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Geothermal Energy

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Prospects for the application of geothermal resources in agriculture in Poland taking account of the natural functions of the countryside

Robert Skrzypczak[1], Beata Kępińska[1*], Leszek Pająk[2] and Wiesław Bujakowski[1]

*Correspondence: bkepinska@interia.pl
[1] Mineral and Energy Economy Research Institute, Polish Academy of Sciences, Wybickiego 7A Str., 31-261 Kraków, Poland
Full list of author information is available at the end of the article

Abstract
Agriculture is among the most promising applications of geothermal energy, and Poland has conditions to develop geothermal use in this sector. Suitable locations for agricultural geothermal installations shall be selected during the planning stage. To support the selection process, the authors chosed and analyzed thematic maps and other information on basic natural conditions for agriculture in Poland, potential conflicts between the operation of possible geothermal agricultural installations and other important functions of the natural environment, valuable natural areas and protection systems, elements of the current agricultural economy, etc. The authors combined them with the spatial distribution of geothermal reservoir parameters suitable for their agricultural applications using CorelDRAW X7 software. As a result, the regions with prospective geothermal applications in a sustainable agriculture can be identified, while maintaining the existing natural functions of the area. An example is given of the energetic, technical and economic calculations for agricultural greenhouses which can be supplied by geothermal resources in an area with existing natural functions, and a relevant study case is presented. The novel approach described in this paper may serve as an example in other countries of agricultural development with the use of geothermal resources.

Keywords: Geothermal resources, Agriculture, Applications, Natural functions, Poland

Introduction

Poland possesses geothermal energy potential which has promise for the development of direct applications in many areas, including agriculture (Górecki et al. 2006, 2011, 2012, 2013). The current uses of this energy source focus on six district heating systems, as well as balneotherapy and recreation, while the application of geothermal energy in the agricultural sector has so far been very low (Kępińska 2020). For several years from 1992 it included the experimental breeding of thermophilic species of fish as well as the heating of greenhouses and the soil in protected cultivation systems (Rosik-Dulewska and Grabda 2001, 2002). This took place in the facilities of the Mineral and Energy Economy

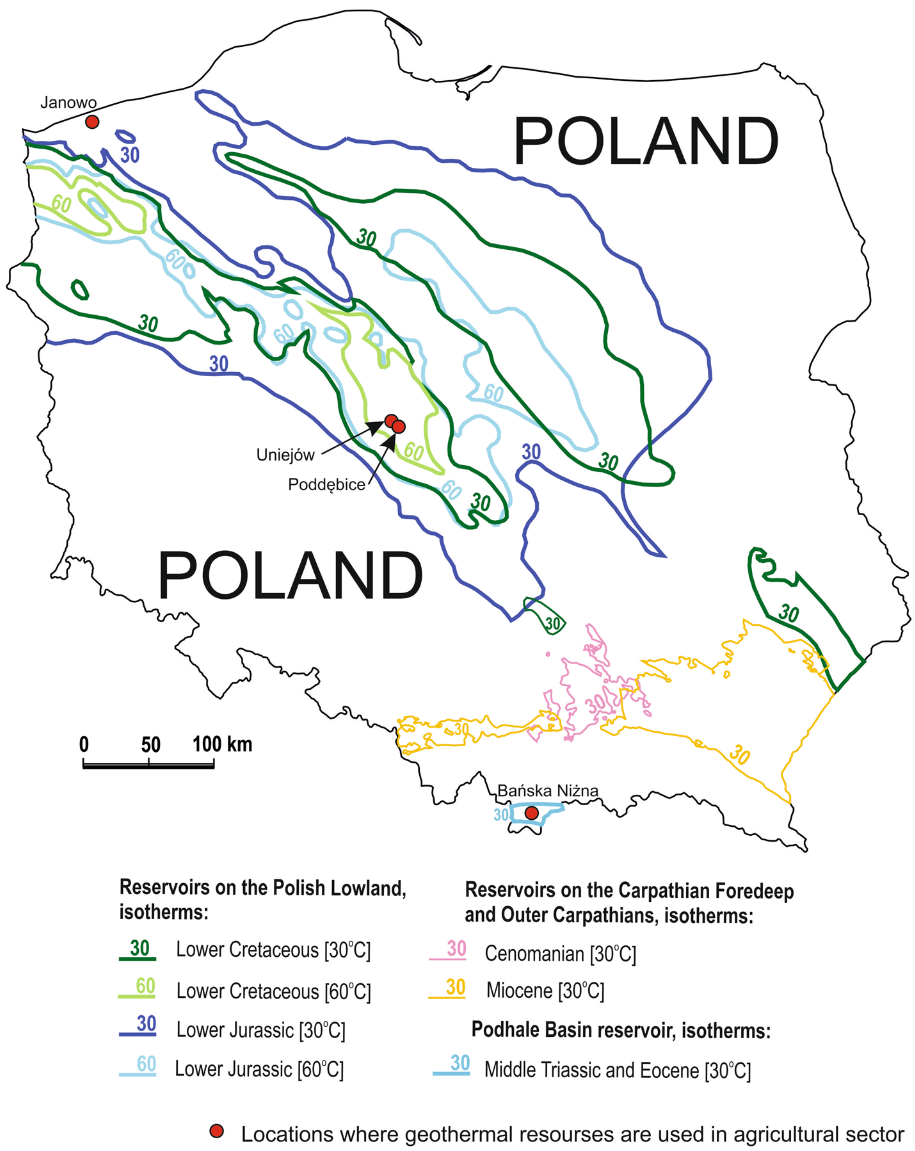

Fig. 1 Map of geothermal water reservoirs proposed for agricultural uses in Poland. Scientific description based on Barbacki et al. (2016); ranges of reservoirs with temperatures > 30 °C and > 60 °C according to maps by Górecki et al. (2006, 2011, 2012, 2013)

Research Institute of the Polish Academy of Sciences (MEERI PAS) in the Podhale region—Poland's first experimental system for the versatile cascade use of geothermal energy and water (Bujakowski 2000). Currently geothermal wood drying is still carried out there. Since 2016, an Atlantic salmon farm has operated in Janowo, West Pomerania. It uses geothermal water and heat from Jurassic sandstones discharged by a borehole drilled in 2012. In two other towns—Poddębice and Uniejów, vegetable processing has recently been carried out on a small scale with geothermal water that primarily meets the needs of geothermal district heating plants and recreation centres. Figure 1 shows, among others, the localities, where geothermal energy has been used for agricultural needs in the country.

Together with the wider development of the use of geothermal energy expected in the years to come, e.g., in district heating, one can also look forward to an increased interest in its applications in agriculture and related fields. The use of such low-carbon, green energy in the production and processing chain shall contribute to environmental improvement and sustainable agricultural development. It will result from, e.g., elimination of local air pollution caused by burning fossil fuels to heat greenhouses or polytunnels. Agricultural uses can also improve the energy efficiency and economic aspects of heating systems based on geothermal source, since they will offer possibilities for its wider cascaded applications (Popovski and Popovska 2003). For this to occur, it is necessary to consider future geothermal facilities and agricultural installations from an energy point of view when planning and designing them and to select appropriate locations. This should result both from typical agricultural reasons and reasons concerning the availability of adequate geothermal energy resources in groundwater, and these should be harmoniously incorporated, for example, into existing systems of areas of high natural value (with various important functions, not only in the natural environment). Moreover, it should also not interfere with the role of some other natural resources of critical importance (e.g., strategic groundwater resources for drinking water or forest resources).

The authors of this paper point out that the richness of many valuable natural areas will facilitate the development of organic agriculture in some areas of Poland with the use of clean geothermal energy.

This article presents the main elements of such an approach to the use of geothermal energy for sustainable development in agriculture and related sectors in Poland, which covers both the issues of resources and energy as well as natural conditions. This approach is proposed for Poland for the very first time.

Agriculture and related sectors are important areas for the direct application of geothermal energy. In this respect, to demonstrate their position among other economic sectors, it is best to refer to the latest synthetic summary of the use of geothermal heat in the world: this was presented for the years 2015–2019 in April 2020 (Lund and Toth 2020). This indicated that in 2019, direct applications of geothermal energy were pursued in nearly 90 countries worldwide. Their total installed thermal capacity in 2019 was approx. 108 GW, while heat consumption totalled 1,020,890 TJ. This was a very large increase compared to 2014, by 52 and 72%, respectively, which shows the overall increasing use of geothermal heat on a global scale. The largest amounts of power and heat were generated by ground (geothermal) heat pumps (58.8% of the total amount of geothermal heat used), followed by recreation and health care (18%) and district heating (16%). The fourth place in this ranking was occupied by agricultural applications, i.e., the heating of greenhouses and protected cultivation (3.5%, 32 countries), with the following spots including aquaculture (1.3%, 21 countries) and crop drying (0.4%, 15 countries). These three types of applications in agriculture and related fields amounted to a total of 5.2% (over 49,400 TJ/y). Other direct applications of geothermal energy in the world in 2019 (in total about 2.4%) included industrial and processing applications, various smaller scale uses (such as ice control of traffic routes/melting snow) and for various other purposes. This classification also included smaller scale applications related to agriculture, such as algae farming, heating of livestock buildings, and irrigation of crops. The percentages provided (including in agriculture) would be significantly higher if heat pumps/shallow geothermal systems (approx. 58% of the geothermal heat used) were not included.

It is worth emphasising that, following Lund and Toth (2020), the comparison of current data (from 2019) and data from 2014 (from the World Geothermal Congress in 2015; Lund and Boyd 2015) for greenhouses indicates an increase in the use of geothermal heat by 23%, while in the case of aquaculture, it is by 13%. In 2019, geothermal heating of greenhouses and protected cultivation (flowers, vegetables, fruit, and tree seedlings) was operational in 32 countries, with Turkey, China, The Netherlands and Russia at the forefront. Aquaculture (fish, other species) using heat and geothermal water were present in 21 countries, most of them in China, USA, Iceland, Italy and Israel. Drying of agricultural crops (cereals, vegetables, fruit, seaweed, wood) using heat from geothermal water was carried out in 15 countries. In addition to Turkey, the Netherlands, and Russia previously mentioned, some other European countries using geothermal for agricultural purposes include Iceland, Hungary, Italy as well as Austria, Greece, France, Slovakia, Germany, North Macedonia, Serbia, and Switzerland (all information given after Lund and Toth 2020).

Another prerequisite for the possible use of geothermal energy may be the functioning of a special form of organisation of agricultural production—organic farms. According to Eurostat (2013), in 2012 the leading European countries in terms of the number of organic farms were as follows: Italy (48,852), Spain (30,462), France (24,425), Greece (23,433), Germany (23,032) and Austria (21,843). At that time, the total value of sales of the products of organic agriculture in Europe reached about 23.4 billion EUR, increasing by about 6% per year, with the largest markets in terms of their retail sales: Germany (EUR 7.6 billion), France (EUR 4.4 billion) and the United Kingdom (EUR 1.1 billion). On the other hand 23,847 organic producers were registered in Poland in 2011, including 23,449 organic farms and 270 processing plants, and the total area of crops used in accordance with the regulations on organic farming was 605,519 ha (Zdrojewska 2013). So in that year Poland was in a leading position in Europe, being third at least in terms of the number of organic farms. Such farms should, as far as possible, use organic methods and raw materials and green energy sources throughout the production and processing chain—such a source (sometimes also raw material) can be geothermal energy.

In the north-western part of Poland, relatively large organic farms were present in terms of holding area. There were many such farms in the southeast, however, much smaller in size. These farms may even show fourfold differences in terms of holding size.

Materials and methods

An analysis of the global uses of geothermal resources for the needs of the agricultural sector and their energy parameters leads to the conclusion that there are geothermal water reservoirs in Poland useful for such purposes. These are, above all, the reservoir parts with the temperatures at least exceeding the 30 °C isotherm. They were marked on Poland's map (Fig. 1) using Geothermal Atlases (Górecki et al. 2006, 2011, 2012, 2013). Then, the authors plotted the isotherm on selected thematic maps (using CorelDRAW X7 software), which were important for the initial consideration of future locations of geothermal facilities for the agricultural sector. These maps consider some vital local conditions that had been neglected before, particularly in the context of sustainable development and avoiding conflicts between the status quo and new projects.

The authors selected the thematic maps based on an analysis and systematisation of cartographic materials developed for specific purposes and derived from different online sources. Thematic working maps—a source of essential data—were arranged to present the following conditions in Poland: soil conditions (soil types, soil moisture, and the risk of hydrological droughts in exemplary time intervals), potential conflicts between the operation in the proposed new geothermal facility for agriculture in reference to other essential functions of the natural environment (e.g., areas of strategic drinking water reservoirs and their protection zones, valuable natural areas—including forests—and their protection systems), selected previous agricultural sites (locations of orchards, field vegetable cultivation, protected cultivation systems, and demonstration farms).

