A Study of Natural and Functional Conditions of Poland in the view of the Geothermal Resources Applications in Agriculture

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A study of natural and functional conditions of Poland in the view of the geothermal resources applications in agriculture

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Abstract

The agriculture and related sectors present one of the most prospective areas for geothermal energy applications. In many countries they have already been introduced, and new investments in this sector have been also observed. Also Poland has the appropriate resources' potential – in a wide range of temperatures, for different crops, as well as in the types of

applications related to agriculture. The use of this green energy can contribute to sustainable development of agriculture.

To achieve this when planning and designing geothermal installations for agriculture, they should be considered from the energy and agricultural points of view, as well as appropriate locations for them shall be selected so that they would be harmoniously incorporated, among others, into existing systems of valuable natural areas (which already play various important functions in the natural environment) and would not interfere with other underground resources of strategic economic importance.

The main aspects of such an approach to the sustainable development of the geothermal energy applications in agriculture and related sectors in Poland, as well as natural circumstances, are presented in this article. Also included are basic energy parameters (based on the results of calculations) and technical and economic parameters for greenhouse facilities in one of the selected prospective locations in the Polish Lowlands, which could be supplied by local geothermal resources, contributing to sustainable development of agriculture.

Keywords: geothermal resources, agriculture, applications, natural conditions, functional conditions, Poland

Introduction

Poland has the geothermal energy potential promising for its direct applications' development in many areas, including agriculture. However, the activity in agriculture to date is symbolic (despite the first pioneering projects in the early 1990s). Together with the wider development

of the use of geothermal energy expected in the coming years, e.g. in district heating, one can also look forward to an increased interest in its applications in agriculture and related fields. Such low-carbon, green energy in the production and processing chain should contribute to environmental improvement and sustainable agricultural development, among other effects. For this to occur, when planning and designing future geothermal facilities and installations for agricultural needs, it is necessary to consider them from an energy point of view and to select appropriate locations. This should result from reasons both typically agricultural and concerning the availability of adequate geothermal energy resources in groundwater, and 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). It should also not interfere with the role of some other natural resources of critical importance (e.g. strategic drinking groundwater resources or forest resources).

On the other hand, the richness of many valuable natural areas will facilitate the sustainable development of agriculture in Poland with the use of the mentioned clean geothermal energy.

The main aspects 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, are presented in this article.

Agriculture and related sectors are important areas for the direct application of geothermal energy. In order to demonstrate their position among other economic sectors in this respect, it is best to refer to the latest synthetic summary of the use of geothermal heat in the world: it was presented for the years 2015-2019 in April 2020 (Lund and Toth [2020](#)). They 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 amounted to 1,020,890 TJ. This was a very large increase compared to 2014 by 52 and 72% (!), respectively, which shows the increasing use of the Earth's heat globally. 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. heating of greenhouses and protected cultivation (3.5%, 32 countries), the following spots included 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). Among other direct applications of geothermal energy in the world in 2019 (in total about 2.4%) were industrial and processing applications, various smaller scale uses (such as ice control of traffic routes / melting snow) and various others – this group there also included smaller scale applications related to agriculture, such as algae farming, heating of livestock buildings, irrigation of crops). The provided percentages (including in agriculture) would be significantly higher if heat pumps / shallow geothermal systems (approx. 58% of the Earth's heat used) were not included.

It is worth emphasizing, following Lund and Toth (2020) that the comparison of the current data (from 2019) and the data from 2014 (from the World Geothermal Congress in 2015; Lund et al. 2015) in case of greenhouses indicates an increase in the use of geothermal heat by 23%, while in case of aquaculture – by 13%. These figures show a high rate of increase in the use of geothermal energy, also in agriculture. In 2019, geothermal heating of greenhouses and protected cultivation (flowers, vegetables, fruits, tree seedlings) was used 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 geothermal water heat was carried out in 15 countries. In addition to the above, geothermal energy is also used for agriculture purposes in many other countries. In Europe, in addition to Iceland, the Netherlands, Italy and Turkey mentioned in the global context, these also include Hungary (on a large scale), as well as Austria, Greece, France, Slovakia, Germany, North Macedonia, Serbia and Switzerland.

In Poland, the application of geothermal energy in the agricultural sector has so far been and still is very low (Statutory work [2016](#); Kępińska [2020](#)). From 1992 for several years it included experimental breeding of thermophilic fish species as well as heating of glasshouses and soil in protected cultivation systems. This took place in Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (MEERI PAN) facilities in the Podhale region – Poland's first experimental system of versatile cascade uses of geothermal energy and water. Currently geothermal wood drying is still carried out. Since 2016, an Atlantic salmon farm operates in Janowo, West Pomerania. It applies geothermal water and heat from Jurassic sandstones accessed 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 used mainly for the needs of geothermal district heating plants and recreation centers (Fig. [1](#)).

