

Regional Energy Planning: Optimising Geothermal Energy Production Under Natural Conditions

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How to cite this article:

Rabe, M., Streimikiene, D., Wojciechowski, A. and Sochacka, M. (2021). Regional Energy Planning: Optimising Geothermal Energy Production Under Natural Conditions. *Acta Montanistica Slovaca*, Volume 26 (4), 784-795.

DOI:

<https://doi.org/10.46544/AMS.v26i4.15>

Abstract

Geothermal energy can be an attractive source of renewable energy in many respects. The purpose of this paper is to assess the role of geothermal energy in the West Pomeranian Region of Poland. The article presents the key principles of geothermal energy development, its role, functions and perspectives in fostering renewable energy usage in the region in question. Strengths, weaknesses as well as opportunities and threats of using geothermal energy are analysed based on the literature review. A regional geothermal energy development model is proposed. The study is based on statistical data. The results of the conducted study show that geothermal energy can be an important source of regional energy supply in the West Pomeranian Region. However, advantages and shortcomings should be taken into account when deciding on the promotion of geothermal energy in the selected region.

Keywords

Geothermal energy, geothermal energy optimisation model, natural conditions, regional energy planning.



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Introduction

The main energy and climate policy of the EU is to facilitate the transition away from fossil fuels towards the so-called "zero free energy" and to deliver on the EU's Paris Agreement commitments for reducing greenhouse gas emissions (GHG) emissions. The Clean energy for all Europeans package describes the most important steps towards the implementation of the energy union strategy, thus delivering to the carbon-free economy target of 2050. The EU has set an ambitious 2030 target of having 32% for renewable energy sources (RES) in the final energy consumption volume. The EU member states have prepared their RES commitments and policy packages to support RES and overcome market barriers for faster penetration of renewables. In addition, renewables provide important opportunities for sustainable regional development and the creation of sustainable energy areas, in particular, energy clusters and energy cooperatives (Raszkowski & Bartniczka, 2018; Savitz & Gavriletea, 2019; Liao et al., 2019; Mariyakhan et al., 2020; Popp et al. 2018). Support for the development of distributed energy generation in energy clusters and energy cooperatives is particularly important from the viewpoint of regional energy systems' planning (Shindina et al., 2018). Among many unconventional sources of energy, geothermal energy has recently become the centre of attention. This type of energy is the Earth's natural heat, accumulated in soils, rocks, waters and vapours filling pores and rock crevices. Enormous amounts of energy are generated in the nucleus, mantle and the Earth's crust. The temperature of the Earth's interior changes with depth and, starting from its surface, increases by approx. 300C per kilometer (Szramka & Różycki, 1999). Poland has natural conditions favourable for the direct use of geothermal energy. The waters currently available for exploitation occur at the depths of about 4 km have temperatures varying from about 20 to 80-950C (Sala, 2018; Dudin et al., 2019). Therefore, the country has good natural conditions to use this potential for district heating development in specific regions of Poland. The following indicators are set in the main Polish energy policy document for 2030 (Ministry of Energy, 2018): to achieve 60% share of coal in power generation and 21% RES in the final energy consumption; improvement in energy efficiency by 23% as compared to the 2007 level and reducing CO₂ emissions by 30% as compared with the 1990 level. The introduction of new nuclear energy is also scheduled for 2033. However, there are important barriers that hamper the use of geothermal energy at local, national, and European levels (Ozgener, 2010; Colmenar-Santos et al., 2018; Romero-Rubio & de Andrés Díaz, 2015; Büyüközkan & Gülerüz, 2017). Therefore, policies and measures need to be taken to overcome these barriers (Boie et al., 2014; Borge-Diez et al., 2015; Lu et al., 2019).

Though Poland has set ambitious targets for renewable energy development in line with the EU energy and climate framework for 2030 and 2050, there are no studies dealing with forecasting geothermal energy development based on local natural conditions of specific regions and integration of a geothermal component into regional energy planning. The paper aims to overcome this gap and proposes the tools for optimisation of geothermal energy development in the selected region in order to implement energy and climate targets in Poland and move faster towards a carbon-free economy.

