Geology, Geophysics & Environment 2025, vol. 51 (4): 427–440

Geothermal water and energy management in Polish district heating – directions for effective use in the Polish Lowlands

Karol Pierzchała[1], Leszek Pająk[2], Barbara Tomaszewska[3], Magdalena Tyszer[4], Beata Kępińska[5], Aleksandra Kasztelewicz[6], Alicja Wiktoria Stokłosa[7], Baldur Pétursson[8]

[1] *Mineral and Energy Economy Research Institute of the Polish Academy of Science, Krakow, Poland, e-mail: kpierzchala@min-pan.krakow.pl (corresponding author), ORCID ID: 0009-0007-4976-7922*
[2] *AGH University of Krakow, Faculty of Geology, Geophysics and Environmental Protection, Krakow, Poland, e-mail: pajakl@agh.edu.pl, ORCID ID: 0000-0002-6341-9218*
[3] *AGH University of Krakow, Faculty of Geology, Geophysics and Environmental Protection, Krakow, Poland, e-mail: barbara.tomaszewska@agh.edu.pl, ORCID ID: 0000-0002-4780-1580*
[4] *Mineral and Energy Economy Research Institute of the Polish Academy of Science, Krakow, Poland, e-mail: mtyszer@min-pan.krakow.pl, ORCID ID: 0000-0002-4456-2828*
[5] *Mineral and Energy Economy Research Institute of the Polish Academy of Science, Krakow, Poland, e-mail: kepinska@min-pan.krakow.pl, ORCID ID: 0000-0002-9859-450X*
[6] *Mineral and Energy Economy Research Institute of the Polish Academy of Science, Krakow, Poland, e-mail: kasztelewicz@min-pan.krakow.pl, ORCID ID: 0000-0003-2889-4889*
[7] *Geothermal Research Cluster, Reykjavík, Iceland, e-mail: aws@georg.cluster.is*
[8] *Icelandic Environment and Energy Agency, Reykjavík, Iceland, e-mail: baldur.petursson@uos.is*

Received: 3 June 2025; accepted: 5 December 2025; first published online: 30 December 2025

Abstract: The possibility of utilising the available potential of the main geothermal reservoirs in Poland, i.e., the Lower Jurassic and Lower Cretaceous, by using the existing infrastructure in the form of still-operating district heating networks is the subject of this work. The suggested solution, therefore, integrates the resource side with the infrastructure side. This approach should significantly accelerate the implementation of the proposed solutions, supporting the achievement of the ambitious objectives of Poland's Energy Policy 2040. Geothermal resources in Poland are characterised by low enthalpy and low temperature. Their temperature is often too low for direct utilisation in systems relying solely on geothermal energy. Existing district heating networks require significantly higher heating medium temperatures during specific periods (when low ambient air temperature is observed). Using gas boilers as peak energy sources while employing geothermal energy as the base load for meeting annual heating demands appears to be an attractive and feasible technical option. Poland, alongside Denmark, Latvia, Finland, Estonia, and Lithuania, is among the countries with the highest density of district heating networks. These networks serve as invaluable infrastructure, reducing the costs associated with geothermal energy extraction. However, this infrastructure is under real threat from the trend towards decentralised energy systems. The liquidation of district heating networks would be irreversible, further exacerbated by the lack of access to clean and alternative energy carriers to replace fossil fuels. It has been demonstrated that in most analysed cases the combination of available geothermal resources and district heating infrastructure can successfully contribute to achieving the assumed goals of Poland's Energy Policy. In the best locations, the share of renewable energy exceeded 80%, with an average of around 50%. The total reduction of CO_2 emissions is estimated as 1.16 million tonnes yearly. The work draws attention to the slow but positive change in the electricity mix, in which the share of RES is growing. This trend is extremely beneficial for popularising heat pumps powered by electricity using geothermal resources as a low-temperature energy carrier.

Keywords: geothermal energy, energetic crisis, ecological crisis, Polish Lowlands, geothermal district heating, Poland

https://doi.org/10.7494/geol.2025.51.4.427 ISSN 2299-8004 | e-ISSN 2353-0790 | Wydawnictwa AGH

INTRODUCTION

The Polish energy sector, particularly the district heating sector, has been dominated for decades by the use of fossil fuels. According to the International Energy Agency (IEA 2025), coal accounted for 36% of the total primary energy consumption in 2023 (equivalent to 1.47 PJ of primary energy), liquid fuels for 33% (1.33 PJ), and natural gas for 16% (660 PJ). In comparison, the use of renewable energy sources and energy from waste stood at 12% (476 PJ), according to the same source. The dependence of the municipal sector on coal was even more pronounced, with approximately 66% of its energy supply derived from coal in 2023 (IEA 2025), 6% from natural gas, and 21% from renewable energy sources (RES) and waste. In 2023, the municipal sector consumed approximately 27% of final energy, the industrial sector 20%, and the transport sector 31%. Thermal energy constitutes around 80% of the total energy consumption by municipal households in Poland and most European countries (CSO 2023, Eurostat 2025). This energy is primarily used for space heating and domestic hot water preparation. The remaining 20% is accounted for by electricity for powering household appliances, audio-visual equipment, computers, and lighting. These data highlight that the municipal sector is one of the principal energy-consuming sectors, comparable to transport and industrial production. Thermal energy has a crucial and often underestimated share in the energy consumption of the municipal sector, particularly in the Polish context. As a member state of the European Union, Poland has committed to implementing the objectives of the European Green Deal, aiming for climate neutrality (EC 2019). Consequently, the Polish economy's share of fossil fuels (including coal) is expected to gradually decline in the coming years. Moreover, Poland's energy transformation is supported by national strategies, notably the Energy Policy of Poland until 2040 (Ministry of Climate and Environment 2021), which outlines plans for a just and sustainable energy transition focused on emission reductions. In line with these documents, the economy based on fossil fuels is to be transformed towards cleaner or entirely emission-free energy sources.

The war in Ukraine has significantly accelerated the energy transition process and the energy market and its carriers are no longer perceived solely through economic criteria. For many years, energy carriers were one of the instruments of political pressure exerted on European countries dependent on moderately priced Russian fuels. Today, efforts are being made across Europe to reduce reliance on energy supply chains originating from Russia. These initiatives are further reinforced by economic sanctions imposed against Russia (Karpinska & Śmiech 2021, Kuzemko et al. 2022). The problems related to fuel availability, stringent legal restrictions on the use of fossil fuels, and the growing public awareness of the detrimental impacts of the current situation are fostering a search for alternative energy scenarios, including geothermal sources among them. It is worth highlighting that geothermal energy is a renewable energy carrier independent of climatic conditions. This paper proposes using geothermal energy as one of the potential additive options contributing to energy security while promoting environmental sustainability, which aligns with national and European plans. Although Poland is not naturally predisposed to the development of geothermal electricity generation, it is essential to note that the dominant energy demand in the Polish climate pertains to heat.

An important advantage is the existence of operational district heating networks, without which the efficient utilisation of geothermal resources would be difficult to envisage. These networks serve as natural allies to geothermal energy by providing an appropriate scale of thermal power and energy demand. While the general trend of decentralisation and the promotion of distributed energy systems is justified in many cases, it has a decidedly negative impact in the context of geothermal energy. Decentralisation certainly reduces transmission losses; however, it is important to recognise that losses associated with the distribution of clean energy, burdened primarily by fixed acquisition costs, are of lesser significance than transmission losses from conventional sources, which entail substantial fuel purchase costs. Thus, the study advocates for the exploitation of both the available domestic energy resources and the still-operational, existing technical infrastructure.