The analysis of the global uses of geothermal resources for the needs of the agricultural sector and their energy parameters leads to the conclusion that also in Poland, there are geothermal water reservoirs useful for such purposes and, above all, their sections defined by the range of 30°C isotherm (at least) in the tops of these reservoirs. They were indicated on the map of Poland (Fig. [1](#)) using Geothermal Atlases (Górecki [sc. ed] et al.: [2006](#), [2011](#), [2012](#), [2013](#)).

Then, the ranges of sections of such reservoirs, along the given isotherm, were transferred to selected thematic maps, which, in the authors' opinion, were important for the initial consideration of future locations of geothermal installations for the agricultural sector – taking into account those important spatial conditions which had not been indicated before, particularly in the context of sustainable development and avoiding collisions in this respect between the current state and new projects, including those which would be considered as “green” themselves. The selection of thematic maps was made on the basis of analysis and systematization of cartographic materials made for different specific purposes and coming from different sources, available on the Internet. Thematic working maps – a source of primary data – have been arranged in order to present the following conditions in Poland: soil conditions (soil types, example soil moisture, example risk of hydrological droughts), potential collisions of the functioning of the proposed new geothermal installations for agriculture with other important functions of the natural environment (areas of occurrence of main strategic drinking water aquifers and their protection zones, areas of natural value – including forests – and their protection systems), selected elements of existing agricultural management (locations of orchards, field vegetable crops, protected cultivation systems, locations of the so-called demonstration farms). The information presented on the selected thematic maps, most of which are presented in this paper, has been supplemented with technical and economic data and results of analysis of energy parameters for two types of greenhouse facilities, typical for the Polish Lowlands, which could be heated by geothermal water heat, if such water occurs in areas of the considered locations of the greenhouses and have appropriate parameters.

Geothermal Reservoirs in the Context of Sustainable Uses of Their Resources for the Agricultural Sector in Poland

The sections of geothermal aquifers in the Lower Cretaceous and Lower Jurassic formations within the Polish Lowlands are considered to be the most prospective for agriculture in Poland. Furthermore, despite the expected lower output capacities of these water intakes, some areas of the Carpathian Foredeep and the Carpathians are given consideration (Fig. 1). These sections are defined by 30°C isotherms, and in the Polish Lowlands – also by 60°C isotherms. In the case of the Polish Lowlands, it is worth noting that Cretaceous reservoirs locally contain water of even drinking quality (fresh water). With regard to the sections of reservoirs defined by the 60°C isotherm, this may facilitate the use of these resources on farms for different purposes simultaneously from a single water intake. This also applies to towns where geothermal water is already utilized for heating purposes or is planned to be utilized for such purposes in the near future. In the case of higher values of geothermal water mineralization, some methods of application in agriculture will require their prior demineralization (e.g. using the reverse osmosis method; Tomaszewska and Szczepański 2014).

Relatively less favorable geothermal conditions are found in southern Poland, due to generally low output capacity of potential water intakes (except for the Podhale region, where they are of high capacity). In the Carpathian Foredeep area (also in its part under the Carpathian overthrust), local uses of geothermal water from small Triassic and Jurassic reservoirs for agricultural purposes is also possible. Similarly, in the Carpathians: in the west – from small reservoirs in three flysch levels, as well as from reservoirs in series of the flysch bedrock – Cenomanian and Middle Jurassic; in the east – mainly in the Miocene reservoir, which is relatively extensive (Statutory work 2016). Especially in the mentioned areas of Poland, as well as in areas where geothermal water with temperatures below 30°C occur, different ways of their agricultural uses are possible. In Poland, according to formal regulations, “*a thermal*

water is groundwater with a temperature of not less than 20°C at the outflow from the intake” (Art. 5.1.2.2); Act of 9 June 2011 (2017). However, water with temperatures from 15 to 40°C (i.e. – within a certain range of temperature values which is not formally recognized as thermal water according to Polish regulations), if fresh, can be used for irrigation of crops, and if it simultaneously exhibits low mineralization and appropriate physico-chemical composition – for aquacultures (Lund et al. 2015). On the other hand, the energy of water with the temperatures of 15-40°C is useful for heating protected cultivation crops, and the energy of water with temperatures of 25-60°C – for heating livestock buildings. The energy of water with higher temperatures (from 30 to over 60°C – higher temperatures are more advantageous) is used in greenhouse heating, agri-food processing, drying, grain and feed processing.

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

Geothermal water reservoirs prospective for agriculture in Poland against the map of soil moisture indicators (Fig. 2) presents image provides exemplary general information, as it shows 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 during months sensitive for agriculture during the year (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 the 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. They are partly due to the soil structure and also depend 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 supply of this water to the soils can be analyzed (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 the crops).