The information presented on the selected thematic maps, proposed for the preliminary stage of analyses, most of which are presented in this paper, was supplemented with technical and economic data and results of energy parameter analysis of two types of greenhouse facilities typical of the Polish Lowlands. Such greenhouses can be heated with geothermal water if adequate parameters occur in the reference areas. The case of Poddębice in the Polish Lowlands is an example of a specific locality fulfilling the above-mentioned conditions, presented later in this article.

Results and discussion

Identification of geothermal reservoirs suitable for sustainable use in agriculture in Poland

The sections of geothermal aquifers in the Lower Cretaceous and Lower Jurassic formations within the Polish Lowlands are considered to be the best prospects for agricultural use in Poland. They are located at depths of 1.5–3 km and consist of medium and coarse grained sandstones interbedded with mudstones and claystones. They are from several dozen to several hundred metres thick. Geothermal water flow rates from individual wells range from several dozen to over 200 m^3/h—as confirmed by the wells already exploited (60–250 m^3/h). Water temperatures at the outflows are in the range of ca. 20–90 °C. The mineralisation is very variable: from below 1 g/dm^3 up to 80–100 g/dm^3 in the deepest parts of the Jurassic formations. However, some exceptions to this trend were confirmed, e.g., in the Poddębice area, where geothermal water coming from a depth of ca. 2 km has a mineralisation below 1 g/dm^3, as presented in a later part of this text.

Some sectors of geothermal aquifers are unconfined. They may be at least partly recharged by infiltration water migrating deep down from the shallow parts of reservoir rocks. These parts are situated right below the cover of permeable Quaternary formations. This type of recharge can facilitate a sustainable exploitation of considered geothermal aquifers for several purposes, including agriculture. In addition sustainable exploitation can be assured by operating both production and injection wells. One should also remember to keep a balance between the maximum production rate and natural recharge of the particular sector of the geothermal reservoir, which facilitates stable long-term exploitation. This will also apply to situations in which geothermal water is used for agriculture.

Furthermore, despite the expected lower output capacities of these water intakes, some areas of the Carpathian Foredeep and the Carpathians (in both cases mainly having sandstones and carbonate rocks as reservoir hosts) are given consideration (Fig. 1). These sections are defined as those exceeding 30 °C isotherms, and in the Polish Lowlands also 60 °C isotherms. With regard to the sections of the reservoirs defined by the 60 °C isotherm, this may facilitate the simultaneous agricultural use of these resources for different purposes from a single water intake. This also applies to localities, where geothermal water is already used for heating purposes or is planned to be so used in the near future. For the Polish Lowlands, it is worth noting that Cretaceous reservoirs locally contain water of drinking quality (fresh water) the mineralisation of which is below 1 g/dm^3 (e.g., in the area of Poddębice which is described later in this paper). Such water may serve both as a heat source and as water for the irrigation of crops. In some cases with higher levels of mineralisation of the geothermal water (from a few to a dozen g/dm^3) one may consider using it for crop irrigation after it has been demineralised or undesirable components have been removed. This can be done, e.g., using the reverse osmosis method which has been described for other potential uses by Tomaszewska and Szczepański (2014). This especially refers to geothermal waters hosted by the Cretaceous and Jurassic formations, where, in some sectors, the mineralisation can reach the level of a dozen g/dm^3 (Górecki et al. 2006). The suggested demineralisation process has to be the subject of further more detailed economic considerations and will require verification for a particular location or project.

Relatively less favourable geothermal conditions are found in southern Poland, due to the generally low output capacity of potential water intakes (except in the Podhale region, where they are of high capacity). In the Carpathian Foredeep area (also in the part under the Carpathian overthrust) local agricultural use of geothermal water found in small Triassic and Jurassic reservoirs is also possible. A similar situation applies in the Carpathians. In the west, geothermal waters are present in small reservoirs in three levels of flysch, as well as in the reservoirs in a series in the flysch bedrock from Cenomanian and Middle Jurassic, and in the east they are mainly in the Miocene reservoir, which is relatively extensive (Barbacki et al. 2016). Especially in those areas of Poland mentioned above, as well as in areas, where geothermal water with temperatures below 30 °C occurs, there are different methods available for facilitating their agricultural use. In Poland, according to formal regulations, thermal water is groundwater with a temperature of not less than 20 °C at the outflow from the intake (CSRP 2017). However, water with temperatures from 15 to 40 °C (i.e., within a certain range of temperature values including water which is not formally recognised as thermal water according to Polish regulations), if fresh, can be used for the irrigation of crops, and if it simultaneously exhibits low mineralisation and appropriate physico-chemical composition for aquacultures (Lund and Boyd 2015). On the other hand, the energy in water with temperatures of 15–40 °C is useful for heating crops in protected cultivation, and the energy of water with temperatures of 25–60 °C can be used for heating livestock buildings. The energy of water with higher temperatures (from 30 °C to over 60 °C—higher temperatures are more advantageous) can be used for heating greenhouses, agri-food processing, drying, and grain and feed processing.

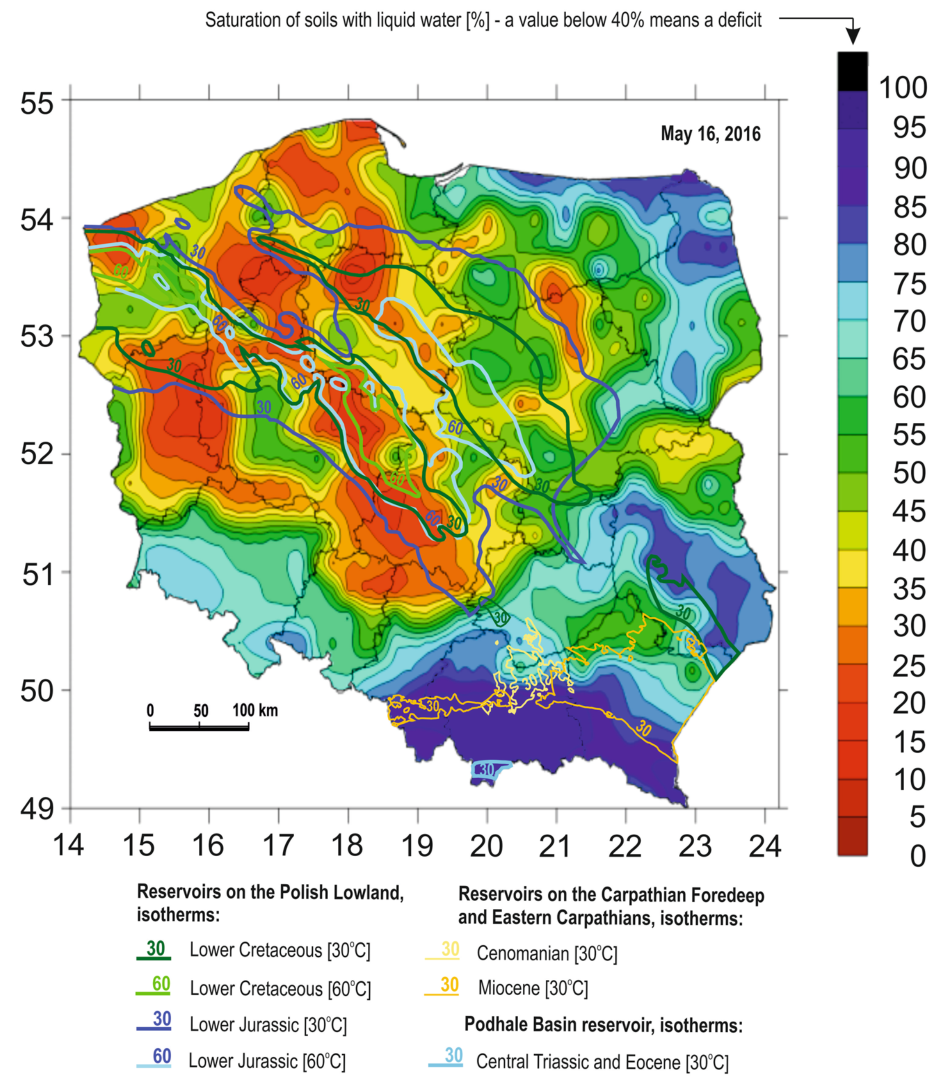

Fig. 2 Geothermal water reservoirs proposed for agricultural uses in Poland against the map of soil moisture indicators. Explanations regarding the soils moisture index: a colorful scale of % saturation of soils with liquid water at a depth interval of 0.7–0.28 m. Scientific description based on Barbacki et al. (2016)*;* ranges of reservoirs with temperatures > 30 °C and > 60 °C according to maps by Górecki et al. (2006, 2011, 2012, 2013); saturation of soils with liquid water according to MARD (2017), IMWM-NRI (2021)—sample data from May 16, 2016

Decisions on the potential locations of geothermal facilities for agriculture, in particular organic farming, are facilitated if the soil types (Map of Polish soils 2020) under which geothermal water reservoirs are located are taken into account. The structure of such farms will have to be planned in relation to the soil types in the area and on the basis of that identification, by the selection of plant species with appropriate requirements in this respect.

Geothermal water reservoirs offering prospects for agriculture in Poland can be compared with the map of soil moisture indicators (Fig. 2). This will graphically present general information as an example, showing as it does an example of the soil moisture conditions on a specific day (16 May 2016). The design of agricultural geothermal installations should take into account changes in the soil moisture situation over periods of several years, using a package of similar maps published periodically, as well as for the months during the year which are sensitive for agriculture (with regard to crops on the farms that would use geothermal waters). The map presents the values of soil moisture indicators, i.e., the saturation of the soil with liquid water at a depth range of 0.7–0.28 m. This range is important for the development of the root system of many arable crops. At the same time, the figure presents spatial trends that are periodically repetitive. This is partly due to the soil structure and also depends on the time and intensity of precipitation. Deficit areas for water retention, i.e., with a coefficient lower than 40% occur periodically in the Polish Lowlands. In Fig. 2, they are marked in yellow, orange, red and brown. These areas are also locations of geothermal reservoirs, so the possibility of a periodic supplementary resupply of this water to the soils can be examined (if their natural parameters would be appropriate for the specific crop species grown on farms in such areas or if the parameters of these waters could be adapted to the irrigation of crops).

The information for the design of systems for using geothermal energy in agriculture (geothermal installation-farming*)* should be complemented by an analysis of meteorological information regarding drought periods. One element of such an analysis is provided by plotting geothermal water reservoirs which present prospects for agricultural use in Poland against a map of drought threats (Fig. 3).

A review of the maps available on the portal of the ISSPC-NRI Institute of Soil Science and Plant Cultivation in Puławy (http://susza.iung.pulawy.pl/mapy/2020,09,R_stracz) which has been publishing periodic graphical reports for successive time intervals of the year since 2009, indicates that, apart from last year 2020, the criteria for defining a drought, as indicated in the Regulation of the Ministry of Agriculture and Rural Development (MARD 2017) for various types of plants, have generally not been exceeded in recent years. Among these plants, legumes serve as the most sensitive indicators of drought. Figure 3 shows an example of the situation on 2.09.2013. On a similar date (12.09.2013) the cultivation of fruit bushes and potatoes in part of the Mazowieckie, Świętokrzyskie and Podkarpackie administrative provinces was also threatened by drought. The figure for legumes suggests that in those areas of their cultivation, where the geothermal water reservoirs mentioned above are present, it would be advisable to periodically supplement the irrigation of soils with this water, especially legume crops, bush fruit and potato crops (always subject to the water parameters being appropriate for the specific plant species, as already pointed out above).