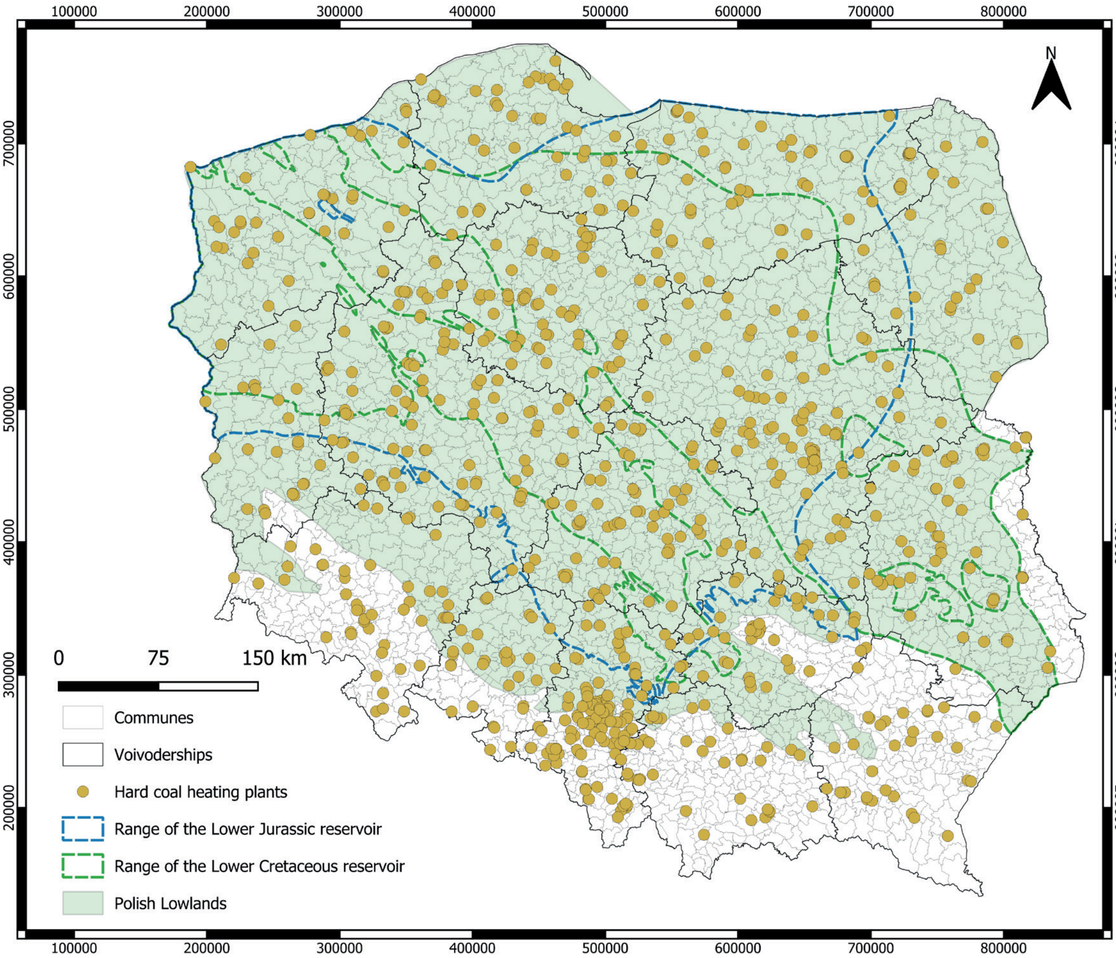

Fig. 1. *Hard coal heating plants with an installed capacity greater than 1 MW, shown against the background of the main geothermal horizons of the Lower Jurassic and Lower Cretaceous formations*

These facilities primarily serve heating purposes and are generally equipped with appropriate district heating networks. The arbitrarily adopted capacity threshold (1 MW) corresponds roughly to the output of a geothermal installation supplying a moderate geothermal fluid flow of approximately 43 m^3/h, assuming the fluid is cooled down by 20°C. The compiled data indicate a significant number of heating installations of the specified capacity located directly within the range of the selected geothermal horizons (Fig. 1).

This study presents the potential for supporting coal-fired district heating plants through the utilisation of geothermal energy resources. A detailed analysis was carried out focusing on the most favourable areas of the Polish Lowlands, aiming to identify coal-fired heating plants that could be progressively modernised into geothermal heating plants or facilities using geothermal energy as the primary energy carrier. The benefits of geothermal energy utilisation include improved energy security, enhanced energy independence, the opportunity to stimulate local job markets, and improved air quality (Kurek et al. 2021, Hajto & Kaczmarczyk 2022, Bujakowski et al. 2023, 2024).

GEOTHERMAL RESOURCE POTENTIAL

In Poland, areas with favourable geothermal conditions largely overlap with regions of increased population density, which is crucial for the further dissemination and utilisation of geothermal resources.

The geothermal resource potential of the Polish Lowlands covers approximately 80% of the country's surface area (Hałaj 2015, Sowiżdżał 2018). Thermal waters in this region occur within Mesozoic and Palaeozoic sedimentary rocks. The resources of the Lower Cretaceous and Lower Jurassic formations are considered the most promising in terms of the potential for energy utilisation of geothermal waters (Hałaj 2015, Sowiżdżał et al. 2016, Sowiżdżał 2018, Nordgård-Hansen et al. 2023). The temperatures of geothermal reservoirs in the Lower Jurassic vary depending on location, generally ranging between 20°C and 80°C, with local maxima reaching up to 120°C at depths of around 3,000 metres below ground level (m b.g.l.). Water mineralisation levels depend on depth but typically range from several tens to over 100 g/dm^3 and locally can exceed even 150 g/dm^3. Productive capacities across most of the area are estimated at above 100 m^3/h, with single wells achieving yields of up to 300 m^3/h. In the case of the Lower Cretaceous, water temperatures usually range from 20°C to over 90°C, and current well outputs confirmed by drilling results range from several tens to around 100 m^3/h (Górecki ed. 2006a, Sowiżdżał et al. 2016). The geothermal energy resources of Poland and their potential utilisation have been thoroughly characterised in a series of geothermal atlases (Górecki ed. 2006a, 2006b, Bujakowski & Tomaszewska eds. 2014). Geothermal energy can potentially be used in many ways, especially, given the temperature ranges, for district heating purposes.

At the end of 2024 there were ten geothermal district heating systems in operation in Poland (Mszczonów, Poddębice, Podhale, Pyrzyce, Stargard, Uniejów, Toruń, Koło, Sieradz, and Konin). Total geothermal capacity installed in mentioned plants was 219.3 MWth and produced 360.2 GWh of heat in 2024 (a 30% increase compared to 2021 production). Share of geothermal energy in total energy production varied in these district heating systems from 4.3% (Toruń) to 99% (Podhale), with an average of 56% (Hajto & Kępińska 2025). Unfortunately, many existing district heating networks were designed with the use of conventional fuels, at a time when energy carriers were inexpensive; thus, little attention was paid to transmission losses. The aim then was to create systems with low construction costs. This resulted in the prevalence of high-temperature solutions, both in network design and in heating installations at consumer facilities. Thus, second-generation and, at best, third-generation district heating networks dominate, especially in low-capacity systems of around 5 MW. It is worth noting that the design temperatures of water during the heating season of most large-scale district heating systems in Poland are approximately 130°C on the supply and around 70°C on the return. Smaller, local heating networks may operate at lower temperature regimes, such as 90/70°C (Pająk et al. 2020). This discrepancy in relation to the available geothermal water resources (above) in the Polish Lowlands necessitates the use of peak-load sources. For this reason, geothermal sources are mostly installed on the return side of the district heating network. This is because the return temperature of the heating network can be lower than the temperature of the geothermal water, allowing the energy to be transferred directly via a heat exchanger. Subsequently, heat pumps are utilised to extract the remaining energy from the geothermal water and transfer it to the district heating supply water. Here, geothermal water is a lower heat source for a heat pump. A similar approach has been implemented in the energy model presented in the methods section.

