systems, this technology enables the extraction of energy from dry rocks that do not contain water or contain water in small amounts. This is done by artificially increasing the hydraulic efficiency of a geothermal reservoir and then introducing a working fluid into it. Working fluid after this process is brought into the power plant or combined heat and power plant (DiPippo, 2016).

The EGS technology was developed in the 1970s in the United States when the group of scientists from Los Amos National Laboratories created the world's first installation in Fenton Hill. Since then, research has been conducted worldwide on the application of this technology (DiPippo, 2016).

In 18 places around the world, i.e. Habanero EGS Project. Paralana EGS Project, Hijori, Pohang, Ogachi, Landau, Ischeim, Basel, Rosemanowes, Fjällbacka, Soultz - sous- Forêts, Groß Schönebeck, Brady's Hot Spring, Raft River, Desert Peak, Fenton Hill, The Geysers, Newberry Volcano (Lu, 2017) there are EGS projects in various phases of implementation, the operation of seven installations was closed, but most of them are continued. From the point of view of implementing the EnerGizerS project, whose primary goal is to analyze the effectiveness of the operation of unconventional geothermal systems using carbon dioxide as a working fluid, the installation in Ogachi (Japan) was an exciting project. It was the only installation in the world that uses carbon dioxide as a working fluid. The experiment was to check how the medium in the form of CO_2 will behave in rock formations. The final result was the creation of a model of CO_2 injection into an injection or production wells in EGS reservoirs.

This paper reviews the most important EGS systems in the world. These projects are located in the European Union, Japan, South Korea, Australia and the United States. The table (Table 1) shows the most important installation parameters.

Table 1. *Main EGS installation parameters (based on Bergur et al.., 2015, Breede et al.., 2013, Lu 2017, Olasolo et al. 2016, Tester 2006)*

NAME	Habanero EGS Project	Paralana EGS Project	Soultz - sous-Forêts	Ogachi	Hijori	Pohang	Groß Schönebeck	Basel	Fenton Hill
POWER	1 MW	3,75 MW	1,7 MW	-	130 kW	1 MW	1 MW	3 MW	60 kW
RESERVOIR ROCK	granite	sedimentary/metamorpfic	granite	granodiorite	granodiorite	granodiorite	sandstone, andesite	granite	granite
TEMPERATURE °C	263 °C	171 °C	260 °C	160 °C	190 °C	-	145 °C	200 °C	192 °C

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The research leading to these results has received funding from the Norway Grants 2014-2021 via the National Centre for Research and Development. The results are part of the Polish-Norwegian project: CO_2-Enhanced Geothermal Systems for Climate Neutral Energy Supply, acronym EnerGizerS, registration number NOR/POLNOR/EnerGizerS/0036/2019.

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INDICATION OF PARAMETERS RELEVANT TO DESIGNING AND SELECTION OF THE LOCATION OF ENHANCED GEOTHERMAL SYSTEMS UTILISING CO_2 AS A WORKING FLUID

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Keywords: cross-impact method, geothermal energy, CO_2 sequestration, Enhanced Geothermal Systems

Abstract

The article presents the preliminary stage of research related to the implementation of the EnerGizerS project, which concerns the use of the EGS technology (Enhanced Geothermal Systems) to obtain and manage geothermal energy, using carbon dioxide as a working medium. In this technology, supercritical CO_2 is responsible for heat exchange between a geological structure and a surface installation.

Applying the cross-impact structural data analysis method, groups of important and less important parameters for the development of CO_2-EGS technology were identified. Strong attention was paid to the parameters important from the point of view of the location of such a system. The research was divided into 3 stages. In the first stage, a group of 18 experts representing various specializations related to the subject of the project was selected among the EnerGizerS project partners. These were: geology (7 experts), reservoir engineering (4 people), environmental engineering (7), physics (1), economics (5), process engineering (12 - including energy), hydrogeology (1), drilling (1)), energy (12), chemical engineer (1), mining law (1), risk and safety assessment (2). Most (14 out of 18) experts indicated more than one of the specializations as their specialities. Then (stage 2), the group of experts, in cooperation with other members from their teams, identified a list of variables on which, in their opinion, the development of CO_2-EGS technology depends, with particular emphasis on the variables limiting/influencing the location of the system. The list initially contained 193 variables/factors which were, according to experts, significant. This list was subjected to the procedure of eliminating similar factors by unifying them. Some factors were merged to form one factor, eventually. The purpose of this stage was to limit the list of factors in order to facilitate filling the so-called matrix of influences (MOI). Ultimately, the MOI consisted of 49 factors. It took about 7 working hours for each expert to complete the matrix. The MOI was filled by assigning individual weights to how one variable impacts others. Each expert provided a completed matrix. On this basis, a final matrix was formed from the expert's individual inputs (arithmetic mean, rounded to an integer number). In the last part of the work, the result matrix was subjected to statistical processing using the Cross Impact method, using the MICMAC version 6.1.2 software. The software is licensed as open-source and its use is free of charge.

Processing of source data allowed to construct diagrams of direct and indirect influence/dependence relations. An in-depth analysis of the obtained data will be part of the next stage of the project, which aim is the selection of factors important for the development of CO_2-EGS technology and the location of the system. Prospective locations will be indicated based on the analysis of the factors considered as significant.

Funding
The research leading to these results has received funding from the Norway Grants 2014-2021 via the National Centre for Research and Development. The results are part of the Polish-Norwegian project: CO_2-Enhanced Geothermal Systems for Climate Neutral Energy Supply, acronym EnerGizerS, registration number NOR/POLNOR/EnerGizerS/0036/2019.

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Narodowe Centrum Badań i Rozwoju

TECHNO-ECONOMIC ANALYSIS OF UNCONVENTIONAL ENHANCED GEOTHERMAL SYSTEMS WITH CARBON DIOXIDE AS WORKING FLUID

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Keywords: enhanced geothermal systems, CO_2, Brayton cycle, economic assessment

Introduction

One of the technologies that can utilize the capture of carbon dioxide is the CO_2-Enhanced Geothermal System (CO_2-EGS), which replaces water as the working fluid. The use of petrothermal energy is possible when hot dry rocks are accessible with temperatures usually above 150 °C. This allows producing both electricity and heat. When CO_2 is used as a working fluid, part (up to 10%) of the circulating carbon dioxide is sequestered in the geological reservoir. This gives an alternative to a conventional CO_2 storage system in saline formations. Within the presented work, the comparative economic analysis study results of CO_2-EGS and conventional CO_2 sequestration for the selected scenario of around 200 thousand CO_2 storage per year, have been presented. In addition, other scenarios of the development and operation of the CO_2-EGS have been presented for both Polish and Norwegian conditions.

Samples and methods

Within the analyzed scenario for the comparative economic analysis, required data were obtained from process modelling of combined heat and power biomass-fired plant with CO_2 capture which was integrated with the CO_2-EGS. In Table 1, the most important energy and economic data were presented for the analyzed scenario.

Table 1. *Basic process and economic data for the selected scenario.*

Process data	Value and unit
CO_2 sequestered	207 276.9 Mg CO_2/year
Electrical energy balance of the CO_2-EGS:	
- gross production of electricity	23 102.85 MWh/year
- electrical Energy own consumption	3 017.72 MWh/year
- net production of electricity	20 085.13 MWh/year
Economic data	**Value and unit**
Total investment costs, incl.:	23 373 859 EUR
- drilling and reservoir stimulation	17 803 800 EUR
- supercritical CO_2 power cycle installation	5 570 059 EUR
Operational costs	393 851 EUR/year
Discount rate	10%
Operation time	30 years

Taking into account the total investment costs, as well as the electrical power of the CO_2-EGS in the analyzed scenario, the unit investment cost was estimated at around 7090 EUR/kW$_{el}$, which corresponds with the cost for such technologies found in the literature. Within the analysis, the 50 to 110 EUR/MWh price range of electricity price was considered, where for the alternative costs of conventional CO_2 storage the range was between 3 and 12 EUR/Mg CO_2. For the comparative economic study, the Net Present Value (NPV) was used, which was defined as follows:

$$NPV = \sum_{\tau=0}^{n} \frac{CF_\tau}{(1+r)^\tau} - I_{tot}$$

where *CF* is the Cash Flow including the difference between income and cost, as well as tax and depreciation, and I_{too} is the total discounted investment cost.

Results

In Figure 1, the results of the comparative study for the selected range of prices and cost for the selected scenario have been presented.

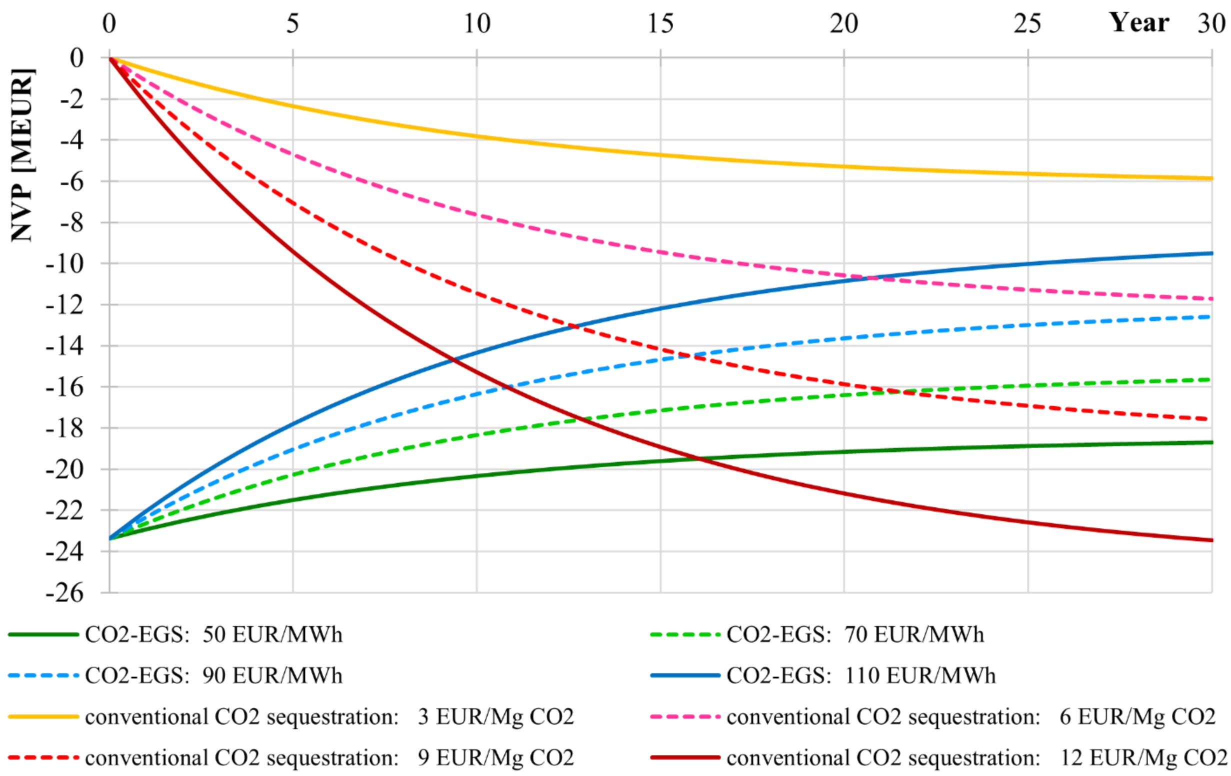

Figure 1. *Results of the economic comparative study.*

As it can be noticed, the CO_2-EGS can be a competitive solution for the conventional CO_2 sequestration in geological formations at the assumed time of operation. The most important and influencing factors of the economic profitability are the total investment cost, especially regarding the EGS reservoir development, as well as the price of electricity. In addition, several technical factors are influencing the economic analysis, which are related to the permeability of the CO_2-EGS reservoir, CO_2 sequestration rate, and the CO_2 pressure and temperature at the outlet of the production well.

Conclusions

Presented results of the preliminary comparative economic study indicate the potential financial benefits resulting from the CO_2 sequestration while CO_2-EGS operation in comparison to the conventional CO_2 storage options. There is a need to further investigate the CO_2-EGS development and operation, both in the area of the geological reservoir and subsurface power generation unit. Those issues are addressed in the Polish-Norwegian Research Project "CO_2-Enhanced Geothermal Systems for Climate Neutral Energy Supply" (EnerGizerS), where for the selected scenarios for both Polish and Norwegian conditions, detailed studies will be performed, including the techno-economic studies.

Within the course of the EnerGizerS project, several scenarios of the CO_2-EGS development and operation have been defined and scored. The most important ones are presented in Table 2.

Tabel 2. *Basic parameters of the defined CO_2-EGS scenarios within the EnerGizerS project*

Parameter	Scenario 1	Scenario 2	Scenario 3
Location	· Poland · onshore	· Poland · onshore	· Norway · offshore
Geological formation	· Gorzów Block · volcanic and sedimentary rocks · 160 °C at the depth of ca. 4.3 km	· Mogilno-Łódź Trout · sedimentary rocks · from 165 to 195 °C at the depths of 5 to 6.5 km	· Åre Formation · sandstone rocks · from 155 to 167 °C at the depths of 4 to 4.7 km
Type of energy generation	· cogeneration · the heat used in district heating system	· cogeneration · the heat used in district heating system	· electricity production only · small potential heat output for platform heat demand
Type of energy cycle	· direct supercritical CO_2 Brayton cycle	· indirect cycle with ORC	· hybrid cycle (direct supercritical CO_2 Brayton cycle and indirect ORC)

As it can be noticed, within the EnerGizerS project scenarios, the cogeneration units will also be investigated, which might increase the economic profitability of the proposed CO_2-EGS, especially when compared with conventional storage of CO_2 captured from industrial or power sectors.

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ANALYSIS OF LEGAL ASPECTS FOR THE LOCATION OF CO2-EGS SYSTEMS IN POLAND

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Keywords: geothermal energy, CO_2 sequestration, Enhanced Geothermal Systems, legal regulations

Abstract
The article presents an analysis of the legal aspects related to the implementation of EGS-CO2 system in Poland. The key formal and legal issues resulting from national regulations on EGS-CO2 were presented, with particular emphasis on detailed requirements in accordance with Geological and Mining Law (Journal of Laws 2020.1064).

As it was pointed in Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amended Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 (Journal of Laws UE L 140 of 05.06.2009, p. 114, as amended), carbon dioxide capture and geological storage (CCS) is a bridging technology that will contribute to mitigating climate change.

The procedures related to the implementation of geological works for recognizing structures for underground CCS differ from the procedure required in the case of thermal waters. The concession is required for exploration work as well as for the injection of carbon dioxide. Obtaining a CCS concession requires hydrogeological documentation in connection with the injection of carbon dioxide, prepared in accordance with the ordinance of 18 November 2016 (Journal of Laws 2016.2033).

The concession is the strongest form of state control of economic activity, which is associated with restricting the freedom of economic entities. It expresses the act of consent of the public authority to the undertaking and performance of the economic activity by a given entrepreneur and constitutes a withdrawal by the state from the monopoly in a given field. The concession is also required for the exploration or recognition of an underground carbon dioxide storage complex, as well as an underground carbon dioxide storage complex. Granting a concession by the Ministry of Environment must be preceded by a decision on environmental conditions. The legal basis here is the Act of 3 October 2008 on the provision of information on the environment and its protection, public participation in environmental protection, and on environmental impact assessments. The essence of the procedure to decide on environmental conditions is to understand the problem and the environmental nuisance of a project. Only on this basis, the impact of the planned conditions on the environment is determined, and then the liquidation or minimization of the identified conditions.

The concession for underground storage of carbon dioxide must specify the quantity and characteristics, including:

- the source of carbon dioxide that will be injected into the underground carbon dioxide storage;
- allowable composition of the carbon dioxide stream that will be injected into the underground carbon dioxide storage;
- information about the hydrogeological unit is understood as a fragment of the lithosphere constituting a spatially and dynamically defined groundwater circulation system, that can be described by the hydrogeological parameters of aquifers and the semi-permeable formations separating them;

- pressure limit values in the underground carbon dioxide storage complex;
- the maximum efficiency and pressure of the injection of carbon dioxide that will be injected into the underground carbon dioxide storage;
- the scope and method of monitoring the underground carbon dioxide storage complex; the minimum amount of financial security.

One of the important elements of the correct application of CCS technology is the reduction of the composition of the carbon dioxide stream, consistent with the primary purpose of geological storage, i.e., the separation of carbon dioxide emissions from the atmosphere, based on the risk that pollution may pose to the safety and security of transport and storage networks and the environment and human health. Acceptable composition of the stream of carbon dioxide injected into the underground storage site, according to Art. 32 sec. 7 point 2 of the Geological and Mining Law (Journal of Laws 2020.1064), what is specified in the concession. Therefore, the entrepreneur was obliged to accept the composition of the carbon dioxide stream after carrying out the risk assessment.

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The research leading to these results has received funding from the Norway Grants 2014-2021 via the National Centre for Research and Development. The results are part of the Polish-Norwegian project: CO_2-Enhanced Geothermal Systems for Climate Neutral Energy Supply, acronym EnerGizerS, registration number NOR/POLNOR/EnerGizerS/0036/2019.

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Directive 2009/31 / EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337 / EEC, European Parliament and Council Directives 2000/60 / EC, 2001/80 / EC, 2004/35 / EC, 2006/12 / EC, 2008/1 / EC and Regulation (EC) No 1013/2006 (Journal of Laws UE L 140 of 05.06.2009, p. 114, as amended)

Act of 9 June 2011 Geological and Mining Law (Journal of Laws 2020.1064)

Regulation of the Minister of the Environment of 18 November 2016 on hydrogeological documentation and geological engineering documentation (Journal of Laws, 2016.2033)

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ESTIMATION OF GEOTHERMAL POTENTIAL USING OIL PROSPECTION DATA

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Keywords: Peribaltic Syneclise, geothermics, compaction, reservoir parameters, modelling

Introduction

Carrying out the energy transformation related to the need to eliminate environmental pollution and reduce the impact of civilization factors that stimulate climate change to necessitate the search for alternative, environmentally neutral energy sources. One of the considered ecological energy sources is the heat of the Earth's interior. The successive depletion of oil and gas fields opens up the possibility of using closed oil wells for the construction of geothermal installations. In addition, as a result of many years of exploration work, extensive information resources have been gathered that can also be used in geothermal analyzes. The main goal of the research presented in this article was to identify the geothermal conditions in the geological medium on the basis of information obtained as a result of oil exploration with the use of research methods successfully used in this prospection. They were made in the area of northern Poland within the geological structure known as Peribaltic Syneclise. The research area is located in the marginal part of the East European Craton in the Polish part of the larger regional structure, i.e. the Baltic Basin. Within its area, for several decades, prospection works for hydrocarbon fields have been carried out, for both: conventional accumulations that are oriented towards the Ediacaran and Lower Cambrian sandstone complexes as well as unconventional ones in the Upper Ordovician and Lower Silurian shale formations. Preliminary analysis of geological data points to the Ediacaran and Low Cambrian sandstone complex as a potential object for geothermal exploration. From the point of view of the assessment of geothermal conditions, the most important thing is to recognize the temperature distribution in the rock medium, the reservoir parameters of rocks and their mechanical parameters responsible for the effectiveness of hydrofracturing treatments. Important conditions for the effective use of geothermal energy are also good reservoir properties of the rock medium, determining the possibilities of accumulation and migration of reservoir media. The industrial accumulations of hydrocarbons are associated with the Cambrian sandstone formation, which is characterized by rather low porosity and permeability. In this situation, it is important to initially recognize the distribution of reservoir parameters, enabling the selection of prospective zones for the location of geothermal installations, as well as the determination of their character. In view of the low values of reservoir parameters, apart from classic low-temperature hydrogeothermics, the possibilities of using EGS (Enhanced Geothermal System) and HDR (Hot Dry Rocks) installations should also be considered. In the research, a set of geological and geophysical data and the results of analytical studies collected during several dozen years of oil exploration work were used. Moreover, palaeothermic and compaction modelling were performed, which are typical calculations used in the analysis of oil systems, as a result of which the temperature and heat flux distributions, as well as the reservoir parameters distributions of the Cambrian sandstone complex, were determined.

Materials and methods

The subject of the presented analysis and considerations is the complex of quartz sandstones immersed at a depth of -4716 to -5000 [m]. They belong to the Ediacaran-Lower Cambrian formations of Łeba, Kluki and Żarnowiec. The methodological research is based on data from the Słupsk IG-1 borehole, on the basis of which changes of hit flux and temperature of the geological medium during the geological time and the influence of mechanical and chemical compaction were modelled (1D). Paleothermal modelling (2D) as well as modelling of the distribution of porosity on a cross-section with a length of 70 km, oriented from NW to SE and located in the marginal zone of the East European Platform. The borehole Słupsk IG-1, drilled in 1974, is located in the onshore part of the Darłowo block. The borehole reached the crystalline substrate, the roof of which was found at a depth of -5078 m, cutting through the Ediacaran - Lower Cambrian quartz sandstones. Below -5000 m, the sandstones pass into conglomerates, which constitute the lower limit of the studied interval.

Borehole geophysics profiling was used in the analyzes and calculations, including measurements of temperature and neutron porosity as well as results of laboratory measurements made on core samples, including vitrinite reflectivity, porosity and permeability. Modelling of temperature, porosity and permeability coefficients is based on a multi-stage reconstruction of sediment burial and palaeothermic conditions changing over millions of years. The tools used in the analysis of petrophysical parameters are petroleum modelling made in the PetroMod 2012.2 program. Changes in the temperature of the rock medium in geological time are related to changes in the heat flux which are estimated on the basis of the calibration of the thermal history of the geological medium using the so-called geothermometers. One of them is the vitrinite reflectivity mentioned above. The most important element of the work is linking the modelling results with borehole and laboratory data. The contemporary porosity and permeability of Cambrian sandstones is the result of the interaction of mechanical and chemical compaction that occurred in this area with increased intensity. The chemical compaction was manifested by cementation with quartz. The compaction processes have shaped today's porosity and permeability drastically lowering their original values.

Results and conclusions

Palaeothermic modelling allowed us to recognize and explain the variability with the depth of the heat flux and to verify the results of previous analyzes of the thermal field parameters in the Słupsk IG-1 borehole vicinity. Low values of reservoir parameters eliminate, in practice, the Cambrian sandstone complex as a potential hydrothermal reservoir level, suitable for the location of geothermal installations. Zones with relatively higher values of reservoir parameters are associated with cracking caused by stresses and tectonic deformations, i.e. in the vicinity of faults and in the top parts of anticlinal bends. They are related to, inter alia, with a known accumulation of hydrocarbons with predominant porosity of the fracture type, which creates an opportunity for their geothermal use, especially in view of the successive depletion of their resources. Relatively high temperatures of Cambrian rocks, combined with the final quartz cementation, forming the mechanical properties of the medium favouring high efficiency of hydraulic fracturing processes, create positive conditions for the effective use of this horizon as a foundation for EGS and HDR geothermal installations.

Funding

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SEISMIC AND WELL LOGGING, AN INDISPENSABLE TANDEM IN THE PALETTE OF GEOPHYSICAL METHODS FOR SUCCESS IN GEOTHERMAL ENERGY

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Keywords: (seismic survey, well logging, geothermal energy)

Abstract

The factor determining the selection of an appropriate location for drilling a borehole in order to obtain geothermal energy is the presence of a reservoir of waters with suitable physical and chemical parameters, in particular temperature and mineralisation. However, the presence of such a reservoir at a certain depth and temperature is not a sufficient condition. Validation of a geothermal reservoir is carried out by precise determination of structural conditions of its occurrence: the size of the structure, porosity, permeability and fracture density of deposit levels. These parameters make it possible to estimate the potential water resources in the deposit and to determine the amount of thermal energy that can be obtained. In order to obtain the above-mentioned information, a number of studies and analyses are required, and a key role here is played by seismic surveys and various methods of well logging measurement.

The general purpose of seismic imaging in geothermal applications is to identify zones with increased porosity or effective fracturing, which allow fluid flow and transport in the rock formation. The separation of these zones is the basis for the optimal location of exploitation wells in a multi-well geothermal system. A multi-well geothermal system is understood as a system of at least two boreholes, where one of them has a production function and the other has an injection function. An important factor in such an arrangement is the presence of a homogeneous reservoir formation so that the injection well can absorb a sufficient amount of thermal water after receiving thermal energy at the surface. Often, however, the reservoir parameters of the formation in the production and absorption wells can show significant differences despite their close proximity to each other (about 1000m in the formation level). The use of dedicated 3D seismic with uniform offset-azimuthal distribution allows the extraction of a number of geomechanical parameters necessary for the advanced analysis of reservoir characteristics.

Well, logging methods, on the other hand, provide precise information on drilled rock formations, their reservoir properties and reservoir water temperature. Measurements during dynamic production tests provide information necessary to optimise the production potential of a well. Advanced studies of the technical condition of the well, are also carried out to confirm its compliance with design assumptions. Well logging also provides services to intensify the productivity of wells or the absorption capacity in the case of injection wells.

Both these geophysical methods seismic and well logging play a major role not only in the exploration and documentation of geothermal reservoirs but are also present during production, monitoring and performance optimisation based on 4D or passive seismic, among others.

APPLICATION OF MINERALOGICAL, PETROPHYSICAL AND THERMAL LABORATORY MEASUREMENTS FOR THE RECOGNITION OF EARTH'S HEAT POTENTIAL – A CASE STUDY FROM CRACOW REGION

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Keywords: thermal conductivity, limestones, mathematical models

Introduction

The thermal conductivity of a geological profile is a crucial parameter for designing borehole heat exchangers (BHEs). The knowledge of the thermal conductivity of the geological profile allows the optimal design of the BHE. In particular, the total depth of wells can significantly reduce the risk of under-or overestimating the BHE heat output and ensure the long-term effective operation of the entire heat pump system.
Thermal conductivity values are characterized by a considerable degree of diversity among different lithologies and particular lithological types. As a result, the assessment of rocks' thermal properties for shallow geothermal energy should not only be based on literature data but, if possible, on thermal response tests or laboratory measurements performed on samples of particular rock formations in the investigated region. Determining the thermal conductivity based on other petrophysical parameters (Fuchs S. et al., 2015; Gegenhuber N., Pimienta et al., 2018; Przelaskowska A., 2018; Przelaskowska A. et al., 2018; Schön J.H., 2011) can be of key importance in the case of a shortage of archival thermal conductivity analyses, which, unlike other petrophysical measurements, are not commonly performed.
Results of the thermal conductivity estimation conducted for limestones from the Cracow area with the use of mathematical models based on mineralogical composition and porosity (Hajto et al., 2020) are presented in this work.

Samples and methods

The investigations were conducted on 22 rock samples collected from four boreholes in the Cracow region: Kopiec-1G, Kopiec-4G, Opatkowice-1, and Trojanowice-24. All of the samples represent limestones of the Upper Jurassic stage. Investigated rocks were microbial-sponge, organodetritical limestones from Kopiec-1G and Kopiec-4G boreholes, and pelitic limestones from Opatkowice-1 and Trojanowice-24, representing a series of detrital sponge limestones. The thermal conductivity values for both dry and saturated samples, quantitative mineral composition and porosity, were determined for all rock samples. To address the large heterogeneity of the pore space (unequal distribution of vugs and fractures), computed tomography was used for the selection of representative samples.
The measurements were conducted with the steady-state method by determining the size of the heat flow through the sample using a FOX 50 LaserComp apparatus. The tests were carried out on samples in the shape of slices of 5 cm diameter and 1.5 cm thickness. The mean temperature was 25 °C, and the difference between the heating and the cooling plates was 20 °C, with 5% accuracy. The measurements were conducted on samples dried for 12 hours at 105 °C (dry samples) and water saturation (saturated) samples.

Results

The thermal conductivity values of the investigated rocks were estimated using mathematical models based on the volumetric content of individual minerals and pore solutions with their corresponding thermal conductivity values. Various calculations were applied: from the simplest layered models to more complicated spherical and non-spherical inclusions models. The calculated values of thermal conductivity were compared with the laboratory-measured values. Correlation analysis of the obtained results was performed, yielding weak to moderate correlations. Therefore, the whole data set was divided into two subgroups: samples of porosity above 4% and samples of porosity below 4%. Significantly better correlations were obtained (R^2 ranging from 0.69 to 0.74) for the group of rocks with porosity higher than 4%, than for the entire set of samples. The group of samples with porosity <4% was discarded for further consideration. The next step was to introduce a correction to approximate the thermal conductivities obtained from the models to the laboratory-measured values. Such a correction can be introduced using the obtained linear equations, provided the correlations are of sufficient quality. Calculations were performed for all models. In each case, the corrected values of thermal conductivity turned out to be much closer to the laboratory-measured values than the values before the correction.

Conclusions

Thermophysical rock properties are key parameters for the assessment of shallow geothermal resources, the future design of geological work, effective heat/cold extraction, and sustainable resource management. From the study of the thermo- and petrophysical properties of the carbonate rocks in the Cracow area, the following conclusions can be drawn:

- The studied Upper Jurassic rocks are a heterogenous formation of limestones, which can be differentiated in structure and fabric. These differences affect their thermo- and petrophysical properties;
- thermal conductivity was assessed by means of mathematical models based on a simplification of the rock's structure, allowing for calculation of the rock thermal conductivity based on the properties of its components;
- the best correlations between calculated and measured thermal conductivity values (R^2 from 0.69 to 0.74) were obtained for the subgroup of samples of porosity higher than 4%. The subgroup of samples of porosity lower than 4% did not show a satisfactory fit of data and was not taken into consideration in the subsequent analyses;
- calculated thermal conductivity values most approximate to the laboratory measurements were obtained by: layer model assuming heat flow perpendicular to the layers consisting of respective components of the rock ($\lambda_{\_harm}$), spherical inclusion model of rock consisting of spherical grains dispersed in the pore solution ($\lambda_{\_sph\_f}$), and non-spherical inclusion model characterized by the presence of extended disk-shaped pores ($\lambda_{\_nsph\_d}$). Each of the three models assumes a structure of the pore space in which the contacts between the framework grains are limited. It appears that these theoretic assumptions can be applied to the investigated rocks where porosity is connected to unequally distributed and sometimes large vugs filled with gas or brines constituting "a barrier" against the heat flow.
- a correction based on the obtained linear equations of the respective calculated models to the laboratory measurements was introduced. The corrected thermal conductivity values are considerably closer to the laboratory measurements;
- the developed measurement workflow allows for the use of mineralogical and petrophysical analysis to identify the geothermal potential of carbonate rocks;

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WELL LOGGING AND LABORATORY INVESTIGATIONS IN GEOTHERMAL PROBLEMS; SELECTED EXAMPLES

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Keywords: geothermal waters, well logging, reservoir properties of rocks, radiogenic heat, thermal conductivity, heat flux and temperature modelling

Introduction

Well logging is the source of extensive data and important information useful in geothermal considerations. Sophisticated well logging methods, dedicated to effective prospection and completion of hydrocarbon deposits, developed for tens of years in the international companies all over the world, under high financial outlays and using innovative research facilities and solutions provide data on porosity, permeability, movable water saturation, irreducible/bound water volume, shaliness, radioactive heat production, temperature and other quantities which can be also used in the geothermal resources prospection and characterization. Well logging measurements and interpretation results are also irreplaceable sources of data on lithology, mineral composition, the salinity of formation waters, fracturing in clastic and carbonate reservoirs. In the literature, there are examples of using wireline and production logging for data impossible to be obtained in another way. Geothermal waters are the main source of thermal energy. Also, hot dry rocks, HDR can produce heat, first of all in the regions of high volcanic activity but also in the areas of high geothermal gradient. Thermal waters resources recognition, prospection and production seem to be easier using the highly developed, well equipped and technically recognized methodologies known in hydrocarbon prospection. Similarly to hydrocarbon reservoirs, water reservoirs are located in clastic and carbonate rocks. So, the methodologies elaborated and still developed for hydrocarbon prospection can be utilized in geothermal resources investigations, scientific studies and engineering.

Material and Methods

The goal of the presentation is to show the ability to use the well logging and results of the laboratory investigations in solving geothermal problems. The authors underlined that well logging methods used for the qualitative characteristics and quantitative determination of reservoir parameters of rock formations were developed and improved for more than 80 years and engineers building new devices, authors of the specialist software for processing and geological interpretation of well logging and petrophysicists gained a huge experience. All logs without any changes and special adopting can be used for exploration of the geological formations being targets of the geothermal investigations and determining porosity and permeability, calculating radiogenic heat, characterizing the quality of geothermal waters. In the authors' opinion, knowledge held by petrophysicists and well log analysts may be used in many ways to solve the geothermal tasks.

A short overview of well logging, from the oldest resistivity logs, spontaneous potentials and calliper, to the most sophisticated based on the magnetic resonance phenomenon and electric or acoustic imaging logs shows that all of them carried the information which can be used. While presenting porosity logs attention was focused on standard neutron, density and sonic logs but also there were shown examples of nuclear magnetic resonance logging to extend the information of accumulation ability and media flow in porous space. There were presented gamma and spectral gamma logs not only for shaliness determination but also for radiogenic heat calculation. Spontaneous potential log, made without almost any costs together with resistivity measurements, was recommended as a source of valuable information on formation water mineralization. Temperature measurement in the borehole was recalled as a standard registration of temperature changes along borehole axis and bottom hole temperature, BHT, registration in the unbalanced state of orogeny and also as the temperature log in the balanced state for the geothermal gradient determination. The role of temperature

measurement in the Production Log and quick, simple way to use it in the evaluation of the cement bond height were also mentioned.
There was underlined that results of laboratory measurements of the thermal conductivity together with results of the radiogenic heat calculations along the borehole profile may be used in the modelling of temperature and surface heat flux, which is important in the credible determination of the regions for heat production by heat pumps. Selected examples illustrating relations between thermal conductivity and radiogenic heat with the lithology were also presented.
There were shown the samples of the interpretation results of electric imaging log for natural and induced fractures identification and was highlighted that processed dipmeter results are also useful in that task. Inter-well correlation based on the characteristic anomalies on well logging was mentioned as the way for spatial illustration of the determined geological horizons.
Completing the information on the versatile use of well logging and results of laboratory investigations there was also pointed out the importance of the correlation equations combining thermal parameters, first of all, thermal conductivity and radiogenic heat with other petrophysical quantities determined from well logging. Equations, published in the specialist literature, determined based on large data sets, credible from the statistical viewpoint can be used everywhere there is a lack of the relevant set of logs, especially spectral gamma.