The potential construction of new facilities for the use of geothermal water in agriculture should take into account the distribution of the main groundwater reservoirs (MGR) in Poland, which constitute a strategic freshwater reserve. It is best to construct such new facilities outside the range of these reservoirs, especially their protection zones (AHLP—areas of highest level of protection, AHP—areas of high level of protection). The utmost caution is required with regard to proposals for MGR during detailed survey of conditions in the field and the implementation of the investment to ensure that the principle of protecting the resources of these strategic reservoirs is maintained. In Fig. 4, the geothermal water reservoirs proposed for agricultural use in Poland are plotted against a map of the main fresh groundwater reservoirs (MGR)

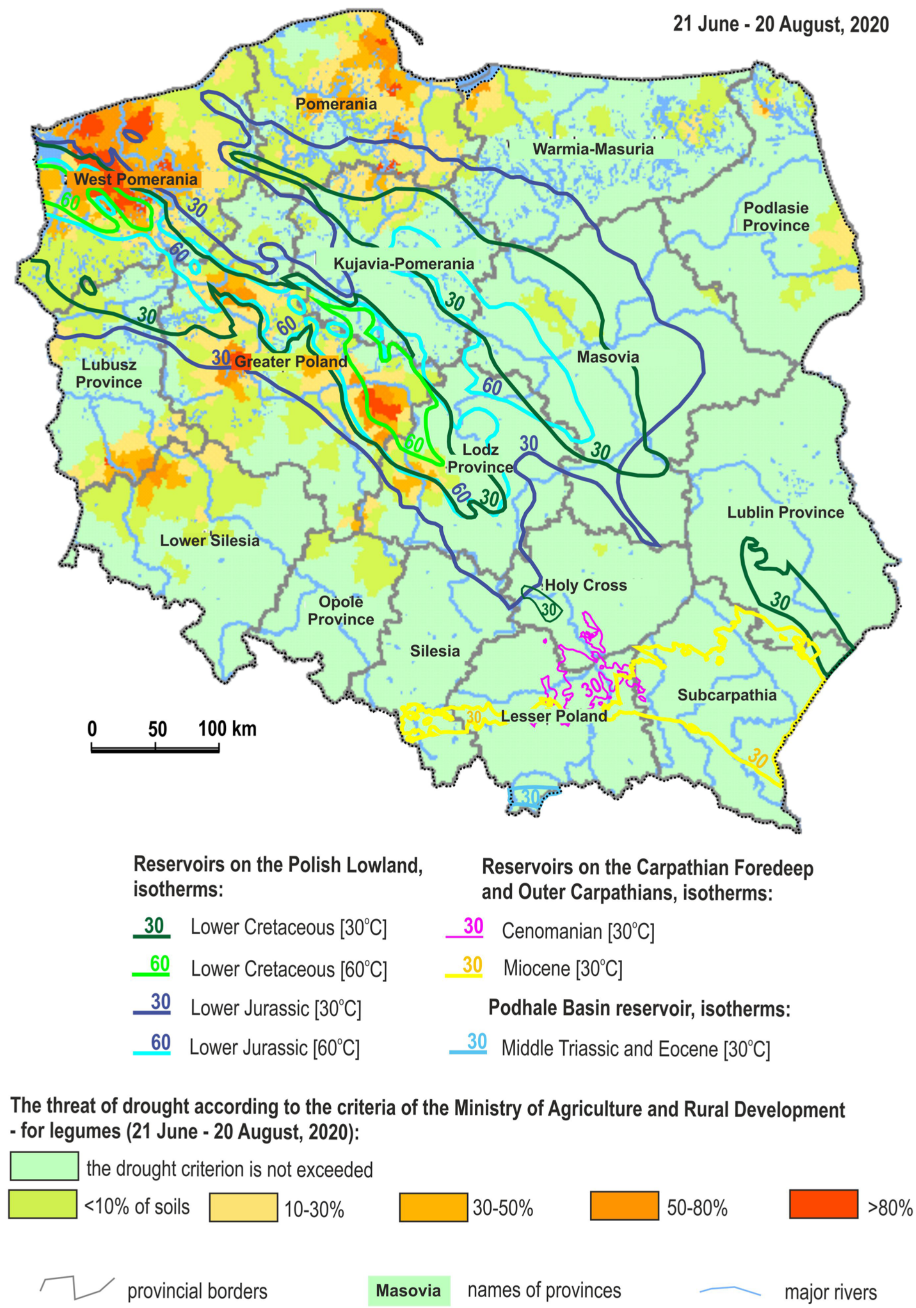

Fig. 3 Geothermal water reservoirs proposed for agricultural uses in Poland against the map of drought threats. Scientific description based on Barbacki et al. (2016); ranges of reservoirs with temperatures > 30 °C and > 60 °C according to maps by Górecki et al. (2006, 2011, 2012, 2013); Map of drought threats according to ISSPC-NRI (2020)—sample data from 21 June to 20 August, 2020

and their protection areas (Fig. 4). The AHLP and AHP areas, which are not shown in Fig. 4 to provide greater readability, in most cases fall within the boundaries of the MGR. The MGR indicated in 1990 are gradually being documented in detail. The map of the MGR published by the Polish Geological Institute–National Research Institute (PGI-NRI 2016) and shown in Fig. 4 illustrates the state of documentation of the

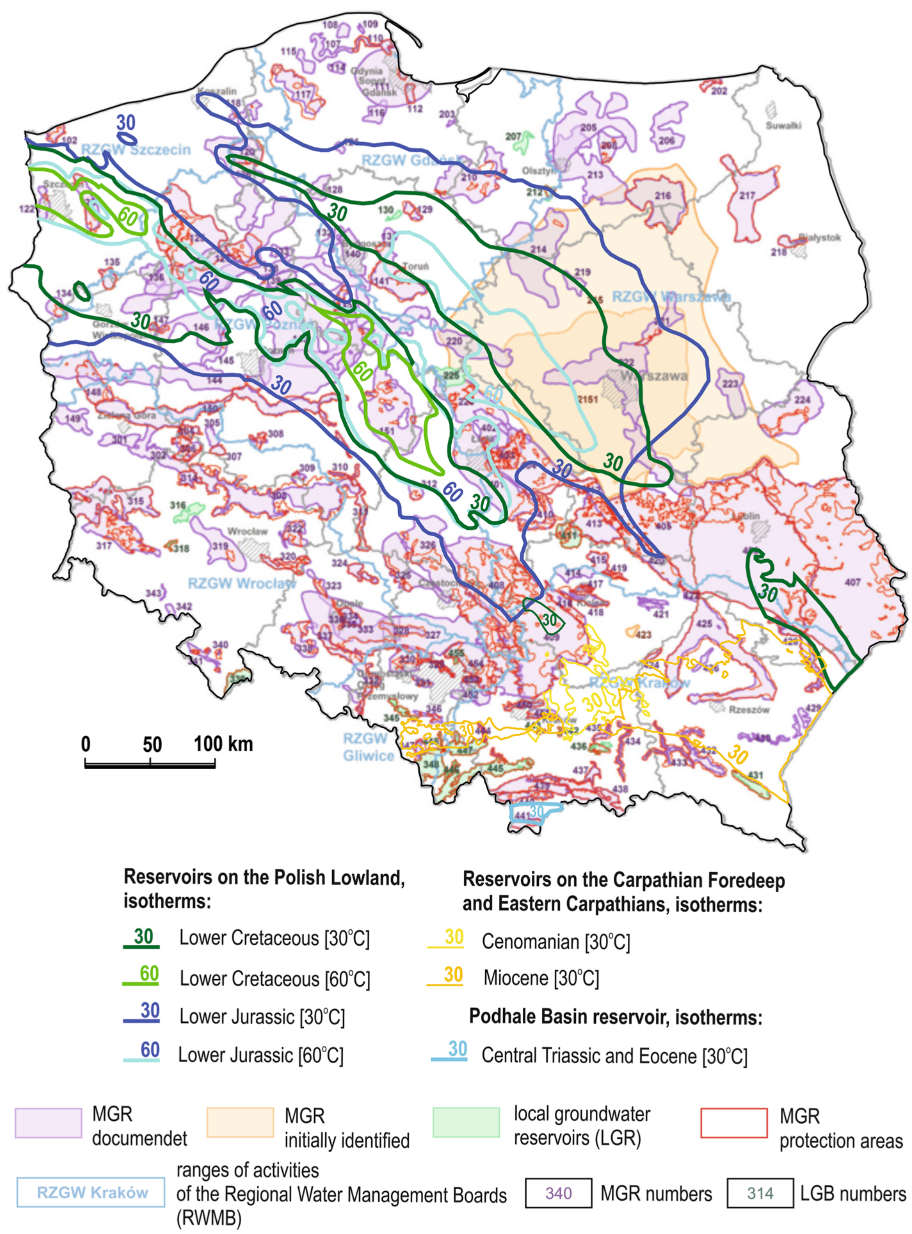

Fig. 4 Geothermal water reservoirs proposed for agricultural uses in Poland against the map of main groundwater reservoirs (MGR—fresh) and their protection areas. Scientific description based on Barbacki et al. (2016); ranges of reservoirs with temperatures > 30 °C and > 60 °C according to maps by Górecki et al. (2006, 2011, 2012, 2013); underlay Map of Main Groundwater Reservoirs (PGI-NRI 2021)—data from November 2016

MGR in November 2016 and is used as a base. This indicates the location of the MGR and indirectly their protection areas.

In a similar manner to the MGR, potential locations of new facilities for the use of geothermal waters in agriculture, especially in organic farming, do not have to be in conflict with the facilities of the system of protection of natural assets. Sometimes they could even enhance their functions, e.g., educational. This is indicated by

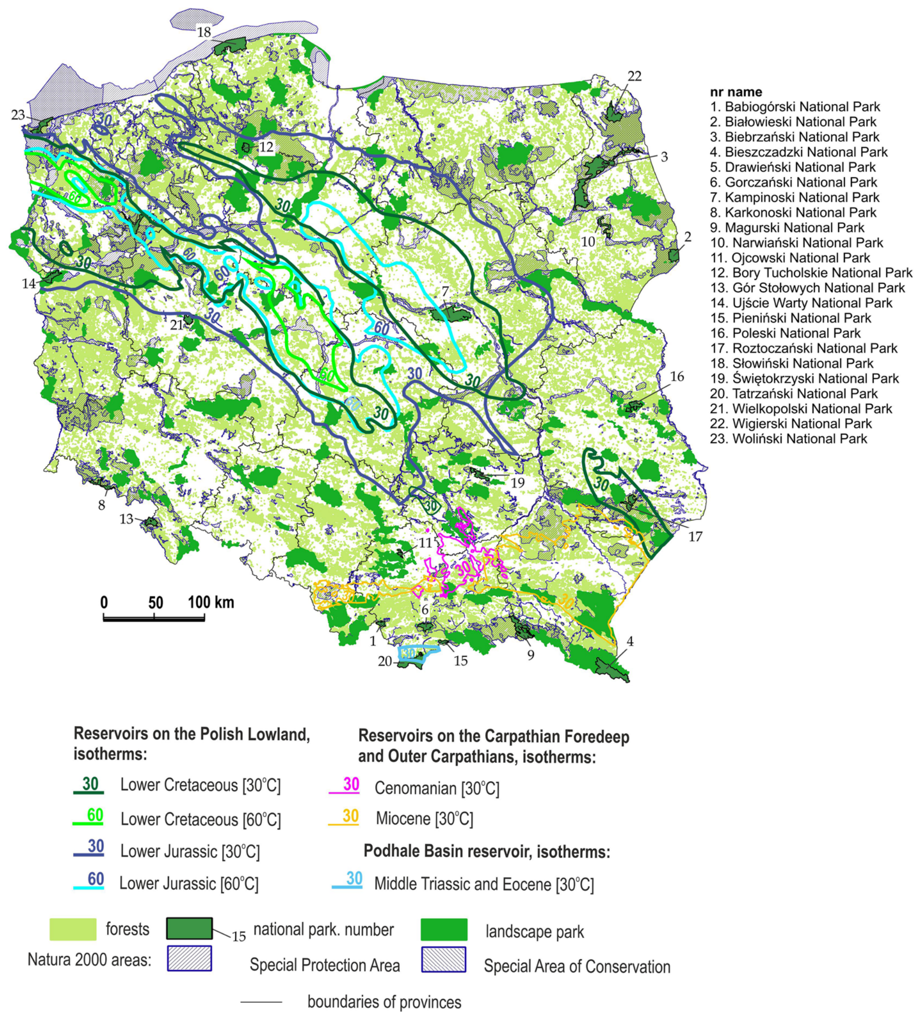

Fig. 5 Geothermal water reservoirs proposed for agricultural uses in Poland against the map of national parks, landscape parks, Natura 2000 areas and forests. Scientific description based on Barbacki et al. (2016); ranges of reservoirs with temperatures > 30 °C and > 60 °C according to maps by Górecki et al. (2006, 2011, 2012, 2013); underlay map of national parks landscape parks, NATURA 2000 areas and forests in Poland (GDEP 2021; HOGC 2021a, b)

a map of geothermal water reservoirs in Poland that are proposed for agricultural use plotted against a map of national parks, landscape parks, NATURA 2000 areas and forests (Fig. 5). The results from this map indicate that geothermal installations for organic farming could be located in the buffer zones of some national parks and landscape parks. This applies in particular to the buffer zones of the following national parks: Bory Tucholskie, Drawieński, Ujście Warty, Wielkopolski, Kampinoski and Roztoczański National Parks. It also applies to sections of the landscape park buffer zones within the 30 °C isotherm of geothermal waters in the Lower Cretaceous reservoir and within the Miocene reservoir in the Eastern Carpathians.