Apart from temperature mismatch, there is also another challenge. High mineralisation levels of water can significantly affect both the exploitation of the geothermal source and its thermal power output. Increasing mineralisation leads to a decrease in the specific heat capacity of water while simultaneously increasing water density. Since mineralisation has a stronger impact on reducing specific heat capacity than on increasing density, the overall result is a decline in volumetric heat capacity. Consequently, higher mineralization adversely affects the estimated thermal power of the geothermal source (GeoModel 2024). However, the key challenges associated with high water mineralisation are scaling and corrosion of the installation. Scaling occurs when secondary deposits precipitate from geothermal waters due to changes in their thermodynamic state. To this end, it is necessary to optimise the cooling temperature and, in special cases, use technical solutions or chemical compounds to improve conditions for operating and injecting cooled water into the rock mass. Similarly, high water mineralisation can contribute to the corrosion of the pipes forming well structures and transmission systems. Using piping that is resistant to these phenomena increases the system's investment and operating costs (Kępińska & Bujakowski eds. 2011, Tomaszewska & Pająk 2012).

Although the general trend towards thermal retrofitting has somewhat improved the situation and enabled the reduction of temperature requirements, the lack of temperature coherence between geothermal resources and network demands remains a major technical challenge. Considering the available geothermal resource temperatures in Poland, these plants will often require peak-load sources (Barbacki 2012, Huculak et al. 2015) such as gas boilers (e.g., Podhale, Mszczonów), biomass (e.g., Uniejów, Poddębice), or absorption heat pumps (e.g., Mszczonów, Pyrzyce) to supplement the geothermal systems. Existing coal-fired installations may also be used as peak sources during the highest energy demand (e.g., Stargard). The development of geothermal district heating is typically accompanied by the recreational use of geothermal waters and energy (Nordgård-Hansen et al. 2023), contributing to local infrastructure development, creating new jobs, and, most importantly, reducing fossil fuel consumption in such facilities (Hałaj 2015, Lund & Boyd 2016, Tomaszewska & Szczepański 2016, Kępińska 2018, Kurek et al. 2021, Tyszer et al. 2021).

METHODS

The assessment of the potential for replacing fossil fuels with geothermal energy in the district heating sector of the Polish Lowlands was conducted by identifying the most promising locations. Categorisation was carried out using several criteria. The first stage involved combining: (1) the locations of existing heating plants utilising hard coal, based on data from the National Centre for Emissions Management (KOBiZE 2021a); and (2) an analysis of geothermal potential, relying on geological, hydrogeological, and geothermal data.

Given the large number of registered heat sources, comprising over 22,000 records (KOBiZE 2021a), verifying the facilities based on more detailed criteria was decided.

A heat source had to meet the following conditions:

1) It had to be a plant-based boiler house or a professional heating plant; power plants and combined heat and power (CHP) plants were excluded, as their primary function is electricity generation, which geothermal energy could not replace effectively.
2) It had to be an installation where hard coal or its variety is combusted, with a nominal thermal output greater than 1 MW.

Based on these criteria, 861 facilities across Poland were selected. In the next step, using QGIS Desktop 3.24.1 software, the locations of these heating plants were compared against the boundaries of areas deemed prospective for geothermal utilization, specifically the Lower Jurassic and Lower Cretaceous formations. As a result, 102 heating plants were shortlisted for further analysis.

Additionally, a more detailed analysis was carried out for those sites located within the boundary of the 70°C isotherm, corresponding to the projected water temperature at the top of the Lower Jurassic or Lower Cretaceous geothermal reservoir. Under Polish climatic conditions, a temperature of 70°C is commonly used to supply district heating networks outside the heating season, specifically for the preparation of domestic hot water at draw-off points at 55–60°C, in compliance with legal requirements set out in the Regulation of the Ministry of Infrastructure of 12 April 2002 on the technical conditions to be met by buildings and their location (Rozporządzenie 2002). Further considerations were made, and the installations were assigned to the municipalities in which they are located. However, no detailed analysis of the energy or environmental effects was carried out for these facilities.

The mathematical model of the energy system was created and developed in Mathcad Prime 10.0.1 software. The energy model created for energy and environmental analyses assumed the cooperation of the existing heating plant with the district heating network, a geothermal source (parameters estimated based on geothermal atlases), compressor heat pumps, and a gas-fired source (Fig. 2).

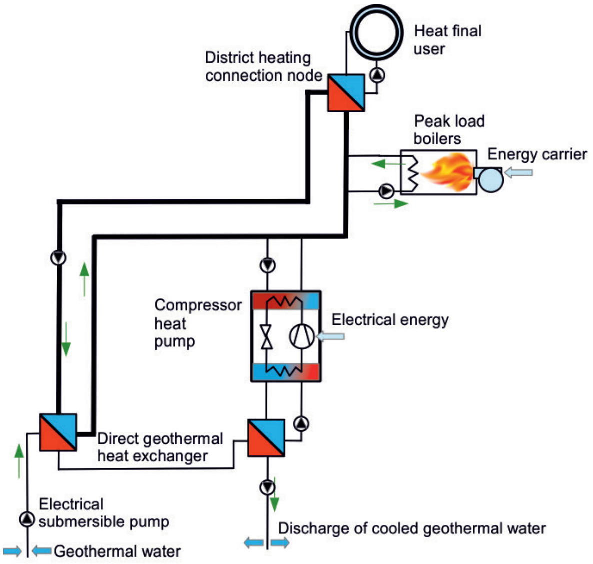

Fig. 2. *Model of energy system*

As previously mentioned, the model assumes the use of a peak-load source, whose key components include a geothermal heat exchanger and a heat pump. The operational principle of the created model is as follows. The return water from the district heating network flows directly to the direct geothermal heat exchanger. The exchanger operates when the temperature of the return water is lower than the temperature of the geothermal fluid at the production wellhead. The geothermal fluid is cooled in the exchanger to the temperature of the return water, with a counterflow plate heat exchanger assumed for this process (temperature difference both in the heat exchanger and heat pump exchanger were assumed to be 2°C). The recovered energy increases the temperature of the network water. If the achieved temperature is insufficient for the district heating supply, and the geothermal fluid (after direct exchange) remains above a temperature close to the annual average ambient air temperature, compression heat pumps are used. These pumps heat the network fluid to the required supply temperature or to the maximum temperature achievable under the constraint that the geothermal fluid is cooled to the annual average air temperature. For calculations, it was assumed that the heat pumps can deliver a maximum outlet temperature of 90°C at the condenser. If, after passing through the heat pumps, the network water temperature still does not meet the district heating requirements, peak-load support boilers are activated. These boilers are assumed to operate on high-methane natural gas. The share of power supplied by the analysed energy sources varies over time and depends on district heating network operating conditions (water flow rate, required supply temperature, and achieved return temperature) as well as geothermal conditions (flow rate, mineralization, reservoir fluid temperature, and well depth). The operating parameters of the district heating network fluctuate with changes in ambient air temperature. It was assumed that the geothermal intake operates year-round at a nominal capacity determined by local geological conditions. In all of the analysed cases, it was assumed that power control within the district heating networks is implemented using full qualitative-quantitative regulation. The parameters of the district heating network were determined based on an assumed indoor design temperature of 21°C, corresponding to the thermal comfort standard. A water-based, two-pipe district heating network is assumed, designed to meet both space heating and domestic hot water (DHW) demands. The variability of DHW demand was adopted based on a typical consumption profile. Changes in flow rate and supply water temperature within the district heating network were dependent on ambient air temperature. Calculations were performed with an hourly resolution (1 year = 8,760 hours). Weather data for each location were sourced from the Photovoltaic Geographical Information System (PVGIS) (EC 2022).

