Leveraging the competitive advantages of end-of-life underground coal mines to maximise the creation of green and quality jobs

Grant Agreement 101057789

Deliverable 2.1

Geothermal energy deployment

Authors

Alicja Krzemień, Beata Kończak, Mariusz Kruczek, Piotr Zawadzki

CENTRAL MINING INSTITUTE

Deliverable 2.1	
Due date of Deliverable	31.03.2023
Start - End Date of Project	01.07.2022 – 31.12.2025
Duration	3.5 years
Deliverable Lead Partner	GIG
Dissemination level	Public
Work Package	WP 2
Digital File Name	D2.1 Geothermal energy deployment
Keywords	mine water, geothermal energy

Disclaimer

Table of contents

List of Figures

List of Tables

Executive Summary

This Deliverable selects, according to the project's needs, the most widespread and reliable units on the market for deploying geothermal energy.

First, an overview of geothermal energy deployment and its potential in mining areas in Poland, Spain, and Slovenia were provided. The report covers various aspects of geothermal energy, including geothermal water parameters, characteristics of geothermal conditions, and technologies for geothermal energy recovery. Additionally, the best technology for mining areas and an assessment of the potential for implementing geothermal energy in mining areas in Poland are presented.

Second, the characteristics of geothermal conditions worldwide and in Europe are discussed. The analyses covered the geothermal energy market and identifies technologies for geothermal energy recovery, such as direct dry steam plants, flash steam plants, binary cycle power plants, and hydrothermal spallation drilling technology. The report also discusses the use of geothermal energy in mining, including closed loop and open loop systems. Furthermore, examples of abandoned and operating mines, such as the SRK S.A. Zakład Centralny Zakład Odwadniania Kopalń (CZOK) in Czeladź (Poland) – „Saturn" pumps station, the "Maciej" Shaft – the abandoned "Concordia" mine, and the "Sobieski" mine were presented.

Third, considerations relating to the energy system for geothermal energy deployment in mining areas and the value chain were prepared. This highlights the potential benefits of using geothermal energy, such as reduced costs and emissions, increased energy security, and job creation. The report also discussed the challenges and barriers to geothermal energy deployment, including geological and technical risks, regulatory frameworks, financing, and public acceptance.

Forth, the potential for implementing geothermal energy in Poland's mining areas was assessed assessment of the potential for implementing geothermal energy in mining areas in Poland was carried out. It identifies the best technology for mining areas based on each technology's potential benefits and drawbacks, the technical and economic criteria, including the availability of geothermal resources, geological and technical conditions, energy demand, and costs. The report each technology's potential benefits and drawbacks also discusses the potential benefits and drawbacks of each technology, such as efficiency, flexibility, and environmental impact. A case study of a demosite installation in Spain were held, and it demonstrates the technical and economic feasibility of geothermal energy deployment in mining areas. The main economic and technical characteristics of geothermal installations were analysed based on data from Hulleras del Norte, S.A., the only coal mining company in which it was possible to collect financial information from its already working two district

heatings in Langreo and Mieres, located in the Central Asturian Coal Basin (Spain). The capital expenditure (CAPEX) was calculated based on total investment versus installed power and on total investment versus energy supplied; operational expenditure (OPEX) was estimated in order to calculate the revenues. The financial outcomes (NPV, IRR and PP) were calculated, followed by a sensitivity analysis.

Finally, the report concludes with a discussion of best practices for geothermal energy deployment in mining areas. It highlights the importance of collaboration among stakeholders, including government, industry, and local communities, and the need for innovative financing mechanisms, such as public-private partnerships, to overcome the barriers to geothermal energy deployment. The report also emphasizes the role of geothermal energy in the transition to a low-carbon economy and the creation of sustainable jobs.

As a conclusion, the report shows that geothermal energy is a promising source of energy for mining areas, and its implementation can create economic opportunities and environmental benefits. The report identifies the best technology for mining areas and assesses the potential for implementing geothermal energy in mining areas. The report concludes with a discussion of best practices and highlights the job creation potential of geothermal energy.

1 Introduction

As the transition process towards a greener economy, many industries are re-evaluating their practices to align with environmental sustainability. One such industry is mining, specifically underground coal mines. While these mines are reaching the end of their economic life, they present an opportunity to leverage their infrastructure for a new purpose: geothermal energy production.

This deliverable is related to Work Package №2 analyses energy harnessing technologies, strengthening technologies, and green hydrogen deployment, and particularly to Task 2.1 “Energy harnessing technologies”. Specific objectives of WP 2 are:

- To select, according to the project’s needs, the most widespread and reliable units on the market for deploying the selected energy harnessing technologies: geothermal, photovoltaic and wind power.
- To select according to the project’s needs the most widespread and reliable units on the market to deploy energy-strengthening technologies: unconventional pumped hydro and batteries.
- According to the project’s needs, select the most widespread and reliable units on the market to deploy green hydrogen.
- To analyse the technical specifications, cost data and operational constraints of the selected alternatives for each renewable energy technology.
- To prepare a detailed assessment of the job creation potential of each alternative per MW installed, per MWh-MW of storage capacity and MW of electrolysers capacity, both for commissioning and operation.

Subtask 2.1.1 Deploying geothermal energy is developed by GIG based on its experience with the development of geothermal energy installations in underground coal mines. This deliverable collect data related to energy harnessing technologies, and additional an attempt was made to collect data regarding geothermal energy units.

2 State of art of geothermal energy deployment

Geothermal energy is the Earth's internal heat accumulated in the rocks and in the waters filling the pores and fissures of the rocks (Polish Geothermal Association 2022). Geothermal energy is heat extracted from deep within the earth in the form of hot water or steam. It is used directly as heating for municipal needs and in agricultural production processes, as well as to generate electricity (using dry steam or high enthalpy brine) (Central Statistical Office 2020). The figure below (Figure 2-1) shows a cross-section through the earth's mantle showing the average temperatures as a function of depth into the earth. It can be seen from the figure that a huge amount of heat is stored in the core and crust of the earth (Central Statistical Office 2020).

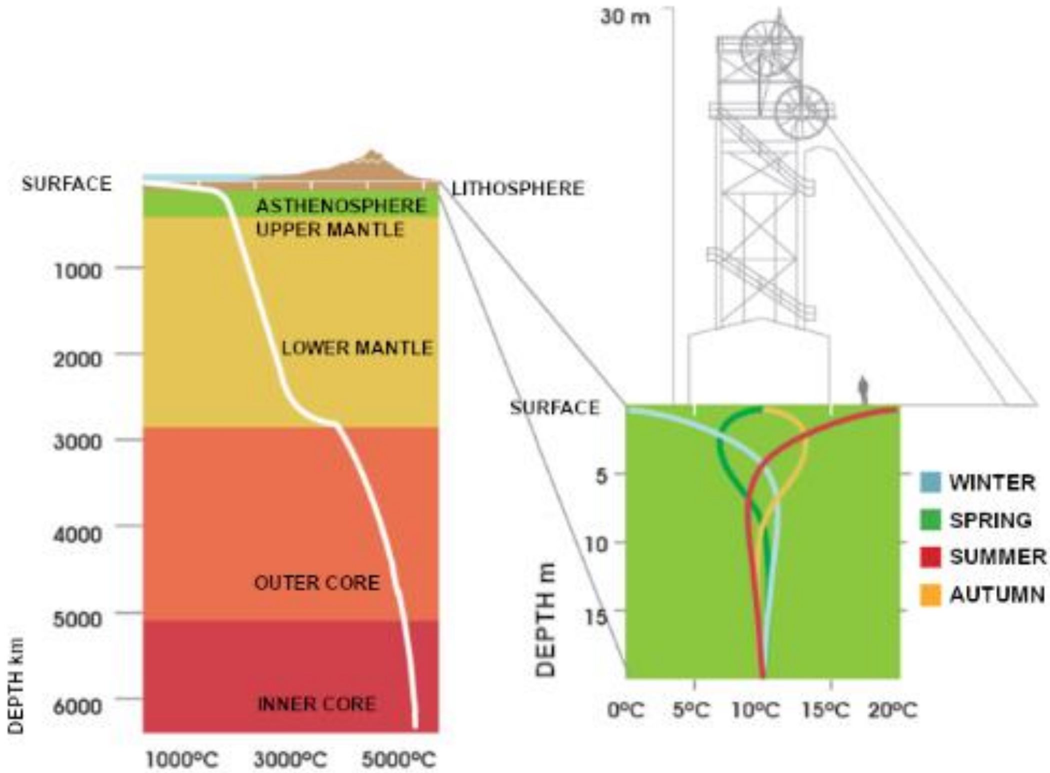


Figure 2-1. Temperatures in the Earth

Source: (Cátedra Hunosa 2023)

The breakdown of radioactive elements takes place in the Earth's nucleus, resulting in a high temperature of up to about 4,500°C. This temperature decreases as it approaches the Earth's surface by 15-80°C/km, depending on rock type and geological conditions. On average, the temperature gradient of the Earth's crust is assumed to be 30°C/km. Temperatures under the Earth's crust reach up to 1,000°C. There is a continuous flow of heat from the Earth's interior to the upper crust and to the Earth's surface (Polish Geothermal Association 2022).

A distinction is made between two forms of geothermal energy, depending on the depth and the heat used: deep geothermal energy and shallow geothermal energy (up to approximately 400 metres). Two deep energy recovery systems are mentioned: petrothermal and hydrothermal (Swiss Seismological Service 2022). Hydrothermal resources refer to water, steam or vapour-water mixtures found in rock fractures, water veins or aquifers and used today. Petrothermal resources are thermal energy stored in dry, heated and porous rocks, and are of prospective importance. In fact, it is possible to drill and exploit petrothermal energy stored at a depth of 5,000m, but it is only practically viable to drill to a depth of 2,000m.

The depth of geothermal water deposits varies considerably from one part of the globe to another, but is most often between 1,000m and 4,500m, or more. These waters are brought to the earth's surface by means of special boreholes. The most widespread use of geothermal waters is in thermal power generation, but there are also great opportunities for its use in other industries. However, geothermal waters reaching temperatures of 120°C and above are cost-effective for electricity generation. The unit cost of geothermal energy is estimated to be about 20% lower than that of thermal energy produced in a conventional heating plant. In thermal energy production, geothermal waters are used as stand-alone heat sources or sources associated with other energy carriers such as conventional or alternative energy (Polish Geothermal Association 2022).

Low-temperature geothermal resources are used to reduce energy demand through use in direct heating of homes, factories, greenhouses or can be used in heat pumps, devices that extract heat from the ground at shallow depths and release it inside homes for heating purposes (Mazovian Energy Agency 2022). High-temperature sources are used in special installations to produce electricity as well as heat.

2.1 Geothermal water parameters

Geothermal energy refers to almost any heat of groundwater or rocks from which the energy can be extracted and deployed. The carriers of geothermal energy are natural formation fluids, usually water, but also oil, natural gas and steam, found in pores and fractures in the rocks that make up the earth's crust, and special fluids such as glycol in vertical and horizontal ground source systems for heating pumps (Mruk 2004).

When considering the use of geothermal energy for the needs of mankind, geothermal deposits in the form of vapour or waters that are suitable for practical use become important. This practical utilisation refers to waters that are at depths that make their economically viable, and technically feasible exploitation possible. At present, it is believed that such practical exploitation, by means of boreholes, is possible for depths of up to 3÷4 km.

With regard to the nature of the energy carrier, we divide geothermal deposits into (Mruk 2004)**:**

- **geothermal vapour deposits** - occurring in areas of modern or recent volcanic activity, where the source of heat that heats the water that turns to vapour is the magma chambers and foci lying shallowly below the surface (1÷3 km). Temperatures in the vapour deposit at a depth of 1 km exceed 150÷200°C;
- **geothermal water deposits** - whose occurrence is characterised by a much greater spread than vapour deposits. The heat that warms geothermal waters comes mainly from the Earth's core, so their occurrence is not limited to volcanic areas. The temperature in vapour deposits at a depth of 1 km is, of course, below 150°C, but these deposits are the easiest to exploit, receive and transmit thermal energy. It is estimated that around 70 countries have geothermal water resources that can be exploited in an economically viable manner.

Europe has significant geothermal resources in both volcanic and sedimentary basin environments. The distribution of geothermal heat fluxes mainly coincides with the figures (Figure 2-3; Figure 2-11 presented in Chapter 2.2), and outlines the main macrotectonic features of the continent.

Waters and other liquids are classified according to the temperature that determines their use. **This classification, based on how the geothermal energy is used, can be presented as follows** (Bujakowski et al. 2010):

1. Geothermal energy for direct use as thermal energy. Media up to 100°C comprising:

- cold fluids - up to 25°C (used as water or glycol in compressor heat pumps with a possible peak source),
- low temperature fluids - from 25÷60°C (used in absorption heat pumps with a possible peak source),
- medium-temperature fluids - from 60÷100°C (used directly at the consumer with a possible peak source).

2. **Geothermal energy for indirect use through electricity generation. Media with temperatures above 100°C comprising:**

- high-temperature fluids - from 100÷150°C (used in binary power plants - producing electricity and heat),
- very high-temperature fluids - above 150°C (used in conventional geothermal power plants).

This classification covers virtually all existing fluids occurring under natural conditions and artificially introduced into the ground, below the ground surface (regardless of their temperature). It is a proposal for an extended and modified Sokolowski's (Sokołowski 1996) classification, according to which low enthalpy waters are divided into:

- cold: up to 20°C
- warm: 20÷35°C
- hot: 35÷80°C
- very hot: 80÷100°C
- superheated: 100÷130°C

The above classifications are particularly applicable to geothermal waters commonly present in Polish hydrogeothermal reservoirs.

Other classifications used are of little relevance or applicability for these conditions, e.g.: the Rowley division divides reservoir waters into four classes (Kapuściński et al. 1997):

- Class I: <100°C
- Class II: 100÷150°C
- Class III: 150÷250°C
- Class IV: >250°C

Class I includes practically the vast majority of geothermal waters recognised in Poland (Bujakowski 2015). With regard to the temperature of the energy source, a conventional distinction is made between high-temperature geothermal (above 150°C) and low-temperature geothermal (below 150°C). According to this division, there are no geological conditions in Poland up to a depth of 5 km. Such conditions may occur in areas of active volcanic activity. In Europe, these include Iceland, Sicily and the Aeolian Islands (Ziemia na rozdrożu 2017).

2.2 Characteristics of geothermal conditions

2.2.1 Worldwide geothermal conditions

The first geothermal power plant was established in 1904 in Larderello, Italy. Since the 1970s, geothermal energy has been used on a much larger scale since the fuel crisis.

Geothermal power plants are currently operating in about 88 countries, including Iceland, New Zealand, the Philippines, the US, Japan and Indonesia, as well as Poland (Huttrer 2021). A road map of geothermal energy development is shown in the figure below (Figure 2-2). Direct use of geothermal energy in 88 countries represents an increase from 82 in 2015 and 28 reported in 1995 (Lund and Toth 2021). Geothermal well operations began in 1958 with the commissioning of a 50 MW power plant in New Zealand. Most of the geothermal wells in operation today date back to 1970s and his 1980s, when the development of geological exploration methods and drilling techniques reduced capital costs and the energy crisis boosted electricity supplies. The price of conventional fuel.

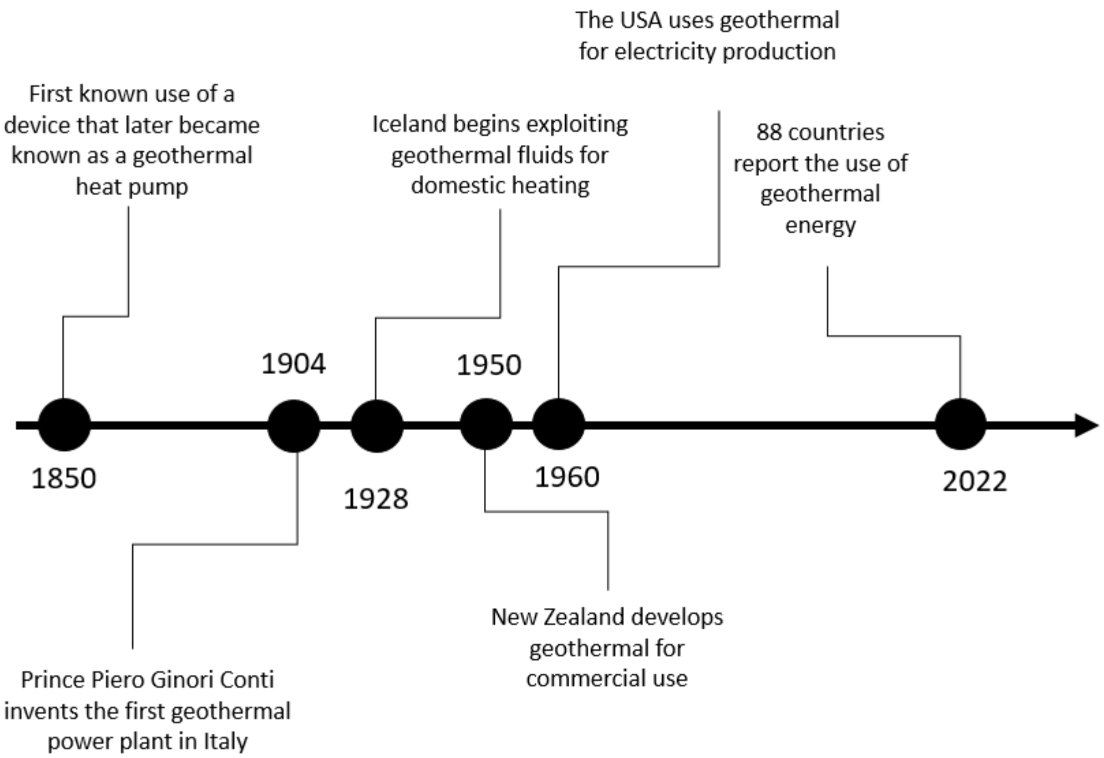


Figure 2-2. Roadmap for the development of geothermal energy worldwide

Source: based on (Lund and Toth 2021; International Geothermal Association 2022)

Most geothermal resources are located near the boundaries of the Earth's tectonic plates. The most active geothermal resources are typically found along the major tectonic plate boundaries where most volcanoes are found. One of the most active geothermal areas in the world is the so-called Ring of Fire that circles the Pacific Ocean. As magma approaches the surface, it heats groundwater trapped in porous rocks and water flowing along jagged rock faces and faults. The hydrothermal function shares her two common components: water (hydraulic) and heat (thermal) (U.S. Energy Information Administration 2022).