Conclusions
Reservoir parameters considered in hydrocarbon deposits and geothermal resources prospection and characterization can be determined from well logs. Archive and contemporary well log data are useful sources of porosity, fracturing, permeability, mineral composition (shaliness) and elastic properties of rocks. Special role-plays various temperature logs and spectral gamma-ray logs. Many petrophysical parameters obtained from well logs can be also obtained in laboratory experiments with the same physical basis as well logging. Despite their point character, direct laboratory measurements construct the platform confirming well logging data, continuous and relatively cheap but indirect and obtained in boreholes in a special environment. In Poland, in various institutions, there is a great amount of well logging data. Archive data can be effectively used in further analyses and complete the new measurements. For investors important is knowledge on the parameters possible to be determined from logs to order proper measurements.

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In the presentation there were used the results published in the article: **Geothermal resources recognition and characterization on the basis of well logging and petrophysical laboratory data, Polish case studies,** Jadwiga A. Jarzyna, Stanisław Baudzis, Mirosław Janowski, Edyta Puskarczyk, ENERGIES, 2021, 14, 850. https://doi. org/10.3390/en14040850. Authors thanks to PGNiG S.A., Warsaw, Poland and Lux Veritatis Co., Warsaw, Poland for allowing well logging and geological data.

ESTIMATING THERMAL CONDUCTIVITY FROM CORE AND WELL LOG DATA

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Keywords: thermal conductivity, well logs, multiple regression

Introduction

Many petrophysical properties of rocks can be determined both by laboratory measurements and well-logs. It is thus possible to apply geophysical data to empirical models based on relationships between laboratory measured parameters and derive continuous thermal conductivity values in well profiles. This issue has been dealt with by many authors (Evans, 1976; Goss et al., 1975; Vacquier et al., 1988; Hartmann et al., 2005). Models, in which the measured thermal conductivity values were related directly to the well log data (Doveton et al., 1997; Goutorbe et al., 2006) were used in case of lack of laboratory measurements. Such models can be applied to large databases, especially when not small scale changes but global trends of thermal conductivity in the whole well profiles are investigated. In Poland continuous thermal conductivity logs were derived for Carpathian flysch sandstones (Gąsior & Przelaskowska, 2006; Gąsior & Przelaskowska, 2008).

The presented work shows the results of the Mezo-Paleozoic rocks from the Carpathian Foredeep representing different lithologies ((limestones, marls, dolomites, sandstones and mudstones) thermal conductivity estimation with the use of well log data (Gąsior & Przelaskowska, 2014).

Samples and methods

The research was conducted on Mezo-Paleozoic rocks from the Carpathian Foredeep. Sixty-two cores from three wells: O-3, P-2 and Zg-1 situated in the Tarnów-Dębica area were measured. The investigated samples are characterized by lithological variety, they represent both carbonate (limestones, marls, dolomites) and siliciclastic rocks (sandstones, mudstones). A number of petrophysical parameters: thermal conductivity, quantitative mineral composition, bulk density, porosity and radioactive elements (thorium, uranium and potassium) contents were measured in order to obtain the widest possible set of laboratory data. Thermal conductivity was measured with the steady-state method by determining the size of the heat flow through the sample using a FOX 50 LaserComp apparatus. The tests were carried out on samples in the shape of slices of 5 cm diameter and 1.5 cm thickness. The mean temperature was 25 °C, and the difference between the heating and the cooling plates was 20°C, with 5% accuracy. Measurements were conducted on samples dried for 12 hours at 105 °C (dry samples) and water saturation (saturated) samples.

Empirical models

Empirical models based on relationships between thermal conductivity and other laboratory measured petrophysical parameters were constructed using multiple regression method. Separate models were constructed for siliciclastic and carbonate rocks. All measured parameters: bulk density, clay minerals, quartz, calcite and dolomite content, thorium, uranium and potassium content, and porosity were analysed. The regression analyses were performed first for all variables and afterwards with the exception of the variable defining the radioactive elements Th, U and K contents. The reason for such procedure is that sometimes, especially in older wells, the spectral gamma log, from which the Th, U and K contents are derived, is not performed at all or covers only a part of the well profile.

The best results (R^2=0,88) were obtained for the model constructed for carbonate rocks taking into account the whole set of data. Slightly inferior results were obtained for siliciclastic rocks (R^2=0,78) what is probably connected with smaller amount of laboratory data. Models derived without the variable defining Th, U and K contents are of similar quality to those obtained for the whole set of data, both for carbonate (R^2=0,85) and siliciclastic rocks (R^2=0,76).

Thermal conductivity predicted from geophysical data

Geophysical well logs provide a continuous record of in-situ conditions with depth. Application of the derived empirical models to geophysical data enabled to prediction of thermal conductivity continuously in well profiles. A set of 7 well logs: density, sonic, neutron, gamma-ray, spectral gamma ray, calliper and resistivity were applied. The correction was introduced for the well diameter and drilling fluid density. Input logs were used to compute porosity and matrix composition (clay minerals, quartz, calcite, dolomite). Bulk density and Th, U and K contents were obtained directly from wireline data. Continuous thermal conductivity profiles were obtained in profiles of three boreholes: Z-2, O-3, P-2 of the investigated area with the use of models constructed for all variables and with the exception of the variable defining Th, U and K contents. Models for carbonate rocks and those for siliciclastic rocks were applied respectively for carbonate and shale/sand lithostratigraphic units of the studied well profiles. Analysis of the obtained results shows good consistency between laboratory data and values obtained from log data. High determination coefficients (R^2=0,86, 0,90) prove the correctness of the applied models.

Summary

We have proposed a method of estimating thermal conductivity using well log data. Geophysical data were applied to empirical models based on relationships between thermal conductivity and other petrophysical parameters: quantitative mineral composition, bulk density, porosity and radioactive elements (thorium, uranium and potassium) contents. Application of the empirical models to geophysical data-enabled obtaining thermal conductivity logs in the three investigated well profiles. In all three boreholes, general trends of thermal conductivity changes are maintained. Correlation of laboratory values and values obtained from wireline data (R^2=0,86, 0,90) show good consistency. The introduced methods enable to the estimation of thermal conductivity values from well logs in the Meso-Paleozoic rocks from the Tarnów-Dębica area. The obtained relationships can be applied both in boreholes with the complete set of well logs and in wells without the spectral gamma-ray logs. The presented mathematical models can be used in different sedimentary basins at a condition that the models will be calibrated on a new, updated data set.

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HYDRAULIC FRACTURING FOR ENHANCED GEOTHERMAL SYSTEMS (EGS)

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Keywords: hydraulic fracturing, rock mass mechanics, assisted geothermal systems, EGS, hot dry rock, HDR

Introduction

Hydraulic fracturing is a well-known stimulation method, used to increase production from conventional and unconventional hydrocarbon reservoirs. In this method, an artificial fracture in the reservoir is created or preexisted fracture is reopened by injection of process fluid at high pressure. Since the 1970s hydraulic fracturing has been also used to create underground heat exchangers in impermeable or poor-permeable hot rocks (HDR), in enhanced geothermal systems (EGS). Hydraulic fracturing in EGS is used to connect at least two wells at a target depth, by a fracture network. The fracturing of HDR rocks is a technological challenge due to design the optimal fracture system design. On the one hand, the system should be characterised by sufficient hydraulic conductivity, on the other hand, should counteract the thermal short-circuiting, leading to a decrease in the temperature of the received liquid (McClure and Horne, 2014).

Complex fracturing project - a key to success

The first and very important principle for designing an effective hydraulic fracturing, both in the hydrocarbon and geothermal reservoir, is full recognition of geological, petrophysical, tectonic and geomechanical conditions of a target zone, and the adaptation of individual technology elements to the specific case. HDR formations are usually crystalline rocks, i.e. granite, granodiorite, monzonite, characterized by high density and mechanical strength (Tester et al., 2016). In several projects, sedimentary rock of similar properties to tight-gas sandstones, are also adopted as a heat exchanger (eg. Tischner et al., 2013). Deposited at great depths, HDR rocks are a subject of very high compressive stresses impact, both of the overburden and horizontal, of values over 100 MPa. Consequently, natural cracks fractures in these rocks are usually closed. In most EGS projects in the world, fracturing lead to opening these natural fractures (hydraulic jacking). In some cases, new fractures are formed (pure opening mode), or a combination of preexisted and new fractures occur (mixed mode). The direction of fracture propagation mainly depends on the tectonic regime of the area. Fractures propagate always in the direction perpendicular to the minimum stress. In the normal faulting regime (extension), where vertical stress dominates, vertical fractures will be created. In the reverse faulting regime (compressive), where the magnitudes of both horizontal stresses dominate, a horizontal fracture propagates. This is crucial to design a fracture system connected two wells of the geothermal doublet, several hundred metres apart. The mechanical strength of the rock defined as the strength of the grains together with the pore space medium in reservoir HPHT conditions is equally important as well. Relation between stress and strain, or strain in different planes is described by elastic parameters (Young's modulus E and Poisso's Ratio v). Their values directly affect the geometry of the fracture, i.e. length, height and width (Figure 1), as well as pumping parameters. An increase of the E modulus leads to an increase in fracturing pressure, fracture length and decrease of width (Moska, 2016). Elastic parameters allow calculating brittleness index - rocks susceptibility for fracking (Rickman et al., 2008; Moska, 2021). In the ductile rocks, the embedment phenomenon rise, which leads to a decrease in the conductivity of the fracture (Masłowski and Labus, 2021), however embedment in HDR rocks is still not well studied.

Several prospective areas have been selected for the EGS system purposes in Poland, both in crystalline formations, volcanites as well as sedimentary rocks (Wójcicki et al., 2013; Sowiżdzał et al., 2021). The mechanical properties of these rocks are most similar to the high strength tight-gas sandstones. Water-based fluids with a small addition of polyacrylamide or natural polymer (slickwater), are usually used for the fracturing of this type of rock (Czupski et al., 2013). Due to the very low matrix permeability, the amount of pumped fluid should be large, hence such treatments are called Massive Hydraulic Fracturing.

Pumping a large volume of slickwater does not cause fracture conductivity damage. Because of very low viscosity, slickwater is characterized by poor transport properties, which requires the use of proppants with smaller grain sizes or ultralight but durable ceramic proppants.

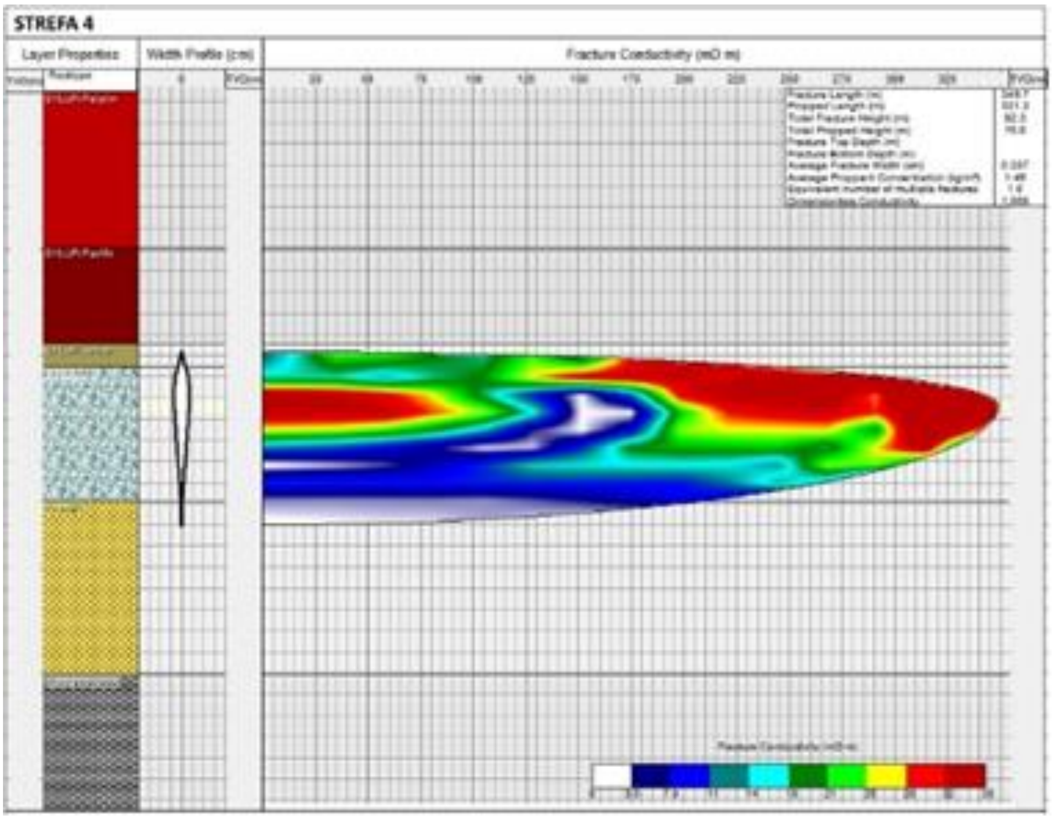

***Figure 1**. An exemplary model of a wing of the fracture. Colour filling means proppant concentration (Kasza, 2019).*

The capabilities of the Oil and Gas Institute in the field of designing hydraulic fracturing treatments in EGS systems.

Reservoir Stimulation Department of Oil and Gas Institute - National Research Institute, for many years provided a back-up for the Polish oil and gas industry in the field of designing hydraulic fracturing treatments. Department has is a fully equipped laboratory, which allows to comprehensive research approach, from petrophysical rock analyzes and geomechanical tests in HPHT conditions, through preparing a fluid composition and rheology tests, up to designing the geometry of fractures in specialized software. The skills and knowledge of the laboratory research team have been confirmed in many realized projects for industry, and by numerous scientific articles in highly scored journals, as well as conference presentations.

Conclusions

The target formations in EGS projects in the world, as well as in prospective areas in Poland are crystalline, volcanic or sedimentary rocks of very low permeability and porosity. These rocks are deposited at a depth of 2000-5000 m, in high-pressure conditions and temperature above 150 °C. Designing effective hydraulic fracturing treatment in this type of rock requires full recognition of the geological and tectonic conditions of a location. The full scope of laboratory works allows for optimal adaptation of individual elements of technology to the specific case. Reservoir Stimulation Department of Oil and Gas Institute - National Research Institute thanks to the unique equipment base and many years of employees experience, has the ability to comprehensively design fracturing treatments for EGS systems in Poland.

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GEOTHERMICS IN POLAND 2021. CASUAL DRILLING OR QUANTITATIVE EXPLORATION - A NEW APPROACHE NEEDED?

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Keywords: Geothermics, Petroleum Exploration, CCS, Quantitative Exploration, 3D Structural–Parametric Modeling

Introduction

Oil & gas exploration in its early days contributed to the rapid growth of the wealth of many brave people in the world. It was enough to read the traces on the surface and drill wells. Nowadays, oil exploration conducted in an overly romantic way can destroy even the greatest fortune.

Contemporary Geothermal energy in Poland from the perspective of a petroleum geologist

The current state of knowledge about geothermal energy in Poland encourages no less courageous investments, although currently they are often financed or co-financed by the State Treasury. What's more, the current state of knowledge encourages independent investments carried out by individual investors. After all, we have excellent knowledge about geothermal energy in Poland, which is transmitted in geothermal atlases showing that hot water is found in almost all of Poland (Górecki et al., 2006a, b; 2010; 2011; 2012; Barbacki et al., 2006). This optimism is fueled even more by the huge resource numbers published in the public domain [e.g. 1]. In the age of the Internet, when each of us is the best physician, these publications can lead to quick decision-making without consultation or in consultation with specialists who have a vague idea of modern energy resources exploration. Meanwhile, everything we see in Atlases (which I co-created - BP) is a huge simplification. Will someone indicate precisely the location of the Old Town in Krakow on the map of Poland on a scale of 1: 2 500 000? And this is the size of a large geothermal field. Will you indicate where the faults are in it, etc.?

As for the resources ... the figures are given in Atlases (Górecki et al., op. cit.), and especially on the Internet [1], indicate that Poland can give energy to entire Europe. These numbers are more or less true, especially those in the Atlases. Meanwhile ... these are the so-called prospective or prognostic resources *(=Resources* in PRMS classification), i.e. simplifying the total amount of heat remaining in the geothermal basin, which are far from the reserves that can be extracted with profit (Nieć, 2016) *(=Reserves* in PRMS). What a huge difference it is can be illustrated in the example of resources and remaining recoverable gas reserves in the Rotliegend formations of Poland. They were estimated by the AGH UST team at $1.61*10^{12}$ m^3 of natural gas, while the industrial reserves documented at that time amounted to $0.12*10^{12}$ m^3 only (Burzewski et al. 2009). These calculations are still the basis for the official PIG-PIB reserves estimates for the Rotliegend basin (Jagielski et al., 2019), it shows how huge is the distance between the prospect of discovery and the discovery itself. Being aware of these disproportions, it is necessary, as the entire world geology, to intensify modern geothermal investments and more.

Geothermics and not only in the world

In times of global warming, the idea of using the Earth's heat is gaining popularity, and despite difficulties such as induced seismicity (Pollack et al. 2020), huge funds are being allocated in the world to the development of new geothermal technologies, such as Enhanced (Engineered) Geothermal Systems (EGS), geothermal energy supported by geological carbon storage in EGS systems (e.g. Brown 2000; Preuss 2006; [3]) and porous geothermal reservoirs, the so-called CO_2-plume geothermal systems – CPG (e.g. Randolph & Saar, 2011a; Salimi & Wolf, 2012; McDonnell, 2020) or fluids coproduced during hydrocarbon production (Tester et al., 2006). Multi-annual and multi-billion programs in this area are developed and generously financed primarily by government institutions in the USA, Australia, Japan and recently the EU [2-6]. These programs not only lead to a sharp increase in the production of heat and geothermal energy but also contribute to the development of clean technologies that bind geothermal energy, hydrocarbon production, hydrogen production, carbon capture as well as energy storage (e.g. Moore et al., 2019; Bogason et al., 2019; Van Horn, 2020). All these programs, in addition to the participation of government institutions, have great support in terms of financing and know-how by the largest petroleum exploration and service companies, such as Equinor, Chevron, Petrobras, Exxon or Schlumberger [7-13]. These programs are also supported by existing *know-how* and a huge amount of new research conducted by research centres such as MIT, Stanford University in the USA, Imperial College in the UK, IFPEN in France, SINTEF in Norway and hundreds of others.

Conclusions

Concluding, geothermal energy has great prospects, but at the moment Polish geothermal energy still seems to be at the romantic stage. This will not change without close cooperation with oil & gas companies and petroleum geologists and geophysicists from scientific centres. The key will be the transfer of knowledge obtained during years of detailed hydrocarbon exploration and quantitative geological analyses, including detailed seismic interpretation, well geophysics and comprehensive 3D structural and parametric modelling. Otherwise, there will be more and more disappointments such as those provided by the Dębica GT1 and Sękowa GT1 wells, or earlier in Toruń, where the main goal, geothermal electricity production, has not been achieved.

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Iceland Liechtenstein Norway grants

Norway grants

THE IMPACT OF AN ENERGY USER CHARACTERISTIC ON THE EFFICIENCY OF DIRECT USE OF GEOTHERMAL ENERGY

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Abstract

In Central and Northern Europe energy used in the residential sector for space and water heating accounts for more than 80% of the final energy consumption, being several times greater than the energy used commonly for cooking, lighting and powering household equipment. Therefore, it is very important to optimize heat supply to consumers connected to district heating systems, while increasing the share of renewable energy sources.

A heating system is characterised by certain technical requirements, e.g. the supply and return temperature and the required flow of water. Heat demand and the temperature of the return water are mainly dictated by the efficiency of the heating systems and weather conditions, but also by the characteristics of the user(s) and the technology used. The selection of appropriate parameters and management of the system is referred to as the control of power delivery.

The inability to reach the temperature required by the energy user (the installation that the end-consumer uses) results in the need to use supporting heat sources (peaking sources). The peaking sources generate additional investment outlays and their use occurs when the supply temperature isn't high enough to meet the consumer's needs. Fossil fuels are most frequently used as supporting heat sources in geothermal heating systems. Reduction of their negative environmental impact and increase of energy efficiency can be achieved by improving the energy characteristic of the final user. The amount of energy generated by peak sources can be reduced or eliminated by adjusting the needs of heat recipients to the capabilities of the source. This, however, also requires making changes in the heating systems. As it involves changes in parts of the installation that are not owned by the energy supply companies, energy companies do not usually undertake such activities. It is also easier to match the capabilities of the energy source to the customer's requirements. Changing the model of heat supply should not only lead to a cleaner energy source but also reduce investment outlays and lower operating costs.

Currently available and commonly used technologies in some cases enable the required supply temperature to the customer's heating system to be reduced even below 40°C (e.g. floor or wall heating). It is also possible to lower the return temperature of the working medium. Increasing the heat exchange surface and the use of other activities favouring the reduction of customer requirements can significantly reduce supply costs of heat and improve the condition of the natural environment. Lowering the temperature of the return water in heating systems also significantly reduces the demand for the extraction of geothermal water, thus protecting geothermal resources. This helps to protect transnational reservoirs of thermal waters if such are exploited.

In the year 2020 the project titled: "Improving the energy efficiency of geothermal energy utilisation by adjusting the user characteristics" started (http://user4geoenergy.net/). The acronym of the project is **User4GeoEnergy**. The project provides a quantitative assessment of the problem described above. Research is aimed at determining whether changes in the heat recipients' installations can bring measurable economic,

energy and environmental benefits. The mathematical approach helps to justify efficiency of possible solutions.

Main activities within the project:

- Exchange of good practices in the management of geothermal district heating systems between the donor countries (Iceland, Norway) and the beneficiary countries (Poland, Slovakia, Hungary), that will increase economic as well as environmental and climate benefits for all.
- Mathematical modelling of geothermal systems (energy source – heat distribution – end users), in order to identify optimal solutions for the supply of geothermal heat in the beneficiary countries, considering geothermal conditions and heat prices on domestic markets.
- The focus will be on individual customers in their homes by providing knowledge, experience, and technical solutions to improve the efficiency of geothermal heating. This will be based on data utilisation and the roles of public and individual sustainable solutions. The project will also focus on encouraging customers to modify heating installations in their homes in order to increase their heating efficiency.

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User4GeoEnergy web page: http://user4geoenergy.net/, 2021.06.09

Iceland Liechtenstein Norway grants

Norway grants

DATABASE OF SELECTED MUNICIPAL HEATING SYSTEMS OPERATING IN POLAND, SLOVAKIA AND HUNGARY IN GEOTHERMAL PROSPECTIVE AREAS

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Keywords: district heating systems, heat networks, geothermal, database

Introduction

Geothermal energy is an underground renewable resource that is common in many countries around the world, however with considerable variations in terms of the depth of occurrence and quality of the source (temperature, flow rate, mineralization). Volcanically active regions that enable the exploitation of high-temperature geothermal resources occupy a relatively small part of the globe compared to medium and low-temperature resources. Still though, in many European countries, these medium and low-temperature resources can be successfully used in district heating systems, provided that the supply and return temperatures in heating networks are sufficiently low. Indeed, the lower the supply and return temperatures in the heating circuit, the more geothermal heat can be used as the baseload energy source. This in turn will reduce the share of fossil fuels burned in peak boilers.

The User4GeoEnergy project (full name: *Improving the energy efficiency of geothermal energy utilisation by adjusting the user characteristics;* http://user4geoenergy.net/) aims to demonstrate the benefits of adjusting the parameters of heat users to the capabilities of the geothermal heat source operating in the municipal heating system. The technological solutions promoted in the project will benefit heating system operators and heat consumers alike. These solutions are based on applying modern technological solutions, especially by lowering the supply and return temperature in heating systems.

Methods

One of the core activities of the project is the development of a mathematical model that will simulate generation, transmission and supply of heat to end-users after applying the solutions developed in the project. To do so, it is necessary to collect a wide range of data that will constitute the input for the model. To this end, one of the work packages is fully dedicated to building a database that will contain a comprehensive characteristic of district heating systems and heat consumers in the following cities:

- Poland: Mszczonów, Sochaczew, Poddębice (using geothermal energy already), Sieradz (not geothermal yet);
- Slovakia: Galanta, Veľký Meder, Sereď (using geothermal energy already), Kežmarok (planned to start using geothermal energy in 2022), Krupina (being investigated to use geothermal energy);
- Hungary: DH of Szeged consists of 23 circuits, of which 2 are already running on geothermal water and 13 are in transition from natural gas to geothermal.

The database consists of individual workbooks for each DH system and in the case of Szeged city – of each heating circuit. In turn, every workbook includes the following sections:

- Part 1 – a short overview of the analysed system, containing most general information about the location of the system, design climatic condition, geological background and geothermal conditions.
- Part 2 – information about geothermal production wells: depth, casing design, wellhead temperature and pressure at the maximum flow rate, mineralisation of water, pumping power required, etc.

- Part 3 – analogous to part 2, but referring to geothermal reinjection wells.
- Part 4 – characteristics of the heat source: energy carriers used, installed capacity vs energy carrier, annual heat production, the efficiency of use; emissions of pollutants from using/burning energy carriers; characteristics of heat distribution loops: design parameters, length, heat losses, pipe materials, insulation, pressure drop, circulation pumps power, age, control system, etc.
- Part 5 – characteristics of heat consumers for each distribution loop: number of users, total ordered heat power, annual heat consumption, average heat consumption per user, average floor space, type of heating system with design supply and return temperature, information on central cooling systems if exist, number of planned new users and their design parameters, etc. Similar pieces of information are gathered for hot tap water.
- Part 6 – general economic indicators: calorific values of burned heat carriers and unit emission factors; unit price of heat carriers; net unit costs of retrofitting actions; net costs of preinsulated pipelines and cost of laying and assembling.
- Annex I – typical meteorological year, consisting of 8760 records for each hour during a year.
- Annex II – well construction schemes.
- Annex III – principal scheme of the heat source.
- Annex IV – data from the DH system operator control system (SCADA).
- Annex V – distribution network situation plan.

Results

The work package *Set-up of the model database* of the User4GeoEnergy project, led by SLOVGEOTERM, is fully dedicated to building the database with the goal to provide comprehensive, reliable and easy to use input data for mathematical models. These models will be simulating the coupled process of heat generation, transmission and consumption at tested locations. There was no intention to make a comparative analysis among them, however, some observations and noteworthy correlations may arise later on. Hopefully, we will be able to present them during the congress. At the moment (June 2021), data is being collected.

Conclusions

In a large territories of Poland, Slovakia and Hungary, thermal waters can be the primary source of energy for municipal district heating systems. For this to happen, it is necessary to make certain changes in DH systems - especially on the side of energy consumers. Lowering temperature requirements by them can significantly increase the degree of use of geothermal resources, thereby, reduce the use of fossil fuels as peak sources.

The database, which is the major deliverable of this project, will probably be the most detailed collection of data on the district heating systems analyzed in the project in these countries ever created. The purpose of the database is to collect all the input data necessary to simulate the solutions developed in the project that can be introduced in municipal heating systems in order to increase the share of geothermal energy.

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WATER-ENERGY-FOOD NEXUS: GEOTHERMAL WATER FOR AGRICULTURE

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Keywords: agricultural irrigation, food security, geothermal brine, renewable energy, desalination

Abstract

The article aims to present the idea to implement a novel approach that integrates renewable energy resources into the agri-food chain, to supply safe and adequate irrigation water. Agricultural productivity is known to heavily depend on the availability of water, energy, and land resources. As the water of varying quantities per area and time is required for production, water quality is also important since the susceptibility of crops to ions and compounds in water also varies. Besides, in many cases, energy costs may represent a significant part of the total internal cost, including costs related to irrigation. Reducing the fossil fuel dependence of agriculture and the agri-food supply chain has a huge potential to contribute to the food security and climate protection of our planet.

Deep (high enthalpy) and/or shallow (low-enthalpy) geothermal resources are used at but not limited to district heating/cooling, spas, drying of crops and grains, and greenhouses. Following heat extraction, geothermal water is generally directed to reinjection wells, yet there are cases where it is given directly to the environment. The development and commercialization of geothermal energy sources may provide great potential to reduce costs in the agriculture sector. What is more, to address the water deficit problem in agricultural areas, the project idea aims to valorize the untapped resource of geothermal water that is abundant in both countries, Poland and Turkey. First, analysis of possibilities for utilizing geothermal water resources with low mineral content (up to 5-6 g/L) as a source of energy and water in agricultural areas is evaluated. Geological and hydrogeological data analyses will be assembled to locate geothermal resources by agricultural water deficit regions in both countries. However large quantities of saline water are produced, its direct use in irrigation hampers agricultural productivity due to high concentrations of ions. Considering the chemical characterization of geothermal resources in Turkey and Poland, ionic species of boron and arsenic pose major concerns. The project proposes to compare performances of four different water treatment technologies for geothermal brine samples taken from Balçova Geothermal Field (TR) and Padhole Geothermal Field (PL): capacitive deionization, CDI (PL), nanofiltration coupled reverse osmosis, NF/RO (TR), ultrafiltration coupled reverse osmosis, UF/RO (PL), and microbial desalination cell- Donnan dialysis, MDC/DD (TR). The operation of treatment modules using renewable energy sources will be also investigated (Figure 1). What is more, once geothermal water is desalinated to meet respective standards, it will be used for irrigation in the field (tomato, Turkey) and at the greenhouse (lettuce, Poland), which is heated using a geothermal source. Soil and plant analyses will be performed to determine yield-related parameters. To achieve a longer shelf life and a higher added value, harvested tomatoes will be dried at a cabinet-type geothermal dryer. The plant residuals will not be wasted, and on the contrary, they will be used for biogas production by anaerobic fermentation. Biogas formation will be evaluated for net energy output and its possible contribution to energizing the treatment modules. Fourth, an analysis of the economy, ecology, and energy impact of geothermal water use in

agricultural areas will be conducted. The project aims to create know-how for supplying clean water and energy in the food production process, based on the exchange of experiences of project partners. Through the production of a safe and adequate amount of water, the Geo4Food project aims to ensure sustainable development in the agriculture sector (Figure 1).

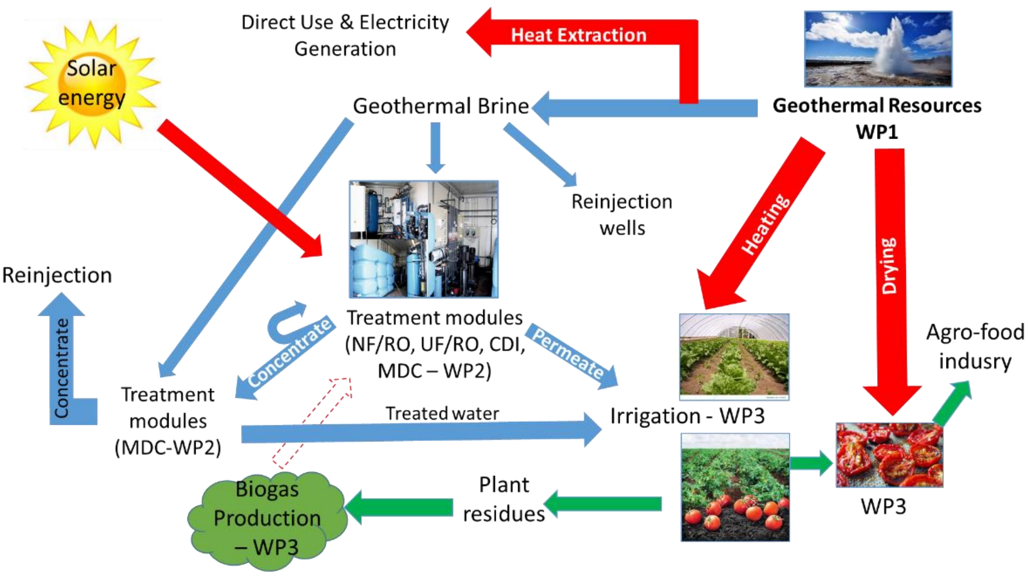

Figure 1. *Proposed scheme of the project with work packages. Arrows represent flows, and they are colour-coded: fluid flows (blue); energy flows (red); product flows (green).*

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HYDROPONIC AND IN SOIL LETTUCE CULTIVATION USING GEOTHERMAL WATER AND ENERGY

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Keywords: geothermal water, geothermal energy, greenhouse cultivation, lettuce, hydroponic

Abstract

Geo4Food aims to establish the management of low-enthalpy geothermal waters as a source of energy and water for agricultural production. Agriculture sectors in Poland do not use renewable energy sources (RES), including geothermal energy for productive purposes. However, increasing the share of RES contribute to improving the environmental impact of the agriculture sector, including the reduction of greenhouses gas emissions. It can therefore be argued that making agriculture and the agri-food supply chain independent from fossil fuel use has a huge potential to contribute to global food security and climate protection. Apart from energetic aspects, water scarcity is an imminent problem for most countries. Globally, the agri-food chain accounts for 80-90% of total global freshwater use, where 70% alone is for irrigation (Bundschuh et al., 2018). Since supplying adequate quantity and quality of water is essential for the sustainability of the agri-food chain, Geo4Food proposes to use untapped sources of geothermal spent water. In order to achieve safe, clean and sustainable irrigation water, Geo4Food has set a couple of objectives.