The model assumed that the energy needs of consumers would be fully met (priority was given to geothermal energy and heat from heat pumps utilising geothermal water) in terms of both power and energy throughout the year, based on typical assumptions for district heating networks in Poland. The parameters of the network and source capacities were taken from data provided by the Energy Regulatory Office (ERO 2022). The reduction in emissions was estimated using indicators based on data supplied by KOBiZE (2021b), by comparing the current state, which uses only coal, to the scenario where geothermal energy and heat pumps are used along with a peak gas-fired source. Emissions were calculated on a global scale. The initially selected 102 locations often had access to Lower Jurassic and Lower Cretaceous resources due to their geographical location. 131 variants utilizing Lower Jurassic (J1) and Lower Cretaceous (K1) resources were created. It was decided that each location would have only one variant (either J1 or K1) depending on the higher share of energy from renewable sources (geothermal and heat pumps). Heating plants in which the predicted water temperature at the top of the geothermal reservoir was relatively low, i.e. below 30°C, were excluded from further analysis. The final 84 heating plant variants, along with the estimated share of renewable energy, coal consumption reduction, and CO_2 emissions reduction, are presented in the following section.

RESULTS AND DISCUSSION

The final 102 locations corresponding to municipalities where heating plants are located within the boundaries of the Lower Jurassic and Lower Cretaceous geothermal reservoir are presented (Fig. 3).

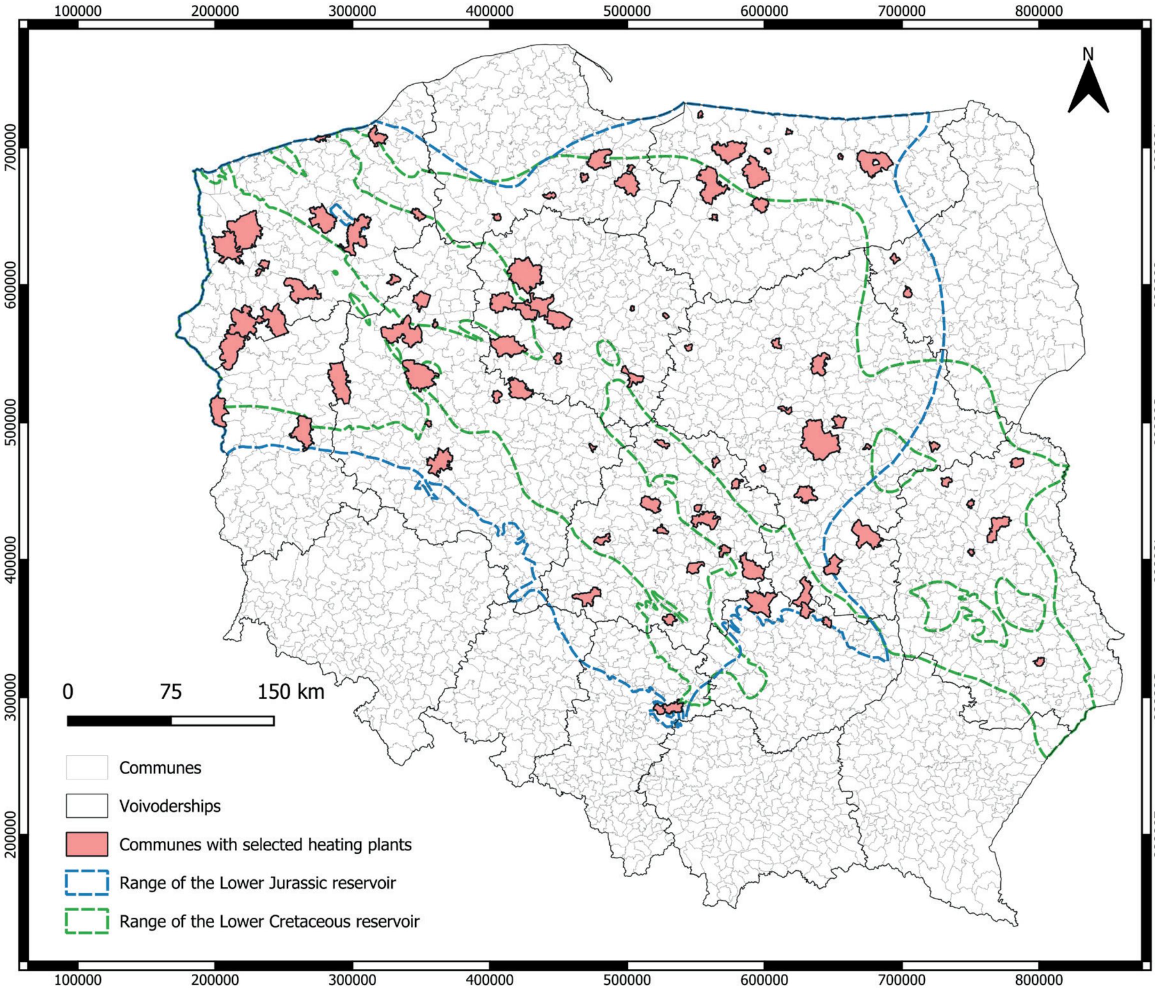

Fig. 3. *Communes with selected heating plants against the Lower Jurassic and Lower Cretaceous reservoirs (Aleksandrów Łódzki, Barlinek, Bartoszyce, Biała Podlaska, Białe Błota, Braniewo, Brzeziny, Bydgoszcz, Chodzież, Chojnice, Choszczno, Ciechanów, Czarna Woda, Czarnków, Dębno, Dobre Miasto, Giżycko, Gniezno, Goleniów, Golub-Dobrzyń, Grójec, Inowrocław, Kętrzyn, Kolno, Koluszki, Koło, Kołobrzeg, Końskie, Koronowo, Koszalin (2), Kozienice, Kutno, Lidzbark Warmiński, Lubartów, Luboń, Łobez, Łomża, Łowicz, Łuków, Malbork, Międzychód, Mińsk Mazowiecki, Morąg, Myślibórz, Nakło nad Notecią, Nowy Dwór Mazowiecki, Oborniki (3), Olsztyn, Opoczno (2), Orneta, Ostróda, Pabianice (2), Parczew, Piła (2), Piotrków Trybunalski, Poręba, Pułtusk, Radom, Radomsko, Radzyń Podlaski, Rypin, Siedlce, Sieradz, Sierpc, Skarżysko-Kamienna (2), Skierniewice, Słubice, Solec Kujawski, Starachowice (2), Stargard, Starogard Gdański, Szczecin, Szczecinek, Sztum, Szydłowiec, Śrem (2), Świebodzin, Tczew, Tomaszów Mazowiecki, Trzemeszno, Wałcz, Warszawa (2), Wieluń, Włocławek (2), Wołomin, Zamość (2), Zawiercie, Złocieniec, Żnin, Żyrardów)*

The total installed heat source capacity in these heating plants exceeds 5.2 GW. In most cases, these are facilities that supply heat to small towns or neighbourhoods, although some have also been identified in large cities and metropolitan areas.