The map used as a base for Fig. 5 particularly well illustrates the distribution of forests, and against this background, the location of borders of national parks and landscape parks in Poland. On the other hand, very important sites of the European

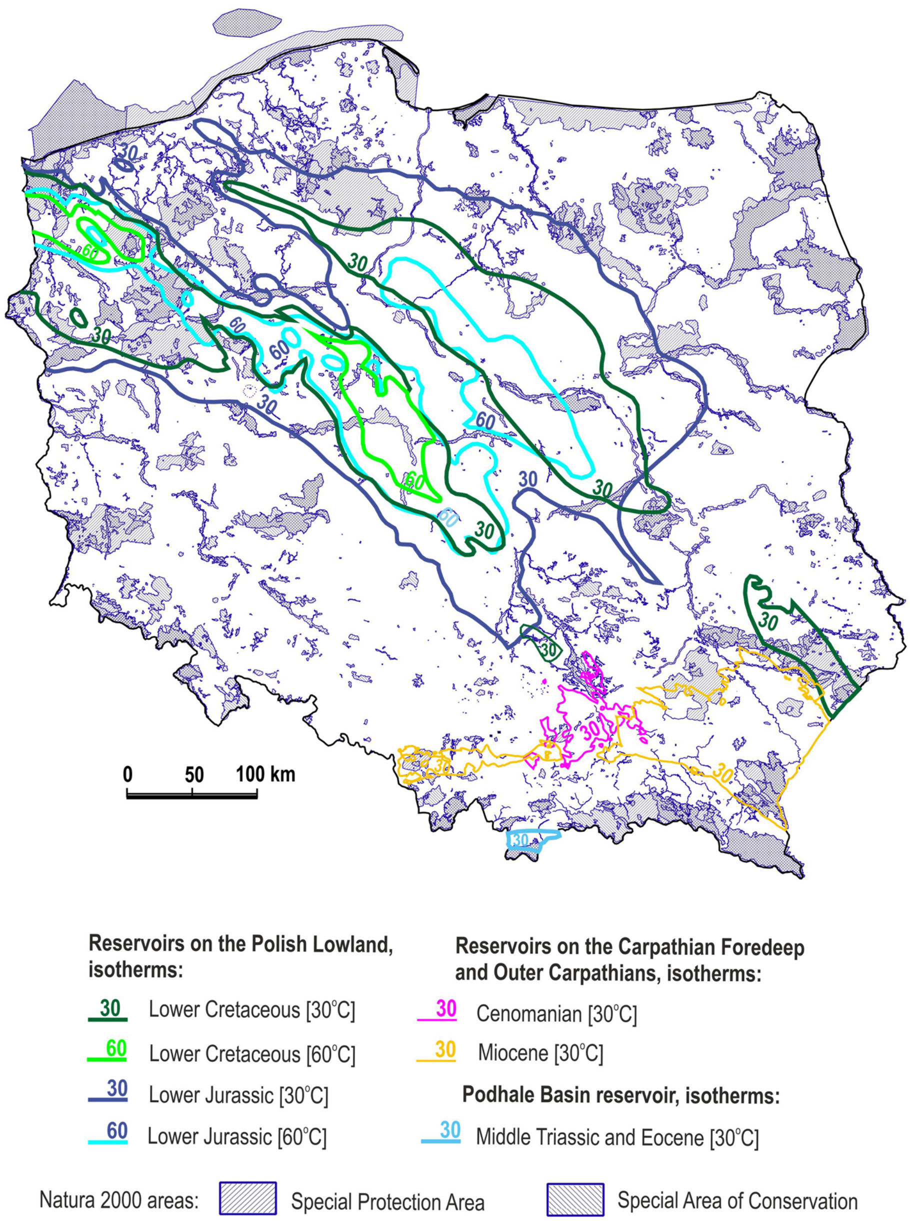

Fig. 6 Geothermal water reservoirs proposed for agricultural uses in Poland against the map of the objects of the European Network Natura 2000 areas. Scientific description based on Barbacki et al. (2016); ranges of reservoirs with temperatures > 30 °C and > 60 °C according to maps by Górecki et al. (2006, 2011, 2012, 2013); underlay the Map of the Nature 2000 areas (GDEP 2021; HOGC 2021b)

NATURA 2000 Network are more clearly presented in the map of geothermal water reservoirs in Poland proposed for agricultural use against the map of the sites of the European Network NATURA 2000 areas (Fig. 6). In turn, the map of geothermal aquifers in Poland which provide prospects for agricultural use plotted against the map of spatial policy directions concerning nature (Fig. 7) in the bottom layer illustrates other very important elements of the nature protection system. These elements are the borders of national parks and landscape parks together with their buffer zones,

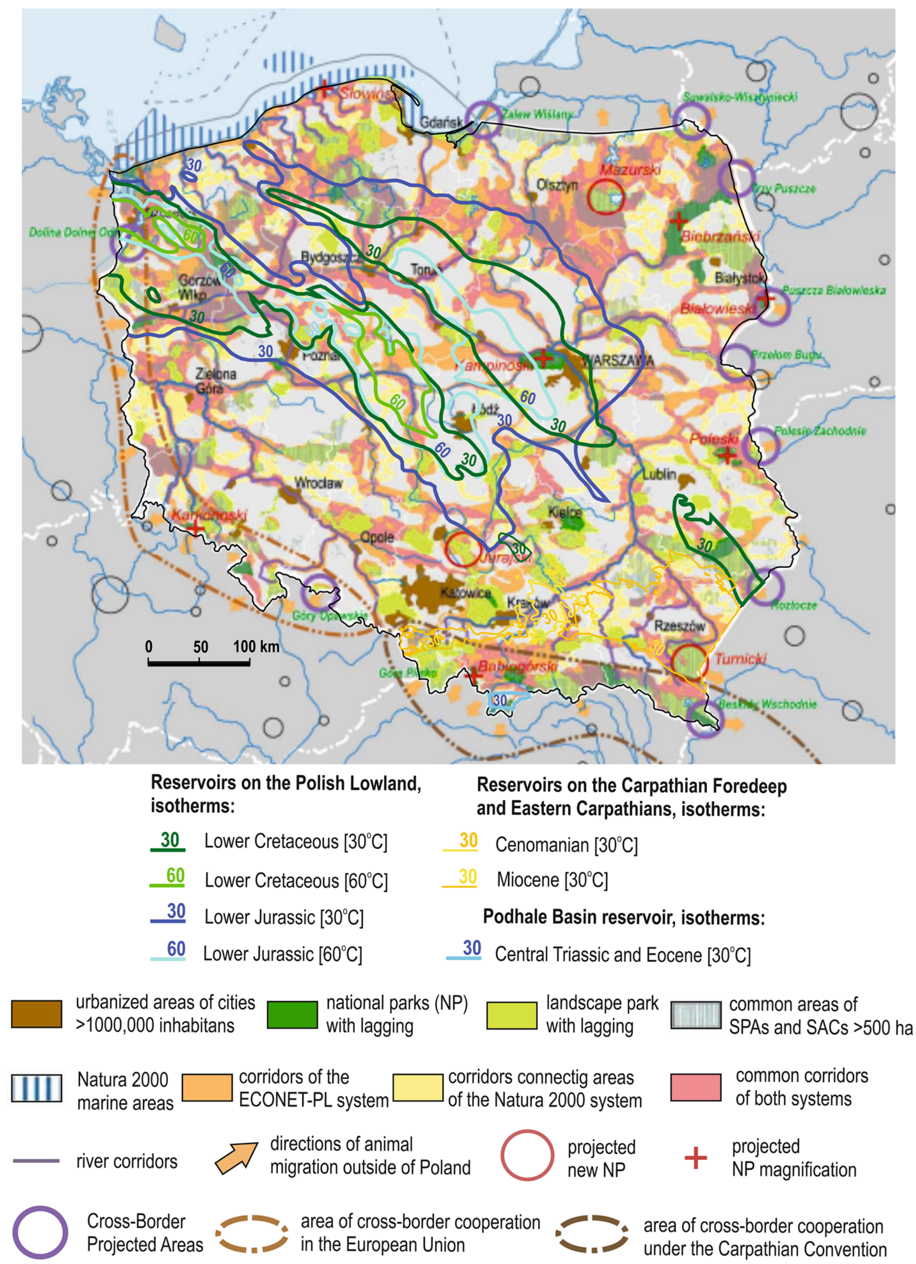

Fig. 7 Geothermal water reservoirs proposed for agricultural uses in Poland against the map of spatial policy directions concerning nature. Scientific description based on Barbacki et al. (2016); ranges of reservoirs with temperatures > 30 °C and > 60 °C according to maps by Górecki et al. (2006, 2011, 2012, 2013); underlay Żuber et al. (2021) including network status in 2010, Helcom BSPA data on sea areas, data of the Institute of Environmental Protection about corridors ECONET-PL in 1996, data of the Mammal Research Institute, Polish Academy of Sciences, Bialowieza, about the corridors connecting Natura 2000 areas in 2006 and data of the National Water Management Board on river corridors in 2010

i.e., the places mentioned above which are especially preferred for locating potential new geothermal installations for agriculture. This layer also shows—and this is very important, too—the ecological corridors of another European system—ECONET-PL as well as corridors connecting the NATURA 2000 system areas (including those running through the buffer zones). Corridors are a dynamic element of protection systems that determine the durability of their natural functional centres (i.e., conventional fixed nature centres); therefore, they should not be used for agricultural purposes.

When considering potential locations for geothermal facilities suitable for agricultural use, they should preferably be located outside the NATURA 2000 system areas. Within the limits of the proposed geothermal reservoirs these are relatively small areas on a national scale, predominantly found in the north–west and south–east parts of Poland. Such facilities should, in principle, also be located: outside habitat areas (SACs) and, in the case of bird sanctuaries (SPAs), outside nesting areas and bird colonies or temporary breeding sites, and also, in principle, outside forest areas. Other sites which should exclude the possibility of locating geothermal facilities are ecological corridors.

Derogations from these general principles would be possible in individual situations. In each case, the criteria for approval or rejection of investment projects related to the use of geothermal energy and water in agriculture should be considered on a case-by-case basis after consultation with the authorities responsible for compliance with nature conservation legislation.

Agricultural structure of Poland as a prerequisite for geothermal energy and water uses

One of the essential agricultural prerequisites for the potential use of geothermal waters and their energy in Poland is the structure of horticultural crops and their territorial distribution. The state in 2002 is discussed by Kulikowski (2007) (unfortunately there is a lack of more recent studies). This study included the following types of agriculture: orchards (53.2% of horticultural crops), field vegetables (33.7%), bush fruit (10.4%), protected cultivation (1.2%), fruit tree and bush nurseries (0.9%), flowers and ornamental plants (0.6%). Other types of culture constituted 1.0%.

In the case of fruit trees, orchards represented more than 10% of the area of municipalities in the SE part of the area identified for the Lower Cretaceous reservoir in the Polish Lowlands by the 30 °C isotherm, and in many areas, where there are geothermal reservoirs potentially useful for agriculture, it was higher than 3% and sometimes 5%. On the other hand, in the case of field vegetables (including crops under protected cultivation): onions constituted 17.7%, cabbage 15.5%, edible carrots 14.6%, cucumbers 9.6%, red beet 6.7%, tomatoes 5.8%, cauliflowers 5.6% and other field vegetables 24.5%. Field crops constituted over 6% of the area of municipalities in many locations, where there are geothermal reservoirs potentially useful for agriculture (especially in the central and south–west part of the Polish Lowlands and in the north–west) and in many other locations also over 4%, and less frequently, over 2%.

The structure of protected cultivation agriculture, for which the use of geothermal resources seems to be particularly useful, is presented in Fig. 8 against the background of the sections of geothermal water reservoirs recommended for their use in agriculture.