Agricultural lands in Poland constitute 46.9% of total land (The World Bank Data, 2018). Poland has over 1.4 million agricultural holdings and they produce 43.2 million tons of crops, accounting for 5.1% of total crop production in the EU (European Commission, 2018). Agriculture was responsible for 15% of PM10 and 12% of benzo(a)pyrene (BaP) emissions in the European Union (EU) in 2015. Furthermore, the agricultural sector contributes to the largest emissions of NH3 (94%), CH4 (53%) (EEA 2017). Poland has been struggling with the problem of exceeding the permissible levels of air pollution for several years. The Polish agricultural sector's electricity consumption for production purposes -without farmer households- was 1633 GWh and heat consumption was 900 TJ in 2016 (CSO 2017a). In agriculture and the agri-food chain, geothermal heat can either eliminate or significantly reduce the energy produced by fossil fuels.

One of the main topics of the Polish team in the project, PAS MEERI is laboratory research focused on geothermal energy use for greenhouse heating and creating model water for irrigation of lettuce plant based on hydroponic and in soil cultivation (Figure 1). Greenhouse heating and lettuce cultivation is realised as a part of the cascade geothermal system of the PAS MEERI Geothermal Laboratory in Bańska Niżna. The UF/RO water treatment facility which is fitted with typical industrial plant components is used on the basis of real geothermal water from the Podhale Geothermal System wells (in-situ tests). The desalination process includes 1) a water pre-treatment facility: mechanical filter, iron removal unit and ultrafiltration module; 2) a two-stage reverse osmosis process connected in series (equipped with spiral wound reverse osmosis membranes) with NaOH dosing before stage two (pH of the feedwater before RO-2 will be adjusted to about 10±0.5) – as an effective boron removal system.

Figure 1. *Hydroponic (left) and in soil (right) lettuce cultivation.*

The first experiment has been done in 2021, based on three water parameters: 100% treated geothermal water with nutrients, a mix of 30% of tap water and 70% treated water with nutrients, and mix of 10% of raw geothermal water with 90% of treated water and nutrients. During lettuce cultivation, water quality was controlled and also, air temperature and humidity. The experiment lasted approximately 6 weeks. Five types of lettuce were used, named: Red Lettuce, Butterhead Michalina, Iceberg Beata, Butterhead Bona, and Butterhead Justyna. All experiments were realized in hydroponic and soil cultivation. Specific tests results and interpretations of water, soil, and plants samples will be presented in near future. The results of the research are very interesting and promising. The final result of the experiments will be some conclusions regarding the possibility of using geothermal energy for heating and treated geothermal water for agricultural irrigation focusing on water influence on growth processes.

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THE CONDITION OF GEOTHERMAL BOREHOLES IN POLAND

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Keywords: geothermal well, geothermal energy, drilling parameters, geothermal water, geothermal drilling

Abstract

Renewable energy sources are increasingly used throughout the world, including geothermal energy obtained through geothermal boreholes. By geothermal borehole we mean a cylindrical mining excavation made with drilling methods, which enables the production or injection of geothermal waters. These openings must be designed and constructed as engineering structures. they must meet the requirements resulting from their location and purpose, to ensure durability, allow for maintenance and enable optimal operational conditions. Their main function is to transport geothermal water. One the most important element to be designed is the construction of the opening. A properly designed structure influences the correct operation procedures. In Poland, most geothermal boreholes occur singly (e.g. Lidzbark Warmiński GT-1, Konin GT-1, Mszczonów IG-1, exploration wells are among them) and in geothermal doublets (e.g. Pyrzyce), as well as in multi-hole systems (Uniejów PIG / AGH-2, Uniejów PIG AGH-1 and Uniejów IGH-1). Table 1 shows the division of selected geothermal wells in Poland.

Table 1. *Selected geothermal boreholes in Poland.*

Borehole system	Production	Injection
Single boreholes (including exploration boreholes)	Białka Tatrzańska GT-1, Bukowina Tatrzańska PIG/PNiG-1, Dębica GT-1, Duszniki Zdrój GT-1, Furmanowa PIG-1, Gostynin GT-1, Kazimierza Wielka GT-1, Koło GT-1, Konin GT-1, Lądek Zdrój LZT-1, Lidzbark Warmiński GT-1, Mszczonów IG-1, Poręba Wielka IG-1, Poddębice GT-2, Poronin PAN-1, , Sieradz GT-1, Skierniewice GT-1, Skierniewice GT-2, Sochaczew GT-1	None
Doublets	Kleszczów GT-1, Toruń GT-1	Kleszczów GT-2, Toruń GT-2
Triplets	Uniejów PIG/AGH-2, Stargard GT-2	Uniejów PIG/AGH-1,Uniejów IG-1, Stargard GT-1, Stargard GT-3
4-boreholes system	Pyrzyce GT-1*, Pyrzyce GT-3*	Pyrzyce GT-2*, Pyrzyce GT-4*
5-boreholes system	Bańska PGP-1,Bańska PGP-3,Bańska IG-1	Biały Dunajec PAN-1, Biały Dunajec PGP-2

* double doublet

In Poland, we can distinguish exploitation wells whose task is to collect geothermal water and absorbent boreholes whose task is to inject geothermal water into the aquifers from which this water was previously taken. Examples of mining wells are Bańska IG-1, Bańska PGP-1, Pyrzyce GT-1, while the absorbent wells are Biały Dunajec PAN-1, Pyrzyce GT-2, Uniejów PIG / AGH-1. Typically, the initially defined purpose of the geothermal well remains unchanged. However, there are exceptions. An example is the geothermal doublet in Stargard, consisting of wells named Stargard Szczeciński GT-1 and Stargard Szczeciński GT-2k. Initially, the role of the exploitation well was played by Stargard Szczeciński GT-1, and the absorbent Stargard Szczeciński GT-2k. Due to the decrease in absorptive capacity in 2007/2008, it was decided to change the roles of the boreholes in the geothermal doublet (Biernat et al. 2012). Unfortunately, there are also negative / unused boreholes or with insufficient water capacity for industrial development, which include e.g. boreholes Sękowa GT-1, Dębica GT-1, Celejów GT-1, Czarny Potok GT-1.

Effective exploration and access to geothermal waters is possible thanks to modern drilling techniques and technology. Currently, the rotary method is used for drilling geothermal boreholes with the right (normal) mud circuit (Sapińska-Śliwa et al. 2017).

Depending on the spatial orientation, geothermal boreholes are made as vertical boreholes (Bańska PGP-1) or directional boreholes (Bańska PGP-3, Stargard Szczeciński GT-2k) (Kępińska et al. 2011, Sapińska-Śliwa et al. 2013). Bańska PGP-3 is a "S" type directional well, while Stargard Szczeciński GT-2k is a type "J" directional well (Biernat et al. 2012, Sapińska-Śliwa et al. 2013).

The very important issue regarding the geothermal wells are the materials that are being used. The individual pipe columns are usually made of steel. This material is susceptible to the corrosive effects of aggressive geothermal waters. In Poland, steel pipes are used most frequently in geothermal wells. In many cases, high-strength unalloyed steels with the designations J-55 (including Pyrzyce GT-4) and N-80 (including Lidzbark Warmiński GT-1) (Gonet et al. 2016) were used. But recent years, the steel pipes used in construction of the boreholes are often lined with plastics and the use of composite pipes with glass fibers is more frequent. Examples of such wells are Pyrzyce GT-2 and Pyrzyce GT-4 where steel pipes with an internal coating were used (Biernat et al. 2010) and Toruń TG-1 where pipes made of glass fibers were used in the structure (Biernat et al. 2012). These projects are aimed at limiting the unfavorable phenomena occurring in the wells, e.g. corrosion. There are also many other methods of reducing corrosion processes and effects and the precipitation of secondary minerals in geothermal installations. Their task is to restore operational parameters in geothermal systems. These methods include: the use of inhibitors, treatments, the so-called soft acid treatment (in various variants) and treatments with solutions of inorganic and organic acids (Kępińska et al. 2011).

One of the most important parameters of geothermal wells is temperature and efficiency. In Poland, the temperatures of geothermal waters at the wellhead range from twenty to nearly 100 ° C. The highest water temperature at the wellhead was achieved in the Konin GT-1 well and, according to various sources, was 95 ° C (www.g-drilling.pl) up to 97.5 ° C (Szafrański 2019). The performance ranges of geothermal wells vary widely. In Poland, one of the smallest documented capacities is 0.9 m3 / h in the Jaworze IG-1 well (Chowaniec et al. 2001). The highest documented capacity of 550 m3 / h was achieved in the Bańska PGP-1 well (Kępińska et al. 2011), and it was under self-outflow conditions. An important issue is also the construction of the lower part of the borehole - the method of geothermal water intake. The most distinguished here are barefoot sections or perforated pipes. In Poland, geothermal water is exploited through boreholes, mainly from Lower Jurassic and Lower Cretaceous deposits.

There are two typical piping patterns for geothermal wells in Poland. First diagram consisting of casing with diameters respectively $18^{5}/_{8}$", $13^{3}/_{8}$", $9^{5}/_{8}$" and 7" or $6^{5}/_{8}$". The second piping scheme is one consisting of casing with diameters of 20", $13^{3}/_{8}$", $9^{5}/_{8}$" oraz $7^{5}/_{8}$" lub 7" lub $6^{5}/_{8}$" (Gonet et al. 2016). Examples include the pipelines of the Lidzbark Warmiński GT-1, Poddębice GT-2, Bańska PGP-1 or Poronin PAN-1 wells.

The Lidzbark Warmiński GT-1 borehole was covered to a depth of 260 m with cladding pipes $18^{5}/_{8}$" in diameter. Then, a column of pipes with an average diameter of $13^{3}/_{8}$" to a depth of 350 m was introduced. The next step was to put the $9^{5}/_{8}$" casing pipes at the depths from 250 m to 850 m and the 169 mm filter pipes to the final borehole depth of 1030 m (Sapińska- Śliwa et al. 2017).

The Poddębice GT-2 borehole was covered with lining pipes up to a depth of 80 m $18^{5}/_{8}$" in diameter. Then a column of $13^{3}/_{8}$"diameter pipes to a depth of 450 m was run. Both these columns of pipes were cemented to the top. The next stage was the installation of $9^{5}/_{8}$" casing pipes at depths from 295 m to 1964 m and 7" and $6^{5}/_{8}$" pipes to a depth of 2065 m (Sapińska-Śliwa et al. 2017).

The Bańska PGP-1 bore was closed to a depth of 20 m with 20 "casing pipes. A column of $13^{3}/_{8}$" diameter pipes was then run down to a depth of 508 m. Both of these pipe columns were cemented to the top. The next step was to run $9^{5}/_{8}$" casing pipes to a depth of 2678 m and $7^{5}/_{8}$" pipes to a depth of 3242 m. The last column of pipes was perforated on the surface with 240 boreholes with an area of 20 mm per 1 linear meter of pipe. Perforation took place in the interval of 2772-3032 m (Sapińska-Śliwa et al. 2017).

The Poronin PAN-1 borehole consists of 20 "pipes, 28 m deep, which are cemented to the top. The next section consists of $13^{3}/_{8}$" pipes laid to a depth of 399 m. This column is also cemented to the top. The $9^{5}/_{8}$" pipes were run to the depth of 2014 m. The interval of 1640 - 2014 m was filled with cement, while the space in the interval of 0 - 1460 m was filled with a thick mud. The exploitation column is made of 65/8 ”pipes laid down to a depth of 3003 m, cemented at intervals of 0 - 1752 m and 1905 - 2995 m. In the interval 1768 - 1855 m, no projectile perforation was made (Sapińska-Śliwa et al. 2017).

Often, there are also other designs in the openings due to the use of different sizes of the pipe columns. However, it should be remembered that the method of selecting the geothermal borehole piping scheme is closely related both to the process of designing the borehole in terms of strength parameters (casing pipe crushing pressure strength, calculation of the forces loosening threaded connections, permissible internal pressure) and the appropriate selection of pipe diameters, clearances and pipe materials with particular emphasis on the aspects of corrosion. Table 2 shows the deepest geothermal boreholes in Poland due to the drilling depth achieved (regardless of the drilling purpose), table 3 shows the best geothermal boreholes in Poland in terms of water temperature at the wellhead, table 4 shows the deepest geothermal boreholes in Poland due to the depth of the geothermal layer, table 5 shows the best geothermal boreholes in Poland in terms of water efficiency, in table 6 the best geothermal boreholes in Poland in terms of heating power (calculated as borehole production rate, temperature at the wellhead, density and specific heat of water, and the square of the average temperature of geothermal water), in table 7 the best geothermal boreholes in Poland in terms of mineralization (the lowest), in table 8 The worst geothermal boreholes in Poland in terms of mineralization (the highest).

Table 2. *The deepest geothermal boreholes in Poland due to the drilling depth achieved (regardless of the drilling purpose).*

Name	**Depth, m**
1. Bańska IG-1	5261
2. Koło GT-1	3905
3. Bukowina Tatrzańska PIG/PNiG-1	3780

Table 3. *The best geothermal boreholes in Poland in terms of water temperature at the wellhead*.

Name	**Temperature, °C**
1. Konin GT-1	95
2. Cieplice Zdrój C-1	87,5
3. Bańska PGP-1	87

Table 4. *The deepest geothermal boreholes in Poland due to the depth of the geothermal layer.*

Name	**Depth, m**
1. Bańska IG-1	3345
2. Bańska PGP-1	3342
3. Skierniewice GT-1	2941

Table 5. *The best geothermal boreholes in Poland in terms of water efficiency*.

Name	**Efficiency, m^3/h**
1. Bańska PGP-1	550
2. Bańska PGP-3	290
3. Biały Dunajec PAN-1	270

Table 6. *The best geothermal boreholes in Poland in terms of heating power*.

Name	**Heating power, MW**
1. Bańska PGP-1	53,78
2. Bańska PGP-3	28,36
3. Koło GT-1	25,72

***Table 7**. The best geothermal boreholes in Poland in terms of mineralization (the lowest).*

Name	Mineralization, g/dm^3
1. Zazadnia IG-1	0,19
2. Zakopane 2	0,33
3. Zakopane IG-1	0,36

***Table 8.** The worst geothermal boreholes in Poland in terms of mineralization (the highest).*

Nazwa otworu	Mineralization, g/dm^3
1. Jaworze IG-2	146
2. Gostynin GT-1	143,5
3. Ustroń IG-3	138,7

In the last five years (from 2015 to 2020) the following geothermal wells were made: Stargard GT-3, Pyrzyce GT-1Bis, Wręcza GT-1, Sieradz GT-1, Koło GT-1, Sochaczew GT-1, Jachranka GT-1, Sękowa GT-1, Dębica GT-1, Tomaszów Mazowiecki GT-1, Kazimierza Wielka GT-1, Koło GT-1, Lądek Zdrój LZT-1. Adaptation of liquidated, depleted oil and gas, exploration and negative wells is carried out, among others on the borehole in Sękowa GT-1. Other reconstructive procedures, incl. lining the steel pipes from the inside with HDPE material took place in Pyrzyce.

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DRILLING PARAMETERS SELECTION FOR COST REDUCTION IN LARGE BOREHOLE HEAT EXCHANGER SYSTEMS

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Keywords: optimization, borehole heat exchangers, heat pumps

Abstract

Nowadays more and more emphasis is placed on renewable energy sources. In consequence, the popularity of geothermal heat pumps is increasing. Heat pumps are devices utilizing external mechanical energy to induce a heat transfer between two systems, with the heat being transferred from the system with lower temperature to the system with higher temperature (which is contrary to the natural flow direction). The heat pump transfers heat from the lower heat body (the system from which low-temperature heat is being drained) to the upper heat body (the receiving end of the exchange).

A lower heat body can come in many forms, such as air, surface water, groundwater, infrastructure, waste or rock mass, with the latter being the most effective. Heat can be drained from rock mass with the use of borehole heat exchangers. One of the most important advantages of borehole heat exchangers is the fact that the rock mass can be used both as a source of heat and cool. In such systems, the heat is used during the heating season, and the cool is used most frequently during the warmer summer months. Unfortunately, the costs of constructing such a device remain rather high. Due to investment costs, rock mass remains out of favour when compared to the heat that can be gained from the air. However, when compared to their geothermal counterparts, air heat pumps are generally less efficient (Coefficient of Performance, COP). Lowering the investment costs would contribute greatly to increasing interest in rock mass as a source of low-temperature heat, which would considerably improve the general efficiency of ecological installations in Poland.

In 2018 AGH purchased the palace complex in Młoszowa, Chrzanów county, Trzebinia municipality. It is meant to become a venue for conferences, meetings, training and didactic work. Because of the need for a new heating system, it has been decided that it will be heated by more than 30 borehole heat exchangers. They will be located on field C of the Laboratory of Geoenergetics at the Faculty of Drilling, Oil and Gas, AGH University of Science and Technology. Such an opportunity allowed to select of the parameters in a way allowing studies on how they affect the overall efficiency of the borehole heat exchanger. For instance, one of the most important parameters is its depth, which has been selected individually for each exchanger. This resulted in the plans to construct the following: 7 boreholes at 100 m deep, 10 boreholes at 150 m deep, 13 boreholes at 200 m deep and 2 boreholes at 300 m deep, so a total number of 34 boreholes. Figure 1 depicts the exact planned location of each borehole in field C.

Another goal set for the project is to broaden the knowledge regarding the efficiency of several specific borehole heat exchanger configurations – among the 34 planned are constructions including U-pipe (single, double, triple), coaxial and 2+1. The project includes specifications for each borehole, but providing materials is the Contractors responsibility. An exception is a series of boreholes that are to be drilled using innovative pipes designed thanks to the BHEsINNO project. Their delivery will be carried out by a Swedish company MuoviTech, which has been working with the Laboratory of Geoenergetics on the Innovation in Underground Thermal Energy Storages with Borehole Heat Exchangers (BHEsINNO)'' project within, POLNOR 2019'' programme.

The main goal of described research, however, will be a survey of drilling parameters, with the main focus on drilling time, drilling pressure, rotational drilling speed and energy consumption. Acquired data will be used by students from Scientific Group, Geowiert'' to construct a computer program, which will calculate the optimal parameters based on data gathered from a few boreholes drilled to learn about geological conditions at the site of a future large installation. This will allow for the remainder of the boreholes to be drilled using parameters that will optimize pure drilling time, operations time, costs, energy consumption and drill wear.

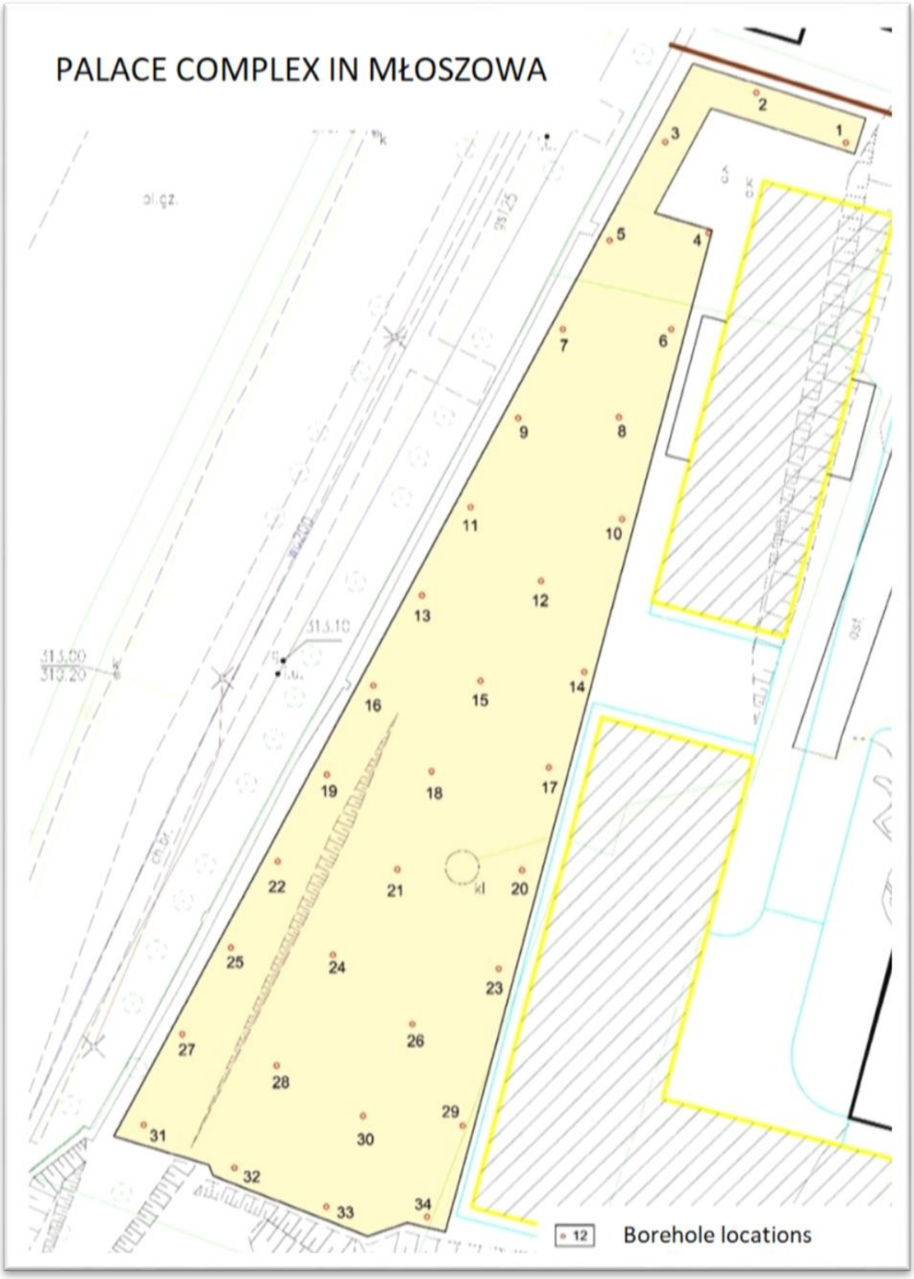

Figure 1*. Field C, where borehole heat exchangers will be constructed and studies carried out.*

In order to increase the application spectrum, the studies should be carried out in conditions that do not cause uncommon complications. Upon completing the work at a site with common conditions, the final program should work in similar conditions. It is because of this reason that it has been decided that the drilling works in Młoszowa should be a perfect opportunity because of the geological profile which can be viewed in figure 2.

The resulting statistical model will be tested (validated) in a place with different geological conditions. If everything is in order, then the program should provide us with data that will allow for the optimal parameters for drilling the following boreholes (after the first few boreholes that are drilled to gather information).
Every borehole will be drilled using the DTH method (DTH - down-the-hole), which is the most popular method when it comes to drilling boreholes for borehole heat exchangers. In this method, the hammer is located directly in the borehole (unlike top hammers which are located above ground). Such a solution requires

additional power besides rotating drilling string, which is usually provided in the form of a flushing medium. In our case, the medium will be compressed air provided from the compressor on the surface, also acting as standard drilling mud – it lifts the cuttings and cools the drill. Air is also directed in the standard drill nozzles. In order to prevent wall collapse, the diameter of both DTH assembly and drilling pipes should be very close to the intended diameter of the borehole. It stems from the fact that the resulting annular space has to be relatively narrow so that the air will be able to reach high velocity which is necessary for a successful cutting removal. Advantages of the DTH drilling method include, but are not limited to, a small number of tools needed, high drilling speed, and high efficiency of drilling.

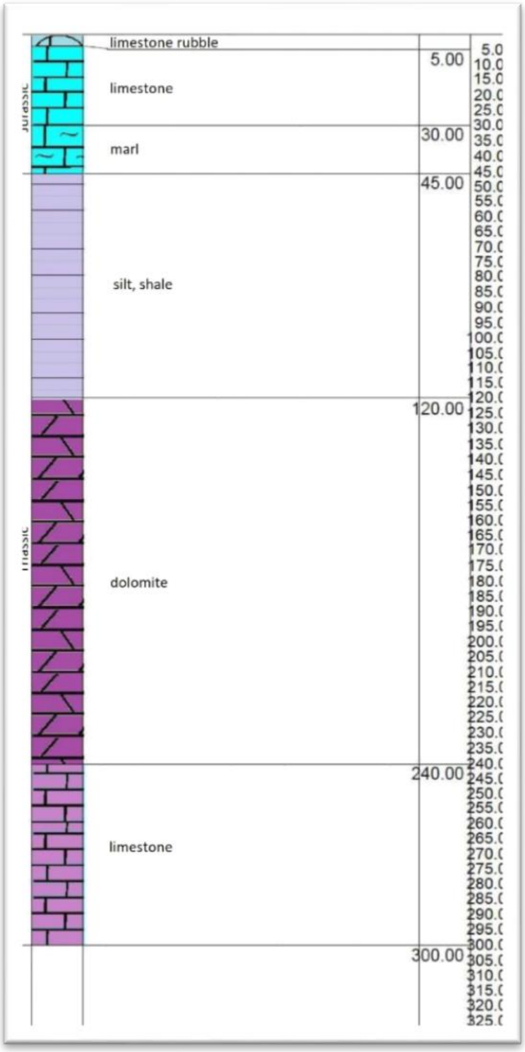

***Figure 2**. Projected geological profile at the location of the installation.*

Drilling will be conducted using two types of drills, with each type of drill being provided by two independent manufacturers.

Working with the drilling team will be a team comprised of AGH students members of Scientific Group, Geowiert''. Their job will be monitoring previously described parameters in real-time, while simultaneously ensuring that everything is proceeding as planned and taking note of any relevant divagations from the planned course of action. Moreover, it will also be their responsibility to measure the parameters that will be optimized in the future, such as pure drilling time or costs, for the purpose of comparing them with data given by the program. Meanwhile, another team will be organising the data and building the program, but most importantly testing the program and deciding whether it is working correctly. Assuming the program is working correctly and having validated this assumption, it shall be ready to be fully tested in a future project at a different location with different geological conditions.

Parameters such as drilling time, hammer runtime, pressure, auger wear and energy consumption will be recorded at a given interval. The value of the interval will correspond to the length of the pipes used during drilling, called drill rods. Data collection will be carried out up to a depth of 100 m below sea level. The optimization program will be created using components of the Statistica program and with the use of the so-called planning of DoE experiences (Design by Experiments). This method is based on the division of data into input data (independent variables) and output data (dependent variables) and the assumption that there is a correlation between these data. The biggest advantage of experiment planning is the reduction of the time and costs needed to run the experiment. Due to the willingness to test the optimization program while drilling in Młoszowa, the data needed for the program will not be collected from all, but only from the first 9 drillings. The last hole will be drilled with the drilling parameters suggested by the optimization program. On the other hand, the data from all 34 wells will be used to optimize the drilling of borehole heat exchangers using ANOVA, specifically multivariate analysis of variance. This one of the most popular statistical methods works well with Statistica and other similar programs. The most important feature of this method is the determination of the interactive effect - the influence of a given parameter on the dependent variable. In the discussed case, the relationship between drilling speed and energy consumption during drilling will be investigated, as well as the impact of these parameters on the drilling cost.

The planned expansion of AGH Laboratory of Geoenergetics will surely provide us with new and crucial information about the possibilities of reducing the time needed to construct such a system while lowering investment expenditures at the same time.

Funding

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THE INFLUENCE OF SELECTED ADDITIVES ON THE THERMAL CONDUCTIVITY OF HARDENED SEALING SLURRIES

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Keywords: sealing slurry, filling slurry, borehole heat exchangers, geothermal energy, thermal conductivity, geoenergetics

Introduction

Currently, one of the most popular methods of using the so-called renewable energy sources is geothermal energy distribution. The development of this field of science and energy is associated with many factors, one of the most important being environmental protection, primarily legal conditions related to pollution reduction and unconventional energy production. "Energy Policy of Poland until 2040", the so-called EPP2040, described in the Annex to the Resolution No. 22/2021 of the Council of Ministers of 2nd February 2021, assumes the optimal, longest possible use of own energy resources through i.a. the development of renewable energy sources, as well as energy efficiency improvement. It is planned that by 2040 all households' thermal needs will be covered by system heat and by zero- or low-emission individual sources, e.g. (geothermal) heat pumps in individual heating and the so-called "deep geothermal energy" in system heating (Polityka Energetyczna Polska). The effectiveness of both shallow and deep geothermal systems depends i.a. on their correct design, including the construction of boreholes.

The most effective method of heat extraction is geothermal water exploitation, however, such a solution is strongly conditioned by the presence of high-temperature aquifers. The most popular solution, available to everyone, which can be performed with any lithology, are borehole heat exchangers (Śliwa et al. 2016), as well as energy piles (Vasilescu 2019). The so-called shallow geothermal energy has been described for a long time (Kemler 1947, Ingersoll 1950). Recently, it became a very popular research topic by scientists from around the world (Lee et al. 2021, Richter et al. 2021, Taussii et al. 2021, Chen et al. 2021).

One of the most important issues related to the design of systems based on geothermal heat pumps coupled with borehole heat exchangers is the selection of an appropriate filling/sealing slurry because it affects the borehole heat exchanger efficiency. The selection should be based on several basic criteria: the highest possible thermal conductivity, the lack of negative environmental impact, appropriate rheological properties. Cost minimization is also a very important aspect (Gonet et al. 2011). In the case of energy piles, apart from the highest possible thermal conductivity of the slurry, its strength is of key importance.

Samples and methods

Currently, the research team of the AGH UST Laboratory of Geoenergetics carries out tests regarding thermal conductivity. The research covered industrial cement mixes, as well as the influence of a single additive on the thermal conductivity of various slurry formulas. To date, the Laboratory of Geoenergetics at the Faculty of Drilling, Oil and Gas, AGH University of Science and Technology, has tested multiple samples of industrial cement mixes and individual cement additives such as graphite, graphene nanopowder, graphene oxide, basalt, sand, etc.

Testing of hardened cement slurries was conducted after 14 and 28 days of curing in simulated borehole conditions. Among others, the FOX50 instrument by TA Instruments (ISO 8301) was used, along with the necessary additional equipment (Figure 1). Hardened cement slurries in the form of discs with a diameter of approximately 2 inches (Figure 2) were stored in water (Figure 3).

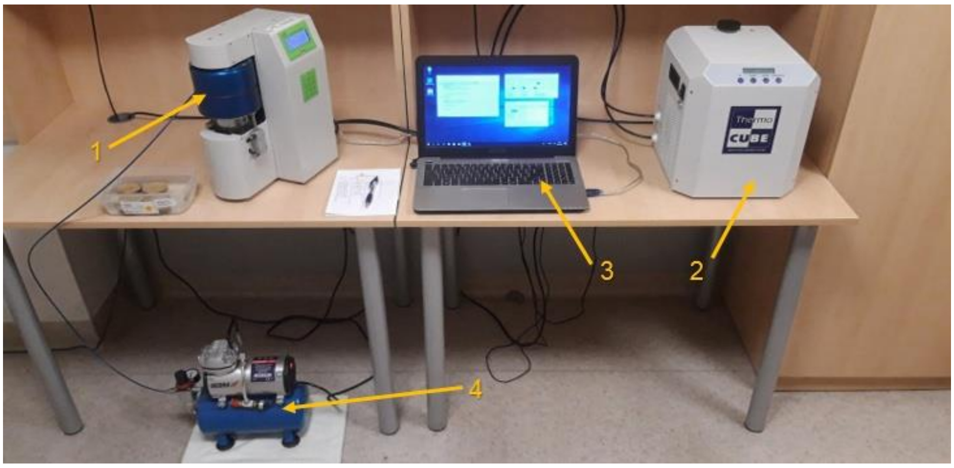

Figure 1. *FOX50 instrument by TA Instruments with the necessary equipment.*

Figure 2. *Hardened cement slurries in the form of discs.*

Results

The aim is to use a slurry with the highest possible thermal conductivity in typical borehole heat exchangers. In deep borehole heat exchangers, it is recommended to use a sealing slurry with increased thermal conductivity in the bottom part of the exchanger, and a slurry with reduced thermal conductivity in the upper part. In geothermal boreholes, the best solution is to use a slurry with reduced conductivity to reduce heat loss during the flow of thermal water from the aquifer to the surface.

To date, samples of cement slurries based on CEM I cement and industrial mixes have been tested. Graphite and graphene in various forms (E.g graphene oxide) have been used as additives increasing the thermal conductivity. Glass microspheres were used as additives reducing the thermal conductivity.

Table 1. *The influence of the additives on the thermal conductivity of the hardened cement slurry.*

Slurry parameters	CEM I	CEM I + graphite	CEM I + graphene oxide	CEM I + glass microspheres
Average thermal conductivity of the slurry [$\frac{W}{m \cdot K}$]	0.6336	0.6945	0.7397	0.56888
Percentage of the thermal conductivity of the slurry [%]	100%	9.5% increase	16.7 % increase	10.2 % decrease

***Figure 3**. Cement discs stored in water.*

Conclusions

As shown in Table 1, the addition of graphite and graphene oxide increases the thermal conductivity of hardened sealing slurries, while the addition of glass microspheres decreases their thermal conductivity.