Additional 40 heating plants within 28 municipalities have been identified within the boundary of the 70°C isotherm (Fig. 4). On the map (Fig. 4), some indicated municipalities extend beyond the considered isotherm area; locations of the heating plants are within the area defined by the specified isotherm. The selected heating plant locations were chosen based on precise geographical coordinates. These heating plants are primarily located in smaller cities.

Energetic and ecological effects were compiled for the final 84 selected heating plants from the initial 102 facilities (Table 1). The majority of the selected locations utilise resources from the Lower Jurassic due to, among other factors, having higher temperatures of geothermal fluid projected in the reservoir.

The analyses indicate that many coal-fired heating plants in the Polish Lowland area could be considered potential sites where geothermal energy could partially or almost entirely replace the current heat source. These plants have access to district heating networks, but the design parameters of most district heating systems often exceed the temperature values of geothermal resources.

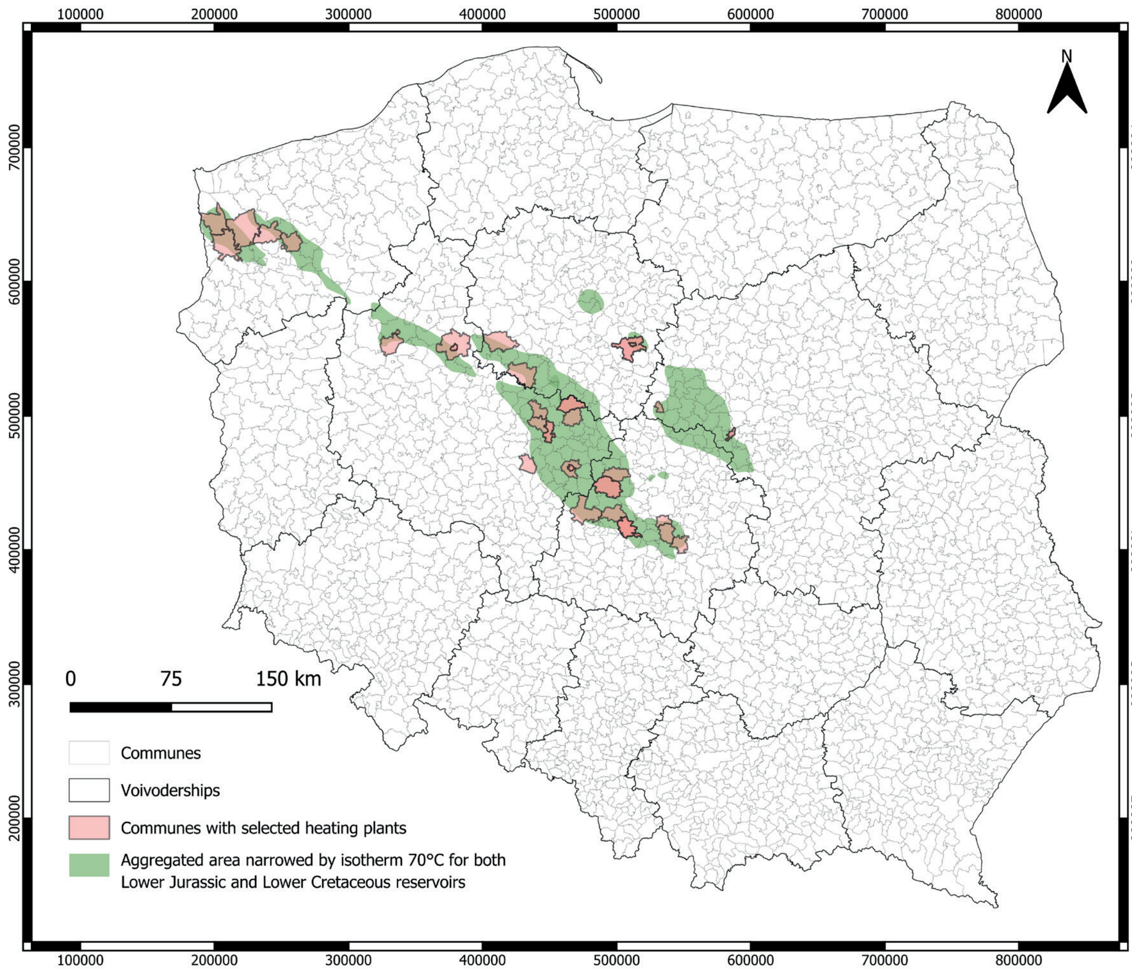

Fig. 4. *Communes with selected heating plants against aggregated area narrowed by isotherm 70°C for both Lower Jurassic and Lower Cretaceous reservoirs (Chociwel, Czarnków, Goleniów, Gostynin, Grodziec, Kazimierz Biskupi, Kleczew, Konin (2), Lipno (3), Lubasz, Łask (3), Maszewo, Mogilno, Moszczenica, Poddębice (2), Police, Rzgów, Sochaczew (2), Sompolno, Szadek, Szczecin, Turek (3), Tuszyn, Warta, Wartkowice, Wągrowiec (3), Wierzbinek (2), Żnin)*

Table 1
Energetic and environmental effects of utilising geothermal energy in selected locations

No.	Location	Share of renewable energy sources (geothermal energy and heat pumps) [%]	Decreased amount of coal [Mg/year]	Elimination of CO_2 in global scale [Mg/year]
1	Aleksandrów Łódzki J1	83	2,870	2,638
2	Barlinek J1	81	5,794	6,463
3	Bartoszyce J1	39	11,057	4,507
4	Biała Podlaska K1	2	27,642	18,954
5	Białe Błota J1	67	2,811	1,483
6	Braniewo J1	22	8,979	5,340
7	Brzeziny J1	64	4,599	3,388
8	Bydgoszcz J1	59	4,401	3,232
9	Chodzież J1	65	6,030	4,066
10	Chojnice J1	62	11,570	9,373
11	Choszczno J1	77	4,085	4,729
12	Ciechanów J1	31	28,169	21,163
13	Czarna Woda J1	9	21,769	19,209
14	Czarnków J1	69	42,777	46,849
15	Dębno J1	67	4,186	2,366
16	Dobre Miasto J1	66	2,487	1,639
17	Giżycko J1	19	10,859	7,800
18	Gniezno J1	76	20,250	25,538
19	Goleniów J1	74	12,336	14,613
20	Golub Dobrzyń J1	86	4,367	5,241
21	Grójec J1	76	3,618	4,160
22	Inowrocław J1	45	38,693	35,930
23	Kętrzyn J1	34	7,709	5,217
24	Kolno J1	33	5,180	3,535
25	Koluszki J1	59	5,342	3,767
26	Koło K1	82	11,945	15,335
27	Konin J1	26	504	122,855
28	Koronowo J1	62	4,481	3,127
29	Koszalin 1 J1	17	26,665	20,431
30	Koszalin 2 J1	17	29,457	22,123
31	Kozienice K1	11	10,887	7,013
32	Kutno J1	78	16,070	17,734
33	Lidzbark Warmiński J1	36	7,291	5,608
34	Lubartów K1	8	7,878	5,414
35	Luboń J1	68	4,517	2,553
36	Łomża J1	7	34,708	23,098
37	Łowicz J1	83	15,036	16,674
38	Łuków K1	6	10,172	7,104
39	Malbork J1	20	20,406	14,100
40	Międzychód J1	70	1,964	894
41	Mińsk Mazowiecki J1	68	1,326	895
42	Morąg J1	51	8,243	4,895
43	Myślibórz J1	74	2,886	1,957