The aim of this paper is to assess the role of geothermal energy use in the West Pomeranian Region. In order to achieve this aim, the principles of geothermal energy development, its role and functions, strengths, weaknesses as well as opportunities and threats of using geothermal energy should be defined. The current situation with geothermal energy usage and the potential of geothermal energy development based on natural conditions in the West Pomeranian Region need to be analysed. Our analysis results in the construction of an optimisation model. The rest of the paper is structured in the following way: section 1 reviews the literature on strengths, weaknesses and opportunities of geothermal energy development; section 2 presents the overview of natural conditions in the selected Polish region in terms of geothermal energy exploitation and assesses the current situation and the potential of geothermal energy resources used in the region along with the policies promoting RRS; section 3 presents our own optimisation model for regional geothermal energy in the selected region; section 4 discusses the case study results and section 5 concludes.

Literature Review

Geothermal energy, also called geothermal energy or geothermal energy, involves the use of thermal energy inside the Earth. In the case of geothermal energy, the fact that the Earth's temperature rises with depth, reaching 6600°C in the very core, is used. Geothermal energy escapes to the Earth's surface naturally, with the power determined at approx. 46 TW (Hollenbach & Herndon, 2001). However, given the huge volume of the Earth, its geothermal resources are almost inexhaustible. It is estimated that geothermal deposits worldwide are around 8×10^{12} EJ (one EJ is equivalent to 27.3 billion m³ of gas). According to some sources, geothermal resources usually have a life span of 30 to 60 years, which means that in world literature view on quasi-renewable geothermal energy (Kaczmarczyk, 2009).

The literature divides geothermal energy into two groups: hydrothermal and geothermal. Hydrothermal resources are water, steam or a mixture of water vapour found in rock crevices or in water veins. In contrast, petrothermal resources occur in rock layers (Collins et al., 2017).

Geothermal energy is taken in by means of boreholes, into which cool water is pumped in and removed hot, heated from hot rocks. It also occurs as a natural source of heat in thermal sources. Geothermal energy is used in approx. 80 countries and the total power of operating geothermal power plants was estimated in 2015 at 1264 MWe. The forecasts for the development of geoelectroenergetics assume that in 2020 the power of the power plant will amount to 21400 MWe (Bertani, 2015). The world's largest producers of electricity from geothermal energy are presented in Table 1.

Tab. 1. The world's largest producers of electricity from geothermal energy in 2015

Country	Generated energy (GWh) per year
United States	16600
Philippines	9646
Indonesia	9600
New Zealand	7000
Mexico	6071
Italy	5660

(Source: Stachel & Sohtysik, 2017)

Due to the operating principle, geothermal power plants are classified into three groups, including dry steam power plants, wet steam power plants and intermediary power plant (Table 2). The type of power plant results from the acquired geophysical fluid (Cucchiella et al., 2018).

Tab. 2. Dependencies of geothermal power plants on the temperature of the geothermal fluid

Geopy temperature (°C)	Power plant types
180 - 300	Direct system (dry steam)
200 - 320	Water expansion system (wet steam)
125 - 165	System with an intermediate factor (saw system)

(Source: Stachel & Sohtysik, 2017)

For the production of electricity, water is used in the form of steam at very high temperatures, above 150°C. Water with a lower temperature is mainly used for heating or cooling rooms, greenhouse farming, and bathing and balneology. Sources with temperatures above 150°C are found only in some regions of the globe. In the European Union, geothermal heating plants already operate in Iceland, Greece, Italy, Turkey, Germany and Austria. In Iceland, 30% of homes use electricity generated from geothermal energy (Kubski, 2017).

As with all types of energy sources, geothermal energy has its strengths and weaknesses and creates opportunities and threats (Table 3).

Tab. 3. Analysis of strengths and weaknesses of geothermal energy in the world

Strengths	Weakness	Chances	Threats
<ul style="list-style-type: none"> • conversion rate for CHP systems at 97%, • low gas emissions greenhouse, • wide access to sources around the world, • independent of commodity markets and currency price fluctuations, • is not dependent on seasonal weather fluctuations, • flexible structure power plant 	<ul style="list-style-type: none"> • requires high temperatures (>90°C) to operate effectively, • low conversion rate for electricity (7-10%), • high costs initial and exploration risks - similar to the mining industry oil 	<ul style="list-style-type: none"> • cost reduction trend it will probably continue - 50% in the last 20 years, • untouched raw materials and markets in Southeast Asia and Latin America, • growing market, the number of countries using energy Geothermal has doubled in the last 30 years 	<ul style="list-style-type: none"> • significant decrease public research funding and development through relatively high initial costs, • carrying out projects may have an impact on the local environment (drilling, etc.), which is not always supported by the community local

(Source: IEA, 2003)

Enthusiasts of geothermal solutions are convinced that its most important advantages include low environmental impact. It does not cause any pollution if it works correctly. Contrary to wind or solar energy, geothermal energy resources are always available, regardless of weather conditions, which affects the profitability of investments and relatively low operating costs, creating at the same time many new jobs (Rzepa, 2018; Kasperowicz et al., 2017).