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INCREASING THE THERMAL STABILITY OF GEOTHERMAL DRILLING MUDS THROUGH THE SELECTION OF CHEMICALS

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Keywords: drilling mud, thermal resistance, geothermal drilling

Introduction

Making geothermal water available requires drilling wells of considerable depth. Due to difficult conditions occurring there, such as high temperature or the inflow of highly mineralized brines, there are high demands in relation to the drilling muds used. Most of the polymeric agents currently used in the washing technology have limited resistance to high temperature, which affects the parameters and efficiency of the drilling muds subjected to such conditions. Polymers are exposed to permanent degradation, especially in the event of simultaneous exposure to high temperatures and contamination with calcium and magnesium ions. In such a situation, while drilling, it is necessary to continuously treat the used fluid by adding successive portions of polymeric agents.

To improve the thermal resistance of drilling muds, appropriate chemicals are introduced into their composition, which has the effect of protecting polymers against degradation. Both laboratory and practical tests carried out by Western drilling mud companies and research carried out at the Oil and Gas Institute show that polymers synthesized on the basis of 2-acrylamido-2-methylpropane sulfonic acid monomer have a positive effect on improving the stability of the drilling mud under unfavourable conditions of high temperature and high salinity. (AMPS). It has been proven that AMPS exhibits high resistance to electrolyte contamination, and it can stabilize the viscosity while reducing filtration.

Another group of agents that are increasingly used in drilling technology are nanoparticles, including carbon nanoparticles such as nanotubes and graphene oxide. The literature shows that the main advantages of drilling muds containing nanomaterials are: reduction of formation damage, a beneficial effect on ensuring smooth operation during drilling, efficiency in reducing drilling mud filtration, increasing thermal resistance, and efficiency in eliminating fluid losses.

Organic salts from the formate group, i.e., sodium formate, potassium formate and cesium formate, have also been used in the washing technology. Due to their very good solubility in water, they allow obtaining solutions of high density, unattainable for many inorganic salts. In addition, they show high compatibility with polymeric agents used in drilling muds by increasing their thermal stability.

Samples and methods

The first stage of the research involved determining the composition of the base drilling mud, which was to be characterized by optimal rheological and structural parameters as well as low filtration. A water-based polymer-potassium mud was used, which uses two mechanisms of inhibition of clay hydration: ionic inhibition and polymer-type inhibition. Next, tests were carried out on the influence of selected agents increasing thermal resistance, which was added to the drilling mud in various concentrations, on the basic parameters of the drilling mud. Next, the drilling mud samples modified by the addition of agents were exposed to a temperature of 130°C for 24 hours. After this time, the samples were cooled to 20°C, and their technological parameters were measured and compared with the results obtained before ageing at high temperature, and based on the obtained results, the effectiveness of individual agents was assessed.

In the course of the research, the following substances were used to increase the thermal stability of the drilling mud:

- poly (2-acrylamido-2-methylpropanesulphonic acid) – PoliAMPS – an organic polymer, easily soluble in water, formed as a result of the polymerization of the AMPS monomer. A 15% solution was used in the research,
- carbon nanotubes – one of the allotropic types of carbon. Its structure resembles a cylinder. There are single-walled and multi-walled nanotubes, nanocoils, nanotoruses and fullerites. Multi-walled

nanotubes with an outer diameter of 10–20 nm, an internal diameter of 5–10 nm and a length of 10–30 μm were used in laboratory tests,
- graphene oxide – an oxidized form of graphene, produced by the oxidation of graphite crystals with a mixture of sulphuric acid, sodium nitrate and potassium permanganate. A solution of graphene oxide flakes with a concentration of 6.2 g/l was used for laboratory tests,
- potassium formate – formate salt successfully used in drilling mud technology, mainly thanks to its high water solubility. Saturated brine with a density of 1.56 g/cm^3 was used in the tests.

Results

The composition of the prepared base drilling mud was based on the following set of structure-forming polymers: xanthan gum, polyanionic cellulose, carboxymethyl cellulose, gelatinized starch. In addition, it contained potassium chloride as an ionic hydration inhibitor and partially hydrolyzed polyacrylamide (PHPA) as a polymer inhibitor and a carbonate blocker. The filtration of the drilling mud prepared in this way had a value of 9.8 cm^3, a plastic viscosity of 38 mPa·s, and a yield point of 20.6 Pa. After heating at 130°C, the viscosity value increased to 12.2 cm^3, while the plastic viscosity and the yield point decreased to 27 mPa·s (decrease by 28.9%) and 11.0 Pa (decrease by 46.6%).

In the course of the research, the drilling mud composition was modified by adding chemicals in various concentrations. In the case of PoliAMPS, the concentrations ranged from 0.5 to 2.0%. The best result was achieved at a concentration equal to 2.0%, when the values of plastic viscosity and the yield point after heating decreased by 20.0% and 35.3%, respectively.

Carbon nanotubes were used in concentrations ranging from 0.25 to 1.0%. They were used both alone and in combination with PoliAMPS. The obtained results show that better efficiency is obtained after combining these two agents. In the case of the combination of 1.0% nanotubes and 1.0% PoliAMPS, the plastic viscosity and the yield point decreased by 17.0% and 37.4%, respectively.

Graphene oxide was introduced into the drilling mud in an amount of 0.1% to 0.5%. As in the case of nanotubes, in addition to independent use, its effectiveness in combination with PoliAMPS was also tested. The most favourable result was achieved with the concentration of graphene oxide equal to 0.5% and PoliAMPS equal to 1.0%. Plastic viscosity after heating was then lower than before heating by 17.0%, and the yield point by 37.1%.

The last tested agent was potassium formate. It was introduced to the drilling mud in the form of saturated brine with a density of 1.56 g/cm^3. Five compositions of drilling muds were prepared, in which brine constituted 25.0%, 37.5%, 50.0%, 62.5% and 75.0%, respectively. Additionally, the combination with PoliAMPS in the amount of 1.0% was also checked. The drilling muds containing 62.5% and 75.0% brine showed a significant increase in the rheological parameters, especially after heating. This indicates the phenomenon of coagulation occurring in them, therefore these drilling muds were not taken into account in further research. The drilling mud containing 50% brine and 1.0% PoliAMPS proved to be the most effective protection against the effects of high temperature. The values of plastic viscosity and the yield point decreased by 7.5% and 9.3%, respectively, which was a much better result than in the case of other tested agents.

The results of measurements of technological parameters of drilling muds before and after heating are presented in Table 1. Figures 1-2 show the changes in the value of the plastic viscosity and the yield point before and after heating at a temperature of 130°C.

Table 1. *Properties of the drilling mud modified with the test agents before and after heating at 130°C for 24 hours*

No.	Drilling mud composition	Density [kg/m^3]	Viscosity [mPa·s]		Yield Point [Pa]	Gel strength I / II [Pa]	Filtration API [cm^3]	pH
			η_{pl}	η_s	τ_y			
1.	2.	3.	4.	5.	6.	7.	8.	9.
1	Base drilling mud	1.06	38	59.5	20.6	2.7 / 3.4	9.8	9.6
		1.06	27	38.5	11.0	1.2 / 1.8	12.2	8.9
2	Base drilling mud	1.06	45	67.5	21.5	3.2 / 4.2	8.6	10.2
	+ PoliAMPS 2.0%	1.06	36	50.5	13.9	1.8 / 3.0	10.6	9.2

3	Base drilling mud	1.06	44	67	22.0	2.8 / 3.5	8.0	9.3
	+ Nanotubes 1.0%	1.06	33	46.5	12.9	1.8 / 2.4	10.6	8.9
4	Base drilling mud	1.06	47	71	23.0	3.3 / 3.8	5.8	9.6
	+ Nanotubes 1.0% + PoliAMPS 1.0%	1.06	39	54	14.4	1.9 / 2.8	6.0	9.0
5	Base drilling mud	1.06	46	69.5	22.5	3.4 / 4.1	6.8	9.1
	+ Graphene oxide 0.5%	1.06	35	48.5	12.9	2.0 / 3.0	10.8	8.5
6	Base drilling mud	1.06	47	74	25.9	3.8 / 4.7	6.2	9.4
	+ Graphene oxide 0.5% + PoliAMPS 1.0%	1.06	39	56	16.3	2.3 / 3.4	9.8	8.9
7	Base drilling mud	1.32	66	101	33.5	4.2 / 5.0	6.2	10.2
	+ HCOOK brine 50.0%	1.32	61	91.5	29.2	3.3 / 4.2	8.4	9.9
8	Base drilling mud	1.32	67	104	35.4	4.4 / 6.0	5.8	10.3
	+ HCOOK brine 50.0% + PoliAMPS 1.0%	1.32	62	95.5	32.1	3.5 / 4.4	6.6	10.0

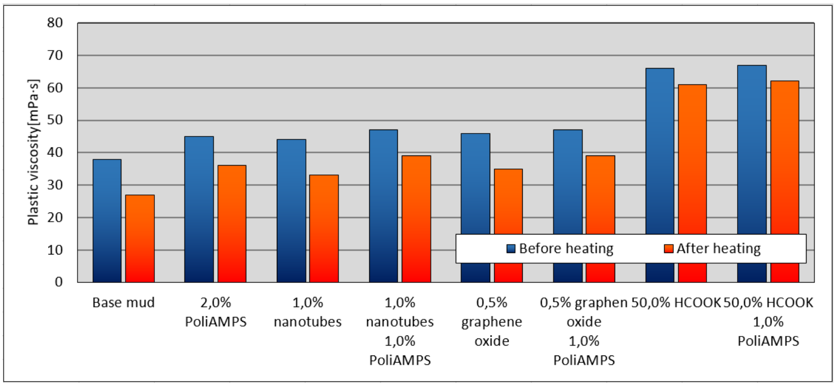

Figure 1. *Comparison of the value of the plastic viscosity of the drilling mud modified with the tested agents before and after heating at 130°C for a period of 24 hours*

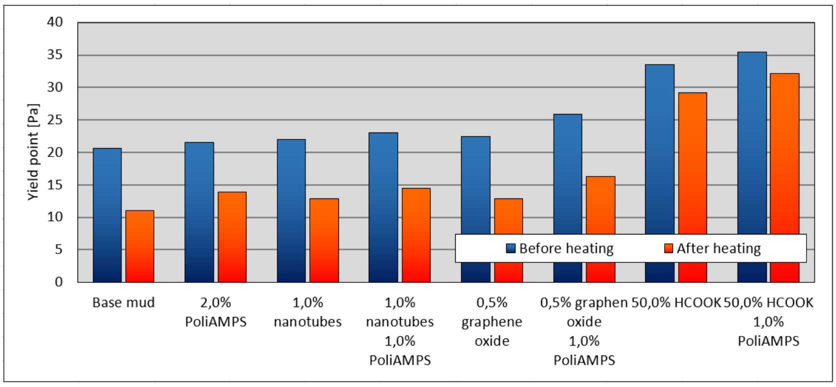

Figure 2. *Comparison of the yield point of the drilling mud modified with the tested agents before and after heating at 130°C for 24 hours*

Conclusions

The analysis of the research results allowed to present the following conclusions:

1. Among the tested agents, which were to protect the drilling mud against the unfavourable influence of high temperature, the most favourable effect was demonstrated by potassium formate in combination with PolyAMPS. However, when the content of the saturated solution prepared using potassium formate was too high in the drilling mud, the rheological parameters increased significantly after the effect of high temperature on the drilling mud. This may indicate the unfavourable phenomenon of coagulation in such drilling muds.

Discarding the drilling muds with 62.5% and 75.0% brine content, the best results were obtained by the drilling mud containing 50.0% saturated potassium formate solution and 1.0% PolyAMPS. After 24 hours of exposure to the temperature of 130°C, this drilling mud was characterized by plastic viscosity and limit values of 62 mPa·s and 32.1 Pa, respectively. These values were lower than before heating by only 7.5% and 9.3%.

2. The influence of the other agents applied during the tests on the improvement of thermal resistance of drilling muds is significantly lower than that of potassium formate. Among the drilling muds modified by the addition of PoliAMPS, the smallest difference between the values of the plastic viscosity of the drilling mud heated at 130°C and the unheated drilling mud was 20.0%, and in the case of the yield point, it was 35.3%. For the most resistant drilling mud treated with carbon nanotubes and PoliAMPS, these results were 17.0% and 37.4%, while in the most thermally stable drilling mud with the addition of graphene oxide and PolyAMPS it was 17.0% and 37.1%.

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Norma PN-EN ISO 10416 "Przemysł naftowy i gazowniczy. Płyny wiertnicze. Badania laboratoryjne".

RESEARCH ON THE THERMAL CONDUCTIVITY OF CEMENT SHEATHS FROM SLURRIES FOR CEMENTING GEOTHERMAL BOREHOLES

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Keywords: Cement slurry, geothermal energy, thermal transmittance, well cementing, geothermal borehole

Introduction

In order to effectively perform the cementing procedure, a key aspect is the correct selection of the technological parameters of the slurry and obtaining the required properties in the internal structure of the formed cement sheath. Such conditions should be ensured each time when designing the slurry composition (Kremieniewski, 2020). However, sometimes there are additional requirements. This is the case when designing slurry compositions for cementing geothermal boreholes (Budownictwo i Inżynieria Środowiska). In such a case, the decisive parameter for the application of the cement slurry is the thermal conductivity coefficient of the cement sheath formed from the cement slurry (Gawin i in., 2000). When sealing a column of pipes in a geothermal borehole, it is essential to maintain thermal insulation at the top of the borehole. This allows minimizing heat energy losses during its transmission to receivers. In this case, a cement slurry should be designed from which samples of the hardened slurry will be characterized by low thermal transmittance (Jiřičková & Černý, 2002). At this point, heat losses should be limited to a minimum. The lower parts of the column of pipes should be sealed with a cement slurry from which the samples will show the highest possible permeability. Thanks to this, it will be possible to efficiently exchange heat energy, and then to recover it on the surface (Roels et al., 2002; Werszko, 2003). Cement slurries contain a number of additives and admixtures – materials that are necessary to regulate technological parameters (Kremieniewski et al., 2021). These are measures reducing the aeration of the slurry, improving the rheological parameters, reducing water filtration into the formation zones, and materials regulating the slurry density. The latter is light fillers (density reduction) or loading materials (density increase).

In order to obtain the appropriate values of the thermal conductivity coefficient, it is important to use materials that, after the binding of the slurry, allow to obtain the required value of the thermal conductivity of the cement sheath (W/m·K) in the borehole.

Materials and methods

Measurement of the thermal conductivity of the cement sheath is carried out using the ISOMET 2114 thermal conductivity measurement system (Figure 1). It is a device used to measure heat flow parameters, with a wide measuring range, and it is designed for cellular materials, insulating materials, plastics, glass and minerals. The measuring range of the device depends on the probe used and covers values from 0.015 W/m·K to 6.0 W/m·K in 7 sub-ranges for various probes [8]. The thermal conductivity of the cement sheath is measured using a surface probe (Figure 2). The method of measurement consists in applying a surface probe to the material to be tested and reading the coefficient of thermal conductivity. On the basis of the obtained results, it is possible to design the slurry composition by using various types of admixtures that change the insulation parameters of the cement sheath.

Figure 1. *The ISOMET 2114 thermal conductivity measurement system*

Figure 2. *Measurement of thermal conductivity of a cement sheath sample*

Research results

Thermal conductivity tests were carried out for the base slurry, which consists of cement and water, with a water-cement coefficient of 0.46. This is a benchmark for further testing. The second slurry is a composition containing 15% of insulating material. This additive was mainly used as an insulating material, but at the same time, it allows to lower the density of the liquid slurry. The slurry compositions are presented in Table 1. Table 2 presents the parameters of the tested slurries.

Table 1. *Composition of selected slurries for measuring thermal conductivity*

COMPOSITION	SLURRY 1 base	SLURRY 2
Tap water	w/c = 0.46	w/c = 0.65
Defoamer		0.5 %
SW liquefier		0.3 %
SW antifiltration agent		0.3 %
Latex		5.0 %
Latex stabilizer		0.5 %
Insulation material		15%
G cement	100%	100%

Table 2. *Parameters of the examined compositions of the slurries*

Parameter	SLURRY 1 base	SLURRY 2
Density [kg/m^3]	**1900**	**1680**
Pourability [mm]	260	210
Filtration [cm^3/30min]	170	300.0
Plastic viscosity [mPa·s]	177	67.5
Flow limit [Pa]	23.0	8.4

Structural resistance [Pa]	3.84	7.68
Water separation [%]	0.2	0.8
Beginning of binding [hour:min] End of binding [hour:min]	05:15 06:00	08:15 09:20
Thermal conductivity coefficient [W/m·K]	1.9498	0.5763

When analysing the obtained test results, it was found that the presence of a 15% concentration of the insulating material causes a significant reduction of the thermal conductivity coefficient. For the base slurry consisting only of water and cement, the obtained thermal conductivity coefficient was 1.95 W/m·K (Figure 3) while the slurry with an insulator had thermal conductivity equal to 0.58 W/m·K (Figure 4). However, it is important to remember that the reduction of the thermal conductivity coefficient may depend on other variables, such as the amount of water in the slurry, the degree of sample drying, as well as the presence of other additives and admixtures regulating the parameters of the slurry. The presented results come from the preliminary tests, as research on this issue is currently underway.

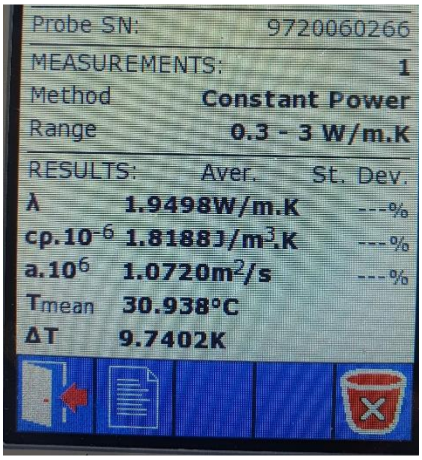

***Figure 3.** Readout of the conductivity coefficient value for slurry sample No. 1*

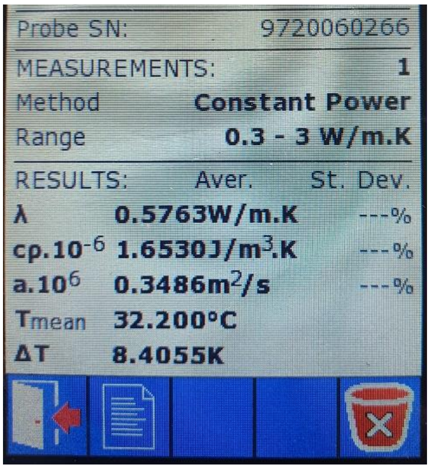

***Figure 4.** Readout of the conductivity coefficient value for slurry sample No. 2*

Conclusions

- The base slurry, consisting only of water and cement, has a thermal conductivity coefficient of 1.95 W/m·K.
- The introduction of 15% of the insulator into the slurry (in relation to the weight of BWOC cement) reduces the thermal conductivity coefficient to 0.58 W/m·K
- The use of cement slurry containing an insulator additive may be appropriate for sealing the upper intervals of geothermal boreholes, where it is required to obtain the lowest possible heat energy loss.
- The coefficient of thermal conductivity may be influenced by additional factors, such as: sample moisture, water-cement ratio, and the presence of additives and admixtures regulating the parameters of the slurry.
- Measurement of the thermal conductivity coefficient for cement sheath samples is one of the most important parameters when designing sealing slurry compositions for cementing geothermal holes.

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User's guide ISOMET model 2114

CEMENT SLURRIES OF VARIOUS SALINITY LEVELS FOR SEALING GEOTHERMAL HOLES IN THE CARPATHIAN REGION

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Keywords: geothermal borehole, cement stone, technological parameters

Introduction

Drilling boreholes of great depth (exceeding 3000m) must take into account the specific conditions at their bottom, i.e., temperatures often exceeding 90°C and pressure above 60MPa. The development of appropriate compositions of cement slurries used for sealing casing for such difficult borehole conditions has often caused many problems.

During the sealing of casing, deep and increasingly complex boreholes require the use of specially developed sealing slurry compositions. With a significant depth of the borehole (where there is very high temperature and pressure), it is a problem to ensure a long pumping time of the cement slurry, which should be characterised by low viscosity, little or no water separation, and the lowest possible filtration. Therefore, it is necessary to select appropriate retardants that are resistant to high temperatures and additives ensuring the appropriate technological parameters of the slurry and cement stone.

Formation waters (brines of different degrees of mineralization) have a significant effect on hardened cement slurry, therefore, cement slurries should contain additives which: increase thermal resistance, delay setting, lower filtration and improve resistance to chemical corrosion caused by reservoir brines.

The laboratory tests presented in the article were performed at the Oil and Gas Institute – National Research Institute. As a result of a series of tests, innovative compositions were developed of cement slurries for sealing oil and geothermal boreholes with increased temperatures (up to about 110°C) in the Carpathian region. Laboratory tests were carried out for both cement slurries and the cement stones obtained from them, and a wider scope of laboratory tests covered cement slurries for sealing geothermal holes with regulated rheological parameters, which can be used in high formation temperatures to seal deep boreholes.

Cement slurries were made with tap water with the addition of potassium chloride in an amount up to 10% *bwow* (in relation to the amount of water). Defoamers were added to the batched water, regulating the setting and thickening time, liquefying and reducing filtration. Cement slurries were made with the addition of latex in the amount of 10% and latex stabilizer in the amount of 1% *bwoc* (both components based on the weight of dry cement). The remaining components: cement, microcement (nanocement), microsilica, hematite and cement were mixed and then added to the batched water. After all the ingredients were combined, the cement slurry was measured by means of laboratory measurements such as density, pourability, readings from the Fann apparatus, water retention, filtration, and thickening time. From selected compositions of cement slurries, samples of cement stones were prepared, and the following factors were tested: the compressive and bending strength of the cement stone, the adhesion of the cement stone to steel pipes, and the porosity of the cement stone.

Materials and methods

The research was conducted for two different borehole conditions, i.e.: 90°C and 60 MPa, 110°C and 75 MPa. Cement slurries were made with tap water with the addition of potassium chloride and other agents regulating technological parameters as well as binding and thickening times. All cement slurries were prepared on the basis of drilling cement G. After all components had been combined, the cement slurry was mixed for 30 minutes and then laboratory measurements were performed. The selected compositions with the best parameters were used for further research on mechanical parameters. The cement slurries bonded for 48 hours in an environment of high temperature and pressure (borehole-like conditions). Then they were placed in autoclaves made of stainless steel and kept in an incubator throughout the seasoning period. The obtained cement stones were subjected to laboratory tests after the assumed periods.

Research results

Detailed results of research on the technological parameters of cement slurries and stones from selected compositions for two borehole-like conditions are presented below: 90°C and 60 MPa as well as 110°C and 75 MPa.

Table 1. *Technological parameters of selected cement slurries in 90°C and 60 MPa.*

	Slurries proposed for sealing boreholes					
Framework composition of the slurry [%]	Dens. [kg/m³]	Pour. [mm]	Filter. **[cm³/30min]**	$Th_{t\ 30}$ [h-min]	$Th_{t\ 100}$ [h-min]	Cs_{28} [MPa]
Water w/c = 0.45 Defoamer 0.3% bwoc Liquefier 0.7% bwoc Antifilter additive. 0.4% bwoc Retarder 0.07% bwoc **KCl 6% bwow** Latex stabilizer 1% bwoc Latex 10% bwoc Hematite 10% bwoc Microsilica 20% bwoc Drilling cement G 100% **Temp. 90°C / Press. 60 MPa (No. 1)**	1910	240	15	5-35	6-44	42.3
Water w/c = 0.5 Defoamer 0.3% bwoc Liquefier 0.6% bwoc Antifilter additive. 0.4% bwoc Retarder 0.06% bwoc **KCl 10% bwow** Latex stabilizer 1% bwoc Latex 10% bwoc Hematite 20% bwoc Microsilica 10% bwoc Drilling cement G 100% **Temp. 90°C / Press. 60 MPa (No. 2)**	1910	260	19	4-05	6-03	29.7

Key:
Dens.- cement slurry density
Pour. - pourability
Filter. - filtration
$Th_{t\ 30}$ – thickening time (30 Bc)
$Th_{t\ 100}$ – thickening time (100 Bc)
Cs_{28} – cement stone compressive strength after 28 days.

Table 2. *Mechanical parameters of cement stones in 90°C and 60 MPa.*

No.	**Temperature 90°C**			
	Compressive strength [MPa]			
	After 2 days	**After 7 days**	**After 14 days**	**After 28 days**
1	31.1	36.2	38.8	42.3
12	21.0	24.5	29.9	29.7
	Flexural strength [MPa]			
1	10.5	11.0	11.0	11.5
2	10.5	11.0	10.5	10.0
	Adhesion to steel pipes [MPa]			
1	3.6	4.2	4.5	4.8
2	3.3	2.9	2.9	3.2

For a dynamic temperature of **90 ° C** and pressure of **60 MPa,** the compositions were prepared with the addition of **6 and 10% KCl**. These slurries had a density of 1910 kg/m³ and did not have water separation. The selected

compositions had low filtration not exceeding 20 cm^3/30 min. The pourability ranged from 240 to 260 mm. For the selected samples, appropriate thickening times were obtained for the given borehole conditions, where the beginnings of thickening (30Bc) above 4h and more were achieved, and the end of thickening (consistency of 100Bc) for these compositions was obtained below 7h.
Compressive strength tests performed at **90°C** showed an increase after each test period and after 28 days they were from 29.7 to 42.3 [MPa], sample No.1 was stronger with 6% KCl, 10% hematite and 20% microsilica. The second measured mechanical parameter of cement stones was their adhesion to steel pipes. The tests performed showed that after 28 days, the adhesion to steel pipes at a temperature of **90°C** was from 3.2 to 4.8 [MPa]. The results of the third and last test are presented in Table 2. They were obtained from measurements of the bending strength of cement stones. For all the tested samples, after 28 days of seasoning, similar values were obtained, exceeding 10.0 [MPa].

Table 3. *Technological parameters of selected cement slurries in 110°C and 75 MPa.*

	Slurries proposed for sealing boreholes					
Framework composition of the slurry [%]	Dens. [kg/m^3]	Pour. [mm]	Filter. **[cm^3/30min]**	$Th_{t\ 30}$ [h-min]	$Th_{t\ 100}$ [h-min]	Cs_{28} [MPa]
Water w/c = 0.55 Defoamer 0.3% bwoc Liquefier 1.0% bwoc Antifilter additive. 0.5% bwoc Retarder 0.24% bwoc **KCl 6% bwow** Latex stabilizer 1% bwoc Latex 10% bwoc Hematite 60% bwoc Microsilica 10% bwoc Drilling cement G 100% **Temp. 110°C / Press. 75 MPa (No. 3)**	2090	235	24	3-35	5-23	20.2
Water w/c = 0.55 Defoamer 0.3% bwoc Liquefier 1.0% bwoc Antifilter additive. 0.4% bwoc Retarder 0.24% bwoc **KCl 10% bwow** Latex stabilizer 1% bwoc Latex 10% bwoc Hematite 50% bwoc Microsilica 10% bwoc Drilling cement G 100% **Temp. 110°C / Press. 75 MPa (No. 4)**	2030	240	32	6-02	6-24	27.8

Table 4. *Mechanical parameters of cement stones in 110°C and 75 MPa.*

No.	**Temperature 110°C**			
	Compressive strength [MPa]			
	After 2 days	**After 7 days**	**After 14 days**	**After 28 days**
3	18.7	19.4	19.9	20.2
4	26.5	25.5	27.1	27.8
	Flexural strength [MPa]			
3	9.5	9.8	11.3	11.5
4	9.0	9.5	9.8	10.0
	Adhesion to steel pipes [MPa]			
3	3.3	3.6	3.8	4.6
4	2.7	2.9	3.3	3.5

Also, for these borehole conditions (110°C and 75 MPa), compositions were prepared with the addition of **6 and 10% KCl**. These slurries had densities from 2030 to 2090 kg/m^3 and did not have water separation. All compositions had low filtration ranging from 24 to 32 cm^3/30 min. The pourability ranged from 235 to 240 mm, which demonstrates the good fluidity of the cement slurries. The developed compositions had appropriate thickening times and consistency of 30Bc obtained over 3h 30min. and 100Bc (end of thickening – no pumping) less than 6h 30min.

The samples of cement stones seasoned at **110°C** were characterized by slightly lower compressive strengths than those developed for temperatures of 90°C and after 28 days they amounted to 20.2 to 27.8 [MPa]. After 28 days, among the samples seasoned at 110°C, the one with the content of 10% KCl, 50% hematite and 10% microsilica turned out to be stronger (sample No. 4).

The tests of cement stone adhesion to steel pipes showed that after 28 days they were comparable to those measured for the temperature of 90°C, and the stronger sample was the one with the content of 6% KCl, 60% hematite and 10% microsilica: 4.6 [MPa] (sample No. 3). The results of the last test are presented in Table 4. They were obtained from measurements of the bending strength of cement stones. For the tested samples, after 28 days of seasoning, similar values were obtained, ranging from 10.0 to 11.5 [MPa].

Conclusions

The article presents innovative formulas of cement slurries for sealing geothermal holes with higher temperatures (above 90°C) in the Carpathian region.

On the basis of laboratory tests, framework compositions of cement slurries were selected, proposed for use in industrial conditions. Tables 1 and 3 present the compositions of slurries with densities from 1910 to 2090 kg/m^3, which can be used to seal operational casing in deep boreholes in the Carpathian region. After selecting the appropriate chemicals, the cement slurries were characterized by good rheological parameters, did not demonstrate water separation and had very low filtration. Cement stones formed after binding the developed slurries were characterized by high mechanical parameters after just 2 days of seasoning. The above compositions are recommended for boreholes where the temperature at the bottom ranges from approx. 90 to approx. 110°C and the pressure from approx. 60 to approx. 75 MPa.

GEOTHERMAL RESOURCES AND LOCAL DEVELOPMENT IN POLAND

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Keywords: geothermal resources, direct use, local development, multi-criteria methods (MCDM), regression models, Poland

Introduction

Among renewable energies, geothermal energy is specific to local production and consumption. In addition to generating heat and energy, geothermal energy creates development opportunities for rural and suburban areas, combining the goals of sustainable development with the expansion of new sectors of the local economy. Therefore, we assume that the local exploitation of geothermal resources produces local added value, additional to energy generation. Moreover, it is assumed that the socio-economic structure of the commune will change when geothermal objects start operating. The aim of this research is to fill the literature gap and establish an empirical link between geothermal resource use and local development. The assumed added value of geothermal energy can be analysed as direct, indirect and induced impact on the economy of the commune. This study attempts to develop a methodology that measures the induced impact associated with socio-economic development. The theoretical conceptualization underlying this research is reflected in endogenous growth theories as well as in regional economics approaches.

This paper presents methods of measuring and determining the type of induced impact of geothermal resources on the local economy. The variety of direct use of geothermal energy, determined by the Lindal model, points to the local use of geothermal resources. Hence, the analysis of the topic begins with the determination of the direct application of geothermal energy locally, ie in the municipality. The dissertation covers examples of Polish communes that use geothermal resources. In order to answer the main research question of the thesis, i.e. what is the impact of the use of geothermal resources on the development of municipalities in which resources exist, models containing local data and geothermal activities in municipalities have been developed.

This approach is based on an analysis of the added value in Polish geothermal municipalities where this energy is used in many forms. The developed model is to present the statistical relationship between the resources exploited and the parameters of local development. The versatility of this study lies in the fact that this model, built for Polish municipalities, is applicable to the analysis of every other geothermal municipality in the world.

Samples and methods

As part of the selected statistical methods, we obtained significant results for eleven municipalities in Poland, where geothermal resources are used, which justify our research assumptions. Research results show the competitive advantage of using geothermal resources in local economies. In addition, we have observed a faster development of geothermal municipalities compared to other municipalities (without access to resources). An innovative application of methods used in regional sciences, which were adapted to this study, was presented. They were used to identify changes in the local economic structure related to the use of geothermal resources. In addition, we have built a local development model with geothermal parameters that can be used in further research on the impact of geothermal energy on local development. As part of the selection of methods, multi-criteria models were used to build a matrix of socio-economic indicators, which were tested with the assumption of a relationship with the parameters of production and use of geothermal resources.

Results

The research aims to provide quantitative arguments for the expansion of the extraction of geothermal resources in Poland and in the world. The work determines the socio-economic value of the local use of geothermal energy, which has not been discussed in the literature so far. Economic links were established between local development and the use of geothermal resources. Geothermal municipalities turned out to have higher competitiveness rates than municipalities that do not use resources. Moreover, the employment structure in geothermal municipalities clearly changes with the use of geothermal energy. Communes incl. of an agricultural nature, they change the economic structure towards services and trade. Undoubtedly, the creation of spa and recreation centers based on the use of geothermal water is a separate development factor in the municipality. Often, these facilities are accompanied by the expansion of heating infrastructure based on hot geothermal water. Thus, the role of geothermal energy in creating added value in local economies can be stated.

Conclusions

All the above-mentioned observations were confirmed by the results of the applied statistical methods. The results of the research constitute a new research phenomenon in the subject of geothermal development in Poland, which initiates further discussion on the role of geothermal resources in local economies.

Acknowledgements

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PROFESSOR ANDRZEJ MICHALIK – DISCOVERER OF HIGHLY MINERALIZED THERMAL (GEOTHERMAL) BRINES IN USTROŃ

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Keywords: Carpathian flysch, water-bearing structures, mineralization, thermal brines, landslides, hydropower structures

Professor Andrzej Michalik (1917-1988)
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Andrzej Michalik was born on 6 August 1917 in Kraków. After graduating from primary school and the H. Sienkiewicz junior high school, he passed his high school leaving exams in 1934. In the same year, he started his studies at the Jagiellonian University in geography but moved to geology in the academic years 1936/1937. Still being a student, in 1938, he was sent by Prof. St. Schitzke from the AGH University of Science and Technology in Krakow to do some field works in Romania. The works, successfully completed, were aimed to search for lime raw materials for the emerging cement industry. The works then done provided an impulse for the Professor's future scientific research. Unfortunately, he was prevented from continuing his studies by the outbreak of World War II. Andrzej Michalik resumed his studies in 1945, simultaneously working as an assistant professor at the Department of Geology, Jagiellonian University.