The information for the design of geothermal uses systems in agriculture (*geothermal installation-farming*) should be complemented by the analysis of meteorological information regarding drought periods. *Geothermal water reservoirs prospective for agriculture in Poland against the map of drought risks* (Fig. 3) presents as one of the elements of such analysis.

The review of the maps available on the portal of the IUNG Institute of Soil Science and Plant Cultivation in Puławy, which since 2009 has been publishing periodic graphical reports for the successive time intervals of the year, indicates that the drought criteria indicated in the Regulation of the Ministry of Agriculture and Rural Development for various types of plants have generally not been exceeded in recent years, in contrast to the current year 2020. Among these plants, legumes serve as the most sensitive for drought indication. Figure 3 shows an example of the situation on 2.09.2013. In a similar period (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, fruit bushes and potato crops (of course, if the water parameters would be appropriate for specific plant species, as already pointed out earlier).

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 reservoir. It is best to implement 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). Possible proposals for the MGRs would require the utmost caution during the detailed recognition of the conditions in the field and the implementation of the investment, so that the principles of protection of the resources of these strategic reservoirs would be preserved. *Geothermal water reservoirs prospective for agriculture in Poland against the map of main fresh groundwater reservoirs (MGR) and their protection areas* (Fig. 4). The mentioned regions of AHLP and AHP, which are not shown in Fig. 4 for its 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 Polish Geological Institute – National Research Institute, PGI-NRI, shown at Fig. 4 and published in Map of Main Groundwater Reservoirs (2016) illustrating the state of documentation of the MGR in November 2016, used as a base, indicates the location of the MGR and indirectly their protection areas.

Fig. 1

Map of geothermal water reservoirs prospective for agriculture in Poland. Scientific description based on Statutory work... (2016); ranges reservoirs with temperatures >30°C and >60°C according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013.

Fig. 2

Geothermal water reservoirs prospective for agriculture 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 [% saturation]. Scientific description based on Statutory work... (2016); ranges reservoirs with temperatures >30°C and >60°C according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; saturation of soils with liquid water (Meteorological... 2020) – sample data from May 16, 2016.

Fig. 3

Geothermal water reservoirs prospective for agriculture in Poland against the map of drought treats. Scientific description based on Statutory work... (2016); ranges reservoirs with temperatures >30°C and >60°C according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; threat of Map of drought treat (2020) – sample data from September 2, 2012.

Similarly as in the case of 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 a map *Geothermal water reservoirs prospective for agriculture in Poland against the map of national parks, landscape parks,*

NATURA 2000 areas and forests (Fig. 5). It results from this map that geothermal installations for organic farming could be located in the buffer zone 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 the sections of the landscape parks 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 illustrates particularly well the spread of forests, and against their background – the location of borders of national parks and landscape parks in Poland. On the other hand, very important sites of the European Network NATURA 2000 are more clearly presented in *Geothermal water reservoirs prospective for agriculture in Poland against the map of the sites of the European Network NATURA 2000 areas* (Fig. 6). In turn, *Geothermal aquifers prospective for agriculture in Poland 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 – e.g. borders of national parks and landscape parks but together with their buffer zones, i.e. the mentioned places especially preferred for the location of 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 naturally functional centers (i.e. conventionally stationary nature centers), therefore they should not be used for agricultural purposes.

When considering potential locations of geothermal facilities useful for agriculture, they should be rather located outside the NATURA 2000 system areas. Within the limits of the proposed geothermal reservoirs these are relatively small areas on a national scale – dominated mainly 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 investments 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.

Fig. 4

Geothermal water reservoirs prospective for agriculture in Poland against the map of main groundwater reservoirs (MGR – fresh) and their protection areas. Scientific description based on Statutory work... (2016); ranges reservoirs with temperatures >30°C and >60°C according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; underlay Map of Main Groundwater Reservoirs (2020) – data from November 2016.

Fig. 5

Geothermal water reservoirs prospective for agriculture in Poland against the map of national parks, landscape parks, Natura 2000 areas and forests. Scientific description based on Statutory work... (2016); ranges reservoirs with temperatures >30°C and >60°C according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; underlay Map by Doroty Kwaśny (2012) and State Forests in Poland (2010).

Fig. 6

Geothermal water reservoirs prospective for agriculture in Poland against the map of the objects of the European Network Natura 2000 areas. Scientific description based on Statutory work... (2016); ranges reservoirs with temperatures >30°C and >60°C according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; underlay the Map of the Nature 2000 areas (2020).