The figure below (Figure 2-3) shows a global map of the suitability of areas for the installation of geothermal power plants adapted from a publication (Coro and Trumpy 2020). The authors performed geospatial and artificial intelligence analysis, as well as the selection and processing of dozens of geophysical parameters potentially related to global geothermal power plants. They then presented the potential of areas for installing high-efficiency power plants (ThinkGeoEnergy 2020a).

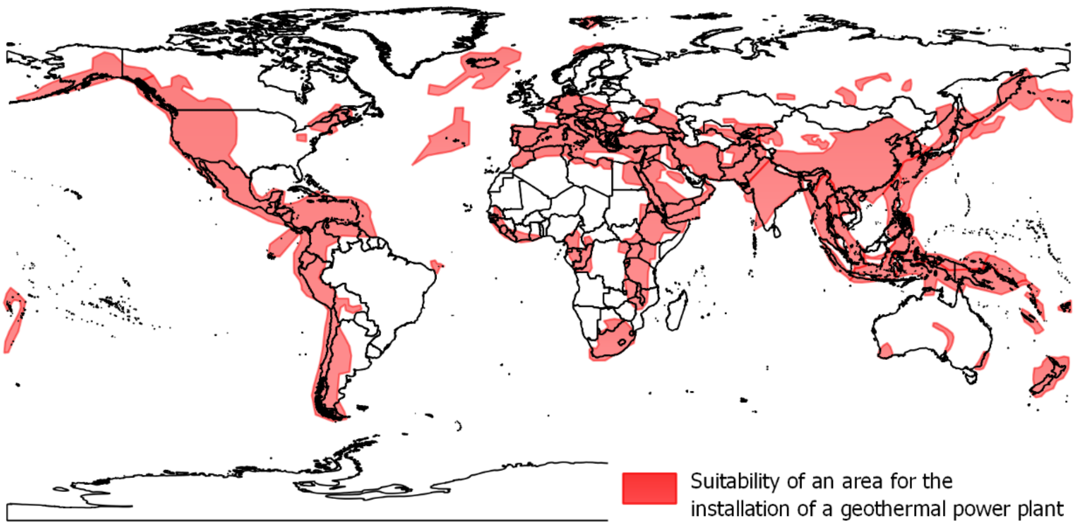


Figure 2-3. Global geothermal map

Source: (Wolfson 2012; Coro and Trumpy 2020; Energy Education 2022)

A total of about 819,000 GWh of electricity was generated from geothermal energy between 2010 and 2020. Since 2010, the amount of electricity generated has been steadily increasing. Between 2010 and 2020, this value increased by more than 20% (Figure 2-4).

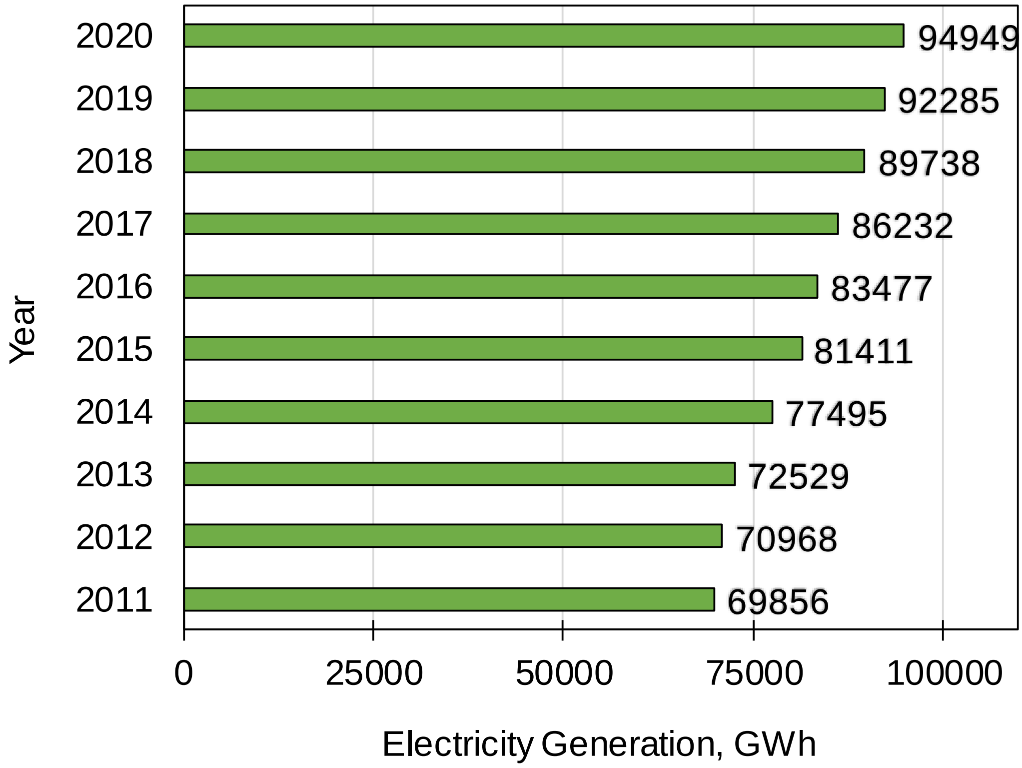


Figure 2-4. Electricity Generation Trends in 2011-2020

Source: based on (IRENA 2022)

Figure 2-5 shows the 10 countries with the largest generation capacity (MW) by the end of 2021. These countries include: the United States, Indonesia, Philippines, Turkey, New Zealand, Mexico, Kenya, Italy, Iceland, and Japan. The rest of the world has 1,097 MW of installed capacity, and by the end of 2022, 16,127 MW of geothermal installed capacity. Global geothermal power capacity increased by 286 MW compared to 2021. Eight countries have added 16 of plants to increase geothermal power capacity. The largest increases were recorded in Kenya (83 MW), Indonesia (80 MW) and the United States (72 MW) (ThinkGeoEnergy 2023).

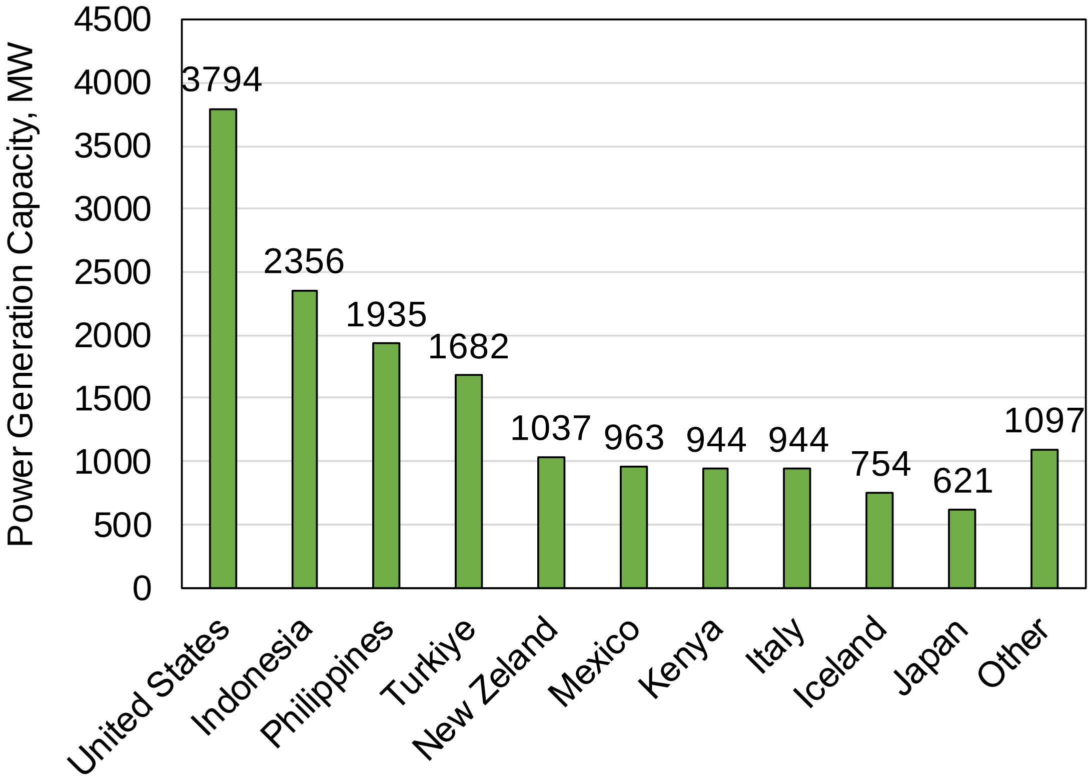


Figure 2-5. Power generation capacity in top 10 geothermal countries in 2022

Source: based on (ThinkGeoEnergy 2023)

2.2.2 European geothermal conditions

Continental Europe is characterized by low to moderate heat flux values (30-40 mW/m^2 to 60-80 mW/m^2). Relatively high values of 80-100 mW/m^2 are found in seismically and tectonically active regions of southern Europe (Kępińska 2008). Due to thermal and geological conditions, Europe has mainly low-enthalpy resources. They are mainly found in sedimentary layers. However, in some regions such as Iceland, Italy, Greece, Portugal (Azores) and Spain (Canary Islands), high-enthalpy resources have been found even at accessible depths. The main exploited geothermal fields are located in the Larderello region (Italy); the Paris Basin (France); the Pannonian Basin (Hungary, Serbia, Slovakia, Slovenia, Romania); several sectors of the European Lowlands (Germany, Poland); the Paleogene Carpathian systems (Poland, Slovakia); and other Alpine and older structures of Southern Europe (Bulgaria, Romania, Turkey) (Antics and Sanner 2007; Kępińska 2008).

Figure 2-6 shows a map of areas with geothermal heat potential in Europe:

a) Temperature at 2000m depth greater than 90°C
b) Temperature at 1000m depth greater than 50°C
c) Likely geothermal hydrothermal resources areas
d) Heat flow density greater than 90 mW/m^2

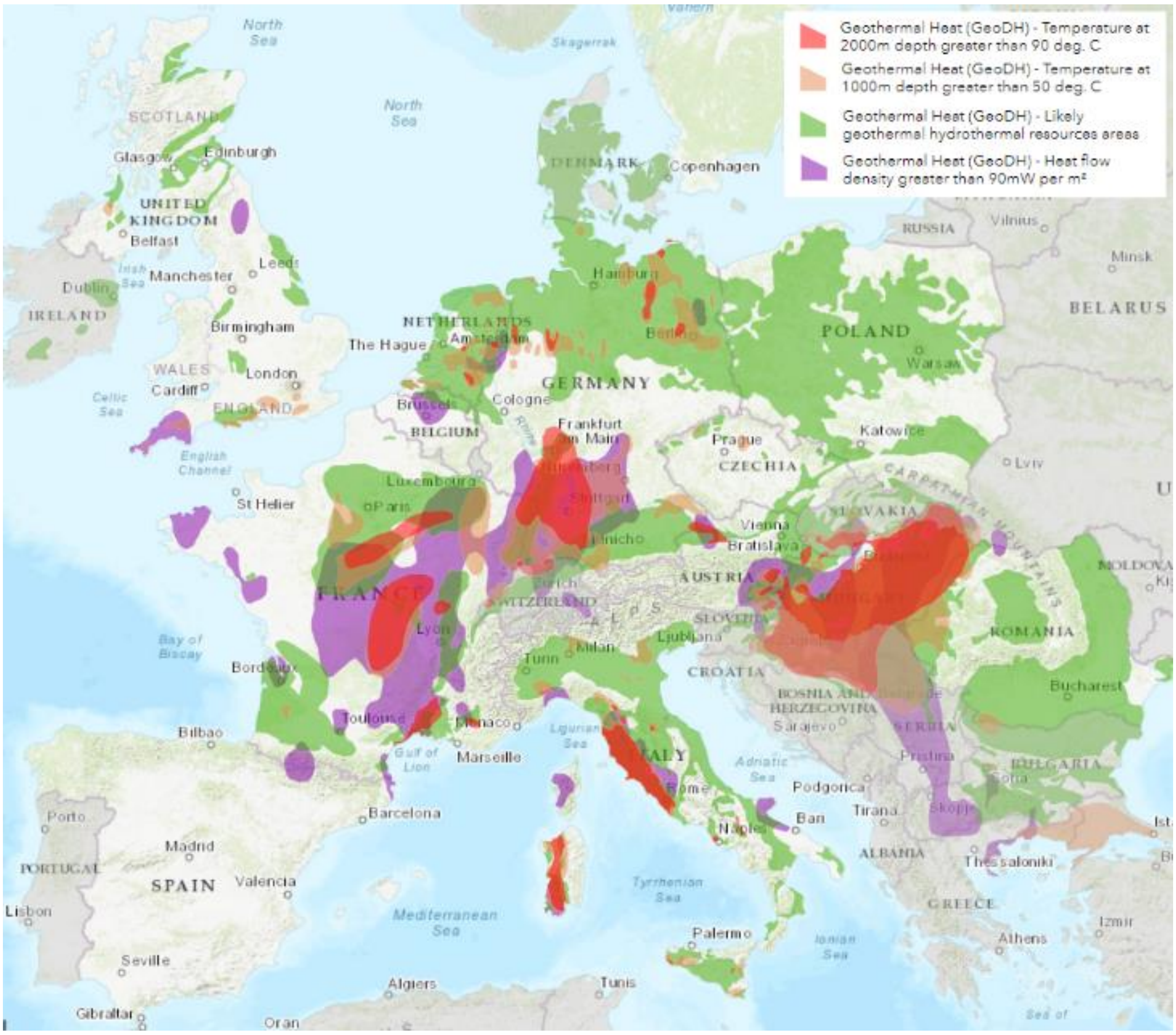


Figure 2-6. Pan-European Thermal Atlas

Source: based on (PETA 2023)

The geothermal energy situation varies in each country, depending on which geothermal technology best suits the available natural resources. They range from energy generation from high-enthalpy resources (Iceland, Italy, Greece, Turkey) to direct utilization of hydrothermal resources in sedimentary basins (France, Germany, Poland, Italy, Hungary, Romania, etc.). Shallow geothermal energy is available everywhere and is mainly used in geothermal heat pump systems. Over 90% of geothermal district heating is networked, emphasizing the efficient use of geothermal energy. These data indicate a strong interest in geothermal district heating in Europe, with dynamics estimated at around 7% per year in terms of installed capacity growth (Garabetian 2020; Garabetian et al. 2021; Hajto 2021; Garabetian et al. 2022).

In 2019, 34 European countries used geothermal energy for district heating. The rapid development of geothermal district heating has been recorded in Europe: France, Germany and the Netherlands. European leaders also include: Poland, Hungary, Italy, Denmark and Switzerland. These countries have shown great interest in investing in geothermal district heating in recent years. The installed capacity of district heating in EU countries in 2019 was estimated at around 2 GWt. The total heat capacity of district heating systems installed in 25 European countries in 2020 was around 6 GWt (5.5 GWt in 2019) (Garabetian 2020; Garabetian et al. 2021; Hajto 2021; Garabetian et al. 2022). According to a European Geothermal Council (EGEC) report published in 2021, 350 geothermal district heating systems were in operation in Europe in 2020 (327 in 2019). It is also significant that 232 district heating systems were already in various stages of implementation.

2.3 Characteristics of geothermal conditions in Poland

Poland is one of the countries with rich resources of low and medium enthalpy geothermal waters. These waters occur in pore spaces or fracture spaces in sedimentary rocks which form part of the earth's crust (Nowak et al. 2000). In Poland, the waters filling the porous rocks are generally found at depths of between 0.7 km and 3 km and have a temperature of between 20 and 100°C. The most beneficial use of geothermal waters appears to be within the Podhale basin, as well as the Grudziądz-Warsaw and Szczecin districts. It is very important to note that in Poland regions with optimal geothermal conditions largely coincide with areas with high density of urban and rural agglomerations, heavily industrialised areas and areas of intensive farming and vegetable production. Cities such as Warsaw, Poznań, Szczecin, Łódź, Toruń and Płock are located in areas rich in geothermal water energy (Mazovian Energy Agency 2022).

2.3.1 Conditions for the use of geothermal energy in Poland

Poland is characterised by variable geothermal parameters due to variable tectonic structure of the Earth's interior. The variability of these parameters is due to the occurrence of several tectonic zones bordering on each other, i.e.: Precambrian East European Platform, Palaeozoic Platform and Carpathian Oregon (Plewa 1994).

The heat flux, depending on the geotectonic formation, ranges from 2.38 to 90 mW/m^2. The thermal gradient is approximately 1.96-3.55°C/100m.