Moderate optimists, recognising the fact of their abundance in us, emphasise that the energy obtained from them can only be a complementary source, and in regions where it has been shown to be profitable and competitive with other carriers (Maciej & Nowak, 2017).

Opponents of geothermal solutions are convinced that the disadvantage of geothermal energy is high investment costs and a long payback period. It is expensive to drill a well depth. The construction of installations in the form of pumps, heat exchangers, pumping stations and pipelines is also a heavy burden. The problem is the high mineralisation of some sources, which causes the deposition of salt on the internal surface of the installation's equipment (Olejnik, 2005).

Geothermal Energy Development in Poland and West Pomeranian Region

Natural Conditions for Geothermal Energy in Poland

Poland has a very good geothermal situation, despite being outside volcanic areas. Three geothermal provinces cover over 80% of the country. The water temperature in these provinces ranges from 30 to 130°C, and the depth of occurrence in sedimentary rocks ranges from 1 to 10km (Majorowicz, 1971).

The Polish Lowland province covers an area of 222,000 km², and deposit temperatures range from 30 to 130°C, at a depth of 1km to 3km. The potential of geothermal resources was estimated at over 32 458 million tons of water containing heat energy.

The pre-Carpathian province covers an area of 17,000 km², and reservoir temperatures range from 25 to 50°C. The potential of geothermal resources was estimated at 1555 million tons of water containing heat energy (Institute for Renewable Energy, 2011).

Whereas the Carpathian province covers an area of 12 thousand km². The potential of geothermal resources was estimated at over 714 million t of waters containing thermal energy (Bujakowski, 2003).

The capacity to use geothermal waters concerns 40% of the country's area and extraction is profitable when the temperature reaches 65°C up to a depth of 2 km, and the salinity does not exceed 30g/l (Sowiżdżał, 2009).

In Figure 1, the geothermal installations in Poland are mapped.



Fig. 1. Geothermal installations in Poland
(Source: Kępińska, 2016)

Geothermal Energy Resources in the West Pomeranian Region

West Pomeranian Region is located in the Province of Polish Lowland in the Szczecin-Łódź geothermal district. In the central part of the province, there is a so-called tectonic area Szczeciński basin, covering the surroundings of Drawno, Drawsko Pomorskie, Chociwel, Nowogard, Goleniów, Police, Szczecin, Pyrzyce, Stargard and Dobrzany (Rabe, 2017).

The volume of geothermal resources of the Szczecin basin is presented in Table 4.

Tab. 4. Geothermal resources of the Szczecin basin

Resource Group	The volume of resources expressed in the TOE
Available geothermal resources	1,1 x 10 ¹¹ TOE
Static resources of geothermal energy	1,13 x 10 ¹⁰ TOE
Static resources - recoverable geothermal energy	2,27 x 10 ⁹ TOE
Available resources	6,98 x 10⁶ TOE

(Source: Sowizdzal, 2009)

The best geothermal disposable resources of the Szczecin basin include within its reach such cities as Stargard, Dobra, Chociwel, Insko and Dobrzany, where the potential was determined at over 35 MJ/m². (Disposable resources - the amount of free hydro-geothermal water level or other balance units, possible to be managed under given environmental conditions, but without indicating the detailed location and technical and economic conditions of the water intake). Temperatures in this area range from 73 to 90°C, to a depth of -2500 to -2000 m a.s.l. Relative geothermal conditions of available resources can boast of such municipalities as Goleniow, Police, Maszewo and the city of Szczecin, where the water temperature is from 50 to 60°C (Regional Office for Spatial Management of the West Pomeranian Region, 2018). The most favourable conditions for the construction of geothermal heating plants in the West Pomeranian Region are given in Table 5.