In 1946 he obtained his M.Sc. degree in geology, in 1951 his PhD degree, in 1954 the title of assistant professor and in January 1973 he was appointed professor of natural sciences. His fascination with geology was undoubtedly influenced by such luminaries of natural sciences of the Jagiellonian University as Marian Książkiewicz, Jan Nowak, Antoni Gaweł, Stanisław Sokołowski and Franciszek Bieda, among others.

Professor Warmus started work in 1945 in the Department of Dynamic Geology of the Jagiellonian University, where he worked as an assistant until 1949. At the end of 1949, he continued his geological activities in the Museum of the Earth in Warsaw and after the incorporation of this institution into the Geological Institute in 1953 he became its employee until 1972. In that period, working in the Carpathian Branch of the Geological Institute (the initial name - Carpathian Field Station IG) with its seat in Cracow, he headed the Laboratory of Hydrogeology and Engineering Geology for 19 years.

In the first stage of his scientific activity, he researched mineralogical composition, petrography, and tectonics of the Tatra massif and comparative studies in Slovak Tatras. He presented the results of his research in scientific treatises and on 6 sheets of the geological map of the Tatra Mts. on the scale of 1:10 000.

In the second stage of his research, he focused mainly on geological and engineering problems in the Carpathians. His works concerned areas of planned hydroelectric power plants in the Dunajec River valley. The pioneering results of his research on areas designated for dams in Czorsztyn, presented in 1956, showed unequivocally that the main prerequisite for dam construction was artificial reinforcement of its foundation. His great knowledge, passion, and reliability in conducting documentation works, as well as his great research intuition were decisive for hydro-technical management of the Carpathian valleys. Another great research achievement of Professor Warmus in the field of engineering geology was his work on slope stability in the Carpathians. In the late 1960s and early 1970s, under his supervision, about 14,000 landslides were registered in the Carpathians. The work done at that time provided the basis for landslide maps at various scales developed in later years.

The third stage of his research involved works on the water-bearing capacity of Carpathian flysch. His field research led to the discovery of water-bearing structures that became the source of ordinary water supply for several localities. The professor made a great contribution in the field of regional hydrogeology, especially in the field of mineral water research. He worked on documenting therapeutic water resources for the emerging health resort in Ustroń. At the end of the 1960s, he prepared projects for the boreholes Ustroń IG 2 and Ustroń IG 3 and made hydrogeological documentation of brine resources drilled in Devonian carbonate rocks. The brines previously identified and documented in Miocene sandstones in the northern parts of Ustroń did not meet the expectations of the health resort. In this situation, Professor A. Michalik in 1972 became an actual discoverer of highly mineralized thermal brines (geothermal) used in Ustroń for healing purposes (Michalik, 1973, 1978). This brine was found in the Ustroń IG 3 (U-3) borehole drilled to a depth of 1837 m in the period 20.07.1971-24.03.1972. The brine concentration during the study reached up to 13.9% and the temperature at the outflow oscillated around the value of 32oC (Chowaniec, 2016).

Professor Andrzej Michalik maintained permanent scientific contacts with foreign scientific centres in Czechoslovakia, Bulgaria, GDR, Romania, Soviet Union and was a trainee of scientific institutions in these countries, as well as a participant in international scientific conferences and symposia. He worked closely with the International Carpatho-Balkan Association and the International Association of Hydrogeologists. Professor Andrzej Michalik's versatile activities earned him recognition, respect, and great scientific authority in the geological environment. His contribution to the development of hydrogeology and engineering geology in Poland is permanent and very well known in the geological community.

In 1972, Professor Andrzej Michalik moved from the Carpathian Branch of the Geological Institute (now OK PIG-PIB) to the teaching staff of the Pedagogical College (now Pedagogical University) in Cracow, where he continued his research on the problems of regional hydrogeology of the Carpathians, especially groundwater outflow, retention, chemistry, and protection of groundwater. Apart from teaching, Prof. Michalik held many administrative posts at the University of Life Sciences, including being elected three times as Vice-Dean of the Faculty of Geography and Biology, Director of the Institute of Geography, Vice-Rector for Scientific Affairs, and Head of the Postgraduate School of Geography. He has been promoted to 170 masters and 7 doctorates. In addition, he has been a reviewer of doctoral and post-doctoral theses, as well as in the proceedings for the conferment of the title of professor. He is the author or co-author of over 100 scientific publications and archival studies (Lach, 1991). In his scientific output, one can observe a transition from basic research to utilitarian and implementation research.

Professor Andrzej Michalik died suddenly on 27 June 1988 in Krakow. He will be remembered as an upright man, an outstanding scientist with versatile scientific interests, extensive knowledge, and vast research experience.

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CONDITIONS OF THE EXTENSION OF THE MINING AREA DEPOSITS OF THERMAL HEATING WATERS IN JELENIA GORA

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Keywords: thermal medicinal waters, deposit protection, Jelenia Góra geothermal system, Sudety Mts.

Abstract

The occurrence of a potential threat to thermal water resources in Jelenia Góra-Cieplice has made it necessary to enhance deposit protection by expanding the existing mining area „Cieplice".

This potential threat to the Cieplice thermal water resource is mainly linked to the drilling of deep boreholes capturing similar thermal waters in Staniszów and Karpniki, at a relatively small distance from the deposit, and the establishment of new mining areas, much bigger than the one in Cieplice there. There are also several approved plans for deep drilling in the vicinity of Cieplice, mostly south of the resort, i.e. along the flow path of Cieplice waters from their recharge area to the outflow in Jelenia Góra-Cieplice. What is more, new investors interested in exploration drilling in search of thermal waters are emerging.

All this calls for expanding the current borders of the mining area „Cieplice". An additional argument in favour of such an extension is a better assessment of the hydrogeological conditions of the thermal water deposit and the 2010 determination of the safe yield of Cieplice medicinal waters and potentially medicinal waters in the area of the Jelenia Góra basin. The recharge and flow directions specified in the „Hydrological documentation determining the safe yield of medicinal waters in Cieplice Śląskie-Zdrój and potentially medicinal waters within the Jelenia Góra basin" (Kapuściński et al., 2010) also imply that the mining area of the Cieplice medicinal water deposit should be larger than it currently is.

In order to provide better protection for the deposit of thermal medicinal waters in Cieplice, the "Appendix to the hydrogeological documentation of medicinal waters in Jelenia Góra-Cieplice" was written in 1998 (Dowgiałło, Fistek, 1998). Its main purpose was to protect the deposit by expanding the mining area created for it and proposing new borders of this area. So far, the existing mining area „Cieplice" has been small and it has covered only the deposit drainage zone. The Cieplice deposit, including the recharge area and water flow paths, is a part of a large Jelenia Góra geothermal system. Any interference resulting in excessive and uncontrolled exploitation of any groundwater in its recharge area and flow zone may significantly affect the quantity and quality of medicinal thermal waters. The recent creation of new, already operating thermal water intakes and the planning of next such intakes in the neighbourhood of Cieplice may be a potential threat to the reserves of this medicinal water deposit.

An important argument in favour of expanding the current mining area as an element of protective measures is a change in the conditions of intake exploitation and increased (since 2014) exploitation of water reserves caused by the launching of the Termy Cieplickie Sp. z o.o. spa. The constant and distinct lowering of water pressure at the C-1 wellhead observed in 2014-2018 may be the evidence of limited reserves of medicinal water deposits.

Based on a detailed analysis of deposit exploitation conditions in the context of the assessed geological and tectonic determinants of thermal water occurrence in Cieplice, including the conditions of water formation, the authors of the "Appendix No 1 to hydrological documentation of medicinal waters in Jelenia Góra-Cieplice" pointed out that an optimal solution would be a mining area encompassing the whole hydrogeological structure of these waters, i.e. covering all the catchment of the Kamienna and the Wrzosówka. As this is a very large area (215.3 km2) whose majority, comprising the Karkonosze and their foreground, is located within the Karkonosze National Park and its buffer zone and additionally protected by Natura 2000 areas, the proposed new mining area covering only the western part of the Jelenia Góra Basin and its mountain rim would suffice.

The proposed mining area stretches over 55.869 km2 and is located in the area of the city of Jelenia Góra, the municipality of Podgórzyn, the town of Piechowice and Stara Kamienica municipality.

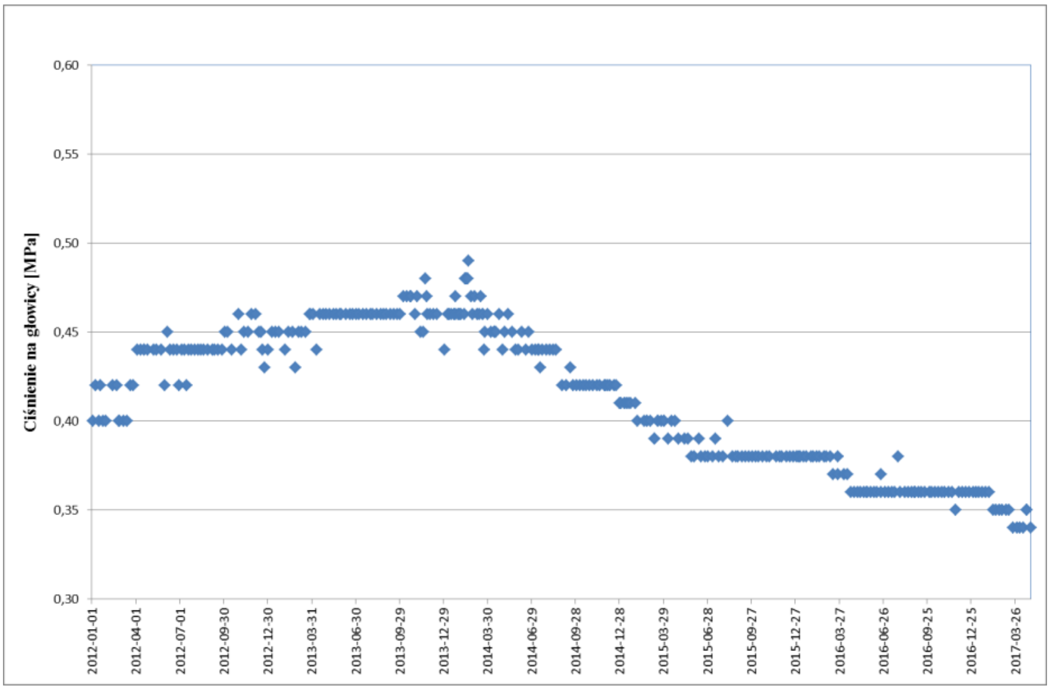

Figure 1. *Pressure changes at the C-1 wellhead in Cieplice-Jelenia Góra.*

Conclusions

In order to enhance the protection of the medicinal thermal water deposit in Cieplice by enlarging the existing mining area „Cieplice", the "Appendix No 1 to hydrological documentation of medicinal waters in Jelenia Góra-Cieplice" was created. Extending the borders of the mining area is essential due to a potential threat to the reserves of medicinal waters in Cieplice caused by the execution of deep boreholes capturing similar thermal waters at a small distance from the resort and the existence of approved plans for deep drilling, as well as further drilling projects aimed at obtaining thermal waters in the vicinity of the Cieplice deposit in Jelenia Góra.

So far, the existing mining area „Cieplice" has comprised only the drainage zone of the deposit, which is part of a large geothermal system in Jelenia Góra area. The borders of the proposed new mining area „Cieplice-1", together with the adjacent area of the Karkonosze National Park and its buffer zone, protect all the deposit including the recharge, flow and drainage zones of medicinal thermal waters in Jelenia Góra-Cieplice

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UNIEJÓW – 10 YEARS OF THE FIRST THERMAL HEALTH RESORT IN POLAND

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Keywords: geothermal heating plant, geothermal plant, geothermal water, geothermal heat, thermal health resort

Introduction

The first borehole in the Uniejów Commune, Uniejów IGH-1, was created on the grounds of Ostrowsko village in 1978. In 1984, the documentation for this well, prepared by the Polish Geological Institute, was approved by the Hydrogeological Documentation Commission at the Ministry of the Environment. In the years 1988-1990, design works regarding geological, hydrogeological, drilling and heating issues, were carried out by the Geothermal Department of the Institute of Energy Raw Materials at the AGH University of Science and Technology in Krakow. Within these works, a geological research project was created, which assumed drilling of three boreholes (Uniejów AGH-1, Uniejów AGH-2, Uniejów AGH-3) to identify geothermal resources and simultaneously constitute the basis for the construction of a geothermal installation in Uniejów based on two geothermal doublets. In the years 1990-1991 two boreholes were drilled: Uniejów PIG/AGH-1 and Uniejów PIG/AGH-2. The Uniejów AGH-3 well has not been drilled to this day.

According to the measurements conducted at that time, the PIG/AGH-1 and PIG/AGH-2 boreholes were characterized by significant productivities of approx. 90 m^3/h in self-outflow conditions at approx. 3 bar pressure and approx. 70°C temperature. The waters present are of the chloride-sodium-bromide variety. These waters, according to the judgment of specialists, have healing properties. In 1992, the Undersecretary of State, the Chief National Geologist at the Ministry of Environmental Protection, Natural Resources and Forestry, in a letter of 24th February 1992, handed over the hydrogeological wells of Uniejów IGH-1, Uniejów PIG/AGH-1 and Uniejów PIG/AGH-2 for the property of the Commune and City of Uniejów Board. The boreholes were transferred with the protocol of 1st April 1992.

In 1997, the Uniejów City Council decided to explore the possibility of using geothermal waters for heating in the city. In 1998, "The profitability study of using geothermal waters in Uniejów for heating, balneological and recreational purposes" was prepared by the Institute of Energy Raw Materials - Faculty of Geology, Geophysics and Environmental Protection at the AGH University of Science and Technology in Kraków under the supervision of Prof. Wojciech Górecki, PhD (Eng.). In March 1999, Aneta Sapińska, MSc, developed a"Preliminary concept for the use of thermal waters in Uniejów".

Due to administrative changes in the country, after 1998 Uniejów was incorporated into the Łódź Province. This resulted in the establishment of the limited liability company "Geotermia Uniejów" on 12th July 1999 - an entity dealing in the production and distribution of thermal energy (central heating and hot water) obtained from geothermal water. The company's shareholders were: the Uniejów Commune and the Provincial Protection Fund Environmental and Water Management in Łódź. In January 2000, a tender was concluded for the task "The city of Uniejów heating system based on thermal waters" and already in May “Geotermia Uniejów” has signed a contract for the implementation of the task. Funds for the task were obtained from a loan granted by the Provincial Fund for Environmental Protection and Water Management in Łódź.

In the period between October 2000 and June 2001, the hydrogeological conditions of the PIG/AGH-1 and PIG/AGH-2 wells exploitation "Geological research on the absorptivity of the Lower Cretaceous aquifer of the Uniejów region" were updated by the Geological Enterprise "Polgeol S.A." at the request of the "Geotermia Uniejów" company - preparation of an annexe to the existing hydrogeological documentation. As part of the work, the reconstruction of the PIG/AGH-2 production well and the PIG/AGH-1 absorption well was performed, and a pipeline connecting these two wells was laid.

In the second half of 2001, the construction of the heating system in the Uniejów city was completed and commissioned. As part of the task, the heating plant was equipped with heat exchangers and an oil peak load boiler room, a pump set for injecting water into the aquifer, and approx. 10 km of a heating network was laid in the city of Uniejów.

On 1st October 2001, the company "Geotermia Uniejów" started the process of supplying public and residential buildings with thermal energy produced from geothermal water. Due to the healing properties of Uniejów geothermal water, in July 2002, part of the office building rooms were adapted to a balneological treatment room to conduct research confirming the effectiveness of Uniejów geothermal water for therapeutic purposes. In two whirlpool tubs, students of the Medical Academy of the time conducted baths of the Uniejów Commune residents and described the improvement of their health after multiple treatments.

The deterioration of the absorptive capacity of the Uniejów PIG/AGH-1 injection well resulted in the necessity to start the reconstruction of the oldest Uniejów IGH-1 well and to perform drainage works in the PIG/AGH-1 well. From August 2004 to September 2005, geological works were carried out to improve the absorbency of the Lower Cretaceous aquifers in the IGH-1 well with additional works in the Uniejów PIG/AGH-1 and PIG/AGH-2 wells along with the implementation of preparatory works - preparation of hydrogeological documentation. The funds for this task were obtained by the company in the form of subsidies from the National Fund for Environmental Protection and Water Management in Warsaw.

In 2004, the concept of building a biomass-fired boiler house was created, which was built in 2006 thanks to the financial support of the ECOFUND. In the years 2006-2008, the heating network on the right-bank site of the city was expanded, and a geothermal network was added to the left-bank side of the city. In 2007, a sports ground with turf heated by geothermal water was completed.

In July 2008, the Uniejów Commune commissioned a thermal and swimming pool complex supplied with geothermal water, the Kasztel Uniejów Hotel&Spa, in which geothermal water is used for bathing in wooden tubs, as well as a Thermal Restaurant using geothermal heat, and a fountain with geothermal water in the Uniejowa town square. In 2008 a small graduation tower with geothermal water was built in front of the Kasztel, and geothermal water fountains in the shape of 17th-century cannons were set up by the Warta river, next to the footbridge from the city’s side. In 2012, the Uniejów Commune expanded the thermal and swimming pool complex. Due to the increased demand for heat, it became necessary to build a heating network leading the geothermal water to the left-bank side of the city in order to provide heat to newly created tourist facilities. In addition to the thermal and swimming pool complex, in 2012, the Artists' Retreat, the Mill Farmstead, and a football field complex were built by the Uniejów Commune. Also in 2012, an external investor built the Medical Spa Hotel “Lawendowe Termy”, which uses heat for heating purposes and geothermal water for swimming and balneological purposes. That year, the spa building "Uniejów Park" was built by an external investor, where heat and geothermal water are used for healing purposes.

In 2017, the limited liability company "Geotermia Uniejów" extended the heating and geothermal network to two newly built apartment blocks at Adama Asnyka Street. The network was built with the company's funds. Two years later, the company built a heating and geothermal network at Reymonta, Targowa and Długa Streets, as an additional supply to the existing heating network at the 700-lecia estate, and as the target connection for the residential blocks under construction at Długa Street. The network was also built with the company's funds. Moreover, the company conducts environmental education for students and all interested parties on an ongoing basis and conducts efforts to use Uniejów geothermal waters in the food, cosmetic and medical industries.

Current status

In 2011, the Uniejów Commune obtained the status of the 45th health resort and the 1st thermal spa in Poland on the basis of Art. 45 Sec. 1 of the Act on Health Resort-Based Medical Treatment, Health Resorts, Areas under Health Resort-Specific Protection and Health Resort Municipalities (2005). Table 1 shows the current (as of 2021) heat supply contracts by individual facilities. Table 2 presents data on heat and water provided by "Geotermia Uniejów". Table 3 shows the detailed chemical composition of the geothermal water from the Uniejów PIG/AGH-2 well.

Table 1. *Summary of the number of heat supply contracts by individual facilities in Uniejów.*

L.p.	Objects	As of the day 1st January 2015	12th December 2015	31st December 2016	31st December 2017	31st December 2018	31st December 2019	31st December 2020	21st December 2021
1	Blocks of flats	13	15	15	17	17	17	17	17
2	Public institutions *	9	9	9	9	9	9	10	10
3	Hotel facilities	15	9	12	12	12	13	13	13
4	Restaurant facilities	6	6	6	5	3	5	5	5
5	Recreational facilities	2	1	1	1	2	3	3	3
6	Individual recipients	95	97	92	82	94	95	93	92
7	Service facilities **	17	18	18	29	21	26	26	26
	Total	**157**	**155**	**153**	**155**	**158**	**168**	**167**	**166**

* offices, school, sports hall, kindergarten, banks, Volunteer Fire Department, Municipal and Communal Cultural Center, public library,
** shops, clinics, accounting offices, hairdressing and beauty salons.

Table 2. *Data on heat and water provided by "Geotermia Uniejów".*

Lp.	Use of heat and water in the year	2019	2020	2021 (January-May)
1	Ordered heat capacity of recipients, MW_t	5,89	5,7	5,62
2	Annual total heat sales, GJ	23 429,2181	24 060,0547	13 399,0539
3	Annual sales of geothermal heat, GJ	2 338,5611	3 742,6847	4 725,0539
4	Annual direct sales of thermal water, m^3	64 8652	765 273	296 407
5	Total annual heat sales from heating plants, GJ including for the purposes of:	2 710,1462	8 804,1889	6 747,3066
5.1	the household and communal sector, GJ	1 490,5805	4 137,9688	3 103,761
	- heating purposes, GJ	1 490,5805	4 137,9688	3 103,761
	- sale of thermal water, m^3	0	120	164
5.2	recreation and balneology, GJ	677,5365	3 433,6337	1 551,8806
	- heating purposes, GJ	677,5365	3 433,6337	1 551,8806
	- sale of thermal water, m^3	648 652	765 153	296 243
5.3	other recipients, GJ	542,0292	1 232,5864	2 091,665
	- heating purposes, GJ	542,0292	1 232,5864	2 091,665
	- sale of thermal water, m^3	0	0	0
6	Coverage of district heating needs, %	77	77	77

In addition to generating heat, the company uses geothermal water to produce food products such as pickled cucumber, sour rye soup, beetroot borscht, and fruit nectars. In addition, cosmetics for human and animal use are produced based on Uniejów geothermal water. Attempts to cultivate algae in this water have also started. The exploitation data of geothermal waters are:

- the efficiency of 68 m3/h, wellhead pressure at self-outflow of 2.6 bar and temperature of 68°C,
- the efficiency of 120 m3/h, wellhead pressure of 7.5 bar and a temperature of 69.6°C with the operation of a submersible pump (according to the license),
- operating parameters do not change with time.

Moreover, there is a gas-fired power plant in Uniejów in a cogeneration system, i.e. producing electricity and heat. Combustion engines powered by natural gas drive the generators which produce electricity, and the engines themselves, due to the combustion process, emit heat also used to heat buildings. There are 4 engines with generators installed, each with an electric power of 0.6 MW and thermal power of 0.8 MW. As a result, the total electric power of the power plant is 2.4 MW, and the thermal power is 3.2 MW. The heat is used to supplement the lacking amount of thermal energy obtained from the geothermal heating plant, which reduced the use of the peak load boiler room, producing the missing amount of heat in the periods of the lowest external temperatures, to a minimum. Electricity produced in the power plant is supplied to communal facilities such as hydrophore plants, sewage pumping station, school, communal residential buildings for collective accommodation, recreational facilities (thermal pool complex), hotel and restaurant facilities owned by the Uniejów Commune. This allows for complete independence from the prices of external electricity suppliers, as the electricity is transmitted through its own transmission networks.

Table 3. *Chemical composition of geothermal water from the Uniejów PIG/AGH-2 well.*

cations	Sodium Na^+ Calcium Ca^{2+} Magnesium Mg^+ Potassium K^+	2300 mg/dm³ 70 mg/dm³ 25 mg/dm³ 21 mg/dm³
anions	Chlorine Cl^- Bicarbonate HCO^-_3 Sulfates SO_4^{2-} Bromine Br^-	3687 mg/dm³ 140,5 mg/dm³ 5,2 mg/dm³ 1,8 mg/dm³
other	metasilicic acid H_2SiO_3	6,1 mg/dm³

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PLANS OF SPA REVITALIZATION IN TRZEBNICA

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Słowa kluczowe: geothermal waters, Trzebnica, Fore-sudetic Monocline

Introduction

Trzebnica is one of southwestern Poland's most attractive towns, whose development has been linked to its natural conditions and cultural background. In the second half of the 19th century, Trzebnica acquired a spa character based on the usage of local ferruginous waters (Kiełczawa, 2016). These traditions continued until just after World War II. An attempt to revive the spa by drilling the Trzebnica IG-1 well in 1974 and capturing thermal mineral waters proved unsuccessful.

Recently, the municipality has taken steps to drill a new, 3000 m-deep well Jadwiga T-1. The investor expects to capture high-temperature waters, which would enable reviving the bygone spa traditions in the town. Such an attempt is justified by manifestations of thermal water occurrence in deep parts of the Fore-Sudetic Monocline and its bedrock. Finalizing this enterprise may result in boosting the economy of the region and improving the natural environment, including the quality of air.

Material and methods

In the vicinity of the planned borehole, a number of magnetic and gravimetric surveys were carried out in the past. In order to find the optimal location of the Jadwiga T-1 well, additional magnetotelluric surveys were conducted in 2019 (Wojdyła, Czarna, 2019). The obtained results confirmed the existence of deep faults shown on geological maps – the regionally significant Hamburg-Cracow fault and the „Trzebnica fault" running across the town. They also indicated the presence, at the depth of c. 1850 m, of a high-resistance structure, in all likelihood corresponding to a granitoid intrusion suggesting possible conditions of thermal water occurrence.

In the geological structure of the Trzebnica area, two structural stages can be identified. The lower one is built of repeatedly metamorphosed deposits of the Baical-Caledonian-Variscan geosyncline. The upper stage is made up of weakly disturbed Permian-Mesozoic sediment series and Cainozoic deposits (Speczik, 1985).

The geological structure of the crystalline bedrock of the whole Fore-Sudetic monocline is complex. It is made up of diverse igneous rocks of granite and granodiorite types, metamorphic rocks of amphibolite facies (gneisses, granite-gneisses and crystalline schists), as well as greenstone facies rocks: phyllites and greenstone schists. Their folded forms determined the course of formation of the sediment cover in the upper Paleozoic (the Permian) and the lower Mesozoic (the Triassic) (Mizerski, 2002). The predicted profile of the designed well Jadwiga T-1 is specified in Table 1.

The discussed area is characterized by a temperature gradient of c. 2.5°C/100 m and heats flux from c. 60 mW/m^2 (Bruszewska, 2000) to c. 85 mW/m^2 (Szewczyk, 2007).

In the LGOM area, WWN of Trzebnica, well-studied geothermal conditions within the Fore-Sudetic monocline deposits point to the existence of a mean temperature gradient of 2.75°C/100 m and a heat flux of 63 mW/m^2 (Downorowicz, 2007). In the unused Trzebnica IG-1 well, the geothermal step of 43.55 m/1°C was determined on the basis of temperature profiling conducted at the depth range of 122-1350 m (Płochniewski, Hordejuk, 1975).

Different authors' views and analysis results obtained in neighbouring deep boreholes enable an assumption that the temperature at the bottom of the planned well will reach about 80°C (Ciężkowski et al., 2019).

There are several aquifer systems in the area of Trzebnica: Quaternary, Neogene, Triassic, Permian and one of crystalline bedrock, but only waters in the Cainozoic system can be used.

Table 1. *The predicted profile of Jadwiga T-1 well (based on Ciężkowski et al., 2019).*

Age	Depth [m]	Lithology
Quaternary	0-81	boulder clays, sands, silts,
Neogene	81 - 285	clays and sands
Triassic	285 – 637	claystones, sandstones, marls, secondarily dolomite, gypsum and anhydrite pockets
	637 – 676	limestones, claystones
	676 - 718	dolomites, anhydrite and claystone insertions
	718 - 879	marly limestones, claystones and marls in the floor
	879-1030	carbonate-clayey deposits, dolomites, claystones, anhydrites
	1030-1350	fine-grained sandstones with claystone interbeds
Permian	1350 – 1630	schists, anhydrites, rock salt, dolomite, claystones
	1630 – 1780	sandstones, conglomerates
Carboniferous/ Lower Palaeozoic	1780 – 1850	phyllites, schists, greenstones, mudstones
Proterozoic	1850 – 3000	granite-gneisses, granodiorites, amphibolites

The predicted level of TDS in these waters may reach 150 g/dm^3 in lower-Permian sediments (Górecki, 2006), while the TDS level in waters in the crystalline bedrock is unknown; one cannot rule out lower levels due to very large circulation depths of waters flowing from the Sudetes. In all likelihood, these will be Na-Ca-Cl, Ca-Na-Cl or Ca-Cl waters containing increased concentrations of the bromide ion as a specific component. One cannot exclude the presence of gases in waters captured in the crystalline bedrock. The presence of large amounts of CO_2 was confirmed in the metamorphic bedrock of the Fore-Sudetic Block, in Odra-5/1 well in Grabina near Niemodlin (Morawski, Sawicki, 1984), c. 80 km SSE of Trzebnica.

The rocks forming the bedrock of the Fore-Sudetic monocline are not generally a good groundwater reservoir. Larger amounts of water may be expected in zones of tectonic loosening, which deep geophysical surveys prove to exist near the planned well. From as deep as c. 1850 m, the well will be probably drilled in crystalline bedrock in the near-fault zone. Therefore, one may expect larger inflows of thermal water with an estimated discharge of c. 30 m^3/h (Ciężkowski et al., 2019).

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CLOSED-LOOP GEOTHERMAL TECHNOLOGY – UNLOCKING COMPETITIVE CLEAN ENERGY ON-DEMAND, AT SCALE

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Keywords: closed-loop; Eavor-Loop™; baseload generation; dispatchable generation

Abstract

One of the key challenges in the development and acceptance of geothermal energy is that we have been limited to permeable aquifers (or creating artificial permeability) or tapping into volcanic hotspots. And yet, at sufficient depth, geothermal energy is available everywhere. Fortunately, a range of proven and emerging technologies could finally make geothermal energy scalable by eliminating the need for a hot permeable aquifer.

One of these technologies is Eavor-Loop™ developed by Canadian start-up Eavor Technologies. The Company has successfully tested its closed-loop design in a demonstration project in Canada and is expecting to prove its commercial viability when several projects enter the drilling phase in 2022. This paper will provide an overview of Eavor-Loop™ using the example of the Eavor-Lite Demonstration Project and outline how it differs from traditional geothermal technologies.

Closed-loop geothermal systems, rely only on conductive heat transfer and have been investigated for many years due to their inherent business advantages including massive scalability, minimal water use, no fracking, no induced seismicity, no corrosion/erosion/scaling, no fluid disposal, and low environmental footprint (see Table 1 below). The development of a true closed-loop system mitigates the exploration risk involved in searching for rare geological areas with both high temperatures and high flow capacity. Therefore, this type of system has the potential to become globally scalable and open entirely new markets.

Table 1: *Comparison of Eavor-Loop™ and traditional geothermal technologies*

Traditional Geothermal	Eavor-Loop™
Open system: water flows through the reservoir, fluid exchange between system and reservoir	Closed system: working fluid circulates in isolation from the reservoir, no fluid exchange
Requires a permeable aquifer and hot convective zone	No need for a permeable aquifer
Requires an electric pump to circulate brine; parasitic load	Driven by a natural thermosiphon, no pumping is required
Can require fracking to increase flow, the potential for induced seismicity	No fracking required, no induced seismicity
Can produce GHD and CO_2 with produced brine	No GHG or CO_2
Continuous water use and ongoing treatment required	Minimal water use, no production of brine requiring treatment
Baseload, not dispatchable	Baseload and dispatchable

The Eavor-Loop™ Demonstration Project ("Eavor-Lite™"), is a full-scale prototype of the technology intended to de-risk the key technical components. The closed-loop system, shown in Figure 1 below, consists of a large U-tube shaped well at 2.4km depth, with two parallel ~2000m multilateral horizontal wellbores, and a pipeline connecting the sites on the surface. Two drilling rigs are operated simultaneously from both sites and used to intersect the multilateral wellbores at depth. A water-based working fluid is circulated in the inlet well, through the parallel wellbores to recover heat by conductive heat transfer with the rock, and rises in the outlet wellbore at a higher temperature. The density difference between the inlet well and outlet well creates a thermosiphon that completely drives the flow, without any pumping power. A test facility on the surface is designed to remove solids, measure all relevant performance data, and cool the water for recirculation into the inlet well.