Table 1 *cont.*

No.	Location	Share of renewable energy sources (geothermal energy and heat pumps) [%]	Decreased amount of coal [Mg/year]	Elimination of CO_2 in global scale [Mg/year]
44	Nowy Dwór Mazowiecki J1	67	15,291	12,446
45	Oborniki 1 J1	79	1,875	1,660
46	Oborniki 2 J1	80	2,643	2,491
47	Oborniki 3 J1	79	3,832	3,778
48	Olsztyn J1	11	51,433	42,185
49	Orneta J1	55	4,638	3,217
50	Ostróda J1	44	11,156	7,840
51	Pabianice 1 J1	71	23,722	29,538
52	Pabianice 2 J1	76	3,955	4,979
53	Parczew K1	12	4,766	3,178
54	Piotrków Trybunalski J1	72	18,844	20,440
55	Pułtusk J1	67	4,345	2,859
56	Radom J1	12	47,571	33,691
57	Radomsko J1	35	19,960	14,338
58	Radzyń Podlaski K1	13	6,002	3,812
59	Rypin J1	74	6,730	5,976
60	Siedlce K1	5	13,611	9,415
61	Sieradz J1	70	18,789	19,417
62	Sierpc J1	81	9,126	10,282
63	Skierniewice J1	32	25,196	21,068
64	Słubice J1	61	4,856	2,836
65	Sochaczew K1	77	3,652	2,427
66	Solec Kujawski J1	64	6,490	6,343
67	Stargard J1	68	23,703	28,185
68	Starogard Gdański J1	16	16,329	13,532
69	Szczecin J1	26	79,716	77,247
70	Szczecinek J1	21	19,611	15,428
71	Sztum J1	51	5,538	4,228
72	Tczew J1	13	20,529	16,650
73	Tomaszów Mazowiecki J1	58	7,339	5,223
74	Trzemeszno J1	84	4,350	5,810
75	Turek J1	65	12,307	12,561
76	Warszawa 1 J1	24	29,503	28,123
77	Warszawa 2 J1	55	11,844	8,749
78	Włocławek 1 J1	69	18,587	15,540
79	Włocławek 2 J1	29	56,606	42,173
80	Wołomin J1	38	19,268	13,936
81	Zamość 1 K1	4	23,038	17,187
82	Zamość 2 K1	7	11,177	8,260
83	Żnin J1	88	8,192	11,480
84	Żyrardów J1	87	19,502	24,779
Total sum			1,204,768	1,163,679

In most reservoirs in Poland, hydrogeological conditions do not reach the necessary temperatures of the water at the wellhead to allow for a direct transition from coal-based heating to geothermal energy. This is because heating installations in final user homes are mostly radiators, and these require higher operating temperatures. Therefore, district heating networks operate at higher temperatures so that the requirements of all consumers can be met. Direct use of geothermal energy in the heating system would be possible if final users had low-temperature heating installations, such as surface (floor or wall) heating. Consequently, the district heating network could also operate at lower temperatures. Therefore, most of the geothermal heating plants in Poland must incorporate a peak heat source (e.g., an existing coal-fired heating plant, gas boilers, or heat pumps) (Barbacki 2012). Such a situation occurs mostly because the supply temperature of the district heating network is higher than the available temperature of geothermal water at the wellhead. The supply temperature of the district heating network changes throughout the year depending on the outdoor air temperature. Under design conditions, it reaches extreme (design temperature) values in winter, which only occur occasionally. The highest water temperatures in the district heating network are observed in winter. During spring, there is a gradual decrease in the operating temperatures, and finally, in summer, the operating temperatures are at their lowest and usually sufficient for domestic hot water preparation.

The analysis of location variants presented in Table 1 leads to the conclusion that if all heating plants utilised geothermal waters from a specific geothermal reservoir, the average total amount of energy derived from renewable energy sources (geothermal and heat pumps) could reach as much as 50% for the entire group of entities. On average, each heating plant would reduce its demand for coal-based energy carriers by over 14,000 tons annually, resulting in a reduction of CO_2 emissions by an average of 13,800 tons per year per heating plant. In total, if all the heating plants listed in Table 1 utilised geothermal energy supported by heat pumps, the annual reduction in coal consumption would amount to 1,204,000 tons. As a result, the global reduction in CO_2 emissions would total 1,163,000 tons. Assuming the current average CO_2 emission price of 65 EUR per ton of CO_2 (Energy Instrat 2025), the annual savings across all heating plants would amount to approximately 75.5 million EUR, which could affect the final energy price for consumers. Equally important would be the improvement in air quality in these locations due to the reduction in coal combustion in favour of geothermal sources with heat pumps. Of course, the analysis includes heating plants that are particularly well-suited for geothermal energy utilisation, which, in cooperation with the existing heating systems, can operate very efficiently when relying on renewable energy. These municipalities in the analysis have an estimated share of renewable energy sources above 80%, including Aleksandrów Łódzki, Barlinek, Golub Dobrzyń, Koło, Łowicz, Oborniki, Sierpc, Trzemeszno, Żnin, and Żyrardów but this does not exclude other locations. It is worth noting that in some cases, a smaller share of energy from renewable sources does not necessarily mean a smaller amount of energy derived from renewable sources. This is because the expected temperature and the flow rate of geothermal water from a single well in the study may represent a relatively small amount of energy compared to the total system demand. However, in terms of quantity, this energy may exceed that of a smaller district heating system with a larger share of renewable energy in the energy production structure.

The research results demonstrate that the energy transition of the country can partially rely on the utilization of geothermal energy. Geothermal energy significantly improves energy independence and enhances the system's energy efficiency. Poland aims to achieve at least 28% of energy from renewable sources in district heating by 2030 (Ministry of Climate and Environment 2021). Many heating plants listed in Table 1 would achieve the 28% target for renewable energy, which is a positive development at the local level in the context of implementing Poland's energy policy plans and goals for the coming years. The findings presented in this study confirm previous research on the potential of the analysed geothermal reservoirs for use in district heating (Górecki et al. 2010, Pająk et al. 2020). Increasing the share of renewable energy sources also enhances the country's energy security and reduces dependence on fossil fuels. On the European energy market, wholesale gas and electricity prices increased by 115% and 237%, respectively, in the first months of the war in Ukraine (Ferriani & Gazzani 2023). Even before the war in Ukraine, Russia was Poland's largest supplier of gas and coal. Due to the EU sanctions imposed on Russia, Poland ceased importing coal from Russia, which, among other factors, was reflected in the increase in the price of this fuel. The most significant rise in coal prices was observed in the third and fourth quarters of 2022. Between the beginning and the end of 2022, the cost of coal (net) for households increased by approximately twofold, and it surpassed the price of natural gas in PLN per gigajoule (Stala-Szlugaj 2023). It is also important to note the ecological aspect of the research conducted. Significant air pollution occurs in areas where fossil fuels are used for energy production (Zgłobicki & Baran-Zgłobicka 2024). This transition toward geothermal energy could help achieve Poland's renewable energy targets and address critical issues related to energy security and environmental sustainability.