Poland has low-temperature geothermal resources that can be used for various purposes in many regions of the country (Polish Geothermal Society 2022). Low-temperature systems with geothermal water deposits are common and occur over much larger areas compared to high-temperature systems. The heat source is mainly the Earth's natural heat flow. In Poland, there are natural sedimentary-structure basins filled with geothermal waters with temperatures ranging from 20 to 80-90°C, and in extreme cases over 100°C. These waters can be used for heating purposes in individual and communal buildings, for domestic hot water preparation, for heating outbuildings, greenhouses, in-ground cultivation, as well as for balneotherapeutic and recreational purposes.

Geothermal vapour deposits (high-temperature, high-enthalpy deposits), on the other hand, occur in areas of modern or recent volcanic or tectonic activity. The direct source of heat is magma located shallowly in the Earth's crust or spewed out as lava during volcanic eruptions. Poland lies outside the zones of modern tectonic and volcanic activity, so extracting steam deposits from great depths to produce electricity is not economically viable at today's technological stage.

The technical potential of geothermal energy is estimated at 1512 PJ/year, which is about 30% of the national heat demand. The studies and analyses carried out so far show unequivocally that there are at least 6600 km^2 of geothermal waters with temperatures of 27-125°C in the area of Poland. These resources are quite evenly distributed over a large part of the Polish territory in separate geothermal basins, sub-basins and geothermal districts.

There are about 30 geothermal-oil-gas-bearing provinces, covering an area of more than 10 million km^2 in Europe. Of this, 32% of Europe's area is occupied by the Central European Province (1.6 million km^2), which contains the following geothermal basins: Old Paleozoic, Devonian-Carboniferous, Permian, Triassic, Jurassic, Cretaceous and Cenozoic (the most abundant in Europe). The waters occurring there have different temperatures and mineralisation. In Poland, these temperatures range from 20-180°C. Over 220,000 km^2 of the Polish territory is covered by sedimentary basins of the Central European Province containing geothermal waters in the following reservoirs (basins): Cambrian, Devonian-Carboniferous, Lower Permian, Zechstein, Triassic, Jurassic and Cretaceous.

Geothermal resources in Poland are mainly linked to the occurrence of thermal waters, which are found in a large part of the Polish Lowlands (about 87% of the country's area) (Sowiżdżał 2018; Ministry of Climate and Environment) as well as in the Carpathians and their foothills and in the Sudetes (Górecki 1995; Sowiżdżał 2018).

Particularly favourable conditions for the use of geothermal energy are found in the area of the Polish Trough, where geothermal energy is currently being used in several places (for heating, bathing and balneotherapy) and several other projects are in progress at various stages of advancement. In many areas of the Polish Lowlands the use of geothermal waters with relatively high temperatures (even above 100°C) and high capacities (even 300 m^3/h) (Sowiżdżał 2010; Miecznik et al. 2015) is feasible. A problem in some regions may be corrosion of the geothermal installation associated with high values of dissolved substances, sometimes even 300 g/dm^3 (especially in the zone of salt diapirs). The reservoirs are mainly composed of sandstone, locally also of carbonates. The main geothermal water resources in the Polish Lowlands are located in Mesozoic groundwater horizons. Paleozoic aquifers are characterised by smaller values of resources (Hajto et al. 2005; Hajto and Górecki 2010a; Hajto and Górecki 2010b).

Geothermal waters are mainly accumulated in Lower Jurassic and Lower Cretaceous formations, but significant geothermal energy resources are also found in Upper Jurassic, Middle Jurassic, Upper Triassic and Lower Triassic formations. The most interesting and promising areas are found in the Warsaw Trough, the Mogilno-Łódź Trough (in central Poland) and the Szczecin Trough (in the north-western part of the Polish Lowlands) (Figure 2-7). The use of thermal waters for heating purposes in individual voivodeships and towns in central Poland should be based primarily on the resources of the Lower Jurassic aquifer.

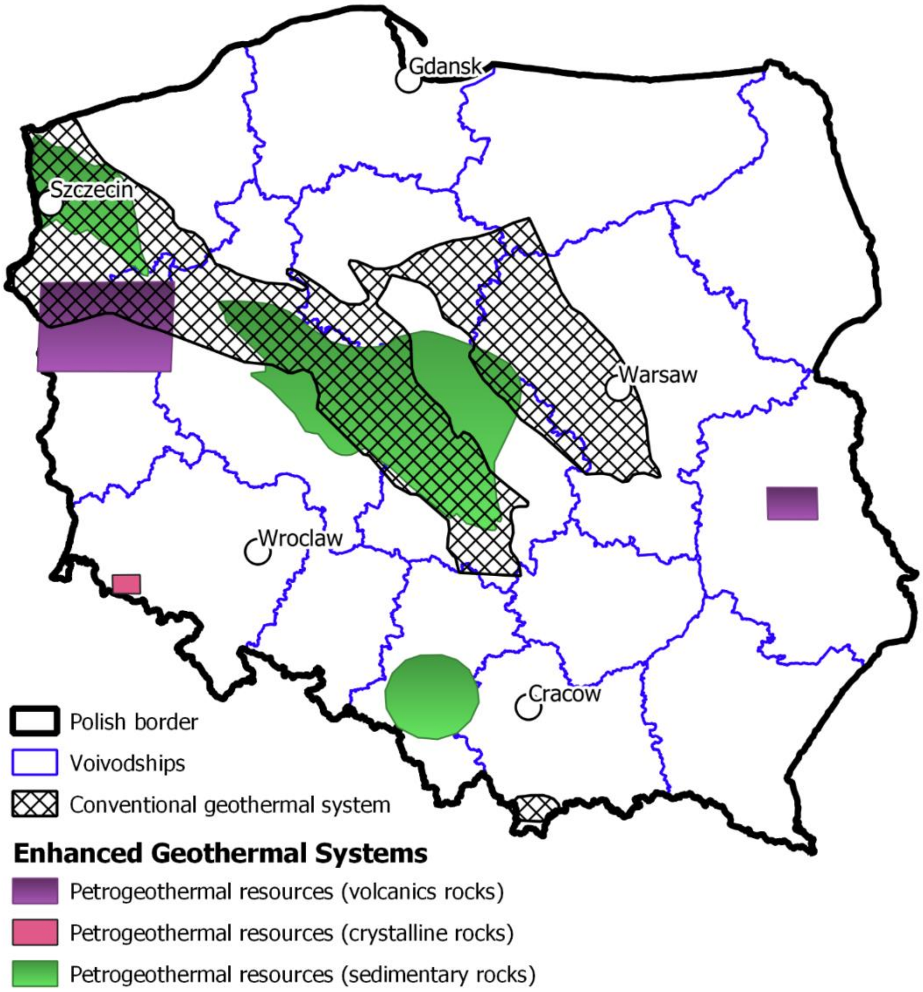


Figure 2-7. Location of the most prospective area for geothermal energy utilization in Poland

Source: based on (Sowiżdżał 2018)

2.3.2 Current use of geothermal resources in Poland

Geothermal energy accumulated in the Earth's subsurface layer can be used throughout the country and is currently the most popular, least invasive and cheapest method of obtaining geothermal energy. Ground source heat pump installations are used for this purpose. There are several geothermal heat plants in Poland, among which are (Figure 2-8) (Polish Geothermal Society 2017; Mazovian Energy Agency 2022):

- Pyrzyce (maximum temperature 61°C, total capacity 48 MW, geothermal capacity 14.8 MW);
- Mszczonów (maximum temperature 41°C, total capacity 10.2 MW, geothermal capacity 2.7 MW);
- Stargard (maximum temperature 78°C, total capacity 10, geothermal capacity 10 MW).

The largest geothermal heat plant in Poland is the "Geotermia Podhalańska" (ESOLEO 2022). It is located on the edge of the Podhalanska Basin, one of the most important geothermal areas in Poland. In Zakopane, at a depth of 1,000m, the thermal waters have a temperature of approximately 26ºC, while at a depth of less than 2,000m in the Bańska Niżna area, the water temperature is max. 86°C. The total installed capacity of the Podhale Geothermal Plant is 80.8 MW, of which the power from geothermal is 40.7 MW. In addition to heating applications, geothermal water can also be used for therapeutic purposes (e.g., spa in Cieplice, Lądek-Zdrój, Konstancin, Ciechocinek). As for the use of geothermal for electricity production, the temperature of geothermal deposits in Poland is 45-75°C, so it cannot be used for electricity production.

Figure 2-8. Location of the most prospective area for geothermal energy utilization in Poland

2.4 Characteristics of geothermal conditions in Spain

Spain stands out for its potential for low- and medium-enthalpy resources in different regions of the country. Geothermal applications in Spain focus on the heating and cooling sector. There is currently no geothermal electricity production in Spain (Colmenar-Santos et al. 2016; Blázquez et al. 2022). The central region of the country is regarded as a promising area for new applications of geothermal energy. Spain, with a potential geothermal energy production of 610 GWt, is therefore a promising EU 28 country for geothermal direct heating and binary cycle power generation (Colmenar-Santos et al. 2016).

Although Spain has potential for different types of geothermal resources (Iñigo et al. 2019):

- Very low temperature geothermal resources (T < 30°C)
- Low temperature geothermal resources (30°C < T < 100°C)
- Medium temperature geothermal resources (100°C < T < 150°C)
- High temperature geothermal resources (T > 150°C)

most of the geothermal resources assessed have low temperatures (50-90°C). The only area where high temperatures are used is the volcanic archipelago of the Canary Islands (Cátedra Hunosa 2023). Deep drilling was carried out to assess the geothermal potential of the more important areas. These major regions are located in the southeast, northeast, northwest and central of the Iberian Peninsula. Other less important areas of Albacete, Lleida, Leon, Burgos and Mallorca were also investigated (Sanchez-Guzman 2005).

Very low-temperature resources are used in closed-loop geothermal systems and open-loop geothermal systems. The formations used in closed-loop geothermal systems occupy the entire periphery as well as the central mountain ranges. Unconsolidated formations occupy extensive areas on both plateaus and in the eastern part of the country. The formations used in open-loop geothermal systems are highly transmissive (> 10^3 m^2/d), supplying open geothermal systems of several hundred kW, just a few meters of drawdown (Sanchez-Guzman 2005; Iñigo et al. 2019).

Low-temperature geothermal resources are found in large sedimentary basins and peripheral mountain ranges and in the Iberian Hercynian Massif. Geothermal energy in low-temperature formations in the first group has been estimated at 15,126 x 10^5 (GWh), while in the second group it is estimated at 736 x 10^5 GWh. The first group includes the Duero, Tajo-ManchaJúcar, Guadalquivir, Ebro and North Cantabrian basins. The second group includes the Bética ranges, the Pyrenees, the Catalan Coastal Ranges and the Iberian Hercynian Massif located in the western part of the Iberian Peninsula (Sanchez-Guzman 2005; Iñigo et al. 2019).

Intermediate-temperature resources describe certain geological basins, which typically contain permeable formations at depths greater than 3.5 km. At these depths, the temperature of the water contained in the permeable formations exceeds 100°C. These include areas located in the Cantabrian, Pre-Pyrenean, Tagus, Guadalquivir and Betic Range basins. The gross potential of these resources in terms of recoverable stored heat in unexplored areas is 541 x 10^5 GWh (Sanchez-Guzman 2005; Iñigo et al. 2019).

The occurrence of high-temperature geothermal resources is related to active volcanism and have only been confirmed in the Canary Islands (Tenerife). The potential existence of geothermal storage zones has been estimated at depths of 2.5 to 3.5 km and temperatures in the range of 200-220°C. Geothermal energy in the form of recoverable heat stored in such a zone has been estimated at 1.82 x 10^5 GWh (Sanchez-Guzman 2005; Iñigo et al. 2019).

2.5 Characteristics of geothermal conditions in Slovenia

The geological and tectonic position of Slovenia is divided into several tectonic units with different hydrogeological characteristics and geothermal conditions. The geothermal and hydrogeological characteristics of the north-east indicate potential geothermal resources, technically feasible for electricity generation, but only with limitations.

The thermal capacity currently installed for the direct use of thermal water energy in Slovenia is approximately 62.06 MWt. Geothermal energy in Slovenia is currently estimated to provide 1,609.48 TJ/year (447.08 GWh/year) of thermal energy for direct use of heat and geothermal ground source heat pumps. The installed capacity is 262.94MWt. Of these values, the direct use of thermal water is 600.03 TJ/yr (62.06MWt; 166.68 GWh/yr) and the remaining 200.88MWt and 1009.45 TJ/yr (280.40 GWh/yr) are GSHP units. The main type of use is currently geothermal ground source heat pumps (63% in 2019), followed by use in resorts and spas for bathing and swimming and space heating (Rajver et al. 2016; Rajver et al. 2019; Rajver et al. 2020).

Natural vapour reservoirs at relatively shallow depths have not been detected in Slovenia. North-eastern Slovenia has been intensively studied in the last decade within the framework of European projects. The area of the most geothermally used sedimentary basin - the Mura-Zala area - has been studied in detail. The Mura-Zala Basin is filled with marine and freshwater Neogene sediments. The Mura-Zala area is characterised by an elevated surface heat flow density (HFD) of more than 0.1 W/m^2, with temperatures >80°C at a depth of 2 km, and maximum temperatures can reach 150°C at depths of 2.5 to 3 km (Rajver et al. 2019; Rajver et al. 2020). Inactive and new potential wells exhibit temperatures between 20 and 72 °C and have a combined maximum capacity of 281 kg/s (24 MWt).

The possible exploitation of medium to high enthalpy geothermal resources is concentrated in the area south of the Ljutomer-Balaton fault, where the Pre-Neogene bedrock consists of clastic and carbonate rocks, which should be more fractured in places. (Rajver et al. 2016; Rajver et al. 2019). Prospective geothermal reservoirs can occur as hydrothermal reservoirs at depths of less than 3 km and at temperatures well above 80°C, hydrothermal reservoirs at depths of 3 to 6 km and at temperatures above 150°C, induced geothermal systems at depths of at least 4 km in poorly permeable metamorphic or magmatic rocks (Rajver et al. 2016).

In the south-eastern part of the Pomurje area (north-east of Slovenia), high-temperature resources are not confirmed, but hypothetically expected in deeper fault zones in the Pre-Neogene basement. South of the Ljutomer-Balaton fault, the Pre-Neogene basement consists of clastic and carbonate rocks, which should be more fractured in places to exploit medium to high enthalpy geothermal resources (Lapanje et al. 2010; Rman et al. 2018; Rajver et al. 2019; Rajver et al. 2020; Ministry of Infrastructure 2021).

2.6 Technologies for geothermal energy recovery

The modern use of geothermal energy is basically realised in two main directions (Bujakowski 2015):

- indirect exploitation, involving the generation of electricity from hot vapours and waters whose temperature exceeds 150°C;
- direct exploitation, involving the extraction of heat from geothermal fluids (mainly water) and directing it to users. This direction is considered to relate to the use of waters with temperatures lower than 150°C. Within this area, a direction related to the use of heat pumps is distinguished, managing low-temperature energy sources with temperatures below 20°C from ground and fluids occurring at shallow depths.

Geothermal is therefore divided into two types (Swiss Seismological Service 2022):

- Shallow - up to 1 km underground
- Deep - up to 8÷10 km underground

Shallow geothermal includes geothermal probes or geothermal loop systems and the use of groundwater heat, as well as energy piles and geostructures. Shallow geothermal penetrates no more than 400m into the subsurface and utilises layers with temperatures between 8°C and 20°C. Geothermal probes are most commonly used to operate heat pumps, which extract heat from the ground, air or water. Shallow geothermal energy via geothermal probes can be used to heat buildings and prepare hot water, with these types of pumps additionally requiring electricity. A heat pump works on the principle of an inverted refrigerator, also needing an energy supply. Provided that a depth of around 200 metres is not exceeded, geothermal probes can also be used to cool buildings in summer. Induced earthquakes are not a problem in shallow geothermal due to the shallow depth and generally closed systems.

Deep geothermal energy reaches rock structures at least 400m into the ground and, depending on the temperatures in the subsurface, a variety of uses are possible. Temperatures of between 20°C and 70°C are found in aquifers (layers of rock or soil that can absorb and retain water) at depths of between 400m and 2 000m. The thermal water found at these depths is not only suitable for bathing, but also for heat production. Systems using water drained from the tunnels can have similar applications.

There are two systems for energy recovery at deep depths (Swiss Seismological Service 2022):

- **petrothermal**

  In petrothermal systems, water is injected into the subsurface under high pressure over several days, usually into crystalline bedrock. The aim here is to reactivate the numerous fault systems in the future reservoir. Through micro-shocks of varying intensities, the permeability of the rocks is permanently increased for water circulation, leading to the formation of an extended geothermal system (EGS). This system serves as an underground reservoir in which fluid circulates and is heated. The earthquakes associated with this process are closely monitored. This is done both to ensure optimal control of induced seismicity and to draw conclusions about the state and extent of the ever-growing reservoir. An artificial circulation is then created through a second well, which pumps heated fluid to the surface using geothermal energy. The fluid circulates in an only partially closed circuit, with reservoir pressure and flow controlled by balanced supply and production rates. The procedure of increasing permeability (stimulation) triggers a series of increasingly smaller earthquakes. In this respect, earthquakes are not an unwanted side effect, but a tool to manipulate the ground. Many of these earthquakes are so small that they are not noticeable to the public. The art of pacing is to create the fault system in such a way that as much volume as possible can flow evenly, without creating the 'shortcuts' that can occur when water flows too quickly from one hole to another before it is sufficiently heated. At the same time, it is necessary to avoid large earthquakes that cause damage. For a commercial petrothermal system to be economically attractive, it should deliver about 50 to 200 litres of water per second at a temperature of 150°C to 180°C. In addition, the water temperature should fall only slowly over a lifetime of about 30 years.