There is a separate category of organic farm in Poland, organic demonstration farms (AACB 2012). It seems that some of these could benefit from the use of geothermal water. In the case of Podhale, cooperation could be established with the geothermal plant in Bańska Niżna and for the Polish Lowlands with, among other partners,

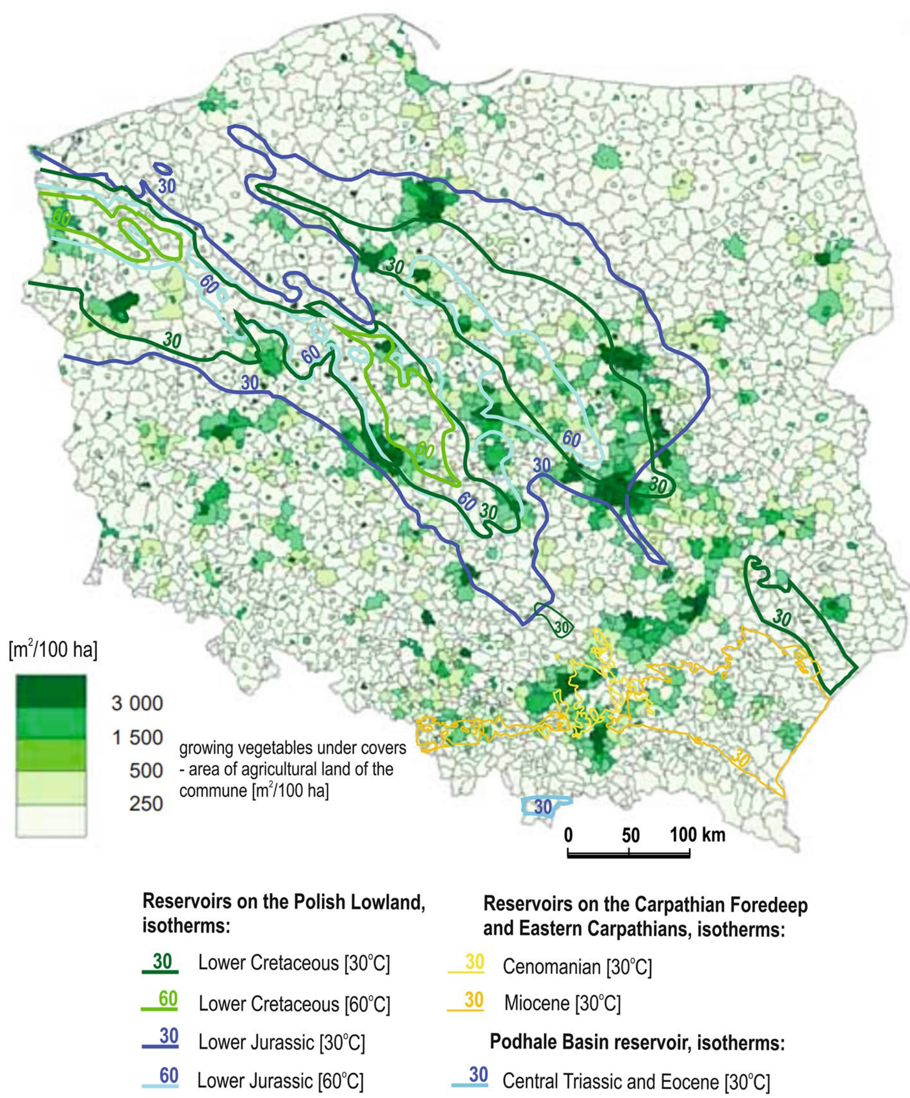

Fig. 8 Geothermal water reservoirs proposed for agricultural uses in Poland against the map of cultivated vegetables under covers. Scientific description based on Barbacki et al. (2016); ranges of reservoirs with temperatures > 30 °C and > 60 °C according to maps by Górecki et al. (2006, 2011, 2012, 2013); underlay Map of vegetables crops under cover (2002 [in:] Kulikowski 2007)

interested heating plants (in 2020, five were operational in this area of Poland, further ones are expected). Future locations of geothermal facilities for organic farming could also be linked to some other demonstration organic farms in the following regions: West Pomerania, Pomerania, Kujavia-Pomerania, Lubusz Region, Greater Poland, Lodz Region, Masovia, Lublin Region, Silesia, Lesser Poland and Subcarpathia. These regions are depicted in Fig. 3.

Examples of preferred greenhouse facilities in Poland potentially using geothermal energy

As mentioned above, among the various possible uses of geothermal water and energy in agriculture, one of the most popular would be their use in greenhouses. The methods and possibilities for direct application of waters will depend on their physico-chemical parameters, including output capacity, temperature, mineralisation, chemical composition, gas content and type. With regard to these factors, the appropriate temperature of geothermal water is particularly important for agricultural applications. If, on the other hand, the mineralisation, physico-chemical composition and gas content deviate from the standards required for the specific crop species grown, etc., it will be necessary to apply suitable methods or technologies to adjust the values of these parameters to an appropriate level.

This chapter focuses on examples of greenhouse systems which can use the energy from the geothermal water often found in the Polish Lowlands as a heat carrier. Uniejów and Poddębice zones were selected for analysis (the location of these towns is shown in Fig. 1. The results of the relevant energy and economic assessments are provided for standard greenhouse installations which are in common use and suitable for the zone selected due to, among other criteria, the prevalent climatic conditions. They are conventionally referred to as large greenhouses (a single large greenhouse facility) and small greenhouses (forming a system of seven small greenhouse facilities). The analyses were conducted taking into account the following assumptions:

- access to geothermal water with a temperature of 60 °C for heating the greenhouses through a central heating system and for warm water preparation (Poddębice is situated in an area, where geothermal water temperatures reach and exceed the specified value, Barbacki et al. 2017; Fig. 1),
- location in the so-called climatic zone II for project calculations according to Polish Standards for the design of heating systems PN–EN 12831 (PCS 2006) (this includes the central section of the geothermal reservoirs in the Polish Lowlands; project parameters: minimum outside temperature − 18 °C, average yearly outside temperature 7.9 °C),
- interior temperature of the facility approx. 26 °C and humidity of air 65%,
- external shell of greenhouse facility providing a heat transfer coefficient at the level of 0.5 W/(m^2 K),
- intensity of air exchange in the facility approx. 0.3 volume/h (where the volume is the volume of air filling the indoor space of the greenhouse).

The assumptions for both types of greenhouse facility were complemented by the characteristics of their energy requirements, which were prepared using a mathematical model. Formulas for the calculation of selected energy values were used, which take into account the Polish Standards for climate zones noted above (PCS 2006).

The large greenhouse facility had a cubature of 225,000 m^3 and energy demand from the central heating plant estimated at 2.4 MW with preparation of the heating water estimated to require 16 kW, while the total heat demand was estimated at 21.8 TJ/y. The structured curve of power demand is presented in Fig. 9, and the structured demand for the temperature and flow rate of the heating medium is presented in Fig. 10. This

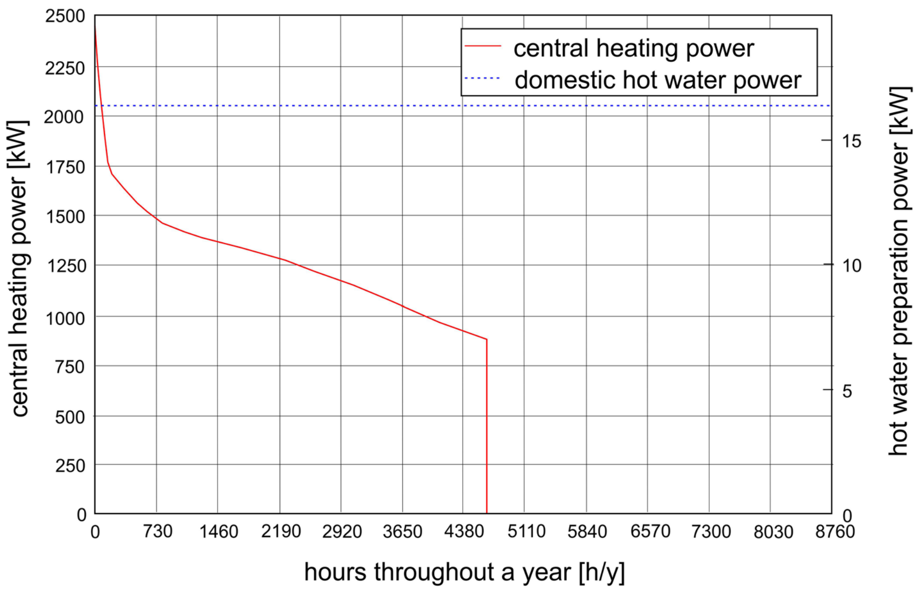

Fig. 9 Structured demand curve for heating power and domestic hot water preparation for the large greenhouse

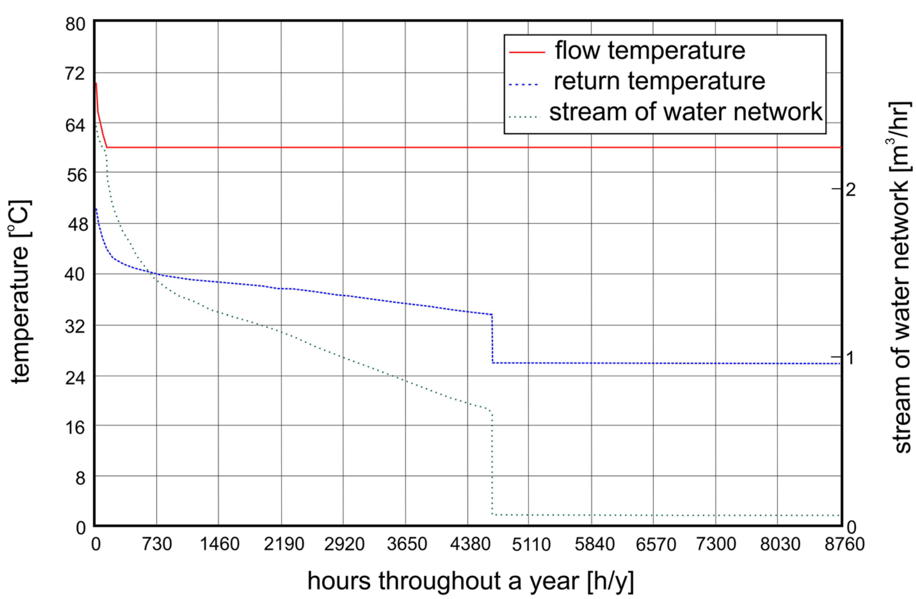

Fig. 10 Structured demand curve for supply temperature and heating medium flow rate as well as return temperature for the large greenhouse

figure shows that a complete (qualitative–quantitative) control of the power delivered was assumed. As the temperature of the geothermal water is not high, quantitative control (consisting in adjusting the required water stream to the greenhouse's requirements) is of dominant importance.

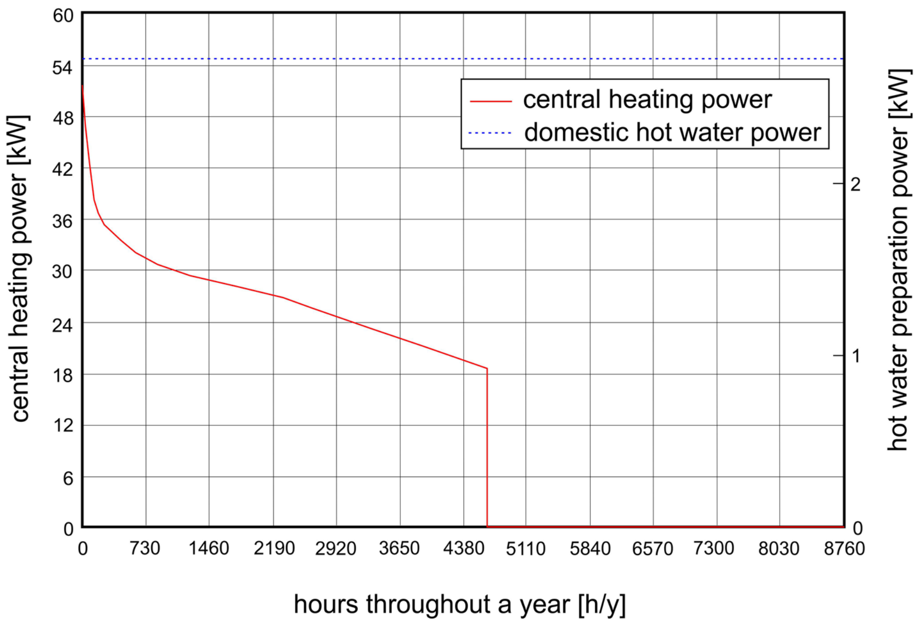

Fig. 11 Structured demand curve for central heating power and domestic hot water preparation for the small greenhouse

The heating power demand was determined from the equation:

$$P(\tau) = P_{\max}\frac{t_{\text{in}} - t(\tau)}{t_{\text{in}} - t_{\min}}, \quad (1)$$

where $P(\tau)$ power demand at time τ, $P_{\max}$ maximum power demand (the demand for power occurs when the lowest design value of outdoor temperature is observed $t_{\min}$), t_{in} assumed inner temperature, $t(\tau)$ outside temperature at time τ, $t_{\min}$ external design temperature according to Polish Standard PN–EN 12831 (2006).