Therefore, it is suggested that increasing the share of renewable energy sources (in this case, geothermal energy) in district heating could help mitigate the effects of the energy and ecological crises and contribute to improving the safety and health of residents using these resources.

It is also important to note that the planned development of nuclear, wind, and solar energy by 2040 (Ministry of Climate and Environment 2021) may make geothermal energy, in combination with heat pumps, one of the most efficient and environmentally friendly heating sources available to Polish residents. Lowering temperature requirements, a general trend in district heating, may further promote the use of geothermal energy, as low-temperature resources are much more widespread (Pająk et al. 2023). Decreasing temperature requirements can be carried out in many ways, depending on their costs and the expected results. The most common measures include insulating external walls, roofs, and replacing windows and external doors. Inside the building, it is advisable to use heat recovery ventilation instead of traditional gravity ventilation. The heating system can be modernised in two ways. The first is that if radiators are installed, they can be replaced with larger ones, thereby increasing the heating surface and lowering the operating temperatures of the system. The second, more invasive method is the installation of surface heating, such as surface heating. Thermal modernisation activities also include reducing transmission losses, which means insulating the district heating network. It is worth noting that in the case of a district heating network, thermal modernisation measures only make sense if all users implement them, and after the changes, individual heating installations are properly adjusted to match the new parameters of heating requirement. The costs and expected outcomes of these measures can vary significantly depending also on the type of building and its users' characteristics and behaviours. Conducting an energy audit beforehand is the most effective approach to determine which retrofit activity will provide the greatest cost-benefit ratio. Measures implemented on the consumer side that reduce a building's demand for thermal power and energy enable the district heating network to operate at lower supply temperatures. This allows for increased cooling of geothermal water within the heating plant, which contributes to a higher share of geothermal energy in the annual energy balance. In this way, geothermal water is preserved, as deeper cooling in the heat exchanger permits a reduction in the flow rate (and thus extraction) of geothermal water.

CONCLUSION

The analysis indicates that many district heating plants in Poland, that are in the prospective areas of the Polish Lowland could potentially replace their current primary energy source, coal based, with geothermal energy supplemented by heat pumps. Unfortunately, the geothermal resources available in this region mostly have lower temperatures than those required by the district heating networks. It is worth noting that district heating system piping could be adequate for delivering the required power to the consumer (temperature difference between supply and return temperature of water), but if the final user's heating installation requires higher operating temperatures, the system will not be able to provide the necessary power. In that case, retrofitting activities must be carried out, e.g., replacing radiators with larger ones. However, as the analysis shows, a geothermal source with heat pumps could provide, on average, about 50% of the energy from renewable sources for the selected group of heating plants. Among these plants, there are locations where the geothermal resources, within the adopted energy model, could provide over 80% of energy from renewable sources (e.g., Koło, Żyrardów), which is a relatively excellent result. These areas usually exhibit geothermal resources that substantially exceed the national average, thereby constituting prominent geothermal hotspots. Replacing coal-based energy sources with geothermal in the mentioned 84 heating plants would lead to an annual reduction of about 1,204,000 tons of coal consumption and a decrease in CO_2 emissions by about 1,163,000 tons. These measures would likely translate into lower energy prices and environmental improvements. The study also identifies a group of 40 heating plants located within the common 70°C isotherm for the Lower Jurassic and Lower Cretaceous formations as prospective locations for using geothermal water to heat only hot domestic water directly.

Key limiting factors in the utilisation of geothermal energy not only include the temperature of the water at the wellhead, but also its production rate. The temperature of the geothermal water may be sufficient for direct use, yet its volume could be too small, thus limiting energy utilization. These challenges, however, can be mitigated through measures such as thermal retrofitting of heat consumers and their heating installations. Such actions reduce both the power and energy demand of final users, lowering the required supply temperature and the achievable return temperature of the district heating system. This can lead to the more efficient use of geothermal resources by enabling deeper cooling of the geothermal water and reducing the volume of water that needs to be pumped, thus conserving the resource.

The research partly supported by The National Fund for Environmental Protection and Water Management (Project No. 450/2021/Wn50/NE-OA-KU/D) and "Excellence Initiative – Research University" for the AGH University of Krakow.

REFERENCES

Barbacki A., 2012. Classification of geothermal resources in Poland by exergy analysis-Comparative study. *Renewable and Sustainable Energy Reviews*, 16(1), 123–128. https://doi.org/10.1016/j.rser.2011.07.141.

Bujakowski W. & Tomaszewska B. (eds.), 2014. *Atlas wykorzystania wód termalnych do skojarzonej produkcji energii elektrycznej i cieplnej przy zastosowaniu układów binarnych w Polsce: monografia* [Atlas of the possible use of geothermal waters for combined production of electricity and heat using binary systems in Poland: monograph]. Polska Akademia Nauk. Instytut Gospodarki Surowcami Mineralnymi i Energią, Kraków.

Bujakowski W., Zacharski P., Bielec B., Tyszer M., Pierzchała K., Tomaszewska B., Pająk L., Kępińska B. & Szczepański K., 2023. Verification of the geothermal conditions in the Polish Lowlands based on data from new drilling performed in the years 2000–2022. *Mineral Resources Management*, 39(1), 193–216. https://doi.org/10.24425/gsm.2023.144636.

Bujakowski W., Zacharski P., Tomaszewska B., Tyszer M., Pierzchała K., Bielec B., Pająk L., Kępińska B. & Szczepański K., 2024. The verification of forecasts of temperature and mineralization of the Lower Jurassic and Lower Cretaceous geothermal waters of the Polish Lowlands based on data from new drillings performed in the years 2000–2023. *Mineral Resources Management*, 40(2), 181–203. https://doi.org/10.24425/gsm.2024.150828.

CSO (Central Statistical Office), 2022. *Energy 2022*. https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/energia/energia-2022,1,10.html [access: 10.04.2025].

EC (European Commission), 2019. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal*. COM/2019/640 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN [access: 10.04.2025].

EC (European Commission), 2022. *Photovoltaic Geographical Information System (PVGIS).* https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#TMY [access: 10.05.2022].

Energetyka24, 2025. *Będzie rewolucja w geotermii? Nowe narzędzie badawcze trafia do Polski*. https://energetyka24.com/oze/wiadomosci/bedzie-rewolucja-w-geotermii-nowe-narzedzie-badawcze-trafia-do-polski? [access: 24.04.2025].

Energy Instrat, 2025. *CO_2 emission allowances price in EU ETS system*. https://energy.instrat.pl/en/prices/eu-ets/ [access: 23.05.2025].

ERO (Energy Regulatory Office), 2022. *Registers and Lists. Concession in areas other than liquid fuels*. https://rejestry.ure.gov.pl [access: 6.06.2022].

Eurostat, 2025. *Energy consumption in households*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households [access: 10.04.2025].

Ferriani F. & Gazzani A., 2023. The impact of the war in Ukraine on energy prices: Consequences for firms' financial performance. *International Economics*, 174, 221–230. https://doi.org/10.1016/j.inteco.2023.04.006.

GeoModel, 2024. *Thermophysical parameters of brines*. https://geomodel.pl/en/thermophysical-parameters-of-brines/ [access: 5.05.2025].