Fig. 7

Geothermal water reservoirs prospective for agriculture in Poland against the map of spatial policy directions concerning nature. Scientific description based on Statutory work... (2016); ranges reservoirs with temperatures >30°C and >60°C according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; underlay Ministry of Regional... (2020) 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, Białowieża, about the corridors connecting Natura 2000 areas in 2006 and data of the National Water Management Board on river corridors in 2010.

Agricultural Structure of Poland as a Prerequisite for the 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. For the state as at 2002 (lack of more recent studies), they were discussed by Kulikowski (2007). This study included the following types of cultures: orchards (53.2% of horticultural crops), field vegetables (33.7%), fruit bushes (10.4%), protected cultivation (1.2%), fruit tree and bush nurseries (0.9%), flowers and ornamental plants (0.6%). Other types of cultures 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 delimited in the Polish Lowlands by the 30°C isotherm for the Lower Cretaceous reservoir, and in many areas of 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 protected cultivation crops): onion constituted 17.7%, cabbage – 15.5%, edible carrots – 14.6%, cucumbers – 9.6%, red beets – 6.7%, tomatoes – 5.8%, cauliflowers – 5.6% and other field vegetables – 24.5%. Field crops in many locations of geothermal reservoirs potentially useful for agriculture (especially in their central and south-west part on the Polish Lowlands and in its north-west parts) constituted over 6% of the area of municipalities, in many other locations also over 4%, and less frequently – over 2%.

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

Another prerequisite for the possible uses of the geothermal energy and water potential may be the functioning of a special form of agricultural production organization – 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 organic agriculture products in Europe reached about 23.4 billion EUR, increasing by about 6% per year, with the largest markets for 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, in Poland in 2011, 23,847 organic producers were registered, 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 (Chief Inspectorate... 2011). So in that year Poland was in the leading position in Europe – 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 northwestern part of Poland, organic farms of relatively large areas were present. There were many such farms in the southeast, however smaller in size. The differences in the size of their areas are even more than 4-fold.

Fig. 8

Geothermal water reservoirs prospective for agriculture in Poland against the map of cultivated vegetables under covers. Scientific description based on Statutory work... (2016); ranges reservoirs

with temperatures $>30^{\circ}\text{C}$ and $>60^{\circ}\text{C}$ according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; underlay Map of vegetables crops under cover (2002; in Kulikowski 2007).

There is a separate category of organic farms in Poland – *organic demonstration farms* (Map of demonstration 2020). It seems that some of them could benefit from the geothermal water uses. In the case of Podhale, cooperation could be established with the geothermal plant in Bańska Nizna and for the Polish Lowlands with, among others, interested heating plants (in 2020, five of them were operational in this area of Poland, further ones are expected). Future locations of geothermal facilities for organic farming could also be linked with some other demonstration organic farms in the following provinces: West Pomerania, Pomerania, Kujavia-Pomerania, Lubusz Province, Greater Poland, Lodz Province, Masovia, Lublin Province, Silesia, Lesser Poland and Subcarpatia. These provinces are depicted in Fig. 3.

Example of Preferred Greenhouse Facilities in Poland Potentially Using Geothermal Energy

As mentioned above, among various possible uses of geothermal water and energy in agriculture, one of the most popular would be their using in greenhouses. The methods and possibilities of direct application of waters will depend on their physico-chemical parameters, including output capacity, temperature, mineralization, physico-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 mineralization, physico-chemical composition and gas content deviate from the standards required for the specific crop, species grown, etc., it will be necessary to apply appropriate methods or technologies to adjust the values of these parameters to the appropriate level.

This chapter focuses on example greenhouse systems for which the use of geothermal water energy, often found in the Polish Lowlands, as a heat carrier was adopted. 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 assessment are provided for standard greenhouse installations which are in common use and suitable for the selected zone due to, among other things, the prevalent climatic conditions. They are conventionally referred to as large greenhouses (single large greenhouse facility) and small greenhouses (forming a system of seven small greenhouse facilities). The analyzes were conducted taking into account the following assumptions:

- access to geothermal water of temperature 60°C for the needs of heating the greenhouses in terms of central heating and volumetric preparation of warm water (Poddębice are situated in an area where geothermal water temperatures reach and exceed the specified value – Statutory work... 2017; Fig. 1),
- location in so-called II climatic zone for project calculations according to Polish Standards of a heating System Designing PN-EN 12831- 2006 (it includes the central part of Polish Lowlands geothermal reservoirs; project parameters: outside temperature -18°C, average yearly outside temperature 7.9°C),
- interior temperature of the facility approx. 26°C and air humidity 65%,
- external partitions of greenhouse facility providing heat transfer coefficient on the level of 0.5 W/(m²·K),

- the intensity of air exchange in the facility approx. 0.3 volume/h (where volume is the volume of air-filled the indoor space of a greenhouse).