- **hydrothermal**

  Hydrothermal systems use existing aquifers in the sediments to pump naturally occurring hot water to the surface. Cost-effective power generation requires aquifers with hot water temperatures of 100°C or higher (hot springs generally do not reach these temperatures). Once the heat has been extracted, the cooled water is sometimes pumped back into the ground through a second borehole. Assuming that there is sufficient water flow at depth, only minimal stimulation of the rock is generally necessary, and therefore no micro-quakes need to occur, as is the case with petrothermal systems. Hydrothermal systems depend on existing aquifers with sufficient integrity and sufficiently high temperatures and can therefore only be realised in specific locations. For this reason, extensive seismic surveys are often a prerequisite for determining a suitable location.

A summary of geothermal technologies depending on the reservoir temperature is shown in the figures below (Figure 2-9).

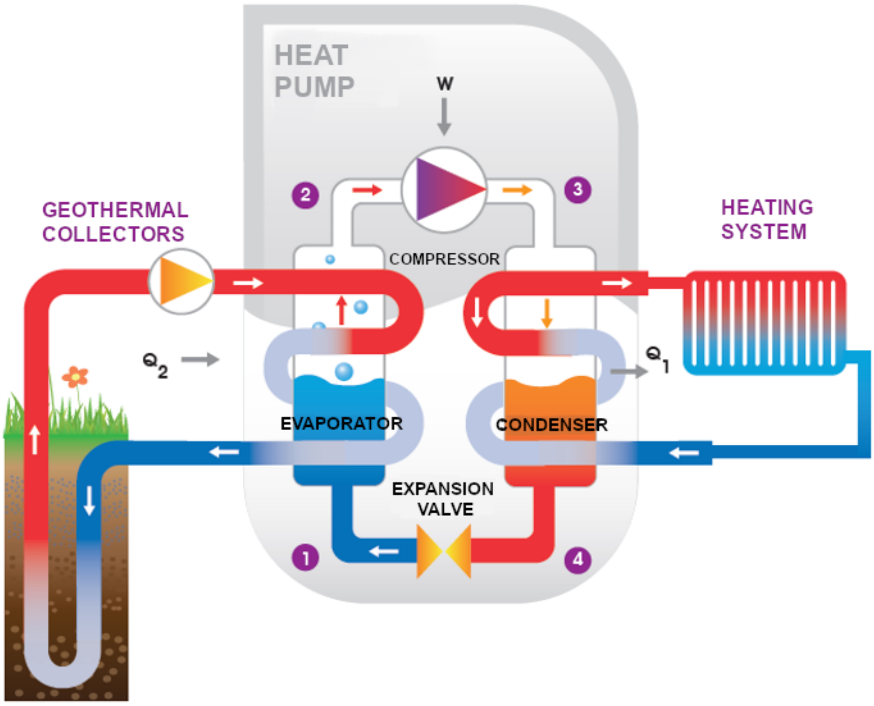


Figure 2-9. Geothermal energy installation – very low temperature reservoir

Source: (Cátedra Hunosa 2023)

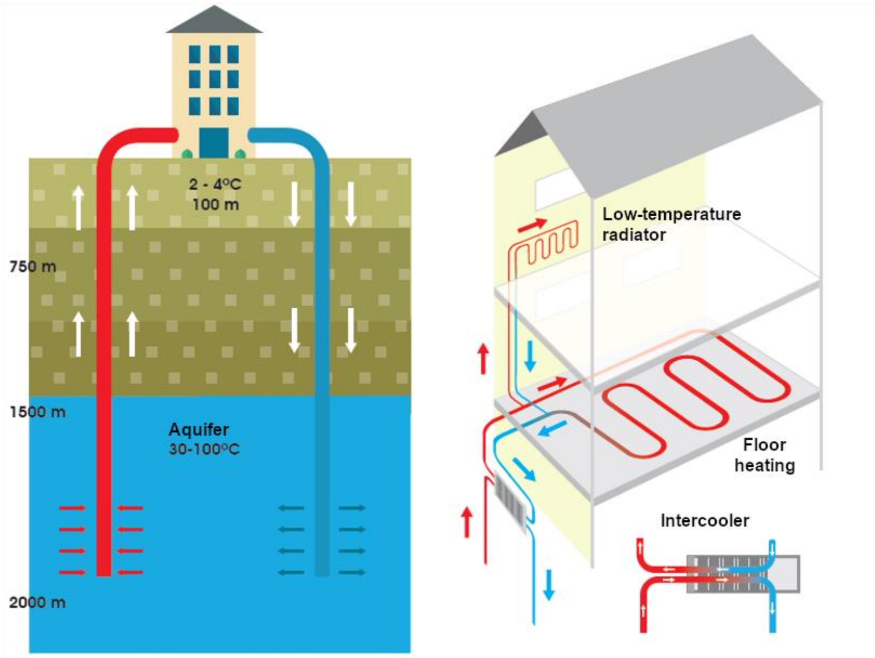


Figure 2-10. Geothermal energy installation – low temperature reservoir

Source: (Cátedra Hunosa 2023)

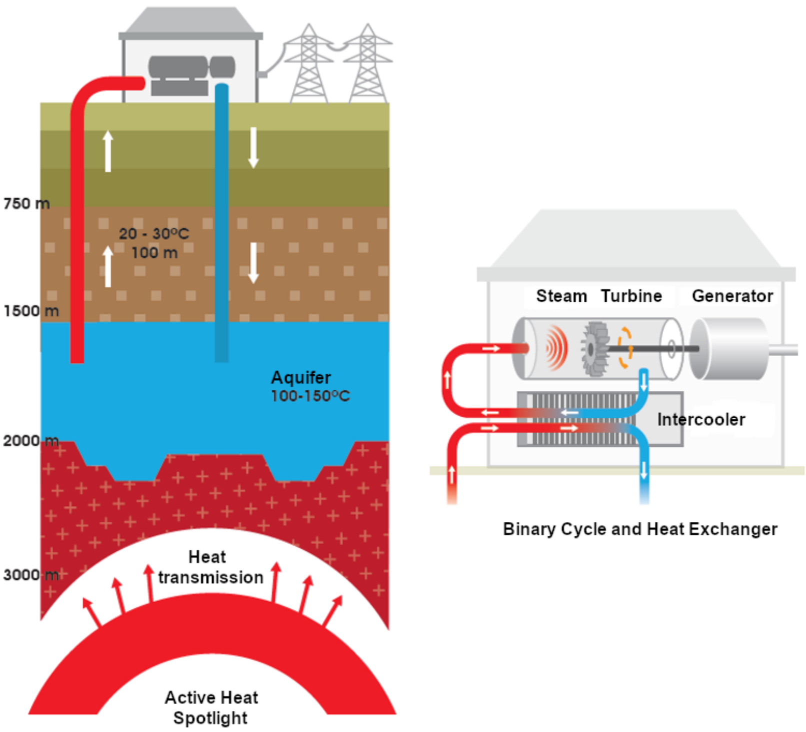


Figure 2-11. Geothermal energy installation – medium temperature reservoir

Source: (Cátedra Hunosa 2023)

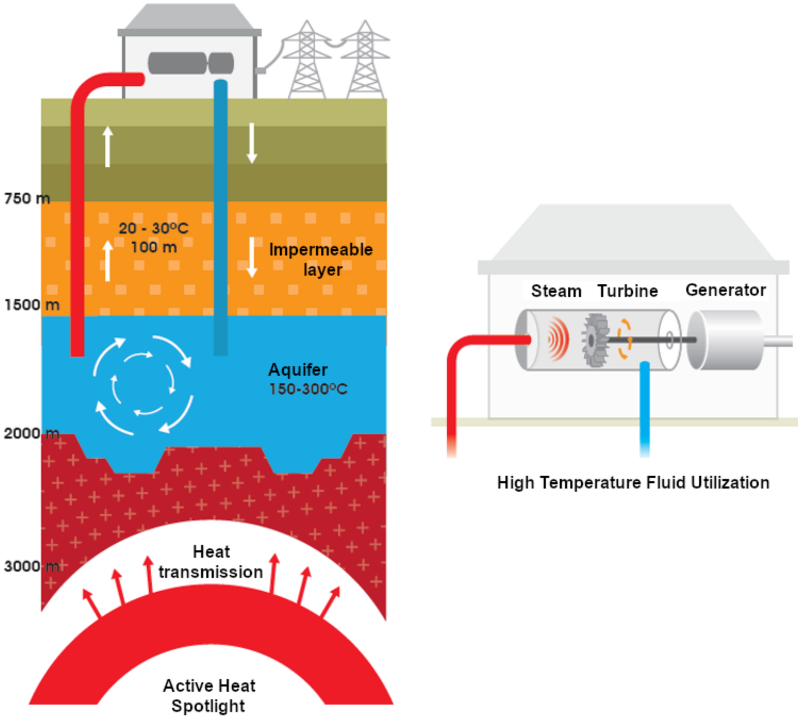


Figure 2-12. Geothermal energy installation – high temperature reservoir

Source: (Cátedra Hunosa 2023)

There are two main types of geothermal resource:

- convective
- hydrothermal

The first is where there is natural hot water or steam that can be brought to the surface. The second is where hot rocks are present. At 350°C, 'direct heating' is possible. At water temperatures above 150°C, a 'flash steam' power plant is justified. If the water temperature is between 100°C and 150°C, then 'binary cycle' power plants can be operated. When the groundwater temperature is below 100°C, geothermal heat pumps (GHPs) are used to heat buildings. In winter, geothermal heat pumps can extract heat from groundwater in a well outside the building and transfer it to heat the air inside the house. In summer, reverse the flow and the same heat pumps can cool the building. In recent years, many new technological solutions have become widespread and have found their way into energy production or use. These include absorption and compressor heat pumps, cogeneration units (so-called heat and power units) for gas, biogas and biomass, current turbines, biomass boilers, low-temperature heating systems, underfloor and wall heating, and many other almost futuristic solutions, such as the production of electricity from ground heat. Many of these solutions have already found their way into geothermal energy development.

Of the different types of geothermal cycles used to generate electricity, the most commonly used in geothermal power plants are (Madhawa Hettiarachchi et al. 2007; Venegas et al. 2015; Shokati et al. 2015): the direct dry steam cycle, the single or double flash cycle and the binary and Kalina cycles.

2.6.1 Direct dry steam plants

Dry steam power plants use steam directly from geothermal reservoirs (Figure 2-13). From these power plants, essentially the only emission is excess steam. The direct dry steam cycle uses a working fluid in the saturated or superheated steam phase that is directly generated in the Earth's interior. After flowing into a separator that removes particulates, the working fluid is used to directly drive the turbine and generate electricity. After leaving the turbine, the working fluid undergoes a cooling phase inside the condenser or is directly discharged to the atmosphere (Prananto et al. 2018). In single and double flash cycles, the working fluid is a saturated liquid at 180-200°C sourced from the Earth's interior. The working fluid enters a low-pressure flasher for evaporation and brine separation. The water vapour resulting from the evaporation process is then separated and directed to the turbine (Yari 2010). The third type of cycle - the binary cycle - uses the lowest temperature of the working fluid. Instead of expanding directly in the turbine, the working fluid enters the heat exchanger and transfers its heat to evaporate a secondary working fluid with a lower boiling point than water (Franco and Villani 2009; Bertani 2012; Hanbury and Vasquez 2018).

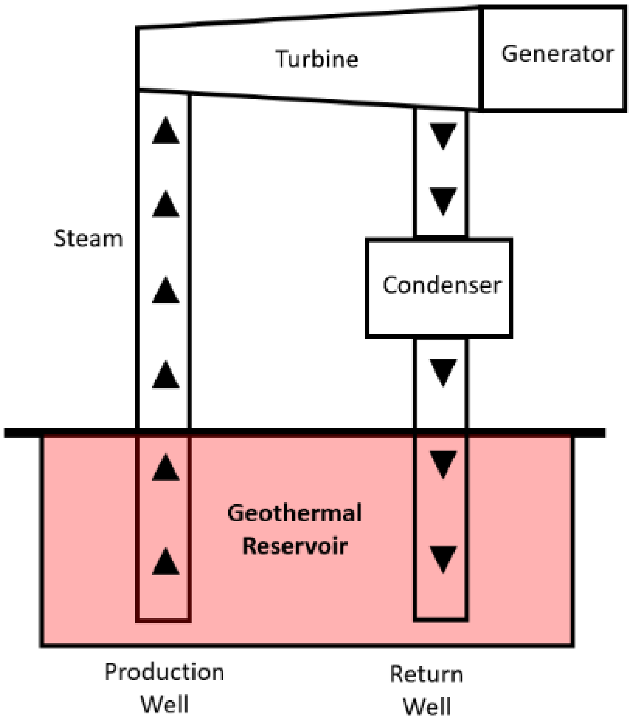


Figure 2-13. Geothermal "direct dry steam" power plant

Source: based on (Igwe 2021)

Because it requires less plant apparatus, direct dry steam is much simpler and cheaper than flash and binary cycles (Hanbury and Vasquez 2018). In addition, the working fluid in a dry steam cycle has a higher enthalpy than both fluids in a flash or binary cycle, so a higher output can be achieved on a single plant unit. In addition, the mass flow rate of the steam has a direct impact on the determination of the power output. A typical unit operating in a dry steam cycle can produce 45 MW of power, which is significantly higher than the corresponding capacities in flash and binary cycles (averaging 30 and 5 MW/unit respectively) (Bertani 2012). Since the dominant working fluid is in the vapour phase, the dry steam cycle provides optimum plant performance (Chamorro et al. 2012). However, as high temperatures and a specific pressure regime are required for the geothermal fluid to reach a steam-dominated state, only 5% of hydrothermal systems operating at working fluid temperatures above 200°C that are of the dry steam type (DiPippo 2015). Considering the high efficiency of the dry steam cycle and the near-zero carbon footprint of geothermal energy production (Abbas et al. 2014), it is important to exploit the maximum potential of geothermal power plants operating in the dry steam cycle.

2.6.2 Flash steam plants

The most common are 'flash steam' power plants (Igwe 2021). They use geothermal water reservoirs with temperatures greater than 150°C to generate steam. This steam is used to drive turbogenerators. The hot water flows through holes in the ground under its own pressure. As it flows upwards, the pressure decreases and some of the hot water boils or transforms into steam. The steam is then separated from the water and used to power the turbine. The residual water and condensed steam are forced back into the tank, making this source sustainable. The remaining hot water can be re-flushed twice (double flash plant) or three times (triple flash) at progressively lower pressures and temperatures to produce more steam.

A control diagram of a flash steam plant is shown in the figure below (Figure 2-14). In this technology, a variable-speed pump moves hot water from the production well to the steam separator. The pump speed is set by the reservoir level. The level control signal is adjusted for changes in steam pressure. This control configuration is called a 'two-element' feedwater system. High-pressure (HP) steam from the separator is sent to the steam turbine, whose speed is controlled by throttling the flow of high-pressure steam. The energy of this high-pressure steam generates electricity, which is transmitted to the grid or to other users (Lipták 2020).

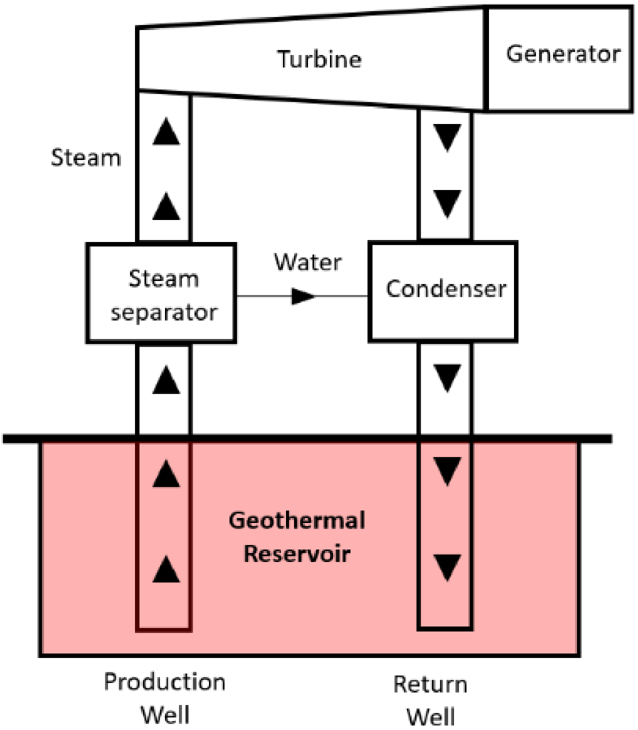


Figure 2-14. Geothermal "flash steam" power plant

Source: based on (Lipták 2020)

2.6.3 Binary cycle power plant

Binary cycle power plants transfer heat from the hot geothermal water to another fluid, which is turned into steam that drives a generator turbine (Figure 2-15). This technology allows electricity to be generated from a resource at a much lower temperature than before. Binary cycle geothermal power plants differ from dry steam and flash steam systems in that the water or steam from the geothermal reservoir never comes into contact with the turbines/generators (Office of energy efficiency & renewable energy 2022). Low to moderately heated (below 204,44°C.) geothermal fluid and a secondary fluid with a much lower boiling point than water pass through a heat exchanger. The heat from the geothermal fluid causes the secondary fluid to turn into steam, which then drives the turbines and then the generators. Binary cycle power plants are closed loop systems and virtually nothing (except steam) is emitted into the atmosphere (Office of energy efficiency & renewable energy 2022). In 2006, a binary cycle power plant was commissioned at Chena Hot Springs in Alaska, producing electricity from a record low liquid temperature of 57°C. Naturally, the secondary fluid has a much lower boiling point than water and therefore flares into steam, which then drives the turbines and then the generators (Lipták 2020).