The annual heating energy demand was determined on the basis of the relationship:

$$Q = \int_0^{1\text{yr}} P(\tau)d\tau, \quad (2)$$

where Q annual energy demand.

The energy demand for the preparation of domestic hot water was determined using a volumetric system which assumes the operation of an installation with a design power of 16 kW throughout the year. The main user of the domestic hot water would be the social rooms and the technical use for hot water (washing, rinsing), as presented in Fig. 9.

Due to the low power requirement for hot water preparation, the required flow rate of mains water (Fig. 10) will be very low outside the heating season. This low water demand is a consequence of using a volumetric hot water preparation system. In the case of similar consumers in the vicinity of a greenhouse, i.e., further away from the location of the source of the heat supply, it will be advisable to use an alternative energy source for hot water preparation in the off-season, e.g., solar collectors combined with electric heaters.

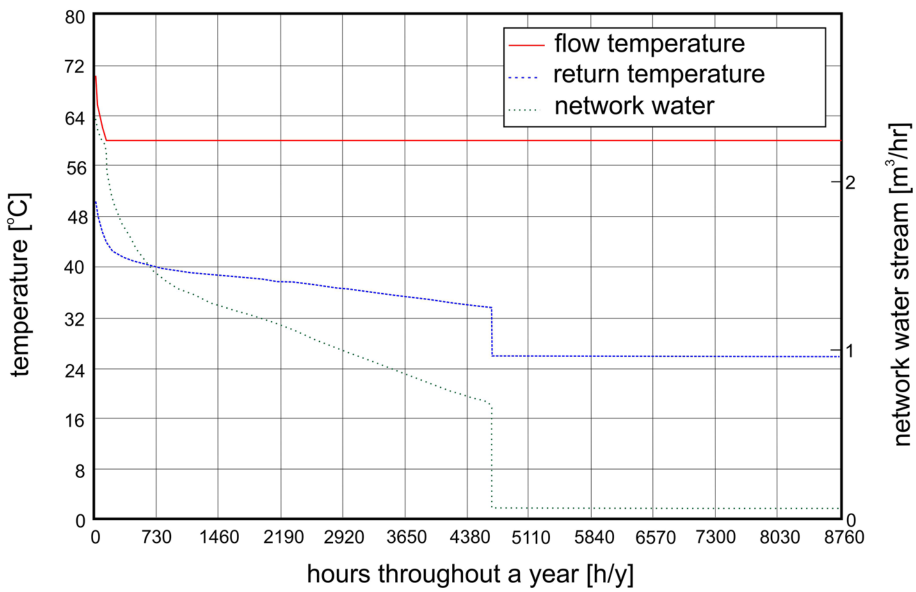

Fig. 12 Structured demand curve for supply temperature and heating medium flow rate as well as return temperature for the small greenhouse

For a small greenhouse facility with a cubature of 98,000 m^3 the maximum power requirement of a single facility was estimated at 51.6 kW for heating, 2.7 kW for hot water preparation and 535 GJ/y for total heat demand. The heating characteristics for such a facility are presented in Figs. 11 and 12.

The assumed value for the temperature of geothermal water from a well (60 °C) necessitates the use of a peak energy source. Its power can be estimated as:

- in the case of the large greenhouse 110 m^3/h · 4.2 kJ/(dm^3 K) · (70–60) K = ~ 1.28 MW,
- in the case of the small greenhouse 2.5 m^3/h · 4.2 kJ/(dm^3 K) · (70–60) K = ~ 29.2 kW.

The time of use of a peaking source use is very restricted, limited to about 150 h/y (Figs. 10, 12) and thus the energy production is also small, and therefore, the peak energy source may use a gas or oil boiler.

The energy calculations for both types of greenhouse facility analysed required the determination of dynamic power demand curves depending on outside temperature. The air temperature distribution during the year was determined using the data available representing a typical meteorological year in the location analysed (MEDLT 2021). The data relate to localities, where meteorological stations which carry out appropriate measurements are located. The nearest station to the location analysed is the station in Łódź from which the data used were obtained. The heat and electricity demand curves as well as the temperature and flux of the factor supplying thermal energy are presented for the type of building analysed in Figs. 13 and 14. The real time electricity demand illustrated for them is regularly arranged into three groups of curves (maximum, average and minimum power requirement). The data was marked with a uniform symbol every 30th record (every 13th hour in the year).

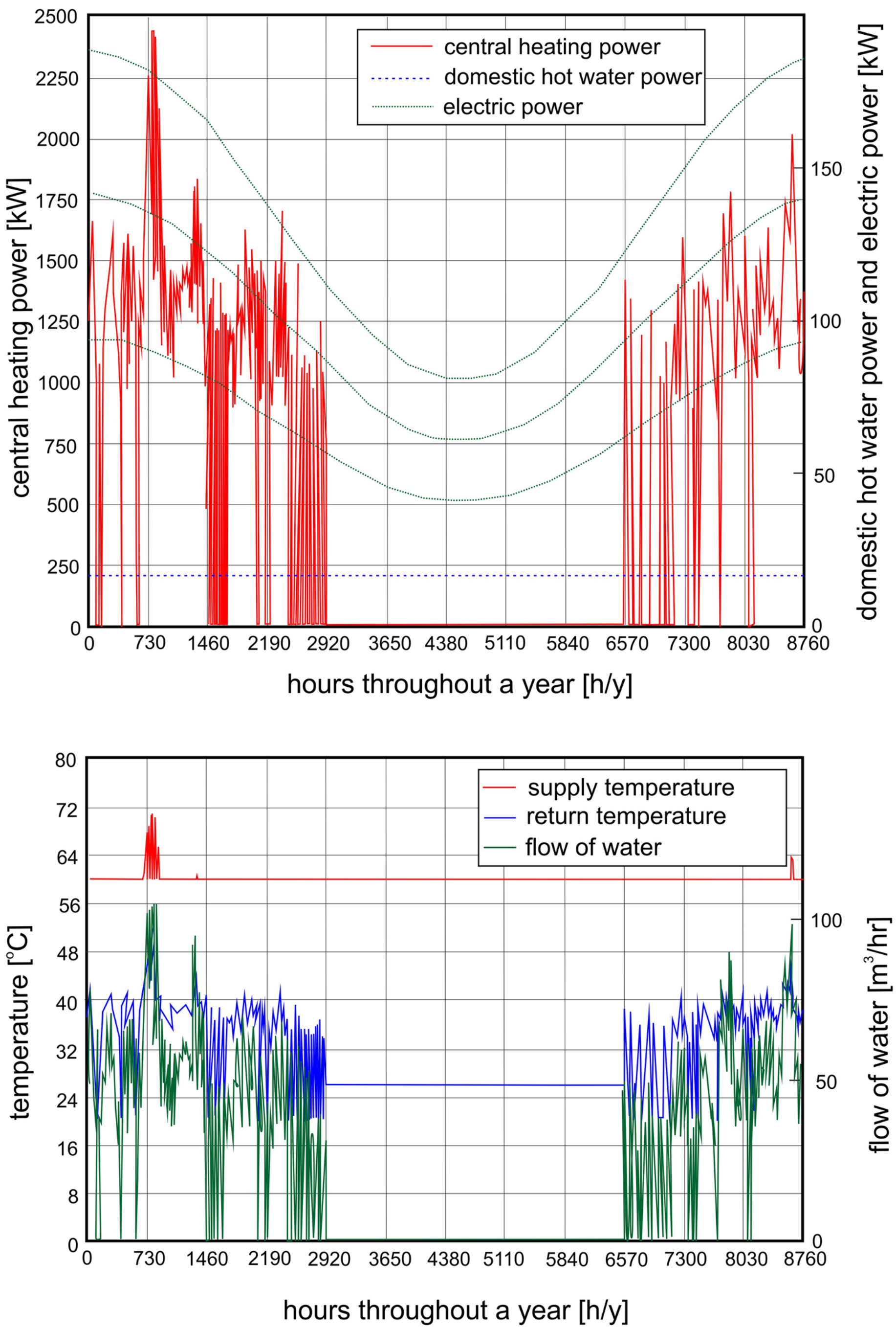

Fig. 13 Dynamic characteristics of the thermal and electrical power demand and the flow rate, supply and return temperature for the large greenhouse. $P_{ch} = 2.44$ MW, $P_{dw} = 16$ kW, $P_{el} = 189$ kW, $Q_{ch} + Q_{hw} = 20.4$ TJ/y, $Q_{el} = 870$ MWh/y. (P_{ch}—power demand–central heating, P_{dw}—power demand–domestic hot water, P_{el}—electric power demand, Q_{ch}—central heat use, Q_{dw}—domestic hot water use, Q_{el}—electricity use)

The electricity demand was determined using a cyclic (sinusoidal) relationship, which takes into account the variability of demand during the day/night and during the year. A clear separation of the three groups of electricity demand curves is only visible on

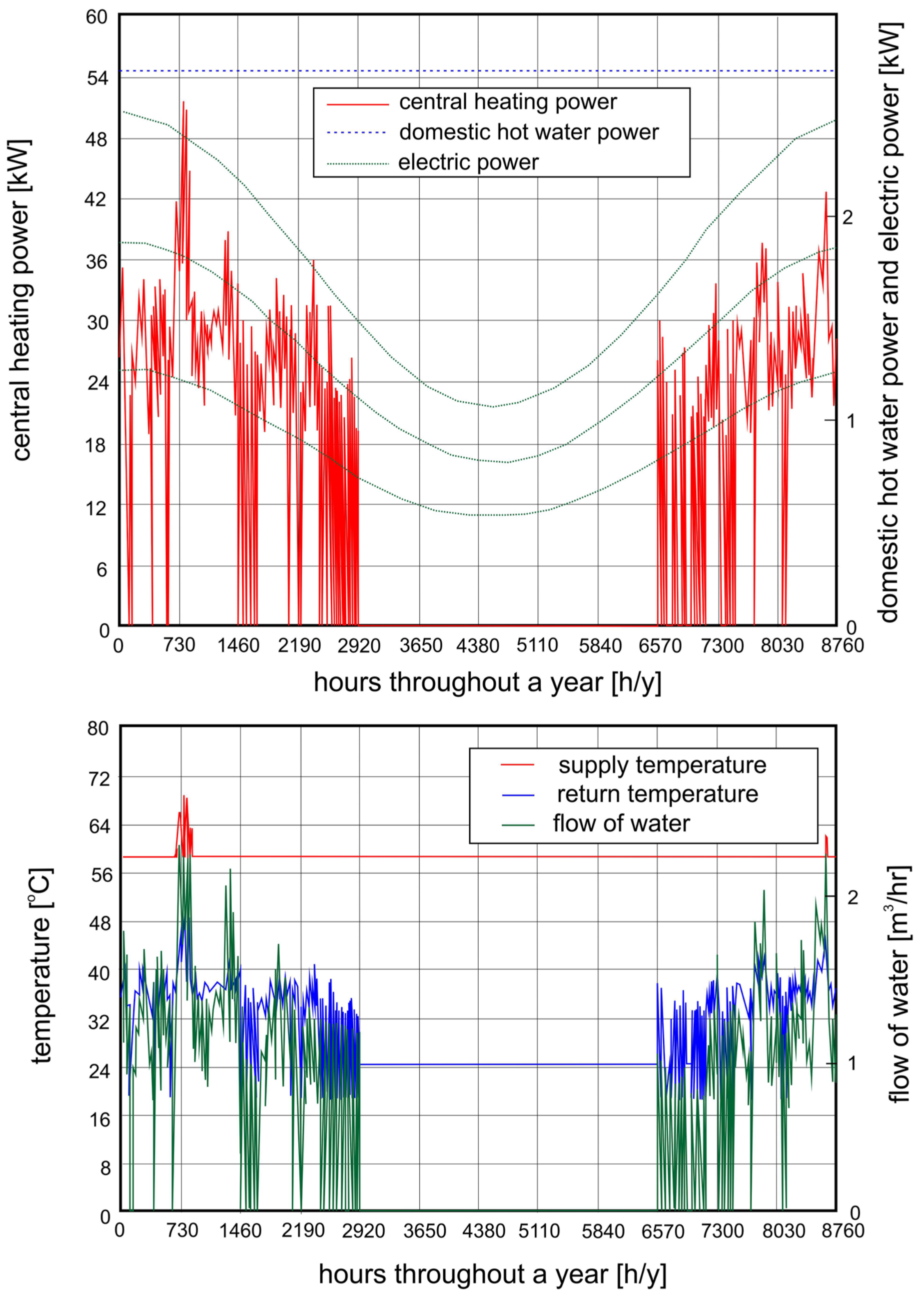

Fig. 14 Dynamic characteristics of the thermal and electrical power demand and the flow rate, supply and return temperature for the small greenhouse. $P_{ch} = 51.6$ MW, $P_{dw} = 2.7$ kW, $P_{el} = 2.5$ kW, $Q_{ch} + Q_{dw} = 506$ GJ/y, $Q_{el} = 11.6$ MWh/y (P_{ch}—power demand–central heating, P_{dw}—power demand–domestic hot water, P_{el}—electric power demand, Q_{ch}—central heat use, Q_{dw}—domestic hot water use, Q_{el}—electricity use)

the chart. In fact, the calculation model used is based on hourly average electricity demand.