Tab. 5. Cities with the most favourable conditions for the construction of geothermal heating plants in the West Pomeranian Region

Very good conditions for the construction of heating plants geothermal facilities.	Good conditions for construction geothermal heating plants	Relatively good conditions for construction of geothermal heating plants
Szczecin	Choszczno	Dębno
Police	Gryfino	Recz
Goleniow	Gostyn	Myślibórz

(Source: Sala, 2018)

In another part of the Szczecin basin, the disposable geothermal energy resources are much smaller. In the eastern part of the province, the temperature of geothermal waters is around 20-30°C. Sufficient conditions for the use of this type of energy are found in the following counties: Police, Goleniow, Szczecin, Pyrzyce, Choszczno, Stargard, parts of Gryfino, Łobeski, Drawski, Wałeczki, Myśliborski (Stachel & Sołtysik, 2017).

The available geothermal energy resources in the West-Pomeranian region are mapped in Figure 2.

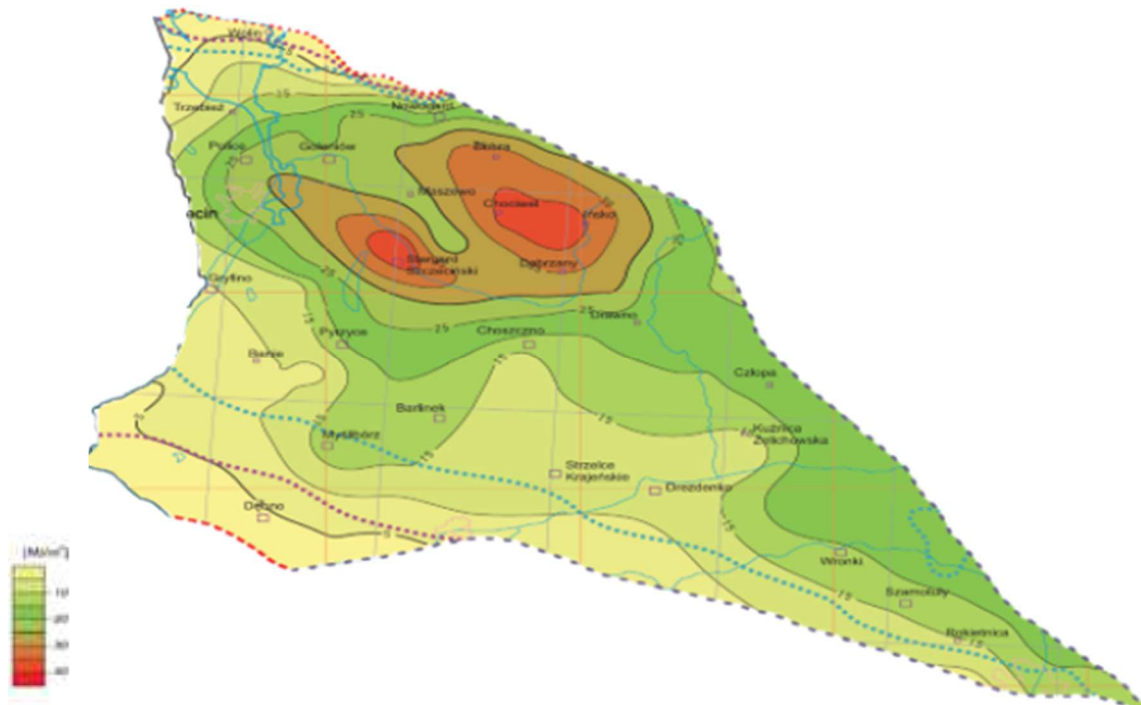


Fig. 2. Map of the unit available geothermal energy resources in the West Poland province (Source: Sowizdzal, 2009)

The heating plant in Pyrzyce was established in 1997. It uses geothermal water extracted from a depth of 1500-1700. Its exploitation is carried out by means of two production holes and two absorbent ones. The approved

capacity is a total of about 370 m³ / h water with an outlet temperature of 64°C. The saltwater table is located 32 meters underground. After the system's modernisation and optimisation in recent years, the total installed capacity of the heating plant is about 22 MW, with about 16 MW coming from gas boilers and 6 MW from geothermal energy (heat exchangers). 20.4 MW comes from the absorption heat pump. The extracted geothermal water is sufficient to heat running water in flats in the summer and autumn. In winter, it is necessary to use gas heat pumps to heat water to 70-80°C. At the moment, around 90% of all heat consumers in this 13,000 city are connected to the central heating network.