Górecki W., Hajto M., Skrzetelski W. & Szczepański A., 2010. Dolnokredowy oraz dolnojurajski zbiornik wód geotermalnych na Niżu Polskim. *Przegląd Geologiczny*, 58(7), 589–593.

Górecki W. (ed.), 2006a. *Atlas zasobów geotermalnych formacji mezozoicznej na Niżu Polskim* [Atlas of geothermal resources of mesozoic formations in the Polish Lowlands]. AGH, Kraków.

Górecki W. (ed.), 2006b. *Atlas zasobów geotermalnych formacji paleozoicznej na Niżu Polskim* [Atlas of geothermal resources of Paleozoic formations in the Polish Lowlands]. AGH, Kraków.

Hajto M. & Kaczmarczyk M., 2022. The potential to improve air quality by increasing the use of deep geothermal energy. *Geology, Geophysics and Environment*, 48(2), 147–175. https://doi.org/10.7494/geol.2022.48.2.147.

Hajto M. & Kępińska B., 2025. *Geothermal energy use – country update for Poland, 2022–2024* [paper submitted for EGC2025, Zurich, Switzerland].

Hałaj E., 2015. Geothermal bathing and recreation centres in Poland. *Environmental Earth Sciences*, 74(12), 7497–7509. https://doi.org/10.1007/s12665-014-3740-5.

Huculak M., Jarczewski W. & Dej M., 2015. Economic aspects of the use of deep geothermal heat in district heating in Poland. *Renewable and Sustainable Energy Reviews*, 49, 29–40. https://doi.org/10.1016/j.rser.2015.04.057.

IEA (International Energy Agency), 2025. *Energy mix – Poland*. https://www.iea.org/countries/poland/energy-mix [access: 27.03.2025].

Karpinska L. & Śmiech S., 2021. Will energy transition in Poland increase the extent and depth of energy poverty? *Journal of Cleaner Production*, 328, 129480. https://doi.org/10.1016/j.jclepro.2021.129480.

Kępińska B., 2018. Przegląd stanu wykorzystania energii geotermalnej w Polsce w latach 2016–2018 [A review of geothermal energy uses in Poland in 2016–2018]. *Technika Poszukiwań Geologicznych: Geotermia, Zrównoważony rozwój*, 57(1), 11–27.

Kępińska B. & Bujakowski W. (eds.), 2011. *Wytyczne projektowe poprawy chłonności skał zbiornikowych w związku z zatłaczaniem wód termalnych w polskich zakładach geotermalnych*. Wydawnictwo EJB, Czernichów.

KOBiZE (Krajowy Ośrodek Bilansowania i Zarządzania Emisjami), 2021a. [Data received from the National Emissions Database for Greenhouse Gases and Other Substances; unpublished data package; received December 2021].

KOBiZE (Krajowy Ośrodek Bilansowania i Zarządzania Emisjami), 2021b. *Wskaźniki emisji zanieczyszczeń ze spalania paliw dla źródeł o nominalnej mocy cieplnej do 5 MW, zastosowane do automatycznego wyliczenia emisji w raporcie do Krajowej bazy za lata 2020 i 2021*. https://krajowabaza.kobize.pl/docs/Wskazniki_emisji_zanieczyszczen_spalanie_paliw_dla_zrodel_do_5MW_automatyczne_wyliczenia_emisji_raport_2020_2021.pdf [access: 27.11.2022].

Kurek K.A., Heijman W., van Ophem J. & Gedek S., 2021. The contribution of the geothermal resources to local employment: Case study from Poland. *Energy Reports*, *7*, 1190–1202. https://doi.org/10.1016/j.egyr.2021.01.092.

Kuzemko C., Blondeel M., Dupont C. & Brisbois C.M., 2022. Russia's war on Ukraine, European energy policy responses & implications for sustainable transformations. *Energy Research & Social Science*, 93(4), 102842. https://doi.org/10.1016/j.erss.2022.102842.

Lund J.W. & Boyd T.L., 2016. Direct utilization of geothermal energy 2015: Worldwide review. *Geothermics*, 60, 66–93. https://doi.org/10.1016/j.geothermics.2015.11.004.

Ministry of Climate and Environment, 2021. *Polityka Energetyczna Polski do 2040 r.* https://www.gov.pl/web/klimat/polityka-energetyczna-polski [access: 10.04.2025].

Nordgård-Hansen E., Fjellså I.F., Medgyes T., Guðmundsdóttir M., Pétursson B., Miecznik M., Pająk L., Halás O., Leknes E. & Midttømme K., 2023. Differences in direct geothermal energy utilization for heating and cooling in central and northern European countries. *Energies*, 16(18), 6465. https://doi.org/10.3390/en16186465.

Pająk L., Tomaszewska B., Bujakowski W. & Dendys M., 2020. Review of the low-enthalpy Lower Cretaceous geothermal energy resources in Poland as an environmentally friendly source of heat for urban district heating systems. *Energies*, 13(6), 1302. https://doi.org/10.3390/en13061302.

Pająk L., Pierzchała K., Miecznik M. & Kasztelewicz A., 2023. Wpływ termomodernizacji budynku na obniżenie temperatury zasilania instalacji grzewczej [The effect of thermal retrofitting of a building on the reduction of a heating system supply temperature]. *Ciepłownictwo, Ogrzewnictwo, Wentylacja*, 54(7–8), 8–12. https://doi.org/10.15199/9.2023.7-8.1.

Rozporządzenie, 2002. *Rozporządzenie Ministra Infrastruktury z dnia 12 kwietnia 2002 r. w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie*. T.j. Dz.U. 2022 poz. 1225 [Regulation of the Minister of Infrastructure of 12 April 2002 on the technical conditions to be met by buildings and their location. Consolidated text Journal of Laws 2022 item 1225].

Sowiżdżał A., 2018. Geothermal energy resources in Poland – Overview of the current state of knowledge. *Renewable and Sustainable Energy Reviews*, 82(3), 4020–4027. https://doi.org/10.1016/j.rser.2017.10.070.

Sowiżdżał A., Hajto M. & Górecki W., 2016. The most prospective areas for geothermal utilization for heating and power generation in Poland. [in:] *EGC 2016: European Geothermal Congress 2016: Strasbourg, France, 19–24 September 2016*, France, 1–7.

Stala-Szlugaj K., 2023. Households in Poland vs. energy carriers: one year after Russia's February 2022 invasion of Ukraine. *Energy Policy Journal*, 26(4), 5–18. https://doi.org/10.33223/epj/171879.

Tomaszewska B. & Pająk L., 2012. Dynamics of clogging processes in injection wells used to pump highly mineralized thermal waters into the sandstone structures lying under the Polish Lowlands. *Archives of Environmental Protection*, 38(3), 103–117.

Tomaszewska B. & Szczepański A., 2014. Possibilities for the efficient utilisation of spent geothermal waters. *Environmental Science and Pollution Research,* 21(19), 11409–11417. https://doi.org/10.1007/s11356-014-3076-4.

Tyszer M., Tomaszewska B. & Kabay N., 2021. Desalination of geothermal wastewaters by membrane processes: strategies for environmentally friendly use of retentate streams. *Desalination*, 520, 115330. https://doi.org/10.1016/j.desal.2021.115330.

Zgłobicki W. & Baran-Zgłobicka B., 2024. Air pollution in major Polish cities in the period 2005–2021: Intensity, effects and attempts to reduce it. *Environmental Research*, 240(2), 117497. https://doi.org/10.1016/j.envres.2023.117497.