The assumptions for both types of greenhouse facilities 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, taking into account the already mentioned the Polish Standards for climate zones (Polish Standard PN-EN 12831 2006).

The large greenhouse facility was characterized by a cubature of 225,000 m³ and demand for central heating estimated at 2.4 MW and for hot water preparation at 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 temperature and flow rate of the heating medium is presented in Fig. 10. This Figure shows that a complete (qualitative-quantitative) control of the delivered power was assumed. Due to not high geothermal water temperature quantitative control (consisting in adjusting the required water stream to the needs) is of dominant importance.

The heating power demand was determined from the equation:

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

where:

$P(\tau)$ – power demand at the time τ ,

$P_{\max}$ – maximum power demand (the demand of power occurs when the lowest value of design outdoor temperature is being observed $t_{\min}$),

t_{in} – assumed inner temperature,

$t(\tau)$ – outside temperature at the 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, assuming the operation of the installation with a design power of 16 kW throughout the year. The main recipient of domestic hot water will be social rooms and technical use of hot water (washing, rinsing) – Fig. 9.

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.

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 are 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 its 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.

For small greenhouse facility with a cubature of 98,000 m³ 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, 12.

Fig. 11

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

Fig. 12

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

Assumed value of geothermal water temperature on a well heat (60°C) necessitates to use of peak energy source. Its power can be estimated as:

- in case of the large greenhouse $110 \text{ m}^3/\text{h} \cdot 4.2 \text{ kJ}/(\text{dm}^3 \cdot \text{K}) \cdot (70 - 60) \text{ K}$
 $= \sim 1.28 \text{ MW}$

- in case of the small greenhouse $2.5 \text{ m}^3/\text{h} \cdot 4.2 \text{ kJ}/(\text{dm}^3 \cdot \text{K}) \cdot (70 - 60) \text{ K}$
 $= \sim 29.2 \text{ kW}$.

Time of peaking source use is very low, limited up to about 150 h/y (Figs. 10, 12) thus the energy production is also small. As the peak energy source can may use a gas or oil boiler.

The energy calculations for both analyzed types of greenhouse facilities required the determination of dynamic power demand curves depending on outside temperature. The air temperature distribution during the year was determined using the available data representing a typical meteorological year in the analyzed location (Ministry... 2020). The data compiled in Ministry... (2020) relate to localities where meteorological stations are located, which carry out appropriate measurements. The nearest station in the analyzed location, from which the data were used, is the station in Łódź. Such curves of demand for heat and electricity as well as temperature and flux of the factor supplying thermal energy are presented, respectively, for the type of the analyzed object type in Figs. 13, 14. The momentary

electricity demand illustrated on 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 thirtieth hour in the year). 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 the chart. In fact, the calculation model used is based on hourly average electricity demand.

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).

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

Table 1 Economic and energetic evaluations for large greenhouse and group of seven small greenhouses assumed to be supplied by heat extracted from geothermal water. Central part of the Polish Lowlands, Uniejów-Poddębice zone (Statutory work... 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 capacity	[kW]	2,400	361.2
Hot water preparation capacity	[kW]	16	18.9
Energy demand (central heating, hot water)	[GJ/y]	21,800	3,745
Design parameters of the heating installation	[°C]	70/50	70/50
Design parameters of installation for hot water preparation	[°C]	60/20	60/20
Investment expenditures	[PLN] ¹	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

¹ 1 PLN (Polish zloty) ~ 0.25 EUR (February 2020)

In order to get energetic effect at the 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.

Discussion of results – opportunities for Sustainable Use of Geothermal Energy in Agriculture (Poddębice Example)

The use of geothermal resources in the agricultural sector is developing in many countries in the world. Sometimes geothermal installations - recently with more and more powers, are built exclusively for this sector, e.g. in Italy. A related special program is being implemented in the Netherlands as a system solution. On the other hand, in Poland, these were (or are) small projects accompanying geothermal thermal power facilities (except for one case of big salmon farm - Fig. 1). At the same time, there are geothermal resources potentially useful for this purpose in Poland. There are also sets of separate information, compiled cartographically, which describe various aspects of the functioning and protection of the natural environment and the functioning of the agricultural sector. Considering a systemic approach to the

indication of areas and locations in Poland the future implementation of geothermal solutions for agriculture, the preliminary stage of associating and presenting such basic spatial information was thought. Collected as a whole, they can lead to many valuable considerations first in pre-design, then in the preliminary design stages, as well as in relation to potentially implemented solutions. On a national scale, this generates a multitude of solutions that are separate in nature, or similar in some aspects only. One of such solutions is the Poddębice area.