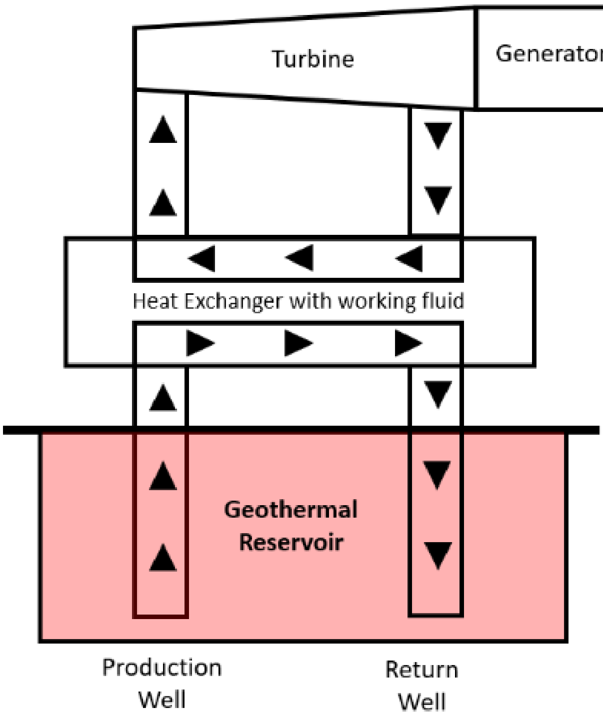


Figure 2-15. Geothermal "binary cycle" power plant

Source: based on (Office of energy efficiency & renewable energy 2022)

2.6.4 Hydrothermal Spallation Drilling Technology

Hydrothermal spallation drilling (HSD) technology is a relatively new method suitable for drilling in hard and friable rocks typically found in deep wells, and more commonly in geothermal wells (Wang et al. 2017). Conventional rotary drilling in hard formation is costly due to the wear and tear on the drill bit, which causes more trips during drilling and thus increases costs. HSD therefore reduces drilling costs by up to 15-20% (Wang et al. 2017). HSD is a type of drilling that involves heating the rock surface so rapidly that the thermal stresses induced in the rock cause damage to the rock surface by creating spalls that are ejected from the surface (Augustine 2009). HSD is characterised by rapid heating of a limited area of rock. This rapid heating induces compressive thermal stresses due to the expansion of the solid with increasing temperature, which leads to the breakdown of the solid into small, disc-shaped flakes or spalls. These flakes or spalls are then violently ejected from the rock surface due to stresses developed at the surface prior to fracture and carried back to the surface by drilling fluids (Wang et al. 2017).

2.7 Geothermal energy – technologies in mining

When underground mines are abandoned, the pumps that kept them dry are often turned off and the mines fill with water. This water is heated by geological processes and the temperature remains stable throughout the year. Heat from abandoned mines is an innovative and practical solution to one of the economy's biggest challenges - the decarbonisation of heat supply. The constantly replenished water in these mines has the potential to be a large enough resource to meet all heating requirements for coalfield areas. It can also be used as heat and energy for gardening, manufacturing and other purposes. In the case of a district heating network, this energy could be transferred to a piped network via a heat exchanger and then distributed to nearby homes. This type of renewable energy technology could help present coalfield areas as more attractive to investors. It could also provide a significant low-carbon contribution to the country's future renewable energy needs (The Coal Authority 2022).

One way of harnessing low-intensity geothermal energy is to convert mine shafts into geothermal boilers that could provide heating and hot water to the population living nearby (European Commission 2009). When the mine is operational, it is possible to get into mining galleries and collect data on ventilation and rock properties and take samples and design better circuits and even plan to close some sections to use them for geothermal energy generation. It is possible to inject water at 7°C into the pipes and get return water at 12°C, which is enough heat gain for use in towns above the mines.

Mine waters are characterised by relatively high volume fluxes and elevated temperatures, sometimes very far above the conventional thermal water temperature limit (20°C). At present, their use in Poland is negligible, although they could serve as a source of cheap heat in areas where mining is developed (Polish Geothermal Society 2017). However, there is a development of this technology in Europe due to the restructuring of the coal mining industry, resulting in the closure of mines in Europe in many regions (Demollin-Schneiders et al. 2005). For example, governmental studies of Scotland's geothermal potential have revealed that the gradients in water temperature vary from 37°C/km to 45°C/km. When the mines are shut down and the pumps that kept them dry are stopped, groundwater that has been heated by geothermal energy from the earth's core to temperatures of 11–20°C near the surface and up to 46°C in deeper coal seams (ThinkGeoEnergy 2020b). On the other side, in Heerlen (Netherlands), a geothermal power plant was commissioned in 2008. This power plant uses the heat from water used to flood mine shafts after mine closures. An 825 m deep tunnel allows access to underground mine water with a temperature of 35°C. The water is used for heating purposes and is stored in other shafts at a temperature of 17°C before being used as a cooling agent (EnergyCities 2023). At the Spanish hospital Vital Álvarez Buylla in Mieles (Asturias, Spain), the energy supply for heating and air conditioning is based on a geothermal system using mine water from the closed and flooded Barredo-Santa Bárbara coal mine. This water is used in Spain's most powerful geothermal power plant, one of the largest in Europe for a geothermal power plant of its kind. There, up to 3.8 MWt of water will be produced when water pumped from the Baredo mine passes through a heat exchanger. The research building at the University of Mieles Campus (University of Oviedo, Spain) is also heated by the same geothermal resource (Lara et al. 2017). More details on the application of these solutions in Spain can be found in Chapter 5 and Chapter 6.

The construction of geothermal boilers in mine shafts would be beneficial because they would not only produce energy, but would also function as open pipe systems without any risk of heat contamination of aquifers. Among the advantages of geothermal energy from closed mines, as opposed to solar and wind energy, are its independence from climatic conditions, the lack of need to build new facilities over large areas and the lack of pollution of the surrounding environment. From the point of view of the industrial sector, geothermal energy would prove lucrative in the long term (European Commission 2009).

Coal mines in the Upper Silesian Coal Basin pump underground water at temperatures above 13°C to the surface (Solik-Heliasz and Małolepszy 2001). In many countries, the low-enthalpy geothermal energy contained in waters at temperatures below 20°C is used to heat buildings and to de-ice road surfaces and viaducts at sensitive sections. For this purpose, boreholes are drilled to collect heat, usually from underground water. Heat is even recovered from surface water at a temperature of 4°C, cooling it down to 2°C in heat pumps. In Poland, in areas of underground mining, there are opportunities to implement similar applications under much more favourable conditions. This is because there are deep mine shafts through which large quantities of groundwater with higher temperatures, i.e. above 13°C, are pumped out. This water is discharged into surface watercourses, at a significant cost to the mines. There are numerous potential heat consumers in the immediate vicinity of the shafts, prompting the search for ways to use geothermal energy for economic purposes (Solik-Heliasz and Małolepszy 2001).

Among the most commonly proposed methods for harnessing geothermal energy in mining areas is the installation of heat exchangers at the outlet of a shaft or dewatering well (Figure 2-16). In plate heat exchangers, the thermal energy from the pumped mine water is transferred to the fluid in a second circuit, which is the lower source of the compressor heat pumps. The use of exchangers in the heat extraction system protects the second circuit from corrosion caused by dissolved salts in the mine water. At the same time, it increases the cost of the installation. Therefore, pumps with a primary circuit adapted to receive heat from brine can be used instead of exchangers.

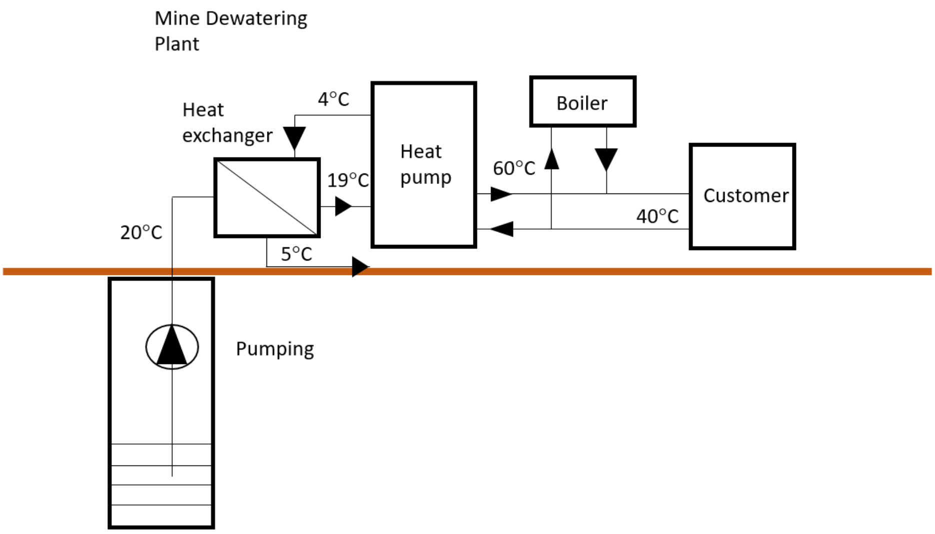


Figure 2-16. Geothermal energy extraction from pumped groundwater at the dewatering plant

Source: based on (Solik-Heliasz and Małolepszy 2001)

A typical method of harnessing the geothermal energy contained in mine waters is heat pumps in combination with open or closed loops (Ghomshei and Meech 2003; Milenić et al. 2010). Heat pumps can be used for both space heating and cooling. In winter the energy is extracted from the water and in summer the energy is transferred to the water. The amount of energy recovered will depend primarily on the size and number of heat pumps installed. These in turn will be based on the temperature and flow of water from or to the mine (Małolepszy 2003). If the water is to be discharged into the environment after the energy has been removed, the water regulations must be consulted to ensure that it meets the requirements. There are two basic types of heat pump-connected geothermal loop systems that can be used with mine water.

2.7.1 Closed loop

Most residential geothermal systems use closed loops, with loops placed in the ground in various ways, or even in a pond or lake if it is nearby (Figure 2-17). Open loop systems are less frequently used. While attractive for direct use of groundwater, open systems are more demanding due to constant well maintenance, induced hydraulic effects, and hydrogeological requirements (Banks 2009; Haehnlein et al. 2010). In mines, closed-loop systems are recommended if the water source is contaminated. This is likely to be the case for operating mines or mines flooded with poor quality water, especially those containing significant loads of salinity. A simple closed loop system includes a shaft heat exchanger connected to a heat pump to provide space heating/cooling in buildings using floor loops (Ghomshei 2007).

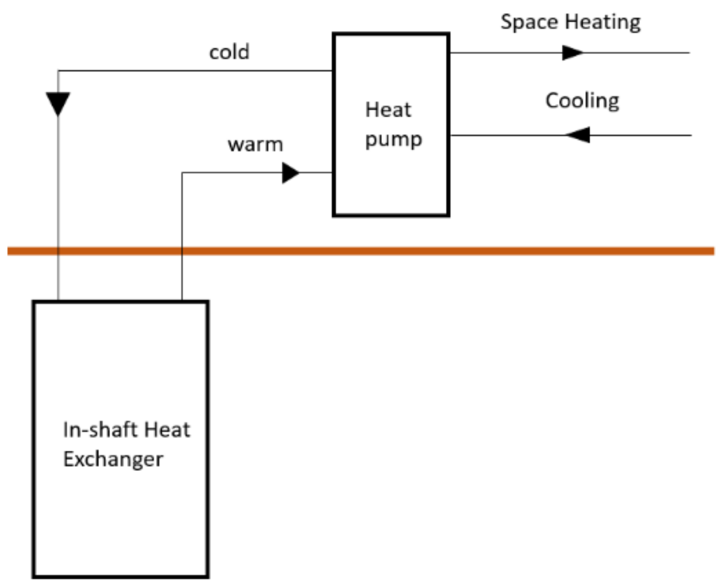


Figure 2-17. Closed loop geothermal system

Source: based on (Ghomshei 2007)

2.7.2 Open loop

Open-loop systems are suitable when there is a large volume of water of reasonable quality (Figure 2-18). This type of geothermal system is therefore encountered in closed mines flooded with water when the water has no problematic characteristics such as extreme pH, suspended solids or hardness. Open loops can be installed in a single shaft, with pipes at different heights or in separate parts of the mine. In winter, water is drawn from the deeper part of the loop, where it is warmer, and pumped back to a higher elevation. In summer, this process is reversed - cool water is drawn from the higher part of the loop and discharged back into the deeper well.

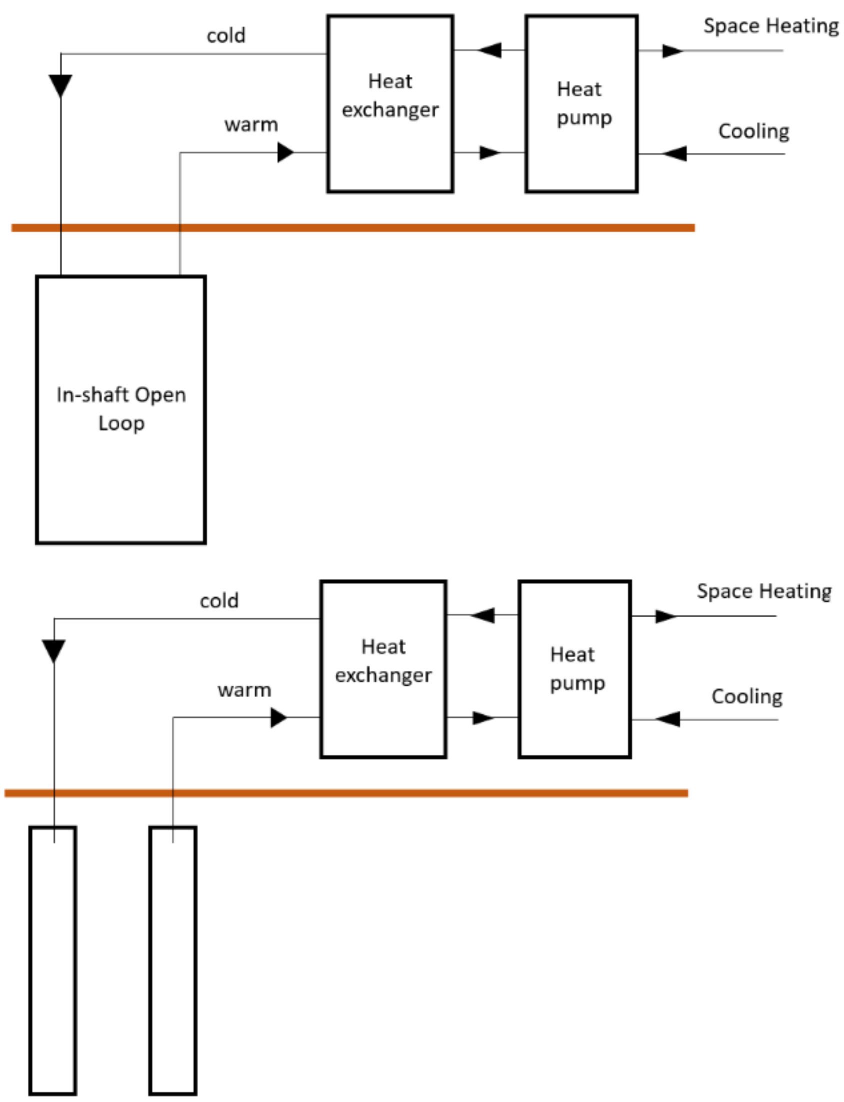


Figure 2-18. Open loop geothermal system

Source: after (Ghomshei 2007)

2.8 Examples from abandoned and working mines

2.8.1 SRK S.A. Zakład Centralny Zakład Odwadniania Kopalń (CZOK) in Czeladź (Poland) – „Saturn" Pumps station

The solution used at SRK S.A. decommissioned Saturn mine is a low-temperature open geothermal system. The dewatering of the decommissioned KWK Saturn is carried out in order to protect the active mines in the northern part of the GZW (Upper Silesian Coal Basin) (Karpiński and Sowiżdżał 2018). It consists of pumped mine water (treated as a heat carrier) being directed, after energy recovery, to an overflow reservoir and then to the Brynica River (Tokarz and Mucha 2013). A very favourable circumstance for the use of heat pumps is the virtually zero cost of pumping. Whether or not heat energy is extracted from the water, there is a need for continuous dewatering of decommissioned mines. This makes the cost of building a pumping station drop out when using heat from the CZOK (Central Department of Mine Dewatering) plant's pumping station. When acquiring heat, additional formal procedures related to obtaining a water law permit or environmental fees for discharging mine water into the river are also eliminated. The pumping units were sunk in the Paul shaft and the surface infrastructure was decommissioned. The volume of water pumped is about 15 m^3/min (900 m^3/h) and its temperature is about 13°C. The waters are of relatively low mineralisation, with high concentrations of iron and manganese compounds. Due to the high content of iron compounds in the pumped water and the possibility of their precipitation on the surface of the intermediate heat exchanger, it is not possible to feed the mine water to the heat pump system without prior treatment. This required the establishment of a mine water treatment plant. Raw water is drawn from an overflow reservoir located by the Paul shaft, from where it is pumped to the mine water treatment building via a feed pipeline. After purification in the filter station, it is directed via a pipeline to the primary circuit heat exchanger located in the CZOK building. After releasing its heat, it is returned to the overflow tank and its excess is discharged into the Brynica River. Mine water is treated using a technology based on oxidation of iron and manganese compounds using air from a compressor and filtration on a mixture of quartz and hydroanthracite deposits. Water in the amount of 23 m^3/h is directed to an aeration column. It is then directed to the filters (two in operation, one in regeneration), where precipitated iron and manganese compounds are removed. The de-gelatinised and de-manganised water is piped to the heat pump plant heat exchanger. Part of the treated water is retained in two tanks, each with a capacity of 13 m^3, providing water for filter flushing. Due to the high iron content of the raw water, periodic cleaning of the Water Treatment Plant feed pipelines is necessary. To meet the heating needs of the building, the heat pump cascade requires a supply of approximately 0.31 m^3/min (18.6 m^3/h) of mine water (less than 5% of the total pumped water). After the heat pump installation became operational, electricity consumption for heating purposes fell to 132.9 MWh/year. This represents a reduction in electricity demand of almost 278 MWh/year (Karpiński and Sowiżdżał 2018).