The Geothermal plant located in Stargard has a capacity of 14 MW. The geothermal intake is characterised by a high water temperature of about 90°C. The operating system is two-hole; the extraction hole and the absorption hole are working. At the moment, about 60% of residents are connected to the central heating network, in this city of 75 thousand. It is worth noting that this is the second installation in Poland (after Podhale) in terms of annual production and sale of geothermal heat (Płocharski, 2017).

Prospects for the Development of Geothermal Energy in the West Pomeranian Region

A particularly important area for the energy direction of geothermal development in the West Pomeranian Region is broadly understood as heating (room heating, agriculture, other areas where heat is needed), which would significantly reduce the consumption of traditional fuels and pollutant emissions and increase the share of renewable energy in many cities (Regional Office for Spatial Management of the West Pomeranian Region, 2018).

The region has very good conditions for exploiting geothermal waters, thanks to its location. These waters can be used in thermal energy. The disposable volume in the region is 6.98 x 10⁶ TOE (a ton of oil equivalent).

Taking into account investment costs, this type of heating system should be located only in places where there will be a significant number of heat recipients. The preferred cities for the development of geothermal energy are Szczecin, Police, Goleniów and Nowogard. Currently, there is also an increase in the use of all types of compressor heat pumps (Rabe et al., 2019b).

Recreation and health care are also promising branches of use. They must meet the criteria of appropriate temperature, mineralisation and intake efficiency. Mineralisation of water for therapeutic purposes should not exceed 50 g / dm³ and a minimum temperature of 28-42°C, while for recreational purposes, 30 g / dm³ and a minimum temperature of 24-30°C, respectively. The most predisposed to use geothermal waters of the lower Jurassic ceiling for therapeutic and recreational purposes (due to its favourable mineralisation and temperature parameters) are the municipalities located in the poviats of Gryfińskie, Myśliborski, Choszczeński and Wałecki as well as partly Goleniowski, Łobeskie and Drawski (Rabe et al., 2019a).

In special cases, in the West Pomeranian Region, it would be possible to produce electricity using waters with temperatures above 80-100°C, in binary installations with low power, usually in cogeneration with heat. With currently known technologies, the production of electricity from a geothermal source must have a minimum temperature of 80-90°C (IEA, 2003).

Another application of geothermal heat may be drying wood. Such facilities are already located at IGSMiE PAN in Podhale, as well as heating the football pitch and walking paths or in fish farming.

Convincing arguments that the given methods of geothermal energy management in the West Pomeranian Region on a larger scale than before are possible and economically effective, it provides the observed development and implementation of many investment projects in Europe (Kępińska, 2016).

Policies to Promote Geothermal in Poland

The Polish Energy Policy 2040, the main energy policy document in Poland, established the requirement that the share of RES in final energy consumption will reach 21% in 2030. This RES target in final energy consumption also includes a 27% share of RES in power generation and district heating and cooling. It is foreseen that in the heating and cooling sector, the share of RES should grow by 1–1.3% annually. The use of energy from biomass and biogas, geothermal energy, heat pumps, and solar energy will contribute to RES target in heating and cooling, while the power sector will be solar, offshore and offshore wind energy, energy from biomass and biogas, and hydropower. However, the changing business environment and technological development constitute major challenges for the heating and cooling sector in Poland. Important issues to be addressed in this sector are the changing of heat market model and tariff policy, extending the obligation to connect consumers to an energy-efficient heating system and developing network infrastructure, regulating district cooling, etc. (Ministry of Energy, 2018).

The Energy Policy for Poland 2040 emphasises that district heating is one of Poland's main strategic directions of energy policy. The main policies and measures to ensure penetration of RES in this are the following: financial, organisational and legal support, by increasing the use of RES and waste in district heating as well as modernising and expanding heating systems and developing new RES technologies for this sector and promoting heat storage facilities and smart networks.

However, support for RES should be based on competitive systems and the least cost decisions to achieve RES targets. Support will be provided in the form depending on the type of source and its size in these forms (Ministry of Energy, 2018):

- auctions – designated for sources generating energy in a manner suitable for commercial purposes;
- feed-in tariff system and feed-in premium system – targeted on the lowest capacity sources and applied to manage energy which is not consumed by small producers;
- grants and repayable aid – a mechanism depending on local needs, distributed in regions;
- a guarantee of origin – a voluntary support instrument – in the form of a certificate; demand for these instruments is generated by consumers who wish to be perceived as environment-friendly companies;
- aid mechanisms targeted on special technologies – a solution designated for sources for which there is no competition in the market, but their implementation is important for the country.