Poddębice town is located in the central part of the Polish Lowlands, within the geothermal water reservoir in the Lower Cretaceous formation, its section defined by the 60°C isotherm (Fig. 1). It is at the same time the area of occurrence of the MGR No. 451 (one of the main strategic fresh groundwater reservoirs in Poland) – 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 center of protected cultivation systems, i.e. with areas of above 3000 m²/100 ha of cultivated vegetables under covers (Fig. 8). Periodically low precipitation saturation occurs in the area, such as in May 2016 (Fig. 2), or drought periods such as in 2012 (Fig. 3), or in the current year 2020.

The geothermal water from Poddębice GT-2 with a temperature of 68-69°C at the outlet and the quality of drinking water now supplies heat primarily for heating purposes – to the municipal district heating network and for domestic hot water preparation. After cooling in heat exchangers, it is also used in recreation, for open swimming pools in the summer and is used in rehabilitation in the county hospital. It is also directed to the local Geothermal Water Drinking Station to a small extent. The remaining part of the water stream (cooled down in the exchangers to the temperature of 55-50°C) is discharged to the technological pond, where it is further cooled down (to the temperature of approx. 30°C) giving warmth to the ambient.

Then it is disposed into the Ner river (Kępińska et al. 2017). This unused heat potential could be successfully applied in agriculture and related areas.

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 means an increase in the production of water from the Poddębice GT-2 well from 190 to 252 m³/h (Einarsson et al. 2017). Strategic plans include increasing the number of heat consumers in the city, as well as supplying water and geothermal heat to the Safari Zoo in nearby Borysew locality, as well as new facilities for aquacultures and other applications.

Agricultural traditions of the Poddębice region and the fact that still over 60% of active residents of the municipality are employed in this sector of the economy make a case for the geothermal resources to be used also in agriculture. A proposal of their comprehensive use, including agriculture, was presented in (Wnęk 2018]. The following part is based on some of the proposals found in that study. Geothermal heat could therefore be used there to heat greenhouses and to heat the growing soil in foil tunnels. The heating system could consist of corrugated thin-walled tubes, or heat sinks placed on the floor, or at a certain height. Water flowing through the piping system as a result of natural convection would transfer heat to the surrounding space. The number of pipes and the heating surface area of the heat sinks 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 pipes or heat sink packs would be placed (Polish Standard PN–EN 12831 2006).

Soil or subsoil heating could also be carried out by receiving heat with direct flow of geothermal water (or geothermally heated process water) through plastic pipes placed underneath or on their surface, similar as solutions described in (Lund 1996).

In the case of foil tunnels, 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 dozens of centimeters above the ground, which would help heat the air in the tunnels. An example of a similar application in previous years in Podhale (MEERI PAS facilities: Rosik-Dulewska and Grabda 2001, Bujakowski 2000, Ney et al. 2001) showed that it facilitates a significant acceleration of vegetable growth and yield.

The geothermal heat could also be used for drying agricultural products (Sapińska-Śliwa 2009). On the other hand, geothermal water, due to its original purity and low mineralization (0.4 g/dm³), could, after appropriate cooling, be used as a raw material for 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 in the agriculture. Such water could even be directly used also in aquaculture facilities (fish farms) at temperatures around 20-30°C, including aquarium ornamental tropical fish, as the example of Greece shows (Arwantis 2017).

Another proposal for agricultural use of energy and water is algae cultivation – directly 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 (Godlewska et al. 2017). Geothermal heat could be used for drying algal biomass.

Conclusions

1. Poland has a prospective potential for geothermal energy to be used in agriculture, among others, which may 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 location selection. In particular – they should fit harmoniously into the 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.
2. 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, among others
 - deposit factors,
 - specific features of farms depending on, among others, soil types, type of cultivated vegetation, variability of hydrological conditions,
 - non-forest areas as preferred for the location,
 - the need to protect the main strategic fresh groundwater reservoirs (MGRs),

- the need to preserve the important natural functions of the systems: legal protection, ECONET-PL and NATURA 2000 and the network of ecological corridors.

3. Greenhouse facilities with the parameters specified in the article (for 60°C supply temperatures, slightly higher or lower) may be the most common places to utilize 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 where there are appropriate parameters of geothermal waters for their energetic use in sustainable development of agriculture (as well as geothermal waters as a raw material) in Poland.
4. Designing of central heating installation is a key factor. Always when geothermal energy application is assumed the heating installation should be designed as low temperature heating system. This reduces the necessity of usage of a peak energy source. The idea of cascaded geothermal systems plays also an important role.
5. The geothermal water resources of Poland are in many cases prospective for the needs of the agricultural sector, including organic farming. Low-mineralization waters with an appropriate physico-chemical composition that can be used directly to heat the growing soil (including irrigation) or to farm fish and other aquatic species would be most useful. Such waters can be found on the Polish Lowlands in a 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 mineralization) can also be used to heat livestock facilities, greenhouses, agri-food processing, crop and feed drying.
6. 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

717 the development of sustainable agriculture, effective prevention of lifestyle diseases,
718 improvement of the quality of health and life of the society, etc.