2.8.2 "Maciej" shaft – the abandoned "Concordia" mine

After coal reserves had been exhausted, the Maciej shaft of the former Concordia mine was converted into a deep well, from which the water drawn at a temperature of approx. 8°C is the bottom source of heat pumps providing heating, domestic hot water and cooling for the bar, restaurant and office (OZE 2015). The Maciej Shaft has been converted into a deep well by Przedsiębiorstwo Górnicze DEMEX Sp. z o.o. At the water station, there are two large retention reservoirs on the Maciej Shaft site where water is stored. The energy required for the heat pumps is obtained from these reservoirs using indirect exchangers. This water is a source of heat in winter and cooling in summer. The water coming from the intake has a constant temperature of around 8-9°C. In winter, the water is pumped through an exchanger (water-glycol) for heat pump operation. This makes it possible to achieve the temperatures necessary for space heating. On the other hand, on hot days, a second exchanger (chilled water-water) is used to cool the rooms. This is so-called passive cooling, so the heat pump does not produce cooling (it uses the temperature of the water extracted from the interior of the earth) and its role is limited to controlling the process taking place. The heat pump works in conjunction with underfloor heating, which is installed throughout the building except on the top floor, as well as with fan coils (only in the glazed entrance area). The heat generated is also fed into the air handling units. Each of these has both a cooler and a heater. The air handling units are partnered with so-called active induction beams located under the ceiling, which can supply both heat and cooling as required. "Active" means that it is possible to supply both air (from the air handling unit with rotary exchanger) and the cooling medium (chilled water) to them. Active beams do not operate on the principle of blowing. The cool air falls from them slowly because it is heavier. As a result, restaurant guests do not experience discomfort, as is often the case with the cold discharge from traditional air conditioning. In winter, the ice water does not circulate and only heated air is fed into the beams. The process heat from the heat pump only reaches the air handling unit and supplements the heat recovered in the recuperation process. The main component of the system is two DHP-R heat pumps with a capacity of 42 kW each (at a bottom source temperature of 0°C). At a free-source temperature of approximately 8°C, the pump output is approximately 52 kW. Between the compressor and the condenser there is an additional 'small' exchanger through which the refrigerant, in the form of hot gas, is passed to the condenser on one side and heating water on the other. The gas downstream of the compressor, on this 'small' exchanger, reaches temperatures of more than 100°C, which makes it possible to prepare large quantities of hot water extremely efficiently and quickly. The DHP-R pump with overheating function protects the DHW tanks against Legionella bacteria.

Two domestic hot water tanks have been installed in the Maciej Shaft complex. The first, with a capacity of 220 litres, works directly with the hot gas installation, while the water in the second, which has a capacity of 700 litres, is heated by the heat pump in the traditional manner.

2.8.3 "Sobieski" mine

The Sobieski Mine is located in Jaworzno and is part of the Tauron Wydobycie group. It is a dual-pit mine conducting mining in two Districts: Sobieski and Piłsudski. Due to hydrogeological conditions, the Sobieski mine is the most unreliable of all hard coal mines in Poland. Underground water inflows have remained at a level of approximately 60 m^3/min (3600 m^3/h) in recent years. In 2014, a project was launched at the Sobieski Mining Plant to install an installation to recover the heat accumulated in mine waters and use it to produce hot water for the mine baths. The heat pump station is located in the Sobieski District and provides heat for the preparation of hot water for the bathhouse. Thanks to selective water extraction, the lower heat source can be water pumped from the 500m level. The pumping station is located next to Sobieski III shaft; the average inflow recorded at this level in recent years has been approximately 21 m^3/min (1272 m^3/h) and has a temperature of approximately 15°C. As part of the investment, a pump station with an intake well was built and a heat pump installation was constructed in the bathhouse building. The two facilities were connected by a transmission main consisting of pre-insulated pipes. Two mine water circulating pumps and one submersible suction pump operate in the pump station, which is connected to the mine water discharge channel from the 500m level. Mine water from the 500m level for the installation is drawn from the canal at a rate of 1.1 m^3/min (66 m^3/h) and then pumped to the bathhouse building. Due to its high mineralisation and chloride and sulphate content, which reinforce the corrosive nature of the water against metals, intermediate exchangers were necessary in the installation. The mine water provides the lower heat source for a system of five dual-compressor heat pumps. The total heating capacity of the system is 420 kW. The system comprises two independent and hydraulically separated cascades. The first consists of three heat pumps, the second consists of two heat pumps. Depending on the current heat demand, the controller switches the cascade of heat pumps on. The domestic hot water, which has been heated to 55°C, is stored in storage tanks with a total capacity of 63 m^3. The storage tanks are equipped with heat exchangers connected to the district heating network in the event of interruptions in the operation of the heat pumps (Karpiński and Sowiżdżał 2018). Thanks to the investment, it was possible to reduce the amount of heat purchased from an external supplier by 780 GJ/month. A schematic diagram of the installation is shown in the figure below (Figure 2-19).

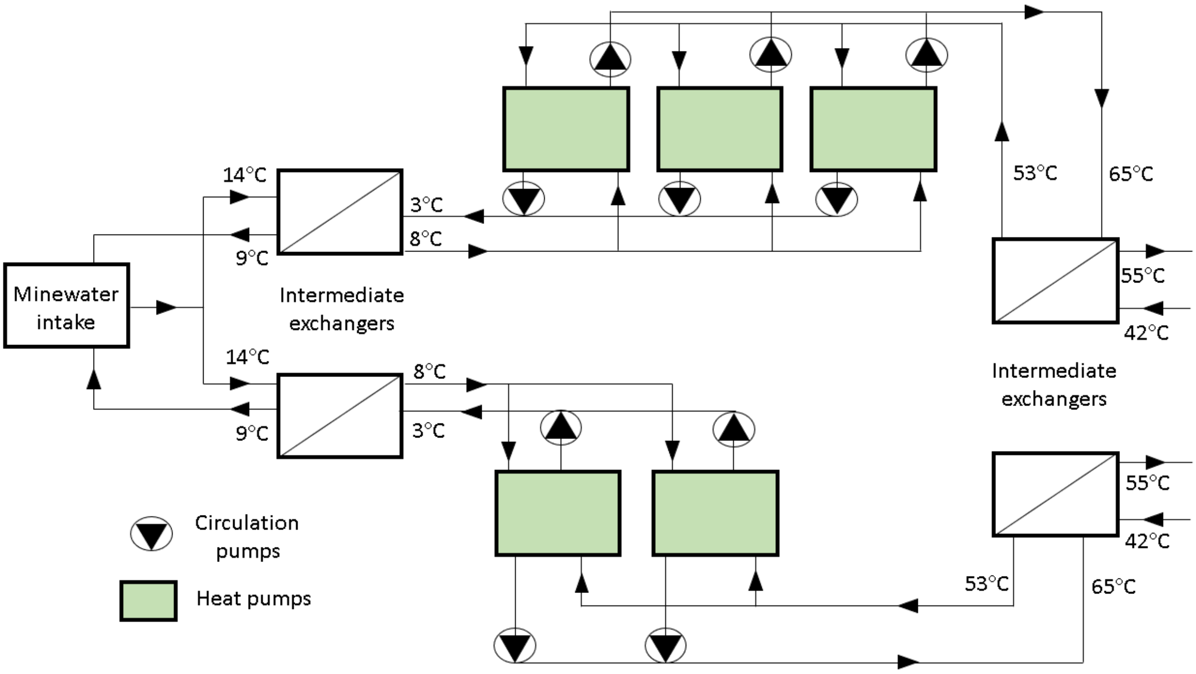


Figure 2-19. Geothermal heat recovery at "Sobieski" plant

Source: based on (Karpiński and Sowiżdżał 2018)

3 Features of the implementation of geothermal energy deployment in a mining area

There are three main motivations for exploiting geothermal energy (Preene and Younger 2014):

1. Financial savings

All mining operations consume thermal energy, which is more or less influenced by the local climate and mining and processing methods. The energy costs associated with heating can be significant. Geothermal energy has the potential to provide heat at a lower unit price than conventional fuels, thus reducing operating costs.

2. Environmental benefits and corporate social responsibility (CSR)

Geothermal systems are classified as low carbon energy sources. Heat from geothermal systems is typically used to replace heat from conventional fossil fuel sources. The use of geothermal energy reduces CO_2 emissions in line with typical CSR targets.

3. Profit from closed old mines

Flooded mines and open-pit mines can be important reservoirs of geothermal heat. The use of these heat stores can potentially create new revenue streams for mining companies and support the sustainability of communities associated with closed mines.

It is important to recognise that the geothermal potential and the associated risks and challenges are unique to each project. Geothermal energy is not a panacea for every mining project, and feasibility depends on various factors such as geology and existing infrastructure. A feasibility study may be required when considering geothermal energy, taking into account the factors discussed later in this document (ESMAP 2012; Preene and Younger 2014). Since mines rarely have water hot enough (85°C) to generate electricity in a binary power plant, direct heating/cooling can be used (with or without the help of heat pumps). The focus is now on the low enthalpy systems that can be delivered for direct heating/cooling.

The key aspects to consider for low enthalpy geothermal systems should answer the following questions (Preene and Younger 2014; Iorio et al. 2020; Pająk et al. 2020):

1. Heat resource

Is the thermal resource in storage sufficient in terms of available heat quantity and heat quality (e.g. peak temperature)? This can be quantified using relatively conventional hydrogeological drilling and modeling programs.

2. Heat availability

Does the heat storage tank have sufficient hydraulic connections and does a structure already exist that can act as an above-ground collector, or can it be easily built with a high degree of thermal performance security? Included sites have readily available and measurable heat and are classified as low risk.

3. Environmental and regulatory factors

Could a geothermal system cause unacceptable environmental impacts or be constrained by regulatory issues? Based on experience in other industries, these risks can usually be quantified and mitigated through good design and planning.

4. Operational and thermal continuity risks

Is there a significant risk of performance degradation or heat supply interruption over the life of the system due to operational issues? Risks include corrosion, fouling or clogging of the system, or excessive heat storage temperature drop due to high heat removal rates. These risks can be quantified by hydrogeological and geochemical modeling.

The last decade has seen a significant increase in the use of low-enthalpy geothermal systems in commercial buildings. Property developers are little different from the mining industry in their desire to manage risk and secure a reasonable return on their invested capital. Experience has shown that these risks are not considered roadblocks, but serve as roadmaps for possible application exploration and research.

3.1 Value Chain Analysis

One approach suggested in the literature is to use a combination of value chain analysis (VCA) and energy sector analysis.

The combination of VCA methodology and energy sector analysis provides a comprehensive assessment that helps outline a vision for future energy sector development, focusing on region-specific issues in a socioeconomic context. Value chain analysis assesses the current state of mining and related activities and identifies the potential socio-economic impacts caused by mine closures. Relevant background information then flows into energy system analysis. Future scenarios are based on energy supply security boundary conditions, taking into account existing infrastructure, knowledge and local development priorities. The analysis thus reveals the consequences of withdrawing from mining activities on the one hand and the relative impact of moving from the status quo to alternative technological options on the other.

This enables a comprehensive assessment that takes into account local characteristics. The value chain analysis evaluates the mining industry from mine to power generation in terms of employment and economic activity at risk from coal mine closures. A complementary energy systems analysis focuses on the diversification of the energy mix, environmental impacts, and assessing the feasibility of alternative energy technologies to coal burning.

Value chain analysis (VCA) is a method used in business planning to examine internal operations. Its objective is to identify the operations that are most important to the company and might be enhanced to provide it a competitive advantage (i.e., those that are the source of cost or differential advantage) (Figure 3-1) (Jurevicius 2022). VCA is one of the most popular techniques for evaluating regional economic consequences and is especially helpful when the sectoral analysis has a micro geographic focus. When one component of the value chain is influenced by new policies or ground-breaking economic or financial events, the VCA can be used to trace and monitor the inter-sectoral flows of capital, financial resources, and labor. Other scholars evaluated the effects of jobs created by the growth of the renewable energy sector using the VCA. All areas of the coal value chain—from coal extraction to power and heat production—are impacted by the cessation of mining operations. By aggregating data by value chain segments, it is possible to trace the relevant industrial processes from upstream to downstream (Gerbelová et al. 2021).

The elements of value chain analysis are presented in Table 1.

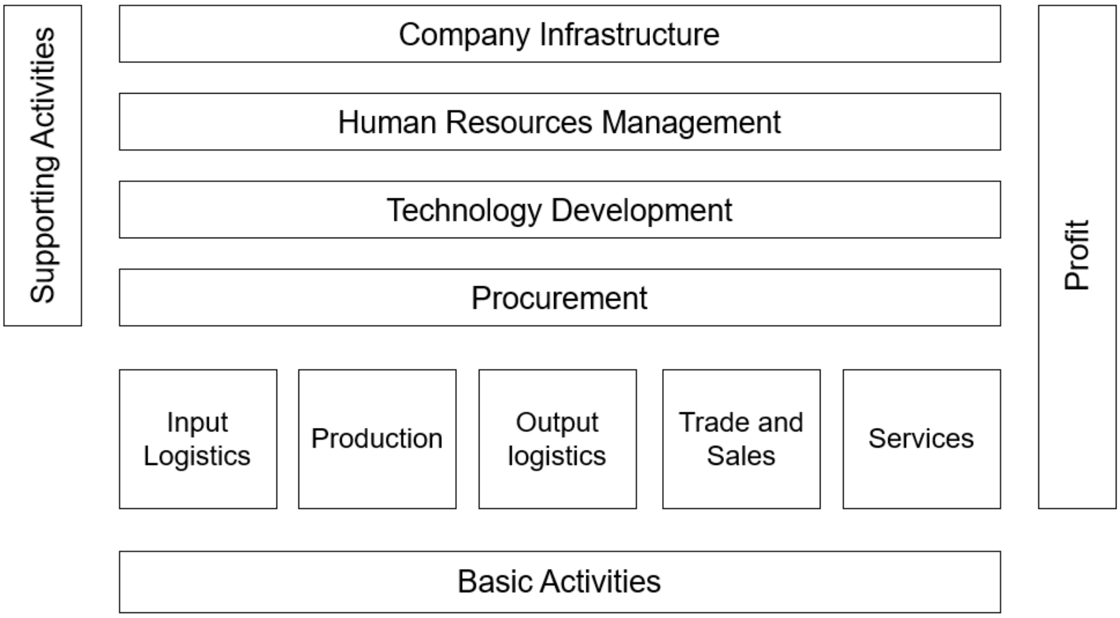


Figure 3-1. Basic value chain structure

Source: based on (Porter 1985)

In general, the basic value chain of the coal industry is defined by four sectors: (1) acquisition of factors of production (Input), (2) extraction and processing of coal (mining), (3) transportation and trading of products (transportation), and (4) final use of coal resources (end market). A simplified diagram of the coal industry value chain is shown in the figure below (**¡Error! No se encuentra el origen de la referencia.**).

Activities involving the provision of production factors are included as input (mining and production equipment, land and extraction rights, acquisition from the government and landowners, etc.) (Gerbelová et al. 2021). Activities involved in production include surface- and underground-level exploration, extraction, and processing. Activities pertaining to input materials and finished goods transportation are included in the term “transportation”. Markets are defined as areas where economic activity that employ coal's products and by-products can be found. The choice to invest in the production elements of the input sector's input sector is driven by the end sector.

VCA assessments provide useful information about economic activity that is directly and indirectly related to the current state of the mining industry. It is a fundamental step in assessing the potential socio-economic impacts caused by mine closure. In addition, VCA provides an opportunity to collect data and map various business activities related to coal, the main activity (Gerbelová et al. 2021).