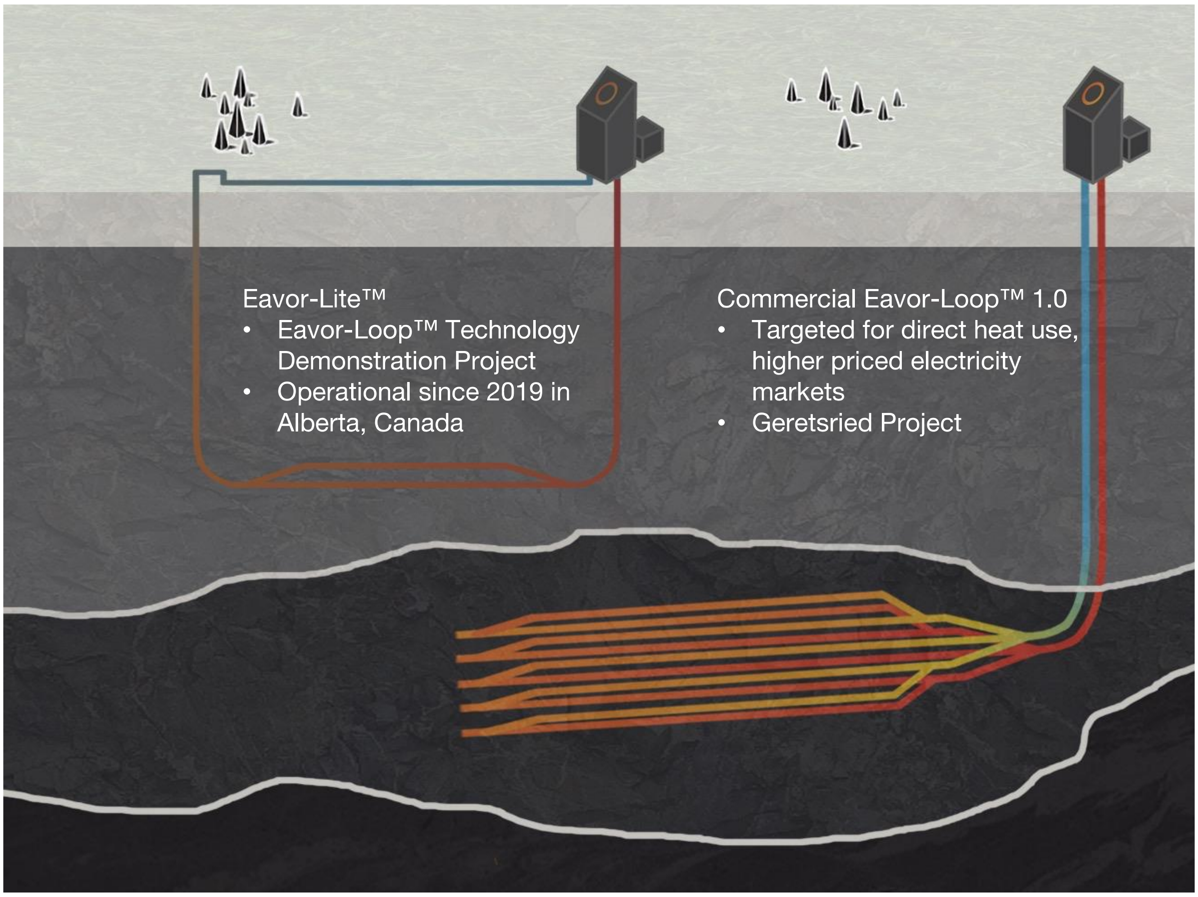

Figure 1. *Eavor-Lite™ and commercial Eavor-Loop™ 1.0 Schematic*

The key technical objectives of the Eavor-Lite™ project were to:

1. Drill and intersect a multilateral Eavor-Loop™ with two laterals
2. Create a closed system by chemically sealing the Eavor-Loop™ using proprietary Rock-Pipe™ completion
3. Validate thermodynamic performance and demonstrate thermosiphon

Having successfully tested the key elements of Eavor-Loop™ technology in the Eavor-Lite™ project the company is working on deploying the commercial-scale designs like Eavor-Loop™ 1.0 – see Figure 1, in suitable markets for electricity, direct heat and cooling applications.

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FROM THE BOREHOLE HEAT EXCHANGER TO THE GROUND ENERGY STORAGE

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Keywords: shallow geothermal energy, borehole heat exchanger, energy storage, cold storage, thermal response test (TRT)

Abstract

The vertical, ca. 100-meter long, borehole heat exchangers are popular low heat reservoirs for heat pumps that are heating and cooling buildings and industrial facilities. The particular examples include highly glazed office buildings and factories that require cold in their technological process. In these cases, the heat pumps with the proper low heat reservoirs have to cover the peak demand for the cold and ensure the appropriate amount of cold. At the same time, economic pressure accompanying new investments effectively reduces the possibility of increasing the number of borehole heat exchangers and encourages hybrid solutions, such as using the low heat reservoir as short-term cold storage. The perfect example of such a hybrid approach is multi-source, reverse heat pumps cooperating with both the ground and the air heat exchangers. By night, the cold is produced with high efficiency and stored in the boreholes. Stored thermal energy is reused for efficient cooling, preferably in the free-cooling mode, during the next few hours.

We proved the possibility of the short-term storage of cold in the field of borehole heat exchangers in several ways. The first analyses were based on numerical simulations. The simulations included both so-called multipole methods (Kwiatkowski et al. 2021, Hellström & Claesson, 2011) and a 3-D model based on the CFD method. The dedicated OpenFOAM (www.openfoam.org) solver was developed and validated to handle the geometrical and material complexity of ground heat exchanger, grout and soil. Secondly, laboratory experiments were carried out in the temperature-controlled climatic chamber involving cooling large, 40 kg heavy soil probes. Thirdly, the actual pilot borehole heat exchangers were tested in the research field located at Euros Energy headquarters in Koprki, near Warsaw. The tests contained temperature profiling and extended thermal response tests with a prolonged duration. Additionally, we analyse archival data gathered from a telemetry system selected from Euros Energy installations with high cold demand, i.e. in Józefów near Warsaw.

The results proved fairly well conditions for short-term cold storage in vertical ground heat exchangers - particularly for periods shorter than 12 hours the energy loss is minimal. Advantageous conditions had been confirmed for silt type soil - both those collected from Koprki and those from quarries in referential localisations - Dobre and Mszczonów.

Numerical research pointed out that thermal preparation of soil as a ground heat storage is essential. The optimal temperature of soil should be lower than 3°C, which is possible when the soil is used as a heat source during winter. In fact, a properly designed and managed low heat reservoir allows reaching desired ground temperature at the beginning of the cooling season. Moreover, when soil temperature ranges from 1°C to 3°C it is possible to carry out cooling based on free-cooling when heat pumps are turned off during the day. During the night, the cold can be efficiently produced using a heat pump with air as a low heat reservoir.

The tests in working conditions similar to actual (12 hours of free-cooling during day-time, 9 hours of storing heat during night-time, 3 hours of idle and additional storing heat on weekend nights) demonstrated the effectiveness of this method of shaping electrical energy demand profile. The carried out R&D works indicate that implementation of short-term ground storage of cold can be treated as the element of shaping electrical energy demand profile system.

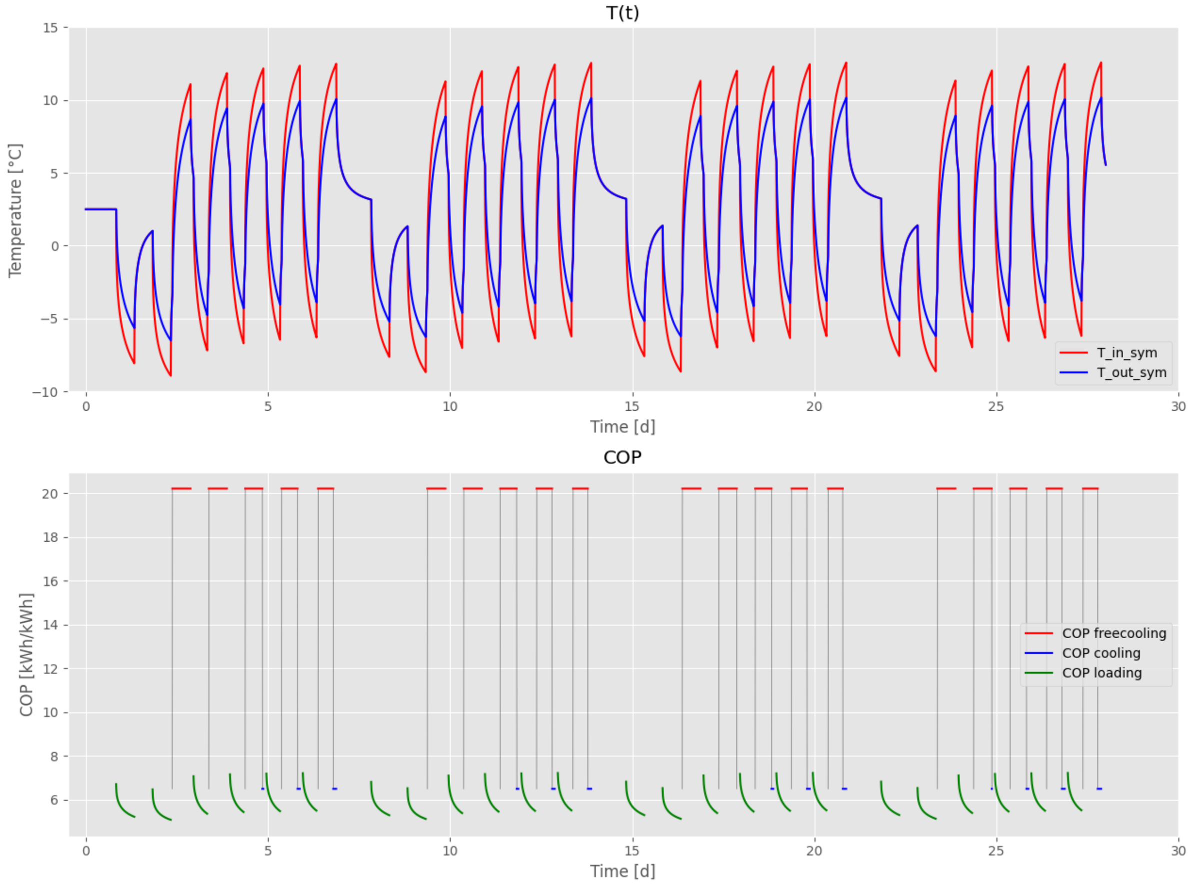

Figure 1. *Temperature profile and COP for ground storage of cold weekly with an additional cold store on Saturday and Sunday.*

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POTENTIAL OF THERMAL ENERGY STORAGE IN THE BOREHOLES (BTES) AND IN AQUIFERS (ATES) IN MOGILEŃSKO-ŁÓDZKA TROUGH

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Abstract

Thermal Energy Storage systems (TES) collect heat or, less frequently, cold in variable conditions of temperature, place or power of energy production. The task of such systems is to mitigate the effects of the time mismatch of energy generation and its use, i.e. better management of energy often coming from different producers, but also the storage of waste heat. The energy stored in the system can be used at a later date when there is a demand for it. This paper presents 2 numerical models of heat storage systems over 30 years of operation:

1. BTES - Borehole Thermal Energy Storage;
2. ATES - Aquifer Thermal Energy Storage.

Raising awareness about climate change and the popularity of renewable energy sources is associated with increased attention to geothermal energy and devices such as heat pumps. According to (IRENA 2018), in 2050 electric heat pumps will become more common in most parts of the world. The main advantage of solutions with heat pumps is the ability to provide not only space heating in cold periods but also space cooling during hot summer days. This solution is possible, for example, in the case of ground source heat pumps. Their use also allows for seasonal heat storage in the ground.

The BTES model was made using the finite element method in the Feflow® program (MIKE Powered by DHI Software). Waste heat was used in this model to improve the operation of the (geothermal) source of the heat pump. The work of the ground source and temperature differences resulting from various scenarios are presented. The heat storage can partially counteract the negative effects of cooling the brine in time. After 30 years of the heat source operation, differences in the source operation temperatures were observed depending on the selected scenario.

Aquifer thermal energy storage (ATES) is sometimes considered as an installation for increasing the efficiency of geothermal systems and utilizing waste heat. The ATES model was also made using the finite element method in the Feflow® program (MIKE Powered by DHI Software) for the Lower Cretaceous formations in the southern part of the Mogilno-Łódź trough in the Tuszyn region. The dynamic model was made on the basis of the static model of geological parameters prepared in the Petrel© software, using innovative methods of interpolating the input data from the Petrel to Feflow environment.

The Lower Cretaceous reservoir is known to be one of the most prospective for geothermal purposes in Poland. The Lower Cretaceous formations are located in the Mogilno-Łódź Trough at depths ranging from 0 to even approx. 2500 m and their thickness ranges from 0 to 600 m. The average water temperature ranges from 20 to approx. 90 ° C. The Lower Cretaceous in the analysed area lies at depths from 78 to 1,375 m. It is believed that the southern part of the trough has a lower geothermal potential due to lower water temperatures. Average temperatures at the chosen location of ATES systems range from 28-37 °C. The model shows the operation of the ATES system for selected scenarios. Efficiency simulation was carried out for 4 systems over 30 years of system operation with equal periods of injection, storage and heat removal during each year of system operation. The simulation results show the potential applicability of ATES in the analysed area for the Lower Cretaceous formations.

The current growing interest in the use of land and groundwater as the so-called "georeservoirs" is caused by the increased interest and the use of renewable energy sources (eg solar collectors) or waste heat, which by their nature are unstable sources and require adjustment of the supply of certain energy with the demand for it. The presented BTES and ATES systems can be used for such purposes. However, their application requires a multidisciplinary approach, the elements of which are presented within this paper.

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GEOTHERMY SUPPORTED BY BIOMASS AND ENERGY CLUSTER STABILIZER

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Keywords: biomass, geothermal energy, cluster, autonomy

Introduction

The world is changing; visible, the old centralized system of generation – transmission – distribution – consumption of energy is not capable of ensuring energy supply security and efficiency in absorbing new technologies of the 21st century.

Therefore, the process is in progress to build an **"Energy Cluster"** in one, or several, local communities. One can obtain not only electric energy but also heat. All that is connected to electromobility.

Energy Cluster

The Cluster can radically reduce dependence on energy transmission from outside and smog generation. How to do it in a few steps is described below:

1. Every house, apartment building, or farm has its electric power station 3 – 10 kW. It can be a photovoltaic installation – PV, a vertical wind turbine – no higher than the trees, a hydropower station (flow-through), a biogas installation – fed by waste material, biomass fed energy generator or a C-GEN installation.
   Every household generates only as much as it needs, but the surplus is sent to the grid or deposited in a "Power Bank", or in a heat buffer. Stationary systems of energy storage are under development and this enables uninterrupted supply 24/7. This makes an off-grid scenario possible. The electric car performs the role of a mobile battery. The possibility to generate electricity from heat is under development – the system of "Peltier cells" or "Stirling engine".
2. The houses are connected in groups of neighbourhood exchange. There is a possibility to exchange energy without payments or in a cooperative system. The model example is "Osiedle Słoneczne" in Kaźmierz commune, Wielkopolska. Detached houses and flats in bigger blocks are exclusively supplied from their power stations. There are no gas, nor heat pumps.
3. The aggregation of such groups in a specific area gives the advantage of big scale. If transmission lines are owned by producers, the costs of transmission by power boards disappear. A good example is the municipality of Ostrow Wlkp.
4. This process leads to the creation of a local autonomous energy area – an energy cluster, which supplies cheap and stable energy for the dwellers. One can combine electricity with heat and electromobility. Another problem are manufacturing plants; in this case, one needs to think about cooperation with a local Power Board.

There is, however, one dark spot in such an idyllic picture – renewables are not stable sources of energy and energy storages (banks) of reasonable capacity are not available. The cluster needs a stable source (25 %) for the whole to work without problems. Such a stabilizer can be:

1. Biomass incinerating installation (or C-GEN)
2. Geotermal installation
3. Local hydropower station

Geothermy

Geothermal plants are excellent sources of heat and can be constructed in the biggest part of Poland. A stable source of heat is essential for dwellers, businesses and administrative offices. In addition, this is the energy obtained without CO_2 emissions, which is important for the fulfilment of climate commitments. Geothermal installations are not very efficient in the production of electric energy; they require the support of another stable source. This source, locally available, is biomass. Of course, it is possible to produce electric energy from heat in many ways, but this has been discussed by other speakers.

Biomass

To fully utilize local sources of biomass one needs to create a dense network of Biomass Processing Centres (BPC). This enables sequestration of CO2 and making money at the same time. Those Centres are much more than the sawmill and should have the following components:

1. A sawmill to produce wooden construction elements with the necessary equipment.
2. Pellet or briquette production plant.
3. Biogas plant with installation to purify the gas to standards of biomethane.
4. Lokal power plant/heat plant (eg. C-GEN technology) together with the production of a component for Permaculture Garden.
5. Permaculture Garden.
6. Rainwater storage tank.

Such centres will not only help to locally fulfil climate commitments GD'50 but can be energy clusters “stabilizers”. They are gradually replacing the centralized system of production – distribution – consumption of electric energy. Such centres are a very attractive business proposal provided that they will encompass all elements of biomass circular economy. Financial results can be improved by oxygen tree plantations and the production of healthy food and healing herbs. The financial mechanism is called “Carbon Credits” which reflects the system of “Carbon Footprint”.

Summary

Problems of climate challenges including an excess of CO_2, CH_4 and H_2O in form of vapour can be solved only by a complex approach encompassing all elements of Green Deal 2050 (with biomass used as a renewable source of energy what is particularly easy in local systems).

The above-mentioned proposals cannot be fully implemented in the present centralized system. All these modern solutions imply the rise of distributed energy systems. They are the base of decentralised distributed cluster systems.

The era of local PROSUMENT is coming!

THE EVALUATION OF RESIDENTIAL HEAT PUMP SYSTEMS POTENTIAL IN HEALTH RESORT RABKA ZDRÓJ

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Keywords: heat pump systems, low-temperature geothermal energy, health resorts, sustainable development

Introduction

Many regions around the world have been struggling with the problem of ambient air pollution. Air quality has become increasingly weaker which makes it necessary to take appropriate measures to protect human health and improve the quality of life. Poland is one of the European countries which recorded significant exceedances of the limit values of particulate matter and benzo(a)pyrene in recent years (EEA, 2021). The main reasons for poor air quality are inefficient combustion of solid fuels and preparation of domestic hot water in individual boilers. The high concentration of pollutants also occurs in the health resort areas, which constitute an important part of the health care system. Therefore, the health resort areas should be a high priority to reduce concentrations of air pollution. The main aim of this paper is to present the proposed solutions based on low-temperature systems supported by heat pumps and define the potential that can be used in the selected research area.

Materials and methods

The health resort of Rabka Zdrój is located in southern Poland, the Voivodeship of Lesser Poland, the poviat of Nowy Targ (Figure 1). The research area belongs to the Rabka Valley, which is located at an altitude of 500-600 m a.s.l. (Kondracki, 2002). The research area is also characterized by the presence of a dense river network. The measurement carried out by Chief Inspectorate for Environmental Protection shows that Rabka-Zdrój has a significant problem with exceeding the daily limit value of PM10 during the heating season. In 2020, 45 days with the exceeding concentration of PM10 were recorded, with a limit value of 35 days in a calendar year. The research conducted in the same year shows that the annual mean concentration of benzo(a)pyrene was 9 ng/m^3, at the 1 ng/m^3 limit value (GIOŚ, 2021).

Figure 1. *Location of the research area.*

The article presents an analysis of the main aspects of using the ground source heat and groundwater heat as a lower heat source for heat pumps. For groundwater, the estimated thermal power of the intakes was calculated, which is one of the main parameters determining the energy potential of groundwater. It was determined based on equation (1) (Buczyński, 2010). The water temperature at the head was adopted as the temperature of water taken from individual intakes. In the absence of information on temperature, the authors used the formula (2). (Pazdro, Kozerski, 1990). Due to the shallow occurrence of groundwater, heat losses associated with the flow to the surface have been omitted. Moreover, it was assumed that the water, after passing through the heat pump, is cooled by 5 °C (Pająk, Tomaszewska, 2016). Based on the results obtained, a map was made for the estimated heating power of the intakes in the research area.

$$Q_{geot} = Q_w \cdot \rho_w \cdot c_w \cdot (T_w - T_z) \quad (1)$$

where Q_{geot}, Q_w, ρ_w, c_w, T_w, T_z are respectively: the heating power of the intake (kW); the efficiency of the intake (m^3/s); the water density, which was set at 1000 (kg/m^3); the specific heat of the water (set at 4,19 kJ/(kg·°C)); the water temperature at the head (°C); the temperature of the cooled water (the temperature at the outlet of the heat pump) (°C).

$$T = t_{avg} + A + \frac{H-h}{g} \quad (2)$$

where T, t_{avg} , A, H, h, g are respectively: the water temperature at the depth of H (°C); the average annual air temperature (°C); the constant depending on the height above sea level; the depth of the occurrence of water (m); the depth of the constant temperature zone (m); the geothermal degree (m).

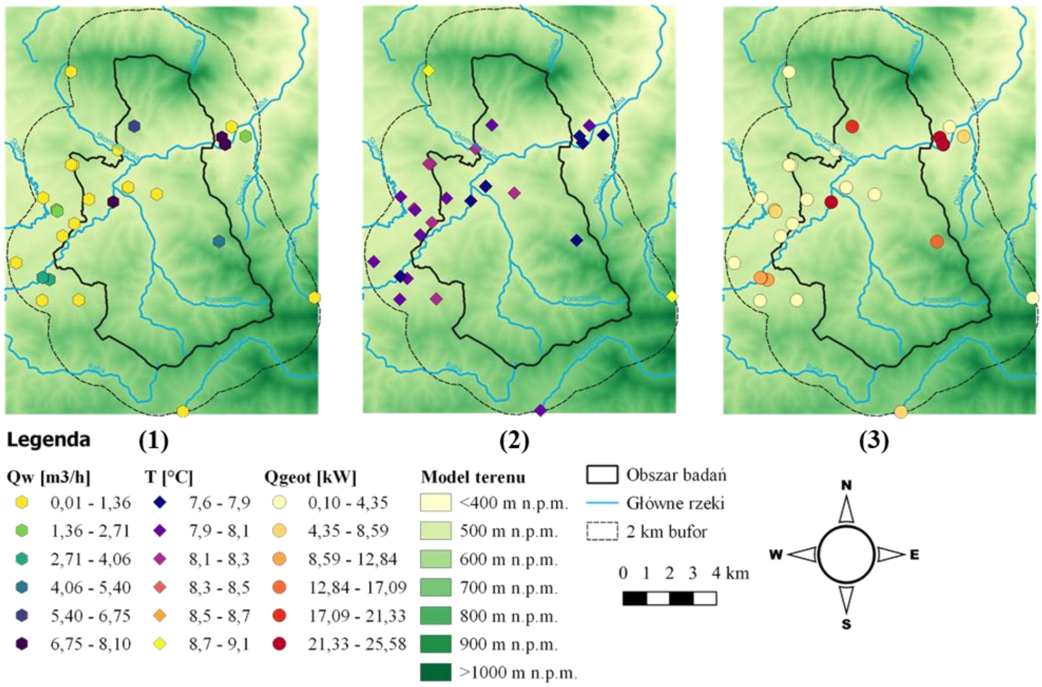
The assessment of the potential for using the earth's heat as a lower heat source in heat pump systems was based on a detailed analysis of geological profiles in the study area (PGI, 2021). On this basis, the main geothermal properties of rocks and soil were identified. Appropriate values of thermal conductivity were adopted for individual rocks, taking into account the moisture content of the deposits. For sandstones, mudstones and claystones, coefficients were determined based on measurements of rock samples from the Obidowa IG-1 borehole. Recommended coefficients were used for other deposits obtained as part of the „Cheap and efficient application of reliable ground source heat exchangers and pumps" (Dalla Santana et al., 2020). The coefficients missing in the above materials were adopted from the VDI 4640-1 guideline (VDI 4640 Part 1, 2010). By equation (3), the weighted average coefficient of thermal conductivity for the selected depths of 30, 60, and 90 m was calculated in each borehole. The obtained results of the analyzes made it to develop maps of the potential for the use of soil heat up to the depth of 30, 60, and 90 m for vertical heat exchangers.

$$\lambda_w = \frac{\sum_{i=1}^{n} u_i \cdot \lambda_i}{\sum_{i=1}^{n} u_i} \quad (3)$$

where λ_w, λ_i, u_i are respectively: the weight average thermal conductivity coefficient [W/m·K]; the thickness of individual precipitates in lithological profile [m]; the thermal conductivity coefficient of individual precipitates in lithological profile [W/m·K].

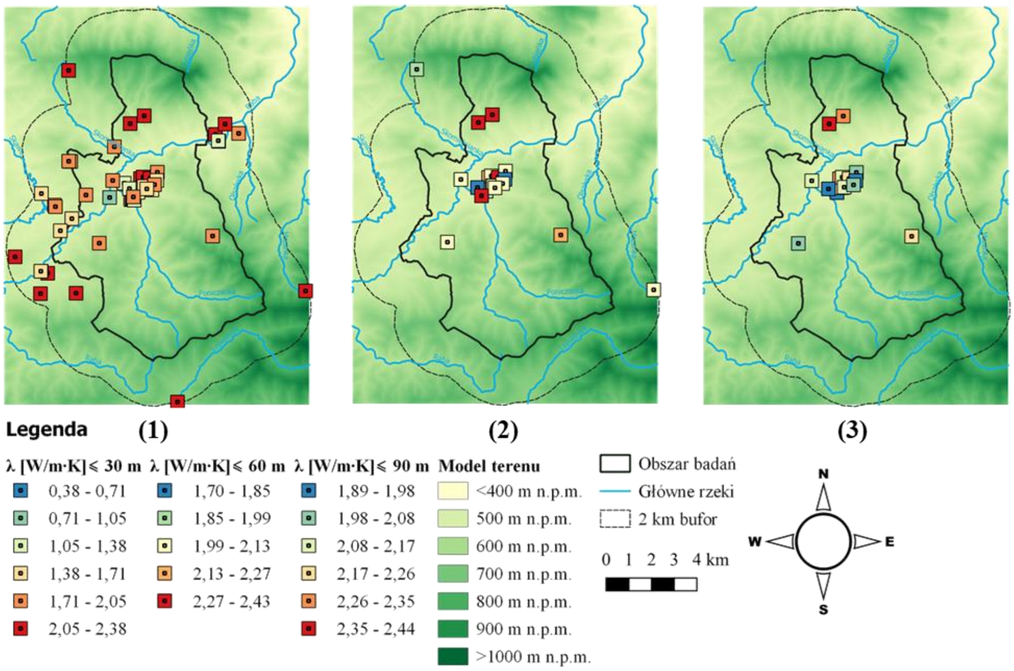
Results

In the research area, exploitation resources of groundwater intakes are between 0,01 – 8,0 m^3/h. The capacity of almost 40% of the considered intakes exceeded the value of 2 m^3/s. The water temperature in the intakes ranges from 7,6 to 9,1 ºC (Figure 2). Groundwater with the highest temperature occurs in the south-eastern and north-western parts of the area. For the shallow occurrence of groundwater, the estimated thermal power depends more on the intake efficiency than on the temperature. It is conspicuous in the example of measuring points located in the southern part of the research area, where the groundwater temperature is the highest, but the lowest efficiency, so the estimated power obtained from the intake is much lower than in the case of high-performance and low-temperature intakes. The estimated thermal power of the intakes does not exceed 5 kW in 55% of cases., while over 30 % of the intakes are in the range from 10.9 to 25.6 kW.



Rysunek 2. *The efficiency of groundwater intakes (m^3/h); (2) estimated groundwater temperature (°C);(3) estimated thermal power of intakes (kW).*

The analysis of the thermal conductivity of the rock mass to the depth of 30, 60, and 90 m, was used to assess the possibility of using vertical ground heat exchangers in the health resort area (Figure 3). The weighted average coefficient of thermal conductivity is respectively: from 0,40 to 2,38 W/m·K for the boreholes to a depth of 30 m, from 1.70 to 2.43 W/m·K the boreholes to a depth of 60 m and from 1.90 to 2.44 the boreholes to a depth of 90 m. The thermal conductivity ≥ 2 W/m·K occurs in more than 40% of boreholes to a depth of 30 m and about 80% of boreholes to a depth of 60 and 90 m. In the southern part of the research area, the use of different depths (60 and 90 m) did not cause significant differences in the achieved thermal parameters due to the appears of homogeneous rock masses.



Rysunek 3. *The estimated value of the thermal conductivity of the rock mass to a depth of:(1) 30 m; (2) 60 m; (3) 90 m.*

Conclusions

The Rabka-Zdrój health resort has been struggling with exceeding the permissible concentrations of air pollutants for several years. This problem affects the exceedance of the annual limit value of benzo (a)pyrene This problem affects the exceedance of the annual limit value of benzo (a)pyrene, and the limit of 35 days a year with exceeding the permissible daily concentration of PM10 dust. The health resort area is an integral part of the health care system, accordingly, it should have a high priority in reducing air pollution concentrations. The article presents an analysis of the possibilities of using groundwater and ground source in low-temperature systems supported by heat pumps, which can replace the currently used heating system based on solid fuels. The heat pump systems based on groundwater achieve a thermal power of 11-25 kW for over 30% of the intakes in the research area, which means that may be used for heating purposes in single-family houses. The carried out analysis for vertical ground heat exchangers shows that in the southern and south-western parts of the health resort there are favourable thermal conditions for the application of this technology. The presented results can be used by the local government and the community. Implementation the low-temperature geothermal systems is a way to increase the environmental values of the health resort and reduce air pollution.

Funding

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VERTICAL TEMPERATURE DISTRIBUTION IN BOREHOLES UP TO A DEPTH OF 200 M B.G.L. IN THE CONTEXT OF GEOTHERMAL DATA FROM THE DEEPER BOREHOLES IN LOWER SILESIA

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Keywords: temperature measurements, borehole temperature profiles, subsurface temperature, geothermal gradient, geothermal heat flux, geothermal anomalies

Introduction

The abstract presents the results of temperature measurements taken in the boreholes located in Lower Silesia, mainly in the Sudety Mts. and partly on the fore-Sudetic block and the fore-Sudetic monocline, carried out in 2019 as a part of the project entitled "Young tectonic zones and geothermal conditions in the Sudety Mts. in the light of geochronological, structural and geothermal studies – stage II" funded by the National Fund for Environmental Protection and Water Management and carried out by the employees of the Polish National Institute – National Research Institute (PGI – NRI). The goal of these studies was to obtain new temperature data from the wells and piezometers up to 200 (m b.g.l.) deep, to calculate values of the geothermal gradient and other selected geothermal parameters and to assess the suitability of temperature measurements results in the context of regional studies on geothermal properties.

Materials and methods

The fieldwork was preceded by a query of data in the geological documentation gathered in the National Geological Archive and databases maintained by PGI – NRI. Technical requirements made it possible to perform measurements for 23 identified boreholes. Temperature measurement was carried with the use of the KLL-Q2 field multimeter (Seba Hydrometrie 2012) and the MPS-D8 (Water quality probes 2012) probe interconnected by a 200 (m) long cable. Due to the fact that the examined holes had a long standoff period, it was assumed that the water in the boreholes remains in a state of thermal equilibrium with the rock environment. Boreholes under influence of groundwater extraction were omitted in these studies.

Shallow subsurface shows high seasonal and annual temperature variability. At a depth at which these changes disappear, which in Poland is about 15-20 (m b.g.l.), there is a zone of nearly constant temperatures also called the neutral temperature zone. Below, subsurface temperature increases accordingly to the value of geothermal gradient (Headon and Others 2009; Banks 2012; Pike and Others 2013). In this work, the term "temperature inversion point" is used to determine the point on the thermogram (a curve showing temperature values against the depth of the borehole), which, under fixed and undisturbed conditions, usually corresponds to the T_{min} value. The following methodology for temperature measurements in the boreholes was adopted: downhole measurements to be taken every 2 (m) up to the depth of 20 (m) below the groundwater table, and below that depth, measurements to be taken every 5 (m).

The heat flow density of the Earth is the amount of heat flowing through a unit of surface in a unit of time. This work provides for the simplification of calculations i.e. omission of conduction and convection, including vertical and horizontal thermal conductivity of pipes and cement, and radiation occurring during the exchange of heat energy with the lithosphere. According to Fourier's law, the Earth's heat flow is calculated as a conductive component according to the formula (7.1) (Karwasiecka and Bruszewska 1997; Banks 2012):

$$Q = -K \cdot G \qquad (7.1)$$

where:
Q – heat flow density (mW/m^2);
K – thermal conductivity of subsurface (mW/m^{O}C), „-” indicates direction of the vector;
G – geothermal gradient along borehole depth H (^{O}C/m).

The geothermal gradient was computed for the selected boreholes for which the measurement series allowing for determination of the computational interval of the profile thickness of about 100 (m) min according to the formula (7.2) (Karwasiecka and Bruszewska 1997):

$$G = \frac{\Delta T}{\Delta H} = \frac{T_n - T_0}{H_n - H_0} \qquad (7.2)$$

where:
G – geothermal gradient along borehole depth H (^{O}C/m);
ΔT – temperature change ^{O}C;
ΔH – thickness of the borehole profile (m);
T_n – final temperature of computational interval ^{O}C;
T_0 – initial temperature of computational interval ^{O}C;
H_n – final depth of computational interval (m);
H_0 – initial depth of computational interval (m).

The following simplification of the calculation procedure was assumed: for each individual borehole the average thermal conductivity value of $K_{av.}$ corresponding to the lithology of the screened sector of the exploited aquifers was adopted. The K_{av} values were adopted after Karwasiecka and Bruszewska (1997). An example of a thermogram and determination of the computational interval is shown in Figure 1.