719

720

721 Abbreviations

722 GW – Gigawatt

723 TJ – Terajoule

724 TJ/y – Terajoule per year

725 °C – degree Celsius

726 M – meter

727 MGR – Main groundwater reservoirs

728 LGR – Local groundwater reservoirs

729 RWMB – Regional Water Management Boards

730 AHLP – Areas of highest level of protection

731 AHP – Areas of high level of protection

732 PGI-NRI – Polish Geological Institute – National Research Institute

733 SACs – Habitat areas

734 SPAs – Bird sanctuaries

735 NP – National Parks

736 EUR – Euro

737 ha – hectare

738 m²/100 ha – square meter per hundred hectares

739 W/(m²·K) – Watt per square meter times Kelvin

740 volume/h – volume per hour

741	m^2 – square meter
742	m^3 – cubic meter
743	MW – Megawatt
744	kW – Kilowatt
745	$P(\tau)$ – power demand at the time τ
746	T – the time
747	$P_{\max}$ – maximum power demand (the demand of power occurs when the lowest value of
748	design outdoor temperature is being observed $t_{\min}$)
749	t_{in} – assumed inner temperature
750	$t(\tau)$ – outside temperature at the time τ
751	$t_{\min}$ – external design temperature
752	Q – annual energy demand
753	m^3/h – cubic meters per hour
754	GW/y – Gigawatts per year
755	kJ – Kilojoule
756	dm^3 – cubic decimeter
757	K – Kelvin degree
758	h/y – hours per year
759	g/dm^3 – grams per cubic decimeter
760	P_{ch} – power demand - central heating
761	P_{dw} – power demand - domestic hot water
762	P_{el} – electric power demand
763	Q_{ch} – central heat use
764	Q_{dw} – domestic hot water use
765	Q_{el} – electricity use

766 PLN – Polish zloty
767 PLN/y – Polish zlotys per year
768 MEERI PAS – Mineral and Energy Economy Research Institute, Polish Academy of
769 Sciences
770 AGH-UST – AGH-University of Science and Technology
771
772

773 Declarations

774 Hereunder, Authors state the following re.

775 Availability of data and materials

776 Some data used as a basis for considerations presented in this paper were obtained from open-
777 sources mentioned in the text. The data elaborated by authors are available at MEERI PAS
778 Kraków, Poland, upon reasonable request. The datasets which neither belong to authors nor
779 their institutions are available at their owners' websites (given also in the References):
780 www.gis-suppot.pl;
781 [https://www.google.com/search?rlz=1C1GCEB_enPL852PL852&q=roleko/index.php/ddemo](https://www.google.com/search?rlz=1C1GCEB_enPL852PL852&q=roleko/index.php/ddemonstracyjne-gospodarstwa-ekologiczne)
782 [nstracyjne-gospodarstwa-ekologiczne](https://www.pgi.gov.pl/en/phs/tasks/8878-gzwp-major-groundwater-reservoirs.html); [https://www.pgi.gov.pl/en/phs/tasks/8878-gzwp-major-](https://www.pgi.gov.pl/en/phs/tasks/8878-gzwp-major-groundwater-reservoirs.html)
783 [groundwater-reservoirs.html](http://2.bp.blogspot.com/-Ivi5nIJc5Fg/VQ3AZXdouSI/AAAAAAAAA0k/oY5ioKupXI4/s1600/mapa.jpg); [http://2.bp.blogspot.com/-](http://2.bp.blogspot.com/-Ivi5nIJc5Fg/VQ3AZXdouSI/AAAAAAAAA0k/oY5ioKupXI4/s1600/mapa.jpg)
784 [Ivi5nIJc5Fg/VQ3AZXdouSI/AAAAAAAAA0k/oY5ioKupXI4/s1600/mapa.jpg](http://2.bp.blogspot.com/-Ivi5nIJc5Fg/VQ3AZXdouSI/AAAAAAAAA0k/oY5ioKupXI4/s1600/mapa.jpg); .
785 <http://susza.iung.pulawy.pl>; <http://agrometeo.pogodynka.pl>;
786 [https://archiwum.miir.gov.pl/strony/zadania/budownictwo/charakterystyka-energetyczna-](https://archiwum.miir.gov.pl/strony/zadania/budownictwo/charakterystyka-energetyczna-budynkow/dane-do-obliczen-energetycznych-budynkow-1)
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788 [content/uploads/2013/01/Koncepcja_Przestrzennego_Zagospodarowania_Kraju_203013.pdf](http://rpo2020.lubuskie.pl/wp-content/uploads/2013/01/Koncepcja_Przestrzennego_Zagospodarowania_Kraju_203013.pdf);

789 <https://www.lasy.gov.pl/pl/informacje/publikacje;>
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793

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795 The authors declare that they have no competing interests.