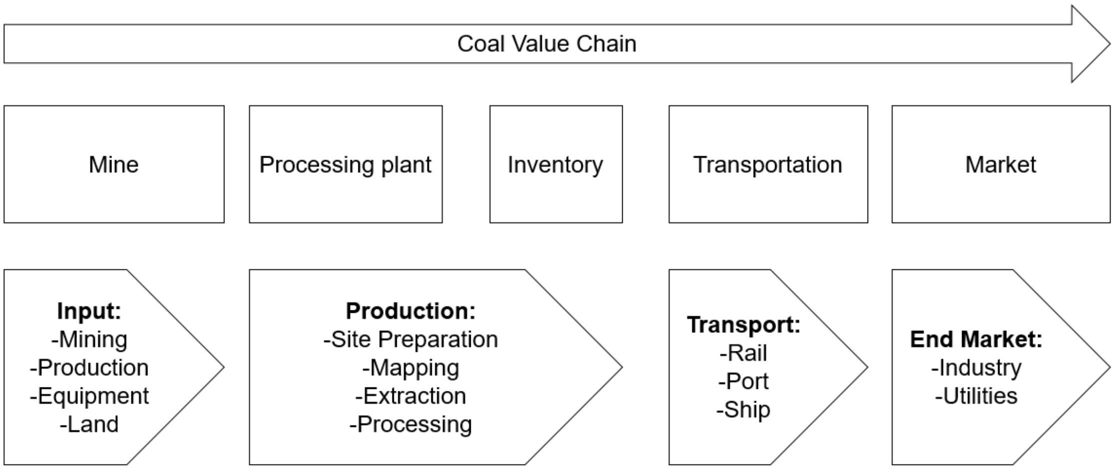


Figure 3-2. Coal Value Chain

Source: based on (Franza et al. 2018; Mckinsey 2020)

Table 1. Elements of value chain analysis

Segments	Description	References
Research Studies	Expand research work on potential locations for geothermal projects in mining areas. Focus on investment opportunities, especially in large cities where significant concentrations of heat demand and large heat markets allow for efficient use of geothermal energy.	(Gerbelová et al. 2021) (ESMAP 2012)
End User Market	In addition to research studies, the interpretation of results and direct identification of specific locations where extraction of geothermal energy from mine water is technically feasible and economical is also important from an investor's perspective. Identifying potential locations for efficient utilization of mine water heat requires not only the presence of sufficient quantity and quality of mine water, but also the heat consumption to exploit geothermal energy in a cost-effective manner. Effective implementation can be achieved by providing investors with comprehensive support in the form of expert advice at a late stage of the investment project cycle. Particularly at the pre-feasibility stage, it increases the efficiency of future investments and shortens the stage of obtaining investment in financing and the time of investment implementation. Problems in implementing the use of geothermal energy in mining areas are also related to the imperfect adaptation of district heating networks and consumer heating systems to the absorption of low-temperature heat. There is a need for a change in planning and incentives to build systems based on heating fluids that operate at lower temperatures, which will increase the use of geothermal energy from mine waters.	(Gerbelová et al. 2021) (Dickson and Fanelli 2003) (Huenges and Ledru 2011)
Funds	The purpose of mining is to make a profit by reducing costs or increasing production efficiency. With continued declines in commodity prices, international competition, and low profit margins, operating costs can have a significant impact on a mine's ability to withstand market volatility. A sudden and sharp drop in commodity prices led to the closure of the mine as it was deemed unprofitable to continue production. As such, mining operators are always on the lookout for even small productivity gains and cost savings. The growth of geothermal energy is hampered by the large upfront expenditures involved in building geothermal heat facilities. Expanding assistance in terms of substance and actors would boost the number of investments made in geothermal heat plants at all phases of development and operation.	(Patsa et al. 2015) (Gerbelová et al. 2021) (Tester 2007)

3.2 Energy System Analysis

Energy systems analysis assesses potential transformational directions in the energy sector towards alternative low-carbon energy technologies. Two proprietary energy modeling tools were used to gain insight into the technical and economic impact of mine closures from different perspectives. Energy system optimization models are suitable for long-term quantification of the impact of energy transitions on energy systems. B. Impact of climate policy on investments in new technological capabilities, energy mixes, commodity flows, energy prices, or carbon dioxide (CO_2) emissions and prices. By implementing regional trends, we can make more accurate statements about possible outcomes at the regional level. The modeling environment takes into account a whole range of technologies characterized by their techno-economic properties and linked by energy flows. This grid provides energy services to society under certain economic and political constraints of the system.

The goal of the methods is to reduce the total cost of the entire system in each period while meeting the demand for energy services. The reference scenarios must be consistent with the EU energy scenario 2050. As for its application, additional scenarios are performed by analyzing the main impacts of phasing out coal production and exploring the required diversification of the energy sector.

The analysis is complemented by an assessment of the power system's resilience to lignite generating capacity outages. The electricity system is analyzed using a unique European-wide harmonized duty and economic availability model (Gerbelová et al. 2021).

4 Identification of best technology for mining areas

Due to the high energy intensity of the mining industry, as well as the increasing demands for green, renewable and sustainable energy, geothermal solutions are being sought at three different stages of mining: during the period of mine exploration/construction, in active/operated and abandoned/flooded mines (Chu et al. 2021) (Figure 4-1).

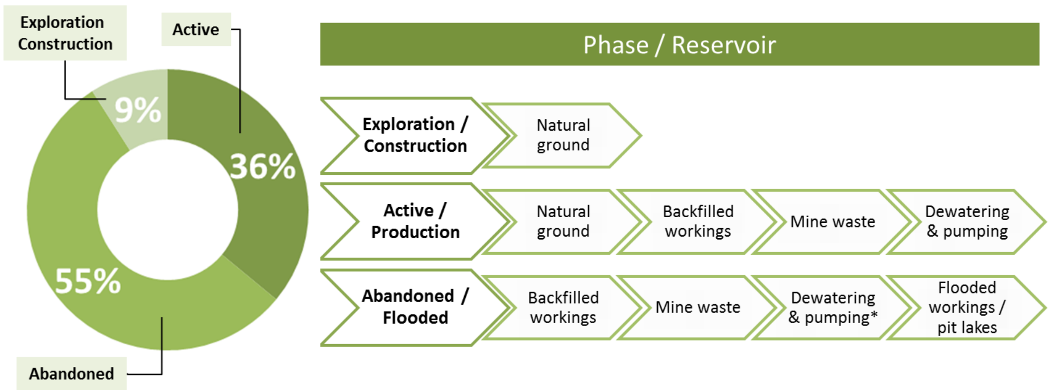


Figure 4-1. Phase division and potential sources of geothermal systems on mining projects

Source: based on (Chu et al. 2021)

A comprehensive report based on data from projects concerning mine-originated geothermal system realized between 1995 and 2016 showed that mine water is the main source of geothermal energy. In active mines there are another types of the geothermal energy sources such as mine ventilation exhaust air and mine waste. Geothermal systems have been developed mainly in abandoned/flooded mines (55% of all projects). This is due to the progressive closure of mines in many parts of the world, especially in the EU. For example, the last underground mine was closed in France in 2004, in the UK in 2015 and in Germany in (Menéndez et al. 2019; Chu et al. 2021).

Low-temperature geothermal systems using water from submerged mines have several advantages over heat extraction from natural aquifers:

- a large amount of water stored in old mine workings with temperatures >20°C,
- large surface area of heat exchange between rock and water resulting from mining,
- well-known geological structure of the system,
- high permeability, resulting in the ability to pump large volumes of water,

- infrastructure for installation of equipment and injection of cooled water (Chudy 2022).

Heat transference from the mine water to the heat pumps can be achieved through different configurations:

- **OPEN LOOP SYSTEM WITH DISPOSAL OF THERMALLY USED MINE WATER** - the most common and simplest are the open-loop systems, in which the mine water is pumped out of the mine and discharged after capturing heat (heating mode) or releasing it (cooling mode). In the open-loop systems water is usually pumped from the vertical mineshaft. Stratification breakdown due pumping allows for mixing of waters of different temperatures and can potentially lead to negative effects on the thermal resource. In some cases the spent mine water is reinjected back into the mine, in a separated location to avoid affecting the temperature of the abstracted water, and causing a decline of the efficiency of heat extraction (Menéndez et al. 2019). Existing open loop geothermal systems include pumping mine water to recover heat on the ground followed by the discharge of thermally used water into: surface watercourses, settling ponds; wells, shafts, horizontal workings that crop out the surface.
- **OPEN LOOP SYSTEM WITH REINJECTION OF THERMALLY USED MINE WATER** - if it is not possible to treat mine water or to discharge it directly to surface water, it is possible to re-inject it into mine workings or another aquifer after heat exchange. The advantage of this is that water resources are conserved while avoiding treatment and disposal costs. On the other hand, it requires the drilling and maintenance of re-injection wells and poses a risk of thermal "feedback" if the connection between extraction and injection points is too direct (Banks et al. 2019).
- **CLOSED LOOP SYSTEM IN FLOODED SHAFT** - in the closed-loop systems the heat exchanger (which may be a steel radiator, or a loop of polythene pipe) is submerged in the mine water (in a flooded shaft or gallery) and a working fluid is circulated to take the heat from the mine water, without contacting it. The working fluid itself is never in contact with the mine water and thus the closed-loop configuration is used for mines with contamination issues or not enough water volume being available (Peralta Ramos et al. 2015; Banks et al. 2019; Menéndez et al. 2019).
- **CLOSED LOOP SYSTEM IN IN SURFACE MINE WATER TREATMENT POND** - in this system a heat exchanger is submerged in the a mine water treatment lagoon (Banks et al. 2019).
- **STANDING COLUMN** - in this system mine water is abstracted from a specific depth in a mine shaft. It is passed through a heat exchanger and some or all of the water is returned to the same shaft at a different depth and different temperature. Any fraction that is not returned, but which is disposed of at

surface, is known as the bleed fraction (if the bleed fraction is 100%, it is simply an open-loop system with disposal). The returned water usually flows along the shaft towards the pump, absorbing heat from (or, if warmer, rejecting heat to) the walls of the shaft. If there is no natural advection of water along the shaft, the heat gain is ultimately sourced from conduction through the surrounding rocks towards the walls of the shaft, and the sustainable heat yield will usually be rather limited. If there is natural water advection along the shaft, this will tend to thermally replenish the system, increasing the heat yield. If the natural advection along the shaft is very large, the reinjected water may flow away from the shaft before returning to the pump, effectively becoming decoupled from the pumping horizon (Banks et al. 2019).

- **MIXED SYSTEM** - one of the solution for mining areas could be also a mixed system consisting of two circuits. In the primary circuit, the mine water passes through a tubular heat exchanger and is discharged into a river (open loop). The secondary circuit provides a flow rate of clean water that passes through the tubular heat exchanger, recirculation to the heat pump (closed loop) (Menéndez et al. 2020)

Figure 4-2 shows a mixed open loop and closed loop system scheme.

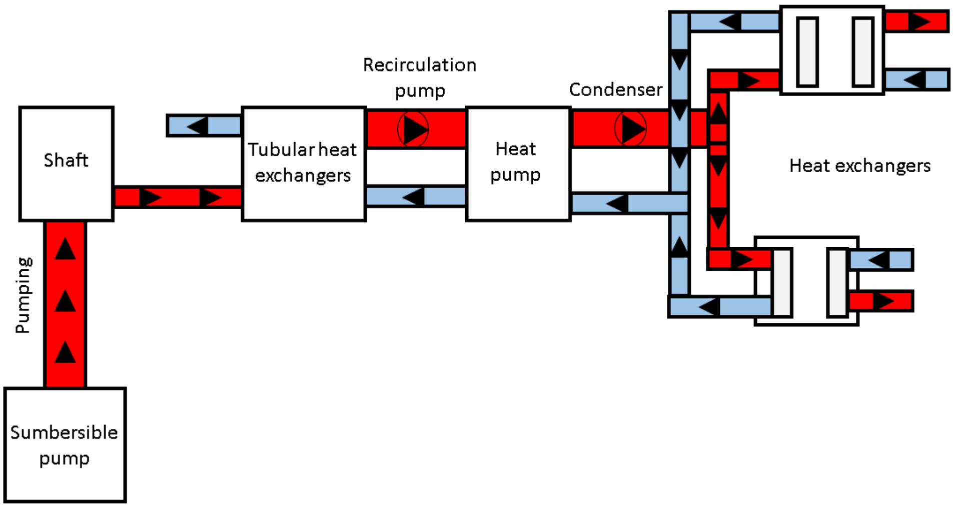


Figure 4-2. Mixed open loop and closed loop system for space heating and cooling of buildings with mine water. Mine water circuit with submersible pumps, tubular heat exchanger, closed loop secondary circuit with clean water and heat pump components

Source: based on (Menéndez et al. 2020)

A comparison of various mine heat recovery methods, together with an analysis of the advantages and disadvantages and recommendations for further use, is presented in Table 2. Table 3 summarizes the advantages and disadvantages of open-loop geothermal technologies for mine areas with recommendations for application at selected locations.

Table 2. Comparison of advantages and disadvantages of open-loop system, closed-loop systems and standing column (Banks et al. 2019)

	Open loop system	Closed loop system	Standing column
Advantages	**Scalable** Open-loop schemes can be up-scaled simply by adding additional heat exchange capacity (and treatment capacity/reinjection boreholes, if necessary). The only limit for heat recovery from mine water are the quantity of pumped or discharged mine water and the temperature differential that can be achieved across a heat exchanger. The largest mine water heat pump schemes are based on open-loop schemes.	**In-dependence from mine water pumping** The submerged closed-loop heat exchangers (in mines or in treatment basins) do not require a constant flow of mine water to function. They can thus be operated independently of any mine water pumping regime. **Managed fluid quality** In a closed-loop scheme there is no needed mine water pumped, reinjected or circulated through heat exchangers/pumps. The fluid circulated is a heat transfer fluid of controlled composition (usually based on a solution of glycol). This obviates any issues with heat exchanger clogging or serious corrosion.	**May avoid licencing issues, need for treatment** Standing column systems can work very successfully if the heat loads are modest. The system doesn't require any additional infrastructure (submersible pump, controls, rising main, recharge main, heat exchangers, heat pump), especially when the deep, large diameter open shaft already exists. No reinjection boreholes, no water treatment and no surface disposal facilities is required. Under some legislative regimes, it may be possible to argue that, as no net abstraction is taking place and as water is being returned to the ground at the same quality as that abstracted, then no abstraction licences or discharge consents are necessary. This will, however, depend on the legal framework in each individual country.

	Open loop system	Closed loop system	Standing column
Disadvantages	**Risk of chemical (ochre) precipitates** Mine waters, especially those from flooded mines, contain a lot of iron compounds. In contact with atmospheric oxygen (or other oxidizing agents), iron precipitates on heat exchangers in the form of ochre. This problem can be solved by using raw, unaerated mine water in which iron remains in a soluble form (Fe^{2+}). It is also possible to add some reagents such as sodium bisulphite ($NaHSO_3$) or sodium dithionite ($Na_2S_2O_4$) prior to heat exchange, in an attempt to maintain iron in reduced form in solution. These reducing agents can be regarded as relatively environmentally benign, oxidizing to form a solution of sodium and sulphate. Some of the raw mine water may also contain ochre particles, even where access to the atmosphere is excluded in above-ground halls. Preliminary mine water testing is required to determine iron and ochre concentrations. Presence modest amounts of ocher particles do not necessarily make the heat exchange scheme impracticable, and can be managed by some degree of maintenance. Where re-injection is practiced, however, the presence of even numbers small amounts of particulate	**Slightly less efficient** The closed-loop scheme requires a temperature differential to absorb heat from the lagoon to the heat transfer fluid. For example, in the system based on mine water at 14 °C, fluid returns from the lagoon to the evaporator typically at around 10.4 °C. This result in a modestly lower heat pump efficiency.	**May not be scalable** The small installation (20 - 103 kW) are working very well but it should be noted the large power amount necessary for pumping water from the deep water level. The heat extractable by a pure standing column arrangement might be limited to no more than 100 W m^{-1} (or several tens of kW for a typical deep mine shaft of several 100 m depth). If natural advection is occurring within the shaft, however, replenishing the thermal resources, significantly greater heat yields might be available.

	Open loop system	Closed loop system	Standing column
	Difficulties in disposing of thermally used water Re-injection of iron-rich mine water can cause a problem due to oxidation of dissolved iron and/or the presence of ochre particles in raw water. This technology will be suitable to waters which: • are already pumped for regional mine water management purposes and which are already treated prior to discharge to the environment, • which have good quality and low iron concentrations that they can be disposed of directly to a surface watercourse, • are of reducing chemical quality and where pre-oxidised ochre and other particles are absent, such that reinjection can be practised.	**Less readily scalable** It is possible to multiply the number of submerged heat exchangers in the aeration pond to increase the heat extraction. However, with lagoon-based technology, the number of units installed is needed to reach its full potential could prevent proper management. This system on a larger scale could only work if exchangers were installed in very large natural lakes and reservoirs, which they do not require desludging or periodic ochre removal.	

Table 3. Advantages, disadvantages and recommendation for choosing open-loop geothermal system (Rudakov and Inkin 2022)

The place for the discharge of thermally used water	Description	Case study	Advantages	Disadvantages	Recommendation
surface watercourses	Water being withdrawn from the flooded mine through the shaft and delivered further to the on-ground heat exchanger connected to the heat pump. After heat recovery. mine water is discharged into surface water bodies. mostly after treatment.	• Barredo colliery in Mieres. Asturias. northern Spain where water quality is acceptable and there is no need for treatment. • Kephaus colliery in Yorkshire in UK.	Helping to maintain a hydrodynamically safe mine water level across the post-mining areas	In some cases the water need to be treatment before discharge into the surface water. Additional costs for cleaning the pumps. pipelines and heat exchangers from solid sludge appearing due to chemical reactions with iron hydroxides or manganese oxides.	The technology could be recommended for the collieries with low water salinity to reduce treatment costs and minimize the environmental impact and for those that drain also neighbouring underground workings and adjacent areas.
settling ponds	In this system heat is recovery with the exchangers installed directly in the pond. In this case. The circulating fluid recovers heat energy from the pond water.		The large low grade heat resource available in the pond during the summer.	Ineffective under low ambient temperatures in the winter season. as well as due to additional energy costs for on-ground water transportation to the settling pond.	The technology can be efficient only during the summer period at the mines with closely located settling ponds.