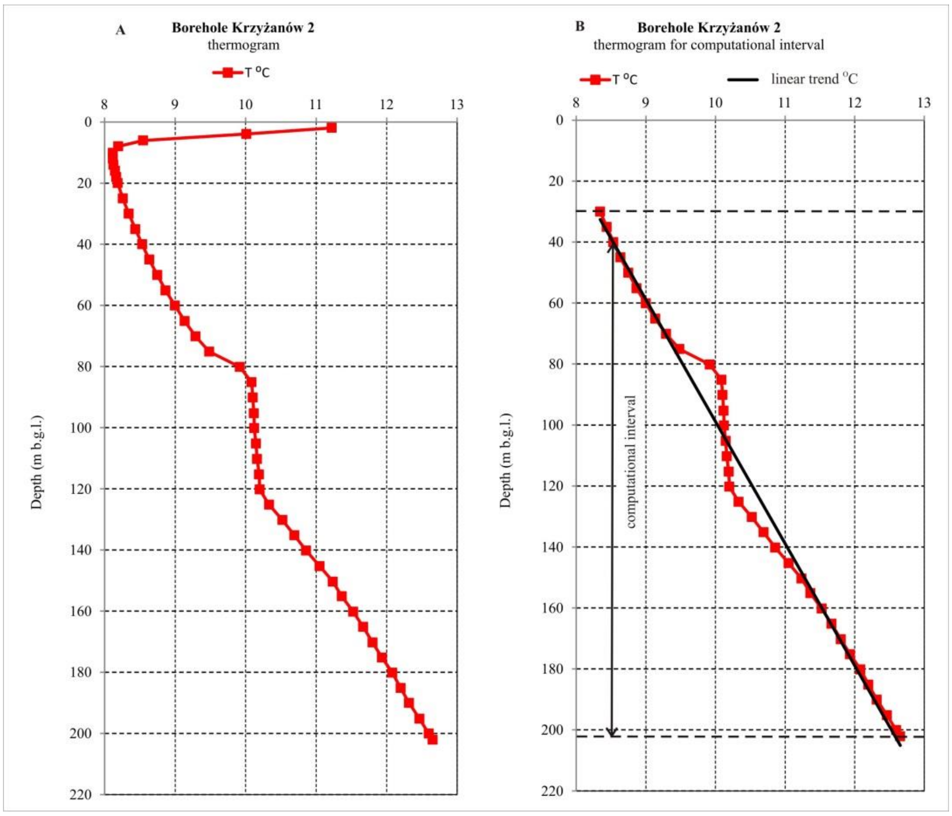

Figure 1. *Thermogram (A) and determination method of computational interval (B) for the Krzyżanów 2 borehole*

Results

The total results of temperature measurements for 23 boreholes are shown in Figure 2. Characterization of the zone of seasonal subsurface temperature changes was possible in the case of 13 boreholes. Its thickness, calculated by determination of the temperature inversion point, ranges from 7.81 to 48.16 (m) and on average equals 19.87 (m), while the temperature measured at the inversion point ranges from 6.89 to 9.91°C and on average equals 8.67°C. Abnormal values, i.e. showing high thickness of the zone of seasonal temperature changes and increased temperature at the inversion point, were observed for the piezometer Wrocław W-1.

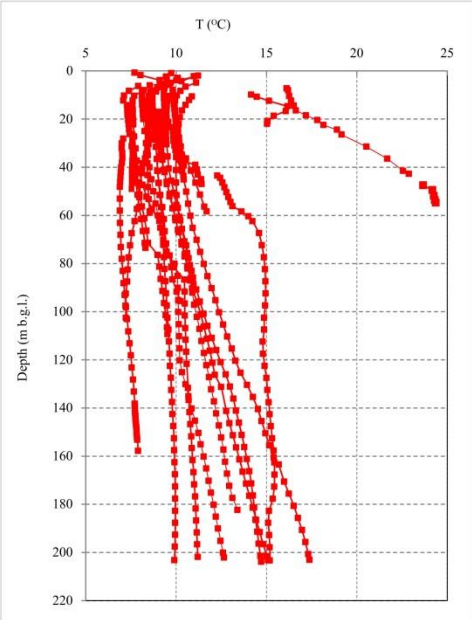

Figure 2. *Total results of temperature measurements for 23 boreholes*

In the framework of these studies the highest temperature values, exceeding 20 °C were measured within the open pit of the Turów Coal Mine. Besides that the elevated groundwater temperatures were measured for the following boreholes: Pełczyn IVP – 17.39 °C, Wałbrzych Stara Kopalnia – 15.45 °C and Stary Waliszów 7R – 15.08 °C. In the case of 9 boreholes, it was possible to calculate the value of the geothermal gradient, which varied between 0.47 and 4.690 (°C/100 m) and showed an arithmetic mean of 2.38 (°C /100 m), as well as the Earth's heat flux, which varied between 11.67 and 88.34 (mW/m^2) and showed arithmetic mean of 50.03 (mW/m^2). For both parameters, the maximum values were calculated for the piezometer Pełczyn IVP, while the minimum ones for the piezometer Grzędy 3P. Table 1 compares the results calculated within the presented studies with the results of earlier research.

Tabel 1 *Values calculated within the presented studies vs. results of earlier research*

Borehole	Geothermal gradient T (°C/100 m)		Geothermal heat flow density Q (mW/m^2)	
	1	2	1	2
Długopole Dolne 6R	3,15	3,11	59,61	59,04
Pełczyn IVP	4,69	4,18	88,37	56,03
Stary Waliszów 7R	3,46	3,67	65,34	62,40

1 – results of the presented studies
2 – values accoring to Karwasiecka and Bruszewska (1997)

Conclusions

The thickness of the seasonal temperature variation zone, as well as subsurface temperatures therein, shows a very strong variation. Increased values of these parameters for the piezometer Wroclaw W-1 can be caused by the effect of the urban heat island. The occurrence of groundwaters showing the elevated temperature is associated with an increased value of the geothermal gradient, which causes vertical temperature convection in the boreholes. Some of them are related to waters from the deep circulation systems connected with the cracks and fault zones. It is assumed that the most significant influence on groundwater temperature has a value of geothermal gradient, favorable hydrogeological conditions and the occurrence of overburden of sedimentary rocks, so-called blanket-rock, constituting thermal insulation of geogenic heat.

The calculated values of geothermal gradient and heat flux, despite the adopted simplifications, in case if the computational interval is at least approximately 150 (m) thick, are to a great extent in line with the results of previous research carried for the boreholes showing much higher depths. They do not differ significantly from the results of previous works both at the national (Majorowicz 1974, Plewa 1994, Majorowicz, Polkowski and Grad, 2019) and regional scales (Karwasiecka and Bruszewska 1997, Bruszewska 2000). The results of these studies confirm that temperature measurements in the boreholes up to 200 (m p.p.t.) depth, are, under certain conditions, to a large extent, an appropriate tool for updating archival thermal data and supplementing the data sets for the areas where there is a lack of the deep boreholes.

Funding

These studies were carried out as part of the project "Young tectonic zones and geothermal conditions in the Sudety Mts. in the light of geochronological, structural, and thermometric research – Stage II", accomplished as a task of the geological survey, on the basis of the agreement no 44/2017/Wn-07/FG-SM-DN/D of 15.02.2017 between the National Fund for Environmental Protection and Water Management and the Polish Geological Institute – National Research Institute.

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ANTHROPOGENIC DISTURBANCES OF SUBSURFACE TEMPERATURE IN WROCŁAW AGGLOMERATION

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Keywords: groundwaters temperature; subsurface temperature, urban heat island, geothermal gradient

Introduction

This abstract presents selected results of groundwater temperature measurements performed between 2020 – 2021 in the piezometers and wells located in the Wrocław agglomeration. The research was carried out under the terms of the project entitled "Assessing energy potential and environmental conditions to support the sustainable development of shallow geothermal energy" funded by the National Fund for Environmental Protection and Water Management and carried out by the employees of the Polish Geological Institute – National Research Institute (PGI - NRI), as a task of the Polish Geological Survey. The results presented here are mainly concerned with the vertical distribution of groundwater temperature and its seasonal variations in the upper zone of the subsurface which has not been the subject of in-depth scientific analysis so far. Presented studies aimed to acquire new temperature data from the boreholes, including vertical temperature profiles, and to analyse and evaluate them in the context of the influence of anthropogenic heat sources as well as the urban heat island effect on subsurface and groundwater temperature.

Materials and methods

The field works were preceded by data query in the geological documentations of the National Geological Archives and databases maintained by the PGI-NRI. Temperature measurements were made with the use of the KLL-Q2 multimeter (Seba Hydrometrie 2012) and MPS-D8 probe (Waterquality probes 2012) connected with a 200 (m) long cable. The boreholes investigated were characterised by a long standoff period, thus it was assumed that the water in the boreholes is in thermal equilibrium with the rock environment. Boreholes under the influence of groundwater exploitation were excluded from the studies.

In the upper part of the subsurface, a strong seasonal and annual variation of temperature occurs. At the depth where the variations disappear, which in Poland is about 15-20 (m b.g.l.), a zone of near-constant temperatures, also called the zone of neutral temperatures appear. Below, the temperature of the subsurface increases accordingly to the value of the geothermal gradient (Headon et al. 2009; Banks 2012; Pike et al. 2013). In this abstract, the term “temperature inversion point” is used to describe the above-mentioned point on the thermogram, which under the steady-state and anthropogenically undisturbed conditions usually correspond to the T_{min} value. In urban areas, numerous various anthropogenic heat sources are increasing the temperature of the atmospheric air and causing the occurrence of the so-called urban heat island effect (Szymanowski, Kryza 2012) which to some extent also influence the temperature of the upper part of the subsurface and groundwater (Buczyński, Staśko 2013).

The studies were carried out in hydrogeological boreholes exploiting the Neogene aquifer, characterized by diverse locations, i.e. in the centre and suburbs, as well as by different management conditions of land and upper subsurface, i.e.: in build-ups, parks and close to underground infrastructure, including district heating. Normally, the following methodology of temperature measurements carried out with gradual lowering of the probe below the water table in the borehole was applied: measurements every 0.5, 1, 2 and 5 (m) to the limiting depths of 5, 10 and 20 (m), respectively. Before taking measurements of water temperature in the borehole, the temperature of atmospheric air was measured each time.

Results

The Wrocław W-1 piezometer is located in Skowroni Park neighbouring the built-up areas. It monitors a Neogene aquifer occurring in sands and gravels at the depth of 78.0-83.0 (m b.g.l.) showing an ultimate depth of 90.0 (m b.g.l.). The thermograms in the upper section of the subsurface of this borehole are characterised by high variability of temperature depending on the season. The highest temperatures were measured in

January 2020 and the lowest in July 2020. The measured minimum temperatures, however, usually occurred at very similar depths of about 40 (m b.g.l.). Results of temperature measurements for the Wrocław W-1 piezometer in selected months of 2020 are shown in Figure 1.

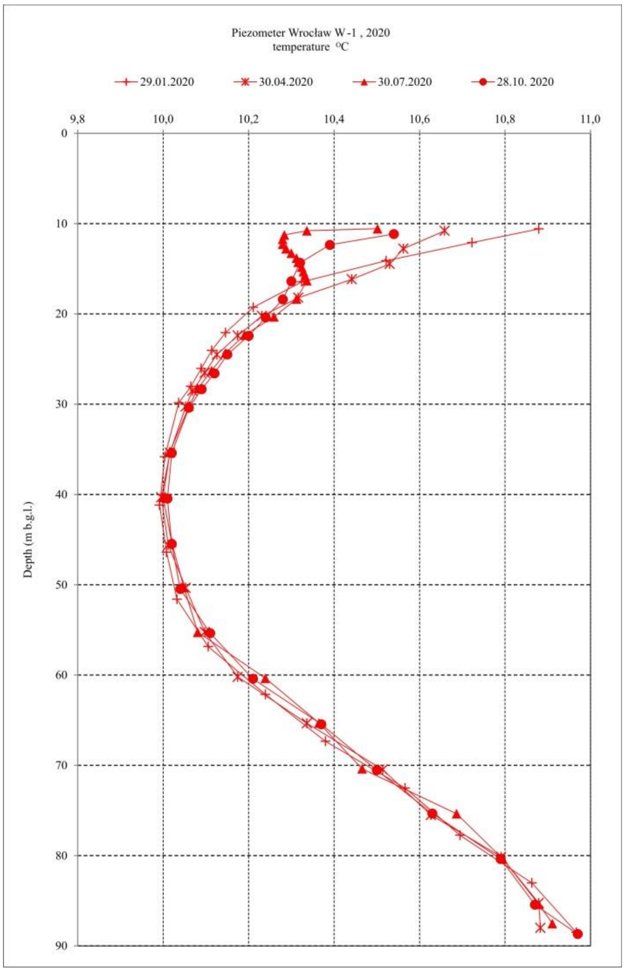

Figure 1. *Results of seasonal temperature measurements for the piezometer Wrocław W-1 in 2021*

Temperature measurements in the boreholes in the Wrocław agglomeration were taken in winter and spring 2021, their results are illustrated in Figure 2. The smallest influence of anthropogenic factors on the temperature of subsurface and groundwater is demonstrated by the borehole Wrocław - Marszowice pole, which is located on a wasteland located on the outskirts of the city. Here, the thickness of the seasonal temperature variability zone is about 17 (m) and the minimum temperature is 10.09 ^{O}C. Below, the temperature increases accordingly to the value of the geothermal gradient. For the boreholes Wrocław W-1 and Wrocław PKP, a strong temperature variability in the top part of the subsurface and an increase of thickness of the temperature disturbance zone occur. The minimum temperatures T_{min} for both boreholes equalled 10.01 and 11.09 ^{O}C and were measured at the depths of 40.31 and 49.02 [m], respectively. Below, the temperature was increasing accordingly to the value of the geothermal gradient. The most significant changes in geothermal conditions in the upper part of subsurface were found for the boreholes located within the boundaries of the built-up area, i.e. Wrocław Szpital Kolejowy, Wrocław Klasztor Bonifratrów and Wrocław Wzgórze Partyzantów. In the case of these boreholes, the thickness of the temperature disturbance zone is so large that it is not possible to identify the point of temperature inversion and the effect of the geothermal gradient on the subsurface temperature in the available thermogram sections.

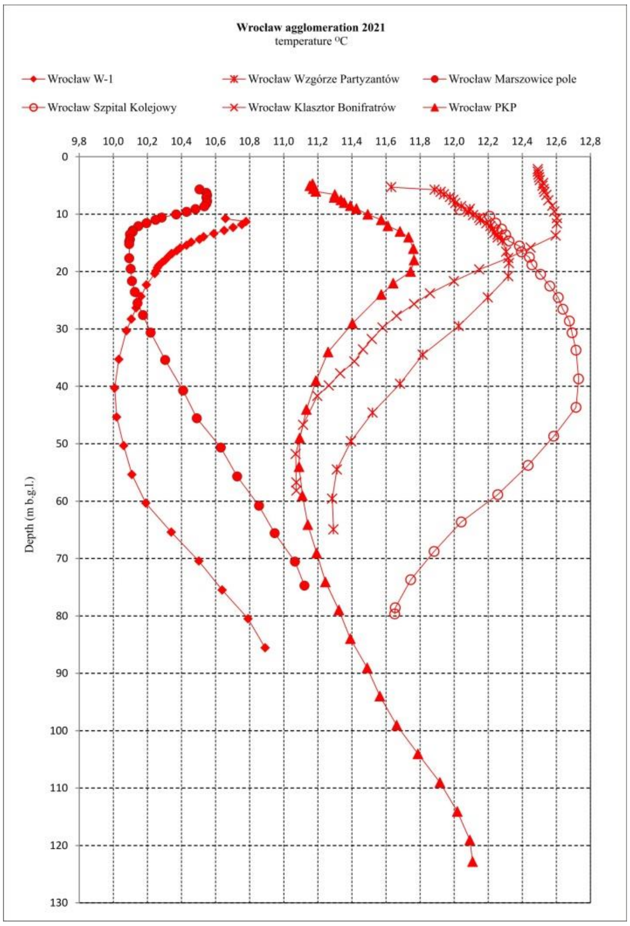

Figure 2. *Results of temperature measurements in the selected boreholes in the Wrocław agglomeration in 2021*

Conclusions

Significant temperature variability of the top part of the subsurface has been confirmed based on the results of temperature measurements (temperature profiling) of groundwater in boreholes for the urban agglomeration of Wrocław. Both seasonal temperature changes, as well as changes depending on the location, land use and use of the top part of the subsurface, have been found. The most significant temperature disturbances are visible in the case of boreholes located in the city centre, which is related to the occurrence of the urban heat island effect and anthropogenic heat sources in the form of ground and underground infrastructure, e.g. district heating and sewerage networks. It should be assumed that the thermal conditions closest to natural ones occur in the borehole Wroclaw-Marszowice pole located in the suburbs.

In the centre, the observed disturbances are so significant that they make it impossible to identify the temperature inversion point and the zone of influence of geothermal gradient value on the temperature increase of the subsurface the borehole profiles available for measurements. This applies to the boreholes Wrocław Szpital Kolejowy, Wrocław Klasztor Bonifratrów and Wrocław Wzgórze Partyzantów. The differences in temperature variability are illustrated by their arithmetic mean, the values of which for the measured temperature profiles of the four above mentioned boreholes were 10,39, 11,46, 12,03 and 12,34°C, respectively. An increase of subsurface temperature in the centre of the Wrocław agglomeration can contribute to a more efficient operation of shallow geothermal installations, including ground heat pumps, and increase the possibility of using the Neogene aquifer for seasonal aquifer heat storage, especially since its extraction was stopped several years ago.

Funding
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TRANSFORMATION OF DISTRICT HEATING SYSTEMS BASED ON ECONOMICALLY EFFECTIVE TECHNOLOGIES OF RENEWABLE ENERGY SOURCES IN THE FORM OF A DISTRIBUTED HEAT PUMP INFRASTRUCTURE

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Keywords: (heating system, heat pumps, Poland's policy, renewable energy, heating network)

Abstract
The heating sector is facing radical changes in the context of, inter alia, Polish Policy until 2040. The solution and support for the system can be local heating networks based on a hybrid model using heat pump technologies.

District heating as defined by Lund et al. (2014) includes a network of pipelines connecting individual buildings in the city to supply them with heat from centralized plants or several distributed district heating units, using available sources for the production of heating or cooling.

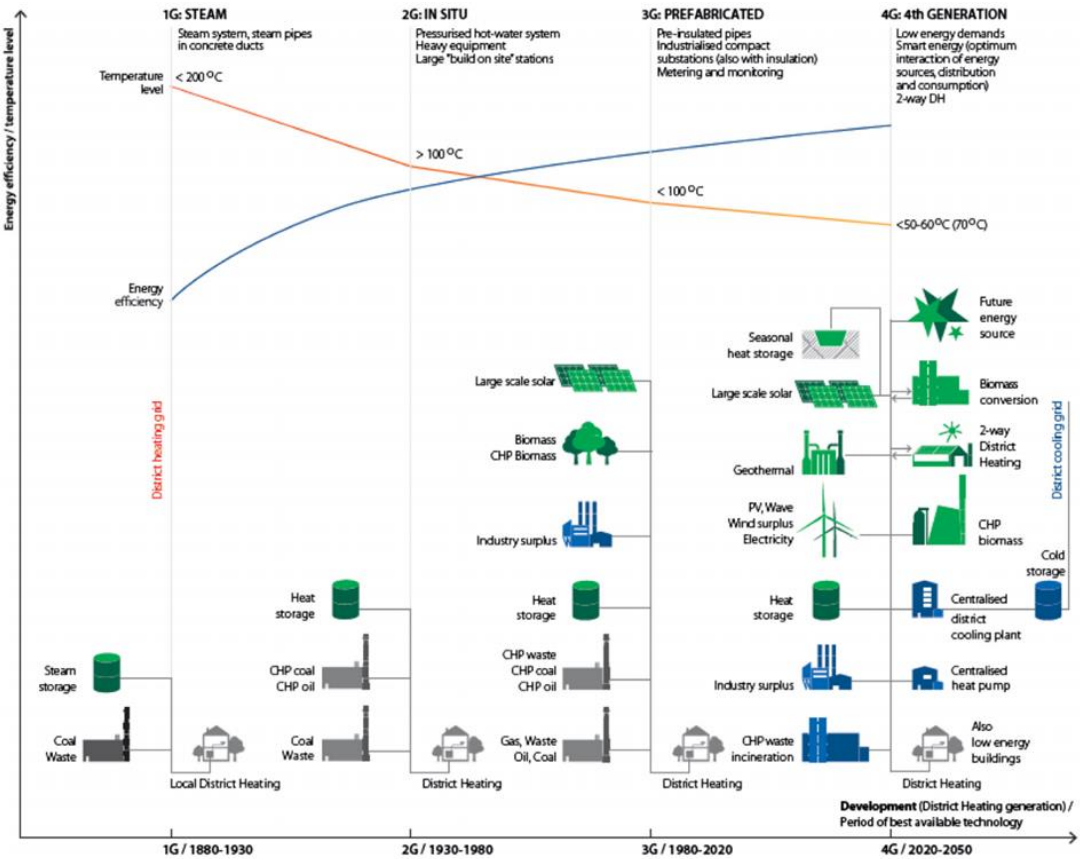

Figure 1. *Comparison of the concept of the 4th generation of heating systems with the previous three concepts. (source Lund et al. 2014)*

4th generation district heating system (4GDH) defined by Lund et al. (2014) is a coherent technological and institutional concept that supports the proper development of sustainable energy systems by means of intelligent heat networks. 4GDH systems are based on a move away from fossil fuels and the efficient use of renewable energy sources, as well as on the functioning of a network structure enabling distributed generation, which may involve interaction with consumers in the future. In addition, these systems provide heat supply to low-energy buildings (implementation of the concept of reducing the demand for space heating) with low network losses in a way in which the use of low-temperature heat sources is integrated with the operation of intelligent energy systems. In order to implement the tasks set out in the fourth generation, district heating systems of cities must take up the challenges of transformation. These issues have been described in many reports and studies, incl. Sorknæs et al. (2020), Lund et al. (2014) and also BV Mathiesen, (2013) in Renewable Energy Transport Scenarios towards 2050 (CEESA 100% Renewable Energy Transport Scenarios towards 2050: Technical Background Report Part 2) and others. The results of these studies indicate, inter alia, on the use of solutions based on the use of heat pump technology.

The analysis carried out on the example of the district heating system of the city of Krakow, the operator of which is a joint-stock company called Miejskie Przedsiębiorstwo Energetyki Cieplnej confirms the commercial use of a heat pump, the so-called high power for the production and sale of heat to the inhabitants of Krakow. According to the definition of PORT PC, the lower margin of a device classified as a high-power heat pump is the heating power exceeding 100 kW. The selection of ground source heat pumps in a vertical or horizontal variant will depend on local conditions for their effectiveness (soil type, geothermal conditions, i.e. the presence, level and flow of groundwater, temperature depending on the depth in a given place, etc.).
Taborek (2019) is characterized by a number of advantages regarding the use of heat pumps instead of the district heating network in Krakow. The construction of a network of distributed heat sources in the form of a distributed infrastructure of vertical and horizontal heat pumps is justified, among others, by in:

- Soil and geological characteristics of Kraków and the surrounding area,
- Possibilities of obtaining external, non-returnable financing under a number of financial instruments,
- Unprofitability of connecting the heating network to selected locations in and around Krakow.

An additional advantage of such a solution is not only the issues of sustainable development but also a number of other benefits, in particular economic. Ground source heat pumps could be located near clusters of multi-family and single-family residential buildings. Therefore, there is no need for infrastructure in the form of threads connecting to the existing network. Obviously, such a condition would exist if the excess heat was to be transferred from the heat pumps to the entire system. In this context, there is also no restriction in the form of distance from the existing transmission network. A distributed system of ground heat pumps requires only the construction of local transmission infrastructure, which is cheaper due to the smaller network length needed for proper operation and lower costs of purchasing transmission network elements (smaller diameter pre-insulated pipes).

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NUMBER OF BOREHOLES IN POLAND AND THE POTENTIAL OF THEIR USE FOR GEOENERGETICS PURPOSES

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Keywords: boreholes, borehole heat exchangers, deep borehole heat exchangers, geothermal energy, geoenergetics

Abstract

Drilling boreholes are mining pits with a circular cross-section, made by different drilling methods used to extract liquid raw materials. The most common raw materials extracted in that way are crude oil, natural gas and water, including geothermal. Currently, European Union countries including Poland, place great emphasis on climate neutrality. Investments in geothermal energy are an important element of energy transformation. Unfortunately, the costs of drilling a borehole can amount to several million zlotys. In the years 2016 - 2018, the National Fund for Environmental Protection and Water Management co-financed 7 projects concerning the exploration and examination of geothermal waters for the total amount of over PLN 133 million. Drilling accounted for the largest part of this amount. The cheaper alternative can be found through adaptation of the old oil, gas and exploration wells for geothermal purposes. As shown by the example of Mszczonów, the reconstruction of a liquidated well and its adaptation for geothermal purposes accounted for only 40% of the cost of drilling a new well (Bujakowski et al. 2005).

However, the liquidation of these boreholes is still a much more popular activity than the adaptation of inactive boreholes. Many factors contribute to the reasons for liquidation. These factors largely depend on the purpose of the boreholes in question. Test or exploitation boreholes are liquidated after completion of the works, i.e. after collecting enough data from the well. The decision to close production boreholes is made based on the degree of use of the deposit. In this type of well, liquidation is performed when a given deposit is used to the maximum or when further mining becomes unprofitable (Wojtyczka 2020).

Boreholes can be changed not only when there are layers with geothermal waters in their profiles. When there is no layer with geothermal water in the borehole, such a bore can be used as a deep heat exchanger. For this purpose, reconstructive procedures should be performed. To adapt the unused bore, additional heat exchanger pipes are installed - most often they are centric pipes. The second equally important condition is the presence of heat consumers. Due to the difficulties with heat transport, consumers should be as close as possible to the openings - which in many cases is not possible since the openings are located far from buildings and infrastructure.

To assess the potential of our country in the field of the re-use of archival wells, the number of boreholes drilled for hydrocarbons was examined. The results are summarized in Table 1. Nevertheless, it should be emphasized that the presented data is limited to boreholes downstream of hydrocarbons only. In fact, there are many more boreholes in Poland. Boreholes for other purposes (eg mapping, hydrogeological, etc.) were not the subject of these studies. Before the Second World War, 45 boreholes over 1000 m were made in today's Poland. Within 40 years this number increased to 5773. It is estimated that so far about 8000 such boreholes have been made. On the other hand, shallower boreholes (up to 500 m deep) have already been made over 150 000 (Wojtyczka 2020).

In addition to geothermal water, thermal energy can also be extracted from boreholes. The openings that cover this are called borehole heat exchangers. An important advantage of borehole heat results is the possibility of storing heat in the rock mass, which significantly improves the efficiency of such a heat source. Most commonly, borehole heat exchangers are drilled up to 300 m. However, borehole heat exchangers can be deeper. In this case, there is a chance that the heat pump will not be needed to draw heat. Old boreholes can also be adapted to borehole heat exchangers. Considering the above data and assuming the average power of the borehole heat exchanger within the range from 20 to 50 W / m of the borehole depth, theoretical potential total powers in individual provinces were calculated. The data in Table 2 is only an idea of the potential.

Borehole heat exchangers are based on the same assumption as geothermal wells - to use them, they must be located near heat and/or cooling receivers. In their case, however, the geological structure is not so important.

Table 1. *Number and size of all drilled boreholes (reservoirs and exploratory) downstream of hydrocarbons in individual provinces*

Province	**Reservoirs boreholes, pc**	**Exploratory boreholes, pc**	**All pc**	**Size of all boreholes, m**
dolnośląskie	389	5	394	610 697
kujawsko – pomorskie	21	1	22	78 226
lubelskie	120	8	128	273 270
lubuskie	295	6	301	674 880
łódzkie	42	2	44	125 701
małopolskie	1681	24	1705	1 592 431
mazowieckie	24	10	34	97 168
opolskie	0	0	0	0
podkarpackie	**4523**	**40**	**4563**	**4 919 413**
podlaskie	0	0	0	0
pomorskie	53	8	61	183 296
śląskie	105	4	109	73 614
świętokrzyskie	61	10	71	38 534
warmińsko -mazurskie	10	9	19	42 480
wielkopolskie	654	20	674	1 721 295
zachodniopomorskie	257	1	258	813 814
Total	**8235**	**148**	**8383**	**11 244 819**

Table 2. *Limits of the theoretical total power of potential deep borehole heat exchangers in Poland*

Province	**Lower limit, kW, for 20 W/m**	**Upper limit, kW, for 50 W/m**
dolnośląskie	7 880	19 500
kujawsko – pomorskie	440	1 100
lubelskie	2 560	6 400
lubuskie	6 000	15 000
Łódzkie	880	2 200
małopolskie	34 100	85 250
mazowieckie	680	1 700
podkarpackie	**91 260**	**228 150**
pomorskie	1 220	3 050
śląskie	2 160	5 400
świętokrzyskie	1 420	3 550
warmińsko – mazurskie	380	950
wielkopolskie	13 460	33 650
zachodniopomorskie	5 160	12 900
Total	**167 600**	**419 000**

Most, as many as 4,563, boreholes behind hydrocarbons were made in the Podkarpackie Province. This region has great prospects for the effective use of borehole heat exchangers, due to high urbanization. In Podkarpacie, adaptations of boreholes were carried out, among others in Krosno (Turaszówka deposit) and in Iwonicz Zdrój (Śliwa et al. 2000). The second place in this ranking was taken by the Małopolskie Voivodeship, while the third place was taken by the Greater Poland Voivodeship. These areas have the best chance of developing old oil wells in geothermal energy. The reconstruction and use of dredged boreholes behind hydrocarbons may be an important factor in the development of geothermal energy in Poland. However, it should be remembered that for the borehole to be used for geothermal purposes, it must be in good technical condition and must be in close proximity to heat consumers. A detailed analysis of the technical condition and location of the described boreholes should be the subject of further tests. It is also important to analyze the possibility of using the well for geothermal purposes before deciding to decommission the well.

The wider issue is the use of boreholes in geoenergetics. Thanks to the existing openings, also the closed ones, it is possible to store energy. The best example is the use of the borehole as a gravity store of electricity. Such an installation works at AGH in Krakow. Thanks to this, it is possible to store solar radiation energy converted into electricity in photovoltaics panels. The introduction of energy into the borehole involves the motor and gearbox carrying the weight inside the borehole. Night illumination of the AGH UST part with the use of energy from the Sun is realized by the weight which, falling in the borehole, drives the generator and recreates a significant part of the electricity. Geoenergetics is defined as geothermal energy and underground energy storage (including heat).

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ADAPTATION OF EXISTING AND ABANDONED WELLS AS DEEP BOREHOLE HEAT EXCHANGERS. TECHNOLOGY OF COMPLETION ASSEMBLY INSTALLATION FOR GEOTHERMAL HEAT EXPLOITATION

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Keywords: deep borehole exchangers, geothermal energy, HDR, well construction

Abstract

The topic of this report is „Adaptation of existing and abandoned wells as deep borehole heat exchangers. Technology of completion assembly installation for geothermal heat exploitation".

In this report, the methods of adaptation of existing dry wells closed wells or depleted well to exploit geothermal heat are presented. Taking into account the number of boreholes drilled in Poland, their geographical location, often in urban areas of communes, towns or cities or in a small distance from them, an idea of utilizing such boreholes and harnessing the heat from the rock mass arises. The report presents that only since the 1980s, more than 4 300 wells deeper than 500 m have been drilled in Poland, including more than 3 500 wells deeper than 1 000 m. The possibility to close part of a borehole that is in contact with the hydrocarbon reservoir by means of a combination of cement plugs and mechanical plugs, confirmed by appropriate tightness tests, creates conditions for utilizing heat, which is manifested by elevated temperatures in the lower part of the borehole, for energy purposes. The authors of this report emphasize that each borehole should be approached individually, by analysing the well and reservoir conditions, geographical location and the possibility of exploiting the acquired energy. Most of those wells were drilled as exploration or production wells for hydrocarbons. Among the above-mentioned wells, apart from those drilled for hydrocarbons, there are also exploration, geological and geothermal wells. Wells were drilled all over Poland, however, most of them are located in the south and west parts of the country. Generally, the wells in the west of Poland have a higher geothermal gradient and these wells should be examined first. Figure 1 shows a map with temperature distribution at a depth of 2,000 m, which reflects the temperature difference that can occur at the same depth depending on the considered area. A large number of wells that have been drilled have unfortunately not been put into production due to lack of adequate flow rate or due to lack of economic viability. There is also a number of wells that have been abandoned after the reservoir has been depleted.

The current policy of the European Union included, among other things, in the plan called European Green Deal and in the RED II Directive on the promotion of the use of energy from renewable sources shows increasing importance on renewable energy in the energy economy of the European Union member countries and show the direction of changes which these countries should aim at. One of the postulates of European Union policy is the greater use of energy from geothermal sources.

The most common and economically viable method of obtaining heat from the rock mass, including reservoir waters, are geothermal wells (Sapińska-Śliwa et al. 2017, Śliwa et al. 2019a). There can be two wells and one of them is used to inject fluid–injection well, while the other receives the heated fluid – production well. If there is a system of several boreholes, then similarly, part of the boreholes is used for fluid injection and part for fluid production, this depends on reservoir conditions. Another method of utilizing heat from the rock mass is the HDR (*hot dry rock*) method. The report briefly presents the HDR method, which uses wells and geothermal heat through using a medium, usually water, in a closed-loop in a reservoir without reservoir water supply (Śliwa et al. 2012).

Nowadays borehole heat exchangers which are constructed in the drilled wells are becoming more and more popular worldwide. The majority of wells drilled for heat exchangers are shallow wells with depths of tens to hundreds of meters (Śliwa et al. 2019b). However, in this report, the authors focus on much deeper wells, even up to 3,000 m, where the bottom temperature is much higher and which could be also used for heat exchangers. The authors of this report present the possibility of using existing wells to exploit geothermal heat. The cost of restoring and adapting existing wells in comparison to the cost of newly drilled ones should be

significantly lower. Especially, cost of adapting currently drilled dry boreholes. In case of obtaining unsatisfactory reservoir parameters, directly before dismantling the drilling rig, they could be adapted to work as borehole heat exchangers. Of course, this refers to boreholes located near agglomerations, where the costs of installation construction and loss of extracted geothermal heat are included in the economic viability. These costs should include financial support for pro-ecological projects.