The auction offers permanent and stable conditions for investing in new RES installations. The auctions enable to channel aid to selected sectors based on least costs, energy security, technical criteria and the needs of local communities (Stavvyskyy et al., 2018; Tvaronavičienė et al., 2018). Therefore, a stable and competitive RES support system is necessary to promote RES, including geothermal penetration in the energy markets, without increasing energy prices or serious disturbances in energy markets. Such economic measures implemented to support RES and necessary legal regulations will contribute to the dynamic growth of new investments in RES. The use of geothermal and heat pumps technologies is envisaged. The geothermal power generation – although at present its use is at a relatively low level, it is estimated to grow at a very fast rate. Major financial expenditures are required to determine geothermal potential, with the degree of certainty being very small, but the use of this type of energy may determine the development of a given region. Heat pumps used in households have become more and more common. Their potential is assessed to be at a level similar to geothermal energy generation. Electricity is required for them to be used, and linking installations with another RES which generates electricity is a good solution.

It is expected that Poland will rely on its own resources to implement the RES target. However, no excess energy production from RES is envisaged, which could be transferred to the other Member States in order for them to achieve their national RES contributions in 2030 (Ministry of Energy, 2018). The new Directive on the promotion of the use of energy from renewable sources (RED II) introduces new obligations for the share of RES in the heating and cooling sector. The heat sector needs funds at the local government level; therefore, the financing should be ensured by municipal utility companies usually having financial problems. The grants, repayable instruments, guarantee funds can be used to provide support to these utilities. This new directive (RED II) emphasises the importance of sustainable energy areas, in particular energy clusters and energy cooperatives. The support for the development of distributed energy generation in energy clusters and energy cooperatives is particularly important from the point of view of the construction of generation sources, networks and control systems in Poland. It is planned that ca. 300 energy sustainable areas will operate at the local level in Poland in 2030. The proposed form of financing: grants, repayable aid, guarantee funds (Ministry of Energy, 2018).

The emission allowance trading system (EU ETS) is the most important market-based mechanism aiming at GHG emission reduction and having a direct impact on the increase of competitiveness of renewables due to internalisation of external costs of fossil fuel generation and increase of energy price of fossil fuel-based plants. Installations eligible for the system belong to specific sectors or meet the defined threshold conditions set out in Directive 2003/87/EC. The number of installations covered by the scheme changes from one year to another (ca. 800 installations in Poland). The modernisation and innovation funds and the continuation of the currently applicable derogation system for the power sector will be introduced from 2021, within the framework of the EU ETS.

Geothermal Energy Development Model in the West Pomeranian Region

The publication presents a renewable energy development model that optimises the regional potential of geothermal energy. According to the Potential report and the use of renewable energy sources in the production of electricity and heat in the West Pomeranian Region, the potential of geothermal waters in the studied area can be used in the broadly understood heating sector. Only in some cases in the West Pomeranian Region, it is possible to produce electricity using waters with temperatures above 80-100°C. It is estimated that the volume of available resources in the province is 6.98×10^6 TOE (81 177 400 000 kWh), of which only 1 per cent of the available geothermal resources can be used to produce electricity (811,744,000 kWh). Available geothermal resources are distinguished temperatures that make them very unattractive from the point of view of electricity generation.

The lexicographic method was used in the geothermal energy development model, which allowed to obtain a compromise solution (Rabe et al., 2020; Ślusarczyk et al., 2016; Popp et al., 2018; Mikita et al., 2017). ACCORDING TO THOMSON REUTERS, the EUA allowance price forecast for 2021-2030 was also used. The time range of empirical research was set for 2018-2030. 25 decision variables were adopted in the model, where the technical and economic parameters were calculated first, and the minimum or maximum levels of balance

conditions were established (Rabe et al., 2019a). The average cost of energy production from various energy carriers (as of 2018) for the model are provided in Table 6.