The values of the parameters for the facilities discussed including those calculated taking into account the aforementioned assumptions and analyses are presented in Table 1.

Table 1 Economic and energy evaluations for a large greenhouse and a group of seven small greenhouses assumed to be supplied by heat extracted from geothermal water; Central part of the Polish Lowlands, Uniejów-Poddębice zone (Barbacki et al. 2017)

Parameter	Unit	Consumer (type of facility)	
		Large greenhouse	Small greenhouses (group of 7)
Cubic capacity	[m^3]	225,000	98,000
Usable area	[m^2]	15,000	1,400
Height	[m]	15	7
Central heating requirement	[kW]	2,400	361.2
Hot water preparation requirement	[kW]	16	18.9
Energy demand (central heating, hot water)	[GJ/y]	21,800	3745
Design parameters of the heating installation	[°C]	70/50	70/50
Design parameters of the installation for hot water preparation	[°C]	60/20	60/20
Investment expenditure	[PLN][a]	2,416,000	380,100
Fixed costs (assumed technical service life of the installation: 20 years)	[PLN/y]	120,800	19,005
Variable costs	[PLN/y]	1,454,420	249,155
Total costs	[PLN/y]	1,575,220	268,160

[a] 1 PLN (Polish zloty) ~ 0.25 EUR (February 2020)

To get an energy effect at a supply temperature lower than 60 °C (indicated in Table 1), one could alternatively:

- increase the surface area of the heating elements, which at their lower temperature would result in a similar heating effect;
- apply auxiliary air heating to increase the value of the heat transfer coefficient (by heated air) from the surfaces of heating elements;
- increase the flow of working medium (thus raising its return temperature) which would increase the average surface temperature of the heating elements.

Opportunities for sustainable use of geothermal energy in agriculture—a case of Poddębice

The methodology presented in this paper as well as some examples of maps (Figs. 1, 2, 3, 4, 5, 6, 7, 8) can, treated as a collective whole, lead to many valuable considerations first prior to the design stage, then in the preliminary design stages, as well as later in relation to the solutions potentially implemented. On a national scale this generates a multitude of solutions that are different in nature or similar solely in some aspects. One such solution is found in the Poddębice area.

Poddębice town is located in the central part of the Polish Lowlands, on the geothermal water reservoir in the Lower Cretaceous formation in a section defined by the 60 °C isotherm (Fig. 1). It is at the same time the area, where MGR No. 451 occurs (one of the main strategic fresh groundwater reservoirs in Poland), see Fig. 4. This area is not wooded and is located far from national parks (Fig. 5) and NATURA 2000 areas (Fig. 6), but close to important ecological corridors (Fig. 7). To the west, there is a large national centre for protected cultivation systems, i.e., with areas of above 3000 m^2/100 ha of vegetables cultivated under covers (Fig. 8). Periodically low saturation from precipitation occurs in the area, for instance in May 2016 (Fig. 2), as well as periods of drought, such as occurred in 2012 (Fig. 3), or last year (2020).

The geothermal water from Poddębice GT-2 has a temperature of 68–69 °C at the outlet with a mineralisation of 0.4 g/dm^3, and it is classified as HCO_3–Na–Ca type water. The reservoir is hosted in Cretaceous sandstones (depth ca. 1960–2060 m below surface) and may be partly recharged by infiltration water migrating deep down from the near-surface parts of reservoir rocks. These parts are situated right below the aboveground cover of permeable Quarternary formations. The water has drinking water quality. More details on its geology, geothermal character, reservoir, exploitation features and parameters in the Poddębice area are given in other publications (Kępińska et al. 2017a, b, c). Currently its primary use is to supply heat to the municipal district heating network and for domestic hot water. After cooling in heat exchangers, it is also used for recreation, for open air swimming pools in the summer and for rehabilitation in the county hospital. A small amount is also directed to the local Geothermal Water Drinking Station. The remaining part of the water stream (cooled down in heat exchangers to a temperature of 55–50 °C) is discharged to an artificial pond, where it is further cooled down (to a temperature of approx. 30 °C) giving off its heat to the environment. It is then discharged into the River Ner (Kępińska et al. 2017). This unused heat potential could be successfully applied in agriculture and related areas as proposed in this paper. One shall add that the potential for agriculture exists in Poddębice both now, when the cooled geothermal water is discharged into the river, and in a situation in which the water is injected back into the ground, which would be a better solution for the sustainable exploitation of a geothermal resource.

The company Geotermia Poddębice Sp. z o.o. and the Town Council are planning to expand the heating system from 10 to 18 MW. This requires an increase in the production of water from the Poddębice GT-2 well from 190 to 252 m^3/h (Kępińska et al. 2017a). Strategic plans include increasing the number of heat consumers in the city, supplying water and geothermal heat to the Safari Zoo in nearby Borysew locality, as well as to new facilities for aquacultures and other applications.

The agricultural traditions of the Poddębice region and the fact that over 60% of active residents of the municipality are still employed in this sector of the economy make the case for the geothermal resources also being used in agriculture. A proposal for their comprehensive use, including agriculture, was presented by Wnęk (2018). The following section is based on some of the proposals found in that study. Geothermal heat could, therefore, be used to heat greenhouses and to heat the growing medium in polytunnels. The heating system could consist of corrugated thin-walled tubes, or heat sinks placed on the ground, or at a certain height. Water flowing through the piping system would transfer heat to the surrounding space as a result of natural convection. The number of pipes and the surface area of the heat radiators would be determined by the size of the greenhouse heating load and the heat output of the heating elements. The increase in energy efficiency of such a system could be achieved, e.g., by cultivating plants on sills under which are placed pipes or heat sink packs (PCS 2006).

Soil or subsoil heating could also be carried out using heat from the direct flow of geothermal water (or geothermally heated process water) through plastic pipes placed underneath or on the surface, similar to the solutions described by Lund (1996).

In the case of polytunnels, geothermal water at a temperature of approx. 40 °C would already be useful for cultivation in heated soil or subsoil. The heating system could be made up of polyethylene pipes placed at a depth of at least 0.25 m. It would also be possible to place additional polyethylene pipes at a height of several decimetres above the ground, which would help heat the air in the tunnels. An example of a similar application was formerly found in Podhale (MEERI PAS facilities: Rosik-Dulewska and Grabda 2001; Ney et al. 2001). This demonstrated that it facilitates a significant acceleration of vegetable growth and yield.

Geothermal heat could also be used to dry agricultural products (Sapińska-Śliwa 2009). On the other hand, geothermal water, due to its natural purity and low mineralisation (0.4 g/dm^3), could, after appropriate cooling, be used as a raw material for the irrigation of agricultural crops (field, greenhouse, protected cultivation). This would save significant amounts of water used for plant irrigation and eliminate the problem of discharging used geothermal water into the environment. This possibility becomes particularly important in view of the growing threat of droughts to agriculture. Such water could even be directly used in aquaculture facilities (fish farms) at temperatures around 20–30 °C, including ornamental tropical fish in aquaria, as is seen, for example, in Greece (Arwanitis 2017).

Another proposal for the agricultural use of energy and water is the direct cultivation of algae in geothermal water (30–35 °C), because the ingredients it contains are essential for their proper growth, which at the same time would reduce the costs associated with providing such compounds. In another variant of algae cultivation, geothermal water (or its heat) could be used to heat water or heat the facility. Geothermal heat can be used for drying algal biomass.

Conclusions

Poland has the potential to use geothermal energy inter alia in agriculture which might contribute to the sustainable development of this sector of economy. To achieve this, it is necessary to plan and design future agricultural geothermal installations properly, both in terms of deposits, energy, agriculture and selection of the location. In particular—they should fit harmoniously into already existing systems of areas of natural value (which already perform various important environmental functions), and should not interfere, for example, with areas with strategic reservoirs of fresh groundwater.

The appropriate choice of the location of new facilities for the different uses of geothermal resources in the agricultural sector should, therefore, take into account inter alia:

- reservoir factors,
- specific features of farms depending on, among other matters, soil types, type of vegetation cultivated, variability of hydrological conditions,
- non-forest areas as preferred for the location,

- the need to protect the main strategic fresh groundwater reservoirs (MGR),
- the need to preserve the important natural functions of the systems: legal protection, ECONET-PL and NATURA 2000 and the network of ecological corridors.

Greenhouse facilities with the parameters specified in the article (in relation to 60°C supply temperatures, this could include slightly higher or lower) may be the places most commonly utilising geothermal energy resources for the needs of sustainable development of the agricultural sector in Poland. This is indicated by the example of Poddębice described in the article. There are many more zones and locations in Poland, where there are appropriate parameters of geothermal waters for their use as an energy resource for the development of agriculture (as well as using the geothermal waters themselves as a raw material).

The design of heating installation is a key factor. When applying geothermal energy it is assumed that the heating installation should be designed as a low temperature heating system. This reduces the necessity to use a peak energy source. The concept of a cascaded geothermal system also plays an important role.

The geothermal water resources of Poland are in many cases potential prospects for the needs of the agricultural sector, including organic farming. Low-mineralisation waters with an appropriate physico-chemical composition that can be used to directly heat the medium in which plants grow (including irrigation), or to farm fish and other aquatic species, would be the most useful. Such waters can be found in the Polish Lowlands in the relatively efficient Lower Cretaceous reservoir (locally these are fresh water reservoirs) and in the Lower Jurassic reservoir. The heat of geothermal waters (waters of different mineralisation) can also be used to heat livestock facilities, greenhouses, agri-food processing plants, and for crop and feed drying.

The use of geothermal energy in agriculture in Poland (similarly to that proposed for the Poddębice region) would translate into an increase in the production of healthy food and the development of sustainable agriculture, effective prevention of lifestyle diseases, and an improvement in the quality of health and life of society, etc.

One shall also point out the availability of separate sets of specialist information, compiled cartographically, which describe various aspects of the protection of the natural environment and the way it functions and of the way the agricultural sector operates. Considering a systemic approach to the definition of areas and locations in Poland suitable for the future installation of geothermal solutions serving agriculture, a preliminary stage was initiated which brought together and presented such basic spatial information. The methodology given in this paper as well as some examples of maps can, treated as a collective whole, lead to many valuable considerations first prior to the design stage, then in the preliminary design stages, as well as later in relation to the solutions potentially implemented.