796

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803 **Authors' contributions**

804 RS and BK worked on data collection and wrote the manuscript. LP carried out the
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[ddemonstracyjne-gospodarstwa-ekologiczne](https://www.google.com/search?rlz=1C1GCEB_enPL852PL852&q=roleko/index.php/ddemonstracyjne-gospodarstwa-ekologiczne) (accessed on 25 June 2020).

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Figures

Figure 1

Map of geothermal water reservoirs prospective for agriculture in Poland. Scientific description based on Statutory work...(2016); ranges reservoirs with temperatures >30°C and >60°C according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013. Note: The designations employed and the presentation of

the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Geothermal water reservoirs prospective for agriculture 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 [% saturation]. Scientific description based on Statutory work... (2016); ranges reservoirs with temperatures >30°C and >60°C according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; saturation of soils with liquid water (Meteorological... 2020) – sample data from May 16, 2016. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Geothermal water reservoirs prospective for agriculture in Poland against the map of drought treats. Scientific description based on Statutory work... (2016); ranges reservoirs with temperatures $>30^{\circ}\text{C}$ and $>60^{\circ}\text{C}$ according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; threat of Map of drought treat (2020) – sample data from September 2, 2012. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Geothermal water reservoirs prospective for agriculture in Poland against the map of main groundwater reservoirs (MGR – fresh) and their protection areas. Scientific description based on Statutory work... (2016); ranges reservoirs with temperatures >30°C and >60°C according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; underlay Map of Main Groundwater Reservoirs (2020) – data from November 2016. Note: The designations employed and the presentation of the material on this map do not imply the

expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

Geothermal water reservoirs prospective for agriculture in Poland against the map of national parks, landscape parks, Natura 2000 areas and forests. Scientific description based on Statutory work... (2016);

ranges reservoirs with temperatures >30°C and >60°C according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; underlay Map by Doroty Kwaśny (2012) and State Forests in Poland (2010). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 6

Geothermal water reservoirs prospective for agriculture in Poland against the map of the objects of the European Network Natura 2000 areas. Scientific description based on Statutory work... (2016); ranges reservoirs with temperatures $>30^{\circ}\text{C}$ and $>60^{\circ}\text{C}$ according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; underlay the Map of the Nature 2000 areas (2020). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Reservoirs on the Polish Lowland, isotherms:

- 30 Lower Cretaceous [30°C]
- 60 Lower Cretaceous [60°C]
- 30 Lower Jurassic [30°C]
- 60 Lower Jurassic [60°C]

Reservoirs on the Carpathian Foredeep and Outer Carpathians, isotherms:

- 30 Cenomanian [30°C]
- 30 Miocene [30°C]

Podhale Basin reservoir, isotherms:

- 30 Middle Triassic and Eocene [30°C]

- urbanized areas of cities >1000,000 inhabitants
- NP (national parks) with lagging
- landscape park with lagging
- common areas of SPAs and SACs >500 ha
- ▨ Natura 2000 marine areas
- ▨ corridors of the ECONET-PL system
- ▨ corridors connecting areas of the Natura 2000 system
- ▨ common corridors of both systems
- river corridors
- ➔ directions of animal migration outside of Poland
- projected new NP
- + projected NP magnification
- Cross-Border Projected Areas
- ⋯ area of cross-border cooperation in the European Union
- ⋯ area of cross-border cooperation under the Carpathian Convention

Figure 7

Geothermal water reservoirs prospective for agriculture in Poland against the map of spatial policy directions concerning nature. Scientific description based on Statutory work... (2016); ranges reservoirs with temperatures >30°C and >60°C according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; underlay Ministry of Regional... (2020) 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, Białowieża, about the corridors connecting Natura 2000 areas in 2006 and data of the National Water Management Board on river corridors in 2010.

Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 8

Geothermal water reservoirs prospective for agriculture in Poland against the map of cultivated vegetables under covers. Scientific description based on Statutory work... (2016); ranges reservoirs with temperatures $>30^{\circ}\text{C}$ and $>60^{\circ}\text{C}$ according to maps by Górecki [sc. ed] et al.: 2006, 2011, 2012, 2013; underlay Map of vegetables crops under cover (2002; in Kulikowski 2007). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 9

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

Figure 10

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

Figure 11

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

Figure 12

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

Figure 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).

Figure 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).