In this report, various completion assemblies both for geothermal well and deep borehole exchangers are presented. For geothermal wells, variants with fibreglass casing as well as steel casing were presented as production casing with the possibility of their replacement after several years of service. For heat exchangers, a variant of final equipment with the use of vacuum insulated tubes (VIT tubes) was presented, which are designed to minimize the heat exchange between the injected fluid, with low temperature, and the received fluid with high temperature (Śliwa et al. 2017a, 2018). A variant with two coaxial casing columns with nitrogen between them as insulation is described. Nitrogen has low pressure due to the use of a vacuum pump to improve insulation. The technology involving the above methods will be described. Hazards that may occur during well completion will be presented. The advantages and disadvantages of each method will be presented. The authors of the report have focused in large part on heat exchangers that do not use reservoir fluid but create a closed circulation system in which the working fluid is pumped from the surface into the borehole where it is heated and then brought to the surface where the heat of this fluid is used to heat the infrastructure.

An important part of proper completion of such a well is sealing the production casing column. The cement should have a relatively high thermal conductivity, which will allow to swiftly raise the temperature and increase the amount of energy absorbed by the injected fluid. Cement with an increased coefficient of thermal conductivity will allow more efficient heat exchange between the rock mass and the circulating working fluid (Śliwa et al. 2017b) and its faster heating, which in turn will allow to achieve a higher flow rate and obtain more power from the borehole heat exchanger.

Geothermal heat is a relatively expensive source of the energy, especially when taking into account the cost of drilling a well. Because of these high costs, before the decision to completely abandon drilled well, the possibility of using it as a borehole heat exchanger should/could be taken into consideration.

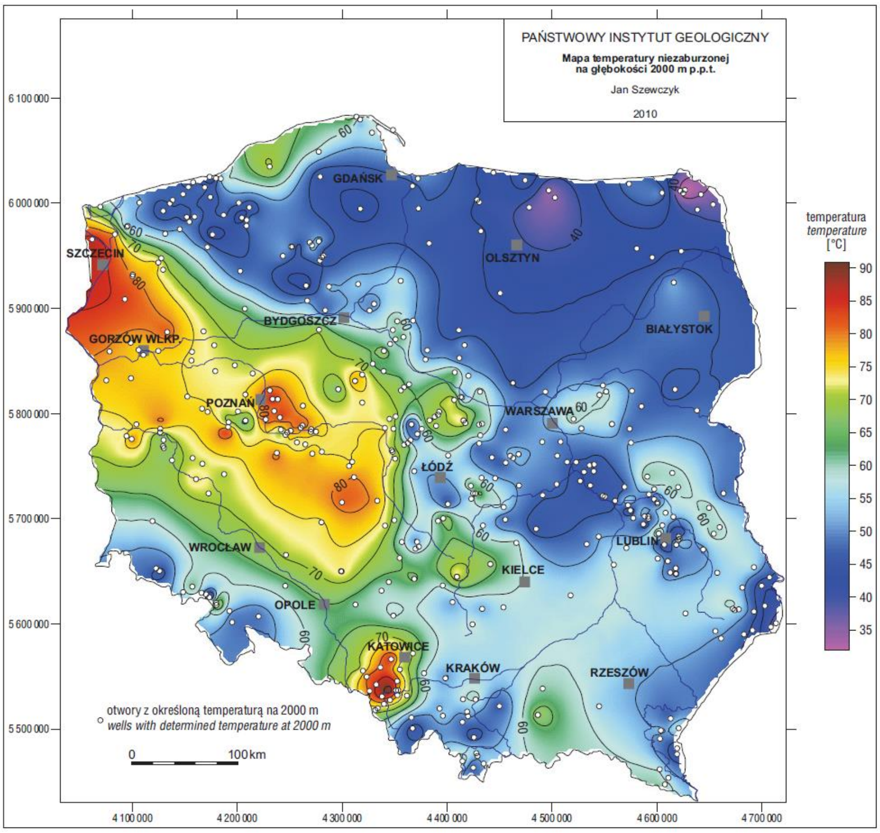

Figure 1. *Map of temperature distribution at 2 000 m depth for Poland (Szewczyk 2010)*

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DEEP BOREHOLE HEAT EXCHANGER BASED ON THE WELL SĘKOWA GT-1

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Keywords: geothermal energy, deep borehole heat exchanger, renewable energy sources, geothermal heat pumps

Introduction

The Sękowa GT-1 exploration and appraisal well-financed by the National Fund for Environmental Protection and Water Management from the program "Geology and mining, part 1 - Understanding the geological structure of the country and management of mineral deposits and groundwater" showed the lack of prospective aquifers for the production of geothermal energy. Approved on February 2, 2021 "Poland's energy policy until 2040" treating, among others on increasing the share of renewable energy sources in system heating, obliges local governments to seek innovative solutions in this area. The municipality of Sękowa (Małopolskie Voivodeship) actively participates in obtaining external funds for financing various investments, including the so-called renewable energy sources. Drilling works in the Sękowa GT-1 borehole ended with the failure regarding its main goal, which was to document the prospective geothermal water deposit, which cancelled the original plans for their use. However, thanks to the adopted national strategy PEP40, in cooperation with the Ministry of Climate and Environment, the National Fund for Environmental Protection and Water Management, the municipality authorities and the scientific community, an optimal, innovative on a national scale variant of the use of the borehole in the form of a deep borehole heat exchanger has been developed.

Samples and methods

Borehole heat exchangers can be used to both extract low-temperature thermal energy from the rock mass and as underground heat storage. On average, they are up to 200 m deep, but some of them are almost 3,000 m deep. Underground heat storage can economically provide heat and cold, depending on the need. In winter, they obtain heat for heating buildings by cooling down the rock mass. In summer, however, they use the chill from the rock mass to cool the interior. Taking cold from the rock mass is equivalent to the introduction of heat into it. The heat obtained from ventilation is transported to the rock mass for re-use during the heating season. Seasonal regeneration of heat / cold resources in the rock mass surrounding the exchanger takes place through natural processes (such as heat inflow from adjacent layers, heat lifting by the filtering groundwater) and in an artificial way (obtaining heat for heating in winter is a process of introducing cold into the rock mass, and obtaining coolness in summer is a process of regenerating heat resources).

In the case of the Sękowa GT-1 well (Figure 1), design works were commenced to adapt the well to the production of thermal energy. Deep borehole heat exchangers are used for heating, their use in refrigeration is not rational due to technological reasons resulting from the natural increase in temperature with depth. In subsequent phases of the pilot program implemented there, it will be possible to use this and the neighbouring wells previously drilled by the oil industry. Figure 2 shows the location of the three considered boreholes: Sękowa GT-1, Gorlice 12 and Gorlice 13.

Drilling of the geothermal well Sękowa GT-1 commenced on June 8, 2020, and was completed on September 11 of the same year, thus reaching the planned depth of 3,000 meters. The tests performed in the interval from 1 500 to 3 000 m deep showed the lack of geothermal waters. In order to enable the adaptation of the negative hole to the deep hole heat exchanger, cement plugs were made in the interval from 2 435 to 3 000 m and then they were subjected to a leak test. At a depth of 2 356 m, a mechanical stopper was fastened, which was also tested. On December 8, 2020, a team of scientists from the Laboratory of Geoenergetics from Faculty of Drilling, Oil and Gas of the AGH University of Science and Technology in Kraków and the Institute of Mineral and Energy Economy of the Polish Academy of Sciences, commissioned by the Sękowa municipality, began work on research and development expertise in the prospect of possibility and validity of geoenergetic use of the Sękowa GT-1 well in the form of a deep borehole heat exchanger. The expertise was delivered to the investor on April 30, 2021.

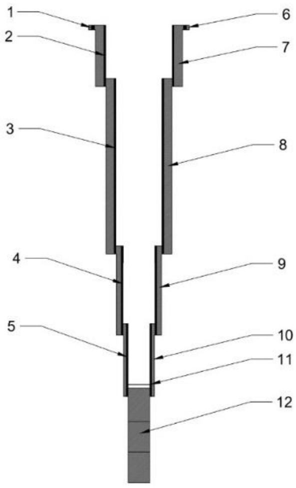

Figure 1. *Structure of the partially closed well Sękowa GT-1, 1 - preliminary column, 2 - guide column, 3 - technical column, 4 – 1st exploitation column , 5 – 2nd exploitation column , 6 - slurry sealing the preliminary column, 7 - slurry guiding column sealing, 8 - technical column sealing grout, 9 - sealing slurry of the 1st exploitation column, 10 - sealing slurry of the 2nd exploitation column, 11 - mechanical plug, 12 - cement plug.*

Figure 2. *Location of three boreholes considered for energy use: Sękowa GT-1, Gorlice 12 and Gorlice 13.*

The Geoenergetics Lab of the Drilling, Oil and Gas Faculty AGH UST performed the tasks related to the adaptation of the partially closed Sękowa GT-1 borehole into a deep borehole exchanger and the assessment of the adaptability of the Gorlice 12 and Gorlice 13 boreholes. The tasks listed below were completed.

1. Analysis of the results of temperature measurements made in the Sękowa GT-1 well in terms of its use as a deep borehole heat exchanger.

2. A variant concept of a deep borehole heat exchanger using the Sękowa GT-1 borehole (made on the basis of the already existing data on the borehole structure supplemented with information obtained from as-built documentation). Indication of the optimal concept. Description of working conditions in cooling (storage) mode.
3. Assessment of the potential and energy parameters of a deep borehole heat exchanger using the Sękowa GT-1 well.
4. Performance of the geoenergetic characteristics of a deep borehole heat exchanger based on the Sękowa GT-1 geothermal well.
5. Assessment of the structure, technical condition, potential and energy parameters of the Gorlice-12 and Gorlice-13 wells (adjacent to the Sękowa GT-1 well) in terms of the possibility and legitimacy of their use in the form of deep hole heat exchangers. The proposed concept of deep borehole heat exchangers using Gorlice-12 and Gorlice-13 wells.
6. Conclusions in the field of technical and technological conditions resulting from the conducted analyzes and works for the subsequent implementation of deep borehole heat exchangers.

Results

The results of the research and analysis carried out by the team of the AGH University of Science and Technology Laboratory of Geoenergetics in Kraków indicate the investment consisting of adaptation of the negative geothermal Sękowa GT-1 well as a deliberate investment. The economic aspect lies in the cost of pipes, which are characterized by high thermal insulation that remains constant during operation. They are an indispensable element of the centric structure of the hole heat exchanger. So far, vacuum insulated pipes have been used in similar adaptations of this type, but costs of purchase and transportation to the place of implementation and assembly puts the profitability of the investment into question. However, the expertise proposed an innovative solution aimed at creating thermal insulation between the water heated from the rock mass, flowing down the annular space and the heated water flowing upwards in the inner column. It was, therefore, possible to reduce the costs of adaptation by more than 30 percent. A diagram of the developed structure is shown in Figure 3.

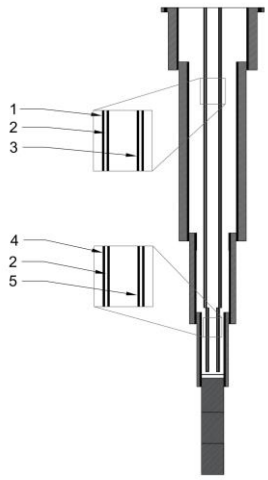

Figure 3. *Construction of the insulating column of the deep borehole heat exchanger based on the negative geothermal well Sękowa GT-1, 1 - outer casing pipe 7" in the insulation column, 2 - vacuum, 3 - internal extraction pipe 3 ½" in the insulating column, 4 - 5" outer casing pipe in the insulating column, 5 - internal extraction pipe 2 ⅞ " in the insulating column.*

Simulations of the operation of a deep borehole heat exchanger based on the negative geothermal Sękowa GT-1 well, located in an area with a much lower geothermal gradient, confirm the economic sense of the planned investment in the long term. Figure 4 shows the geoenergetic characteristics of a borehole heat exchanger with the following parameters: heat carrier water from 0°C or glycol solution below 0°C, heat carrier flow

10 $m^3 \cdot h^{-1}$, initial temperature on the surface 10°C, initial temperature at a depth of 3 000 m 87°C.

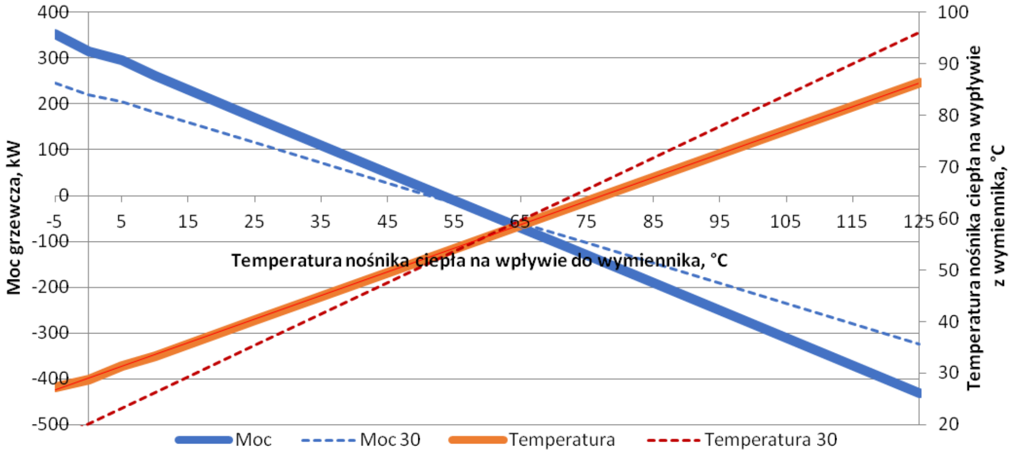

Figure 4. *Geoenergetic characteristics of a deep borehole heat exchanger based on the Sękowa GT-1 geothermal well after one year and after 30 years of continuous heat operation at a constant heating power.*

Conclusions

The adaptation of negative, closed or liquidated boreholes into deep borehole heat exchangers is becoming increasingly popular in the world. An example of such investment is the adaptation of the oil and gas well in Kiskunhalas in Hungary, closed in the 1960s and adapted in March of 2021 Collecting thermal energy from a 2 000 m deep borehole, it will enable heating of buildings with an area of 20 to 30 thousand square meters. This is mainly due to the anomalously high geothermal gradient at the level of 50 to 60°C/km, which characterizes the Hungarian region.

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HYBRID INSTALLATION OF AN ENERGY SOURCE BASED ON THE DEEP BOREHOLE HEAT EXCHANGER SĘKOWA GT-1

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Keywords: hybrid energy source, geothermic, deep borehole heat exchanger, heat pumps, solar energy, photovoltaics

Introduction

The proposal of hybrid installation, assuming the use of a borehole heat exchanger as a source of low-temperature energy was developed within the framework of the "Research & development expertise in the field of possibilities and validity of geothermal energy extracted by the well Sękowa GT-1 by using it as a deep borehole heat exchanger" (2021). The work was done on a basis of a contract agreement between the Sękowa Commune and Mineral and Energy Economy Research Institute, Polish Academy of Sciences.

The Expertise was initiated by the Ministry of Climate and Environment in cooperation with the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (MEERI PAS), the Geoenergetics Laboratory of the Faculty of Drilling, Oil and Gas AGH-University of Science and Technology LG FDO&G AGH-UST) and the Sękowa Commune. It was financed by the National Fund for Environmental Protection and Water Management. The Expertise became the basis for the pilot installation proposal to use the given borehole as a deep heat exchanger and to build a hybrid energy source based on it for local needs.

The presented results come from Part B of the Expertise (developed by the MEERI PAS team under the leadership of W. Bujakowski). It aimed to propose a source that would be able to meet the power and energy demand of a selected group of recipients. It was based on the results of Part A of that Expertise (developed by the team of LG FDO&G AGH-UST under the leadership of T. Śliwa), which concerned, inter alia, proposals for the construction of a deep borehole heat exchanger based on the negative geothermal Sękowa GT-1 well, assessment of its potential and energy parameters, geoenergetic characteristics, assessment of the effects of its application (these issues are included in a separate abstract).

Materials and methods

The simulation of an energy source was done by using the lumped parameter model. The parameters determined during the modelling process were temperature, pressure and mass flow of the medium as well as its type at the nodal points connecting the individual important elements of the installation. Several possible variants of a hybrid energy source were analyzed. They differed from each other in terms of the scope of the analyzed users and the type of primary energy carriers and devices used for the conversion of primary energy into usable energy. A wide group of energy recipients was analyzed, initially consisting of 8 recipients with a total demand for a maximum power of 1.1 MW. This variant was called variant A. This power significantly exceeded the power of the heat pump installation cooperating with the deep borehole heat exchanger. Additionally, some of the analyzed objects were significantly distant from the exchanger. Their inclusion in one system would require quite long connections. An extensive network increases the required investment outlays. Moreover, additional thermal energy losses and high flow resistance occur. Some of the analyzed objects are already used for heating purposes air source heat pumps. Therefore, it was decided to concentrate the group of users, to two facilities located directly in the near surrounding of the Sękowa GT-1 well. Finally, the group of users consist of the existing sports field, including its infrastructure, and a planned sports and recreational facility, which will be a swimming pool with an annual energy demand of 3 350 GJ/year (according to a project). This variant was called variant B.

The group of those two objects reduced the demand for heating power to approx. 420 kW, and the demand for thermal energy at the level of 3 768 GJ/year. Nine configurations of the hybrid energy source were analyzed, including the reference option assuming the use of natural gas and grid electricity to cover the needs of the users. Additionally, the source included various configurations of heat pumps (PC) - using the borehole heat exchanger based on the Sękowa GT-1 well, gas boilers (KG) used as a peak heat source, solar thermal collectors (KS), cogeneration modules (simultaneous production of electricity and heat) driven by natural gas (MCP), photovoltaics (PV). In the preliminary stage of the work, it was assumed the energy self-sufficiency of the facilities. However, due to the high level of capital expenditure, that exceeded the assumed level of PLN 5 million, this option was abandoned. Due to the capital expenditure exceeding the assumed level of PLN 5 million for the installation of the energy source, this option was abandoned.

Results

A comparison of investment outlays is presented in Figure 1 and 2 compares operating costs, Figure 3 net variable costs of energy generation, Figure 4 compares the share of renewables in the overall balance of its consumption, while Figure 5 shows a comparison of specific CO_2 emissions in on a global scale, for individual variants, taking into account the current fuel mix used to produce electricity from the power grid (KOBiZE, 2020). Emission for the gas boiler was determined on the basis of pollutant load indicators by KOBiZE (2021).

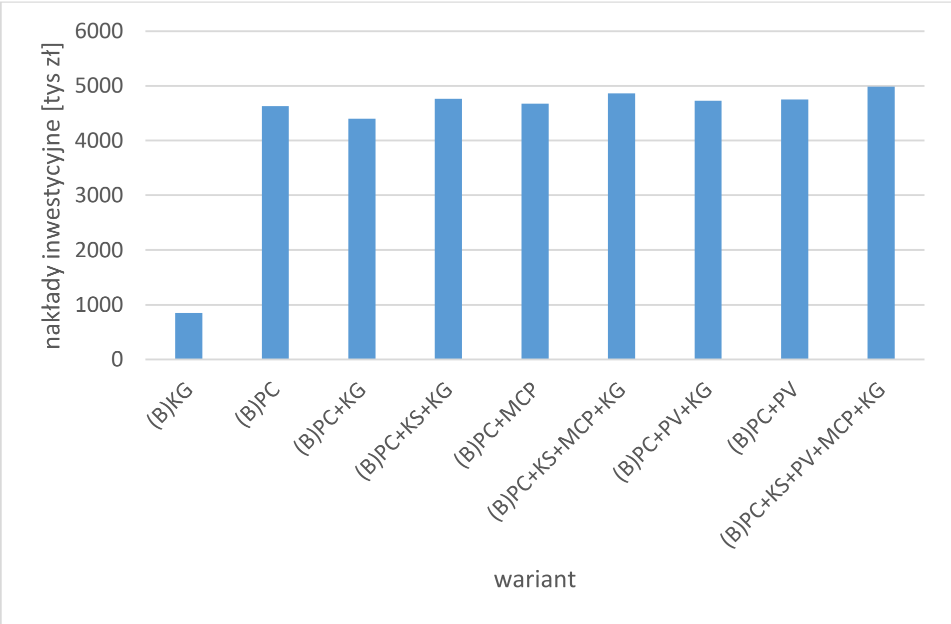

Figure 1. *Comparison of the anticipated net investment expenditures characterizing the variants, abscissa defines the variants and the axis of ordinate investment outlays in thousands of PLN (1 PLN=~0.26 $, 1 PLN=~0.22 €)*

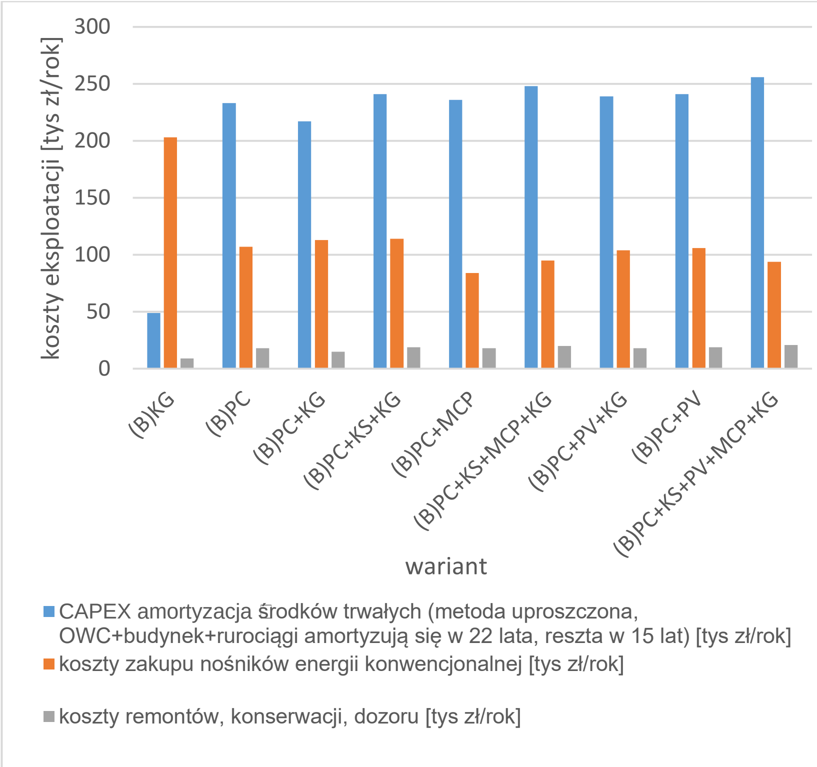

Figure 2. *Comparison of the annual net operating costs of an energy source installation in the variants, abscissa defines the variants and the axis of ordinate the costs of source of energy exploitation in thousands of PLN (the blue rectangles – CAPEX, the orange rectangles – costs of energy carriers, the grey rectangles – maintenance costs)*

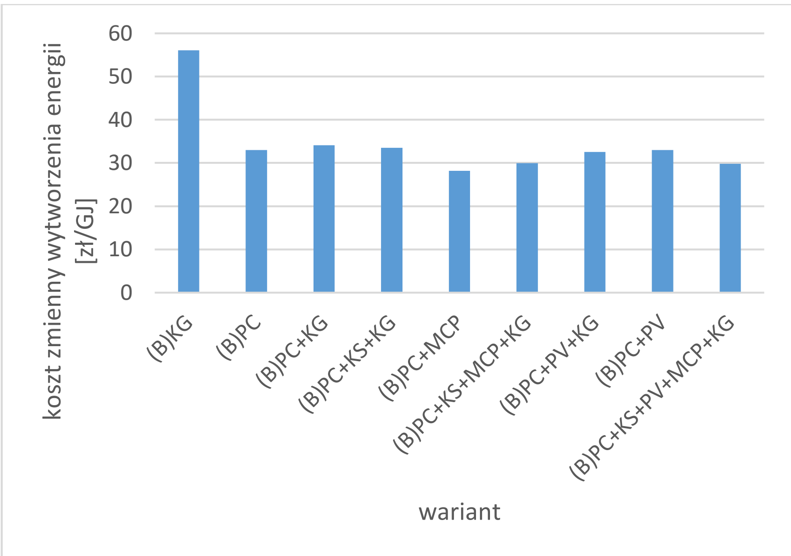

Figure 3. *Comparison of net unit costs of energy generation taking into account variable costs only, abscissa defines the variants and the axis of ordinate the unitary operating costs of energy production in PLN/GJ*

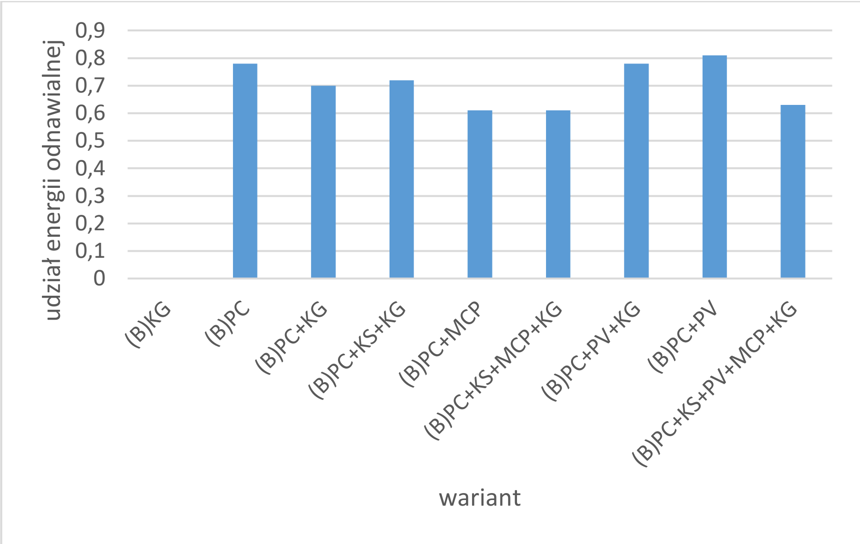

Figure 4. *The share of renewable energy in the overall balance of its consumption for the analysed variants, abscissa defines the variants and the axis of ordinate the share of renewables*

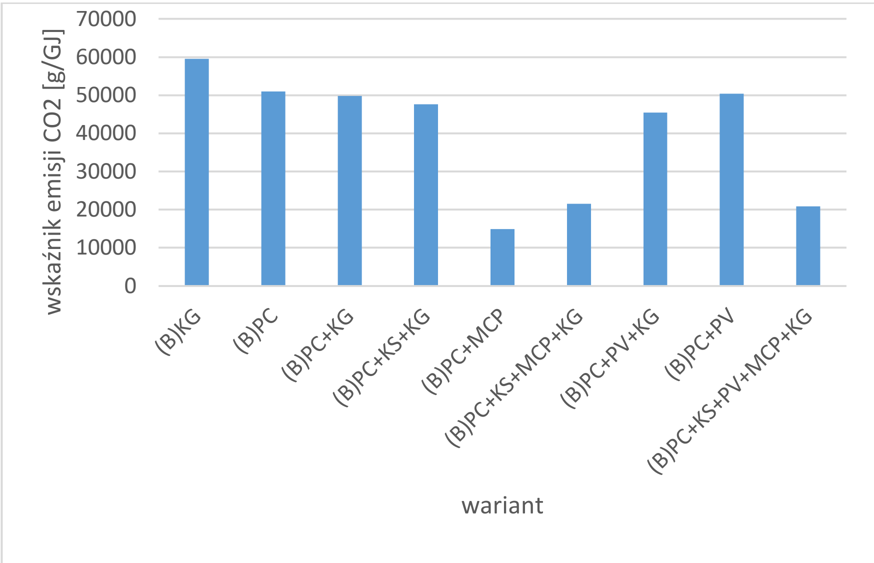

Figure 5. *Comparison of the unitary CO_2 emissions on a global scale for individual variants, taking into account the current fuel mix used to produce electricity in the power origins on the electricity grid, abscissa defines the variants and the axis of ordinate the unitary CO_2 emission [g/GJ]*

Conclusions

All variants were limited by the level of investment outlays, it should not exceed PLN 5 million, with the recommended level of PLN 4.7-4.8 million. If the expenditures are lower than those listed, it means that the users' needs have been covered with lower investment expenditures (e.g. option (B)PC+KG).

The optimal variant considering the lowest required capital expenditure is the variant assuming the use of natural gas boilers (B)KG – it is called the reference variant. The second variant, which can be considered optimal in terms of the required level of investment outlays, is a variant (B)PC+KG (Figure 1). The optimal variant due to the lowest unitary costs of energy production (Figure 3) is a variant (B)PC+MCP. The optimal variant assuming the highest share of renewable energy as the priority (Figure 4) is the variants (B)PC+PV, (B)PC and (B)PC+PV+KG are slightly worse. If considering the lowest CO2 emission as the priority, the optimal variant is (B)PC+MCP (Figure 5).

It can be noted that the most frequently mentioned option is a variant (B)PC+MCP. It assumes the cooperation of cogeneration modules and heat pumps. It appears twice in the criteria mentioned. It is optimal due to the lowest CO_2 emission and due to the lowest variable costs of energy generation.

The variants assuming no use of the cogeneration modules (Fig. 4) have the largest share of energy from renewable sources in the overall energy consumption balance. At the same time, the use of the modules causes a decrease in CO_2 emissions. The use of the modules reduces the carbon footprint associated with the generation of thermal energy (Fig. 5). CO_2 emission characteristic of variants assuming the use of thermal-current modules is almost 3 times lower than other variants. This is, of course, related to the origin of the grid electricity consumed in other variants. Electricity is still produced in Poland with very low efficiency, from hard coal and lignite (over 80%). The cogeneration modules produce electricity from cleaner fuel in a more efficient way.

With the change in the structure of the mix of fuel used to produce electricity, the situation may become more favourable for other variants - those consuming network electricity. However, it should be remembered that the technical life of the devices may be shorter than the expected change period due to the energy transformation. The cost of heat generation (Fig. 3) for all analyzed variants is lower than the base variant (B)KG, which assumes the use of gas as the only energy carrier. This is an important conclusion because it indicates the possibility of achieving positive economic effects of the operation and the return of investment expenditure.

The lowest cost of heat generation is associated with the variants assuming the use of thermal current modules. It is interesting to compare the costs of energy production in the (B)PC+PV+KG and (B)PC+PV variants - in the first, gas boilers were introduced, partially reducing the expenditure related to the purchase of heat pumps. The money saved was invested in increasing the surface of the PV cells (in the variant with a boiler there are more than twice bigger PV surfaces than in the variant without a boiler). The level of investment outlays is similar. In the variant assuming the use of boilers, slightly cheaper energy would be produced, with a similar share of renewable energy and a lower CO_2 emission factor is observed. This proves the advisability of using an appropriate composition of hybrid energy sources.

Pilot project proposal

A comprehensive analysis of various variants of a hybrid energy source based on the Sękowa GT-1 deep borehole heat exchanger showed that if it was to be a pilot installation demonstrating the possibilities of technology, new trends and in line with the idea of transforming the energy sector towards RES and zero-emission economy, the optimal be a variant using (next to the heat pump) a heat pump, supported by PV cells. Heat pumps are devices that perfectly combine the sectors of clean electricity and heat generation. The diagram of this variant is shown in Figure 6. It will be the basis for the pilot project of a hybrid energy installation based on the Sękowa GT-1 deep borehole heat exchanger. The project will have research, implementation and practical significance also on a national scale.

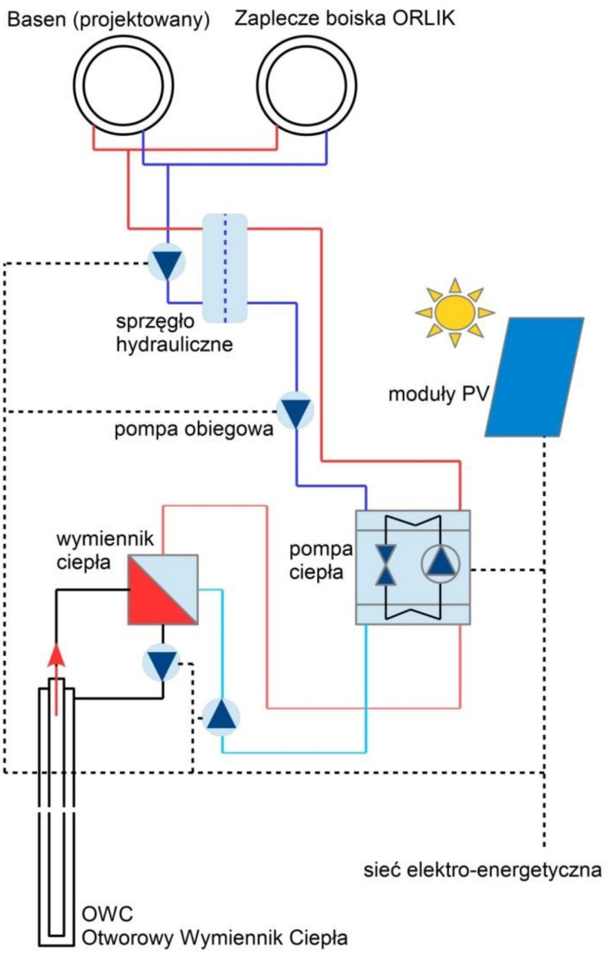

Figure 6. *A scheme of a hybrid energy source based on a deep borehole heat exchanger Sękowa GT-1. A variant recommended as a pilot project*

OWC Otworowy wymiennik Ciepła: [deep] borehole heat exchanger, wymiennik ciepła – heat exchanger, pompa obiegowa – circulation pump, pompa ciepła – heat pump, sieć elektro-energetyczna – electrical grid, sprzęgło hydrauliczne – hydraulic clutch, moduły PV – PV modules, Basen (projektowany) – swimming pool (planned), Zaplecze boiska ORLIK – ORLIK pitch back room

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