Tab. 6. The average cost of energy production from various energy carriers (as of 2018)

Name of the technology	Cost of electricity production PLN / kWh
Conventional energy	0.72
Energy from co-firing	0.93
Solar power stations	0.40
Wind farms	0.24
Biomass power plants	0.28
Hydroelectric power plants	0.20
Geothermal power plant	0.28
Energy from biogas plants	0.70
Energy from biofuels	1.10

(Source: Regional Office for Spatial Management of the West Pomeranian Region, 2018)

Objective function parameters from x_1 to x_{15} include energy production costs, ecological costs, certificates, and EUA allowance prices (Table 7).

Tab. 7. Cost factors for each type of energy (in PLN / kWh)

Types of energy	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}
Costs of production	0.72	0.93	0.20	0.20	0.40	0.24	0.24	0.24	0.70	0.70	0.70	1.10	0.28	0.28	0.28
Cost of the certificate	0.00	0.00	0.12	0.12	0.12	0.12	0.12	0.20	0.12	0.12	0.2	0.12	0.12	0.20	0.12
Ecological costs (cost of EUA allowances)	0.0316	0.0252	0.0006	0.0006	0.0007	0.0006	0.0006	0.0006	0.0116	0.0116	0.012	0.012	0.0004	0.0004	0.001
Total costs	0.69	0.90	0.07	0.07	0.27	0.11	0.11	0.03	0.56	0.56	0.56	0.96	0.15	0.07	0.15

(Source: own study for the needs of the model)

Whereas the parameters of the objective function, from x_{16} to x_{25} , include costs of producing energy from energy crops (Table 8).

Tab. 8. Cost of energy production from energy crops (in kWh/ha)

Energy resources	x_{17}	x_{18}	x_{19}	x_{20}	x_{21}	x_{22}	x_{23}	x_{24}	x_{25}
Manufacturing cost	0.18	0.35	0.17	0.07	0.04	0.5	0.34	0.5	0.21

(Source: own study for the needs of the model)

The author's model also assumes that, in 2030, energy production in the study area will amount to 11,956.08 GWh. The price of allowances in 2030 will be at the level of 23.04 euros, i.e. 0.14 PLN per kWh.

The following decision variables have been applied to the model:

- x_1 – generating non-renewable energy (kWh);
- x_2 – generating energy from co-firing (kWh);
- x_3 – generating water energy (kWh) from existing installations (until the end of 2017);
- x_4 – hydropower generation (kWh) in new installations (from January 2018);
- x_5 – solar energy generation (kWh);
- x_6 – generating energy from windmills at domestic (kWh);
- x_7 – generating energy from wind farms (kWh) from existing installations (until the end of 2017);
- x_8 – wind energy (kWh) in new installations (from January 2018);
- x_9 – generating energy from biogas (kWh);
- x_{10} – generating energy from biogas in high-efficiency cogeneration with a total installed electrical capacity of less than 1 MW in (kWh);
- x_{11} – biogas energy generation (kWh) in new installations (from January 2018);
- x_{12} – generating energy from biofuels (kWh);
- x_{13} – generating energy from biomass combustion (kWh) from existing boilers (until the end of 2017);
- x_{14} – energy generation from biomass combustion (kWh) from new boiler installations (from January 2018);

- x_{15} – power generation from geothermal energy
- x_{16} – total annual electricity production from various energy sources (kWh);
- x_{17} – energy willow of the yield (kWh);
- x_{18} – yield value of miscatus (kWh);
- x_{19} – poplar yield (kWh);
- x_{20} – sidaz yield (kWh);
- x_{21} – yields of Jerusalem artichoke (kWh);
- x_{22} – size of rape grown for biofuels (kWh);
- x_{23} – size of cereals grown for biofuels (kWh);
- x_{24} – the size of maize grown for biogas (kWh);
- x_{25} – beet harvest for biogas (kWh).

The objective function (minimised) in the hydropower development model in the West Pomeranian Region consisted of three components:

- costs related to production,
- costs related to certificates,
- costs of EUA allowance prices,
- loss of soil fertility.

In the optimisation model of hydropower development, only one function ($L(x)$) was minimised, which was a component of the above components.

The purpose function of the decision model is as follows:

$$L(x) = 0.69x_1 + 0.90x_2 + 0.07x_3 + 0.07x_4 + 0.27x_5 + 0.11x_6 + 0.11x_7 + 0.03x_8 + 0.56x_9 + 0.56x_{10} + 0.56x_{11} + 0.96x_{12} + 0.15x_{13} + 0.07x_{14} + 0.15x_{15} + 0.18x_{17} + 0.35x_{18} + 0.17x_{19} + 0.07x_{20} + 0.04x_{21} + 0.5x_{22} + 0.34x_{23} + 0.5x_{24} + 0.21x_{25} \rightarrow \min$$

Side conditions are as follows:

The boundary conditions assume that all variables must be non-negative.
 $x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 + x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} + x_{15} = x_{16}$ - total energy production.