Abbreviations

AACB: Agricultural Advisory Center in Brwinów; AGH-UST: AGH-University of Science and Technology; AHLP: Areas of highest level of protection; AHP: Areas of high level of protection; CSRP: Chancellery of the Sejm of the Republic of Poland; EUR: Euro; GDEP: General Directorate for Environmental Protection; GDSF: General Directorate of the State Forests; HOGC: Head Office of Geodesy and Cartography; IMWM-NRI: Institute of Meteorology and Water Management-National Research Institute; ISSPC-NRI: Institute of Soil Science and Plants Cultivation-National Research Institute; LGR: Local groundwater reservoirs; MARD: Ministry of Agriculture and Rural Development; MEDLT: Ministry of Economic Development, Labour and Technology; MGR: Main groundwater reservoirs; MEERI PAS: Mineral and Energy Economy Research Institute, Polish Academy of Sciences; NP: National Parks; PCS: Polish Committee for Standardization; PGI-NRI: Polish Geological Institute-National Research Institute; PLN: Polish zloty; PLN/y: Polish zlotys per year; RWMB: Regional

Water Management Boards; SACs: Habitat areas; SPAs: Bird sanctuaries; °C: Degree Celsius; dm^3: Cubic decimetre; g/dm^3: Grams per cubic decimetre; ha: Hectare; h/y: Hours per year; GW: Gigawatt; GW/y: Gigawatts per year; K: Degrees Kelvin; kJ: Kilojoule; kW: Kilowatt; m: Metre; m^2: Square metres; m^2/100 ha: Square metres per hundred hectares; m^3: Cubic metres; m^3/h: Cubic metres per hour; MW: Megawatt; P_{max}: Maximum power demand (this power demand occurs when the lowest design value of outdoor temperature is being observed tmin); P_{ch}: Power demand–central heating; P_{dw}: Power demand–domestic hot water; P_{el}: Electric power demand; $P(\tau)$: Power demand at time τ; Q: Annual energy demand; Q_{ch}: Central heating use; Q_{dw}: Domestic hot water use; Q_{el}: Electricity use; ***T***: Time; TJ: Terajoule; TJ/y: Terajoule per year; t_{in}: Assumed inner temperature; $t(\tau)$: Outside temperature at time τ; t_{min}: External design temperature; W/(m^2 K): Watts per square metre times Kelvin; volume/h: Volume per hour.

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Authors' contributions
RS and BK worked on data collection and wrote the manuscript. LP carried out the calculations. RS and LP prepared the figures. BK and WB directed the project, providing ideas and goals as well as logistical support. All the authors proofread the manuscript and provided their comments and insights. All the authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

Author details
[1] Mineral and Energy Economy Research Institute, Polish Academy of Sciences, Wybickiego 7A Str., 31-261 Kraków, Poland. [2] Department of Fossil Fuels, Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology, Mickiewicza 30 Ave., 30-059 Kraków, Poland.

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References
AACB-Agricultural Advisory Center in Brwinów RB. Katalog Demonstracyjnych Gospodarstw Ekologicznych. Radom; 2012. Available from: https://docplayer.pl/4578761-Katalog-demonstracyjnych-gospodarstw-ekologicznych-radom-2012.html.

Arvanitis A. Exploitation of low enthalpy geothermal resources in Greece. CRES Geotherm. Work. Dev. Bilater. Relations Geotherm. Energy F.-Work. (EEA Grants 2009-14). Mati, Attica, Greece; 2017:47. Available from: https://www.researchgate.net/publication/329428080_Exploitation_of_Low_Enthalpy_Geothermal_Resources_in_Greece.

Barbacki A, Bielec B, Bujakowski W, Dendys M, Hołojuch G, Kasztelewicz A, et al. Statutory work: Research the energetic parameters of renewable energy sources on a basis of selected areas including rational energy management's aspects—analysis of geothermal resources' parameters in selected Polish regions in terms of their use in ecological agriculture in conditions of rational energy management. MEERI PAS, Kraków, Poland; 2016:66. (in Polish, English abstract). Unpublished.

Barbacki A, Bielec B, Bujakowski W, Dendys M, Hołojuch G, Kasztelewicz A, et al. Statutory work: Research on renewable energy parameters on the example of selected zones, including aspects of rational energy management—analysis of geothermal resources' parameters in selected regions of Poland in terms of their use in ecological agriculture in conditions of rational energy management. Kraków, Poland; 2017:64. (in Polish, English abstract). Unpublished.

Bujakowski W. The pilot project of a geothermal heat recuperation cascade system for fish and vegetable breeding, the MEERI PAS Geothermal Laboratory (Podhale Region, Poland). Proc. World Geotherm. Congr. 2000, Kyushu - Tohoku, Japan, May 28–June 10, 2000. International Geothermal Association; 2000: p. 3379–3383. Available from: https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2000/R0642.PDF.

CSRP-Chancellery of the Sejm of the Republic of Poland. Act of 9 June 2011, Geological and Mining Law (Journal of Laws of 2017, item 2126; consolidated text), p. 9430–9488. Sejm Rzeczypospolitej Polskiej; Available from: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=wdu20111630981.

Eurostat. Facts and figures on organic agriculture in the European Union. 2013:44. Available from: https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/trade/documents/report-organic-agriculture-eu-2013_en.pdf.
GDEP-General Directorate for Environmental Protection. Access to Geospatial Data-Environmental information. 2021. Available from: https://www.gdos.gov.pl/access-to-geospatial-data?
Górecki W [sc. ed.], Hajto M, et al. Atlas of geothermal resources of Mesozoic formations in the Polish Lowlands. Kraków, Poland. AGH University of Science and Technology; 2006:484.
Górecki W [sc. ed.], Hajto M, et al. Atlas of geothermal water and energy of the Western Carpathians. Kraków, Poland: AGH University of Science and Technology; 2011:772.
Górecki W [sc. ed.], Hajto M, et al. Geothermal atlas of the Eastern Carpathians. Kraków, Poland: AGH University of Science and Technology; 2013:791.
Górecki W [sc. ed.], Sowiżdżał A, et al. Geothermal atlas of the Carpathian Foredeep. Kraków, Poland: AGH University of Science and Technology; 2012:418.
HOGC-Head Office of Geodesy and Cartography. Dane z państwowego rejestru granic i powierzchni jednostek podziałów terytorialnych kraju—PRG. 2021a. Available from: http://www.gugik.gov.pl/pzgik/dane-bez-oplat/dane-z-panstwowego-rejestru-granic-i-powierzchni-jednostek-podzialow-terytorialnych-kraju-prg.
HOGC-Head Office of Geodesy and Cartography. Dane zawarte w bazie danych obiektów ogólnogeograficznych – BDOO. 2021b. Available from: http://www.gugik.gov.pl/pzgik/dane-bez-oplat/dane-zawarte-w-bazie-danych-obiektow-ogolnogeograficznych-bdoo.
IMWM-NRI-Institute of Meteorology and Water Management - National Research Institute. Agrometeo-meteorological forecast for agronomy. 2021. Available from: https://agrometeo.imgw.pl/monitoring/rozklad_opadow.
ISSPC-NRI-Institute of Soil Science and Plants Cultivation - National Research Institute. Mapy zagrożenia suszą 2020-06-11–2020-08-10 Rośliny strączkowe. 2020. Available from: http://susza.iung.pulawy.pl/mapy/2020,09,R_stracz/.
Kępińska B. Geothermal energy country update report from Poland, 2015–2019. Proc. World Geothermal Congress 2020 Reykjavik, Iceland, 2020:14. Available from: https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01005.pdf.
Kępińska B, Hajto M, Pétursson B, Einarsson ÓP, Pająk L, Þorgilsson G, et al. Geothermal Energy Utilisation Potential in Poland—town Poddębice. Study Visits' Report Reykjavík, Iceland, Kraków, Poland. 2017a:123. Available from: http://www.eeagrants.agh.edu.pl/poddebice/study-visits-copy-2/.
Kępińska B, Pająk L, Bujakowski W, Kasztelewicz A, Hajto M, Sowiżdżał A, et al. Geothermal utilization potential in Poland—the town of Poddębice Part 2. Selected energetic aspects of current and future geothermal district heating in Poddębice. Tech. Poszuk. Geol; R. 56, nr 1. 2017b:23–38. Available from: http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztech-3ca421c2-993a-44f2-a139-f98a3ec20d79/c/TPG_2017_1_Kepinska_geothermal-part2.pdf.
Kępińska B, Pająk L, Bujakowski W, Kasztelewicz A, Hajto M, Sowiżdżał A, et al. Geothermal utilization potential in poland-the town of Poddębice Part 1. Selected reservoir and exploitation aspects of current and further geothermal district heating and other uses' development in Poddębice. Tech. Poszuk. Geol.;R. 56, nr 1. 2017c:3–21. Available from: http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-dc8ddec3-1b67-46cc-9378-bc635f9c9ba4.
Kulikowski R. Horticulture in Poland. Spatial distribution, crop structure and role in agricultural production. Przegląd Geogr. 2007;79(1):79–98.
Lund JW. Lectures on direct utilization of geothermal energy. Reykjavik, Iceland: United Nations University Geothermal Training Programme; 1996:123. Available from: https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-1996-01.pdf.
Lund JW, Boyd TL. Direct utilization of geothermal energy 2015 worldwide review. Proc. World Geotherm. Congr. 2015 Melbourne, Australia, 19–25 April 2015:31. Available from: https://www.unionegeotermica.it/pdfiles/usi-diretti-energia-geotermica-nel-mondo.pdf.
Lund JW, Toth AN. Direct utilization of geothermal energy 2020 worldwide review. Proc. World Geotherm. Congr. 2020 Reykjavik, Iceland, April 26–May 2, 2020: International Geothermal Association; 2020: 39 pp. Available from: https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01018.pdf.
Map of Polish soils. 2020. Available from: http://www.wiking.edu.pl/article_print.php?id=46.
MARD-Ministry of Agriculture and Rural Development. Regulation of the Minister of Agriculture and Rural Development of March 22, 2017 on the value of the climatic water balance for individual species of crops and soils. Journal of Laws 2017, item 732. Minister of Agriculture and Rural Development; Available from: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20170000732.
MEDLT-Ministry of Economic Development Labour and Technology. Typowe lata meteorologiczne i statystyczne dane klimatyczne dla obszaru Polski do obliczeń energetycznych budynków-Otwarte Dane 2021. Available from: https://dane.gov.pl/pl/dataset/797,typowe-lata-meteorologiczne-i-statystyczne-dane-klimatyczne-dla-obszaru-polski-do-obliczen-energetycznych-budynkow.
Ney R [ed.], Bujakowski W, Barbacki A, Graczyk S, Hołojuch G, Kazanowska A, et al. Selected problems of geothermal applications. Part II. Studies. Dissertations. Monographs. Vol. 92. Kraków, Poland: MEERI PAS; 2001: 5–48 (in Polish, English abstract).
PCS-Polish Committee for Standardization. Polish Standard PN-EN 12831. Heating installations in buildings. 2006.
PGI-NRI-Polish Geological Institute-National Research Institute. Major Groundwater Reservoirs—GZWP [MGR]. 2016. Available from: https://www.pgi.gov.pl/aktualnosci/display/9309-glowne-zbiorniki-wod-podziemnych-gzwp.html.
Popovski K, Popovska-Vasilevska S. Prospects and problems for geothermal use in agriculture in Europe. Geothermics 32(4–6):545–555. 2003. Available from: https://www.sciencedirect.com/science/article/pii/S0375650503000865?via%3Dihub.
Rosik-Dulewska C, Grabda M. Wykorzystanie ciepła niskotemperaturowych wód geotermalnych w produkcji ogrodniczej pod osłonami. Tech. Poszuk. Geol. 2001;(R. 40, nr 5): p.163–73 (in Polish, English abstract). Available from: https://www.infona.pl//resource/bwmeta1.element.baztech-article-BPZ1-0034-0042.
Rosik-Dulewska CZ, Grabda M. Development and yield of vegetables cultivated on substrate heated by geothermal waters Part I: bell pepper, slicing cucumber, tomato. J Vegetable Crop Product. 2002;8(1):133–44. https://doi.org/10.1300/J068v08n01_14.

Sapińska-Śliwa A. Technical and economic conditions for thermal water management in Uniejów. AGH University of Science and Technology; 2009:165. (in Polish, English abstract). Available from: http://docplayer.pl/23604486-Warunki-technologiczno-ekonomiczne-zagospodarowania-wody-termalnej-w-uniejowie-rozprawa-doktorska.html.
Tomaszewska B, Szczepański A. Possibilities for the efficient utilisation of spent geothermal waters. Environ Sci Pollut Res (springer Verlag). 2014;21(19):11409–17. https://doi.org/10.1007/s11356-014-3076-4.
Wnęk M. Possibilities of optimal use of geothermal heat on the example of Poddębice. AGH University of Science and Technology; 2018:94. (in Polish, English abstract). Unpublished.
Zdrojewska I. Raport o stanie rolnictwa ekologicznego w Polsce w latach 2011–2012. Warszawa; 2013: 86 pp. (in Polish, English abstract). Available from: https://www.gov.pl/web/ijhars/raport-o-stanie-rolnictwa-ekologicznego-w-polsce.
Żuber P, Sudak S, Zagrzejewska M, Baucz A, Boniecka I, Krukowski J, et al. Koncepcja przestrzennego zagospodarowania kraju 2030: 290 pp. Accepted by The Council of Ministers on 13th Dec 2011. 2021: 290 pp. Available from: http://rbgp.pl/wp-content/uploads/2019/03/01_Koncepcja_Przestrzennego_Zagospodarowania_Kraju_2030.pdf.

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