$x_{16} \geq 11956080000$ kWh - energy generation for the needs of the studied region.

$x_3 + x_4 + x_5 + x_6 + x_7 + x_8 + x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} + x_{15} = 0.27 x_{15}$ - 27% of total renewable energy production.

$x_6 + x_7 + x_8 \geq 3575088000$ kWh - generating wind energy

$x_8 \leq 840,000$ kWh - generating energy in newly created wind installations from 01/01/2018

$x_9 + x_{10} \geq 41376000$ kWh - generating energy from biogas

$x_{13} + x_{14} \geq 238200000$ kWh - generating energy from biomass combustion.

$x_9 + x_{10} = 30450000x_{23} + 10960000x_{24}$ - generating energy from biogas combustion.

$x_{11} + x_{12} = 10500x_{21} + 15000x_{22}$ - generating energy from the combustion of biofuels.

$x_{13} + x_{14} = 238200000$ kWh - generating energy from biomass combustion.

$x_{15} \leq 811\,774\,000$ kWh generating energy from geothermal energy.

$x_2 \leq 6907531938$ kWh - maximum energy generation from co-firing.

$x_3 \geq 313770000$ kWh - hydropower generation.

$x_4 \leq 319141000$ kWh - generating new hydropower

$x_5 \geq 9590000$ kWh - minimum solar energy production.

Description of the model's construction is in the article by Rabe et al. (2019a).

Discussion of Results

Model optimisation with this objective function gives the following solutions given in Table 9.

Tab. 9. The results of optimisation model

Types of energy	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}
Energy production	0	7065.5	300.5	9.6	307.2	0	3575.08	95.5	30.45	12.96	54.06	0	238.2	160.2	106.83
Energy resources	x_{17}	x_{18}	x_{19}	x_{20}	x_{21}	x_{22}	x_{23}	x_{24}	x_{25}						
Crop size	0	0	0	0	0	0	0	0.0423	0						

(Source: own study for the needs of the model)

Considering the obtained solution, it can be noted that the total energy production is 11956.08 GWh (i.e. covers the demand of the studied area), of which 7065.50 GWh is energy production from co-firing, 300.55 GWh

is hydropower generated in hydropower plants created until December 31, 2018; 9.60 GWh is hydropower generated in installations after 2018.

9.59 GWh is solar energy generated in installations until 2018, and 278.4 GWh is energy generated after 2018. 3575.08 GWh is wind energy generated in wind farms created until 31.12.2018, and 95.50GWh is energy produced in new wind farms created by the end of 2030.

43.37 GWh through installations producing energy from agricultural biogas, and 54.06 GWh is new energy generated from installations from biogas from sewage treatment plants and landfill biogas. 238.20 GWh of energy was generated in existing biomass burning boilers. In contrast, 162.20 GWh of existing boilers was established after 2018. 106.83 GWh is energy generated from geothermal power plants. The average cost of building one MW of energy will be PLN 9 725 018.

Conclusions

Geothermal energy can be a reliable alternative energy source for the West Pomeranian Region. Its numerous benefits for the energy balance and ecology of this region are obvious and difficult to overestimate. Geothermal energy is part of the principles of sustainable development. It allows significantly lower use of non-ecological energy sources since it provides a cheap energy source. It can bring measurable benefits to local communities, local government authorities and tourists as well. Considering favorable geothermal conditions in the region under consideration, the development of geothermal plants should be expected.

However, new and updated policies and measures are necessary to overcome the main barriers to geothermal energy penetration in the West Pomeranian region. Currently available policies and measures are already targeting economic barriers and providing financial support in subsidies, etc. However, regulatory barriers such as unstable governmental policies and low public acceptance of geothermal energy projects due to Not In My Yard (NIMBY) syndrome and low awareness of the potential benefits of such technologies require additional measures such as demonstration projects and support for RERS infrastructure, including energy storage facilities. Also, support for geothermal R&D would be important to overcome technological barriers to the penetration of these technologies.

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