The place for the discharge of thermally used water	Description	Case study	Advantages	Disadvantages	Recommendation
wells	The pumped water can be re-injected through wells after thermal use back to the underground workings.	• Near the cities of Shettleston. Glasgow. Lumfinance. Fife in Scotland (the United Kingdom) • Heerlen in the Netherlands	Water resources are not depleted. Water and salt balances are maintained treatment and disposal costs are minimized.	Requires drilling and maintenance of back-injection wells and creates the risk of thermal “short circuit” between the pumping and discharge points if reinjected water is heated insufficiently before withdrawal.	The technology for the collieries with additional shafts or big diameter wells for reinjecting thermally used water; underground workings must be hydraulically connected with the main shaft to provide heating water along its underground flow path.
shafts	Systems with reverse discharge to the same shaft, recover heat from surrounding rocks along the circulation path.		The costs to transport thermally used water are significantly reduced.	Technical constrains associated with water volume in the shaft and the flow path length sufficient to heat the discharged cooled water.	The technology for the collieries with low drainage flow rate. The considerable zone of flooding and a high geothermal gradient.
horizontal workings that crop out the surface	Systems with reverse discharge into horizontal workings deliver thermally used water into the shaft with the installed pump. Water flows through an upper horizontal gallery., which crops out near the watercourse.		The costs of cooled water transportation can be significantly reduced.		The technology for the collieries with such underground geometry and workings are of quite limited distribution and more typical of mountainous areas.

The choice of the method of heat recovery from mine water depends on many factors, including possibility of re-injection of mine water, ochre particles and others.

When choosing a geothermal technology, not only technical and economic aspects of the technology, **but also environmental aspects should be taken into account**. This is particularly important in post-mining and post-industrial areas which, due to the degrading activity of industry, have lost their ability to provide ecosystem services. The quality of surface waters to which loads of pollutants are discharged together with industrial sewage or mine water is very low. For this reason, when choosing technologies based on an open-loop system, an environmental analysis should be carried out in order to limit the negative impact of mine water on the environment.

In open loop system, thermally used mine water is pumped out of the mine and discharged into the environment (e.g. surface water). Open loop system would be appropriate where water pumping is taking place and the mine water is desalinated before discharge. In so far as there is a condition for using an open system because pumping is carried out in active and closed mines (protection of neighboring mines), no mining company in Poland uses mine water treatment processes in a full scale (except for the elimination of suspended solids in water ponds) prior to discharge to the receiver. Mine water treatment is hereby understood as desalination process, i.e. elimination of mainly chloride and sulphate load (membrane treatment and evaporation processes). Often, among the methods of mine water treatment in open loop system, chemical methods are suggested to remove, e.g. iron. However, the high load of chlorides and sulphates in the mine waters discharged into the environment is still negligible. Open-loop systems also often requires additional costs for cleaning pumps, pipelines and heat exchangers from solid sludge from chemical reactions with iron hydroxides or manganese oxides (Ni et al. 2012).

Examples of such solutions, where mine water after heat recovery is discharged to surface water (usually after treatment) are the Barredo mine shaft in Mieres (Asturias, Spain), where the water quality is acceptable and there is no need to treat it, and the Kephaus mine in Yorkshire (Great Britain) (Roslin and Esterle 2016; Loredo et al. 2016; Rudakov and Inkin 2022). In the case of the Barredo mine shaft in Mieres, although the iron content of the mine water was relatively low, there were problems with clogging the plate heat exchangers with iron hydroxide deposits, resulting in a decrease in efficiency (Loredo et al. 2017). However, experience has led to the conclusion that plate heat exchangers are more susceptible to clogging than tube/shell-and-tube heat exchangers. This shows that not only appropriate selection of technological equipment, but also operational problems should always be taken into account, even if water quality is acceptable. At the design stage, efforts should be made to minimize the number of potential errors and failures that may occur at the operational stage.

The most common of the open-loop systems is the discharge of thermally used water to surface water. An alternative solution may be to retain the thermally used mine water and re-inject it. However, this solution can be significantly more expensive than a conventional open loop system or closed loop system, as it requires the drilling and maintenance of re-injection wells. This solution also poses a risk of thermal "feedback" if the connection between extraction and injection points is too direct.

In closed-loop systems, the heat exchanger is immersed in a flooded shaft or gallery, and the working fluid circulates to extract heat from the mine water, without any contact. The working fluid itself never comes into contact with the mine water, so the closed loop system is used in mines where there are problems with contamination or insufficient water quality. Submerged closed heat exchangers do not require a constant flow of mine water to operate. Thus, they can work independently of the mine water pumping regime.

There are more advantages in a closed-loop system compared to an open-loop system, mostly in environmental terms. Given the technological progress, it is certainly possible to use pumps with equivalent efficiency as in the case of open systems. From an environmental point of view, a closed loop system with tube or shell-and-tube heat exchangers immersed in a flooded shaft or gallery is recommended. In this way, the need to use or even build large water reservoirs can be eliminated if the existing water pond is insufficient.

Another key factor that should be analysed before choosing a geothermal technology are economic aspects, related primarily to the end-user of heat (heat demand, required water temperature, distance of users from the mine).

The economic feasibility of a geothermal plant depends on the distance from the mine to potential users. When the distance increases, the investment cost (a pipeline network must be installed) and the energy consumption by the circulation pumps increase, decreasing the overall efficiency. Investment cost of a geothermal plant with a distance to potential users of 2 km amounts to 1230 €/kW, much more than conventional systems such as natural gas condensing boilers, which can be installed in the center of thermal energy consumption, without pipe network, having an investment cost of about 120 €/kW (Menéndez et al. 2019).

Due to variations in both the quantity of pumped water, its temperature and also its quality, a geothermal system mining areas should be selected after a feasibility study, including the feasibility study based on numerical model. Numerical models can be used to define the hydrogeological behaviour of the mining reservoir and to predict the long-term temperature of the water under different scenarios of exploitation, in order to define the suitability of flooded mines as a sustainable thermal resource.

4.1 Assessment of the potential for implementing geothermal energy in mining areas in Poland

4.1.1 Active and abandoned mines in Poland

Coal has been classified as one of the key fuels used in Europe. The total hard coal production in Europe in 2021 was 57 million tons, ca. 50% less than in 2010 and 79 % less than the 277 million tonnes of 1990 (Figure 4-3) (EUROSTAT 2022). Although Poland is still a major coal producer, in order to achieve the EU's net-zero carbon emissions target by 2050, the Polish government will gradually close the mines until 2049 (Polska Grupa Górnicza 2020).

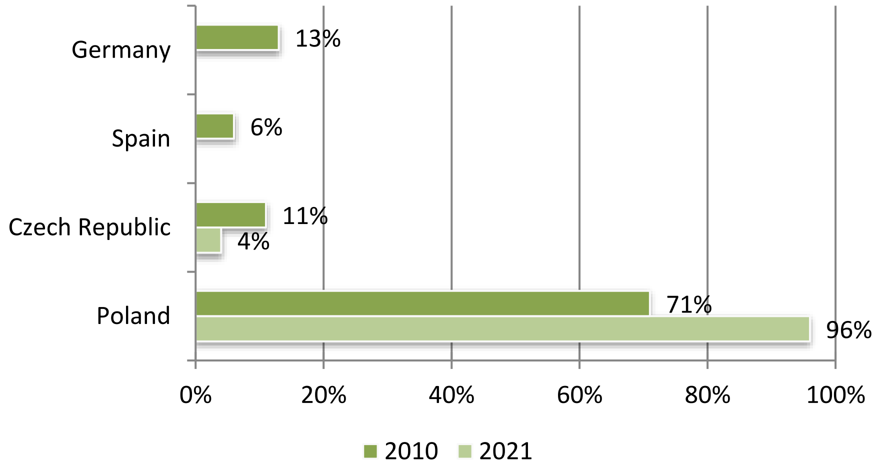


Figure 4-3. Hard coal production in 2010 and 2021

Source: based on (EUROSTAT 2022)

Coal can be found in two regions in Poland. These are the Upper Silesian Coal Basin (USCB) and the Lublin Basin (Blaschke et al. 2016) (Figure 4-4).

Figure 4-4. Hard coal and lignite reserves in Poland

Source: based on (EURACOAL 2022)

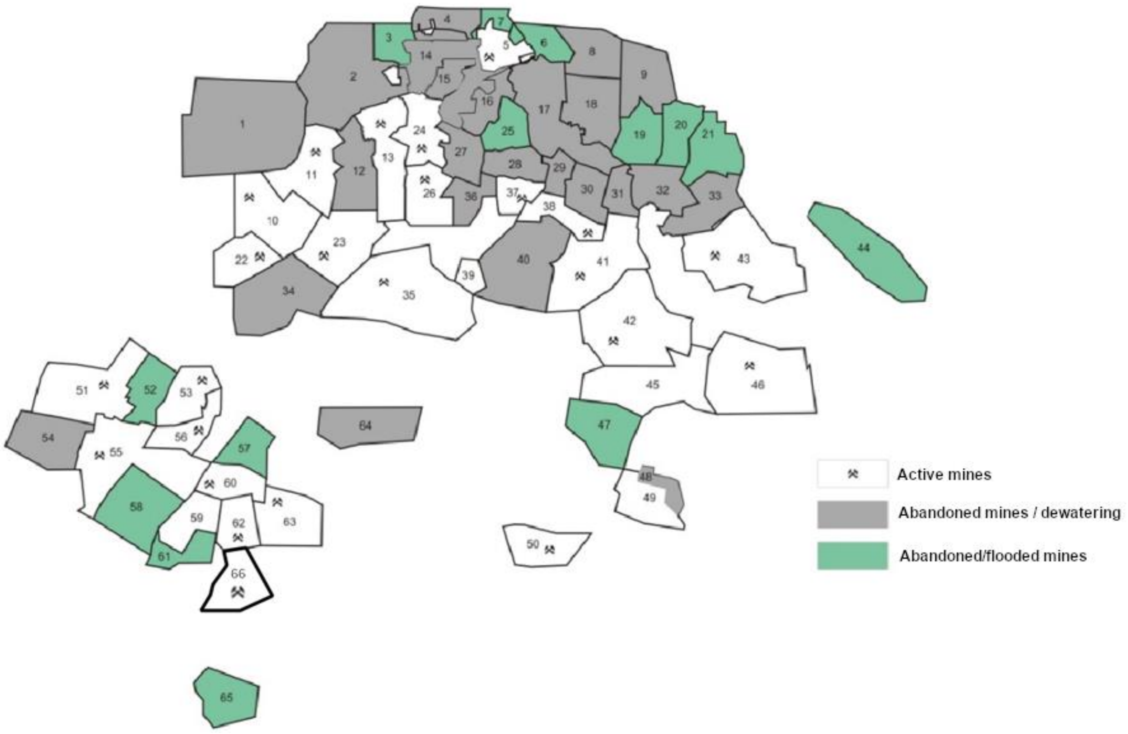
In Upper Silesian Coal Basin (Southern Poland) there is one experimental mine (KD Barbara, Mikołów) and 19 active mines, including:

1. KWK Borynia-Zofiówka
2. KWK Budryk
3. KWK Knurów Szczygłowice
4. KWK Pniówek
5. KWK Jaworzno-Bzie
6. KWK ROW
7. KWK Ruda
8. KWK Piast-Ziemowit
9. KWK Sośnica
10. KWK Bolesław Śmiały
11. KWK Wujek
12. KWK Mysłowice-Wesoła
13. KWK Murcki-Staszic
14. ZG Brzeszcze
15. ZG Janina
16. ZG Sobieski
17. PG Silesia

18. ZG EKO-PLUS (small private mine)
19. ZG Siltech (small private mine) (Xevgenos et al. 2020).

The 20th active mine (KWK Bogdanka) is located in the Lublin Basin.
The figure below presents the localisation of abandoned and active coal mines in Poland (Figure 4-5).

Even though the coal mines are closing, most of the mines that are or will be abandoned have to be continuously dewatered to avoid the uncontrolled discharges of mine water at the surface. After mine closure, pumping is usually resumed and adjusted so the discharge equals the recharge to keep a permanent flooding level. This created underground reservoir can be regulated and can be given several uses: geothermal and hydraulic energy generation, industrial or drinking water supply, support of rivers' ecological flow.



1 – SRK S.A. CZOK Gliwice; 2 – SRK S.A. CZOK Pstrowski; 3 – SRK S.A. KWK Miechowice; 4 – SRK S.A. CZOK Powstańców Śląskich; 5 – Węglokoks Kraj KWK Bobrek-Piekary; 6 – SRK S.A. KWK Jowisz; 7 – KWK Andaluzja; 8 - SRK S.A. CZOK Grodziec; 9 - SRK S.A. CZOK Paryż; 10 – JSW S.A. KWK Knurów-Szczygłowice Ruch Knurów; 11 – PGG S.A. KWK Sośnica; 12 – SRK S.A. KWK Makoszowy; 13 – PGG S.A. KWK Ruda Ruch Bielszowice; 14 – SRK S.A. KWK Centrum; 15 – SRK S.A.CZOK Szombierki; 16 – SRK S.A.CZOK Barbara-Chorzów; 17 – SRK S.A.CZOK Siemianowice; 18 – SRK S.A CZOK Saturn; 19 – SRK S.A CZOK Sosnowiec; 20 – SRK S.A CZOK Porąbka Klimontów; 21 - SRK S.A Kazimierz Juliusz; 22 – JSW S.A. KWK Knurów-Szczygłowice Ruch Szczygłowice; 23 – JSW S.A.KWK Budryk; 24 – PGG S.A. KWK Ruda Ruch Pokój; 25 - KWK Polska; 26 - PGG S.A. KWK Ruda Ruch Halemba; 27 – SRK S.A. Pokój I; 28 – SRK S.A.CZOK Kleofas; 29 – SRK S.A. CZOK Katowice; 30 – SRK S.A. Wieczorek I w likwidacji; 31 – SRK S.A. Mysłowice; 32 – SRK S.A. CZOK Niwka-Modrzejów; 33 – SRK S.A. CZOK Jan Kanty; 34 – SRK S.A. CZOK Dębieńsko; 35 - PGG S.A. KWK Bolesław Śmiały; 36 – SRK S.A. Śląsk; 37 - PGG S.A. KWK Staszic-Wujek Ruch Wujek; 38 – PGG S.A. KWK Staszic-Wujek Ruch

Murcki – Staszic; 39 – Barbara Experimental Mine; 40 – SRK S.A. Boże Dary; 41 – PGG S.A. KWK Mysłowice – Wesoła; 42 – PGG S.A. KWK Piast Ziemowit Ruch Ziemowit; 43 – Tauron Wydobycie ZG Sobieski; 44 - KWK Siersza; 45 - PGG S.A. KWK Piast Ziemowit Ruch Piast; 46 – Tauron Wydobycie ZG Janina; 47 – PGG S.A. KWK Czeczott, KWK Piast Ziemowit Storage Tank; 48 – SRK S.A. Brzeszcze – Wschód; 49 – Tauron Wydobycie ZG Brzeszcze; 50 – PG Silesia Sp. z o.o.; 51 - PGG S.A. KWK ROW Ruch Rydułtowy; 52 – KWK Rymer; 53 - PGG S.A. KWK ROW Ruch Chwałowice; 54 – SRK S.A. KWK Anna; 55 – PGG S.A. KWK ROW Ruch Marcel; 56 – PGG S.A. KWK ROW Ruch Jankowice; 57 - SRK S.A. KWK Żory; 58 - SRK S.A. KWK 1Maja; 59 – SRK S.A. Jas-Mos - Rydułtowy I; 60 – JSW S.A. KWK Borynia-Zofiówka Ruch Borynia; 61 – SRK S.A. KWK Jastrzębie (Jas-Mos); 62 – JSW S.A. KWK Borynia-Zofiówka Ruch Zofiówka; 63 – JSW S.A. KWK Pniówek; 64 - SRK S.A. KWK Krupiński; 65 – SRK S.A. KWK Morcinek; 66 - JSW S.A. KWK Jastrzębie-Bzie (where KWK – Coal Mine; CZOK - Central Department of Mine Dewatering)

Figure 4-5. Map with active and abandoned hard coal mines in Poland

Source: based on (Bondaruk et al. 2015; Xevgenos et al. 2020)

After mine closure, there are 3 possible scenarios for dealing with mine water and the drainage system:

- the pumps are switched off and the mine gradually fills with groundwater until it overflows at the surface via a shaft top, an unplugged exploration borehole, a sough, tunnel or adit;
- the mine continues to be pumped to prevent it filling with water and threatening other working mines downdip;
- the mine, or interconnected mine system, continues to be pumped at one locality (or a limited number of localities) in order to prevent uncontrolled outbreaks of water at the surface (Banks et al. 2019).

4.1.2 Determining the parameters for implementing geothermal technology

In order to be able to design a heat pump configuration at the chosen location, an extensive analysis of data on the quantity and quality of the mine water, the temperature of the mine water and the requirements of heat consumers is necessary.

This study presents the information necessary for the selection of the best geothermal system technologies and their subsequent design.

Polish hard coal mines are among the deepest in the world. All hard coal is deep mined at an average working depth of approximately 600m, with some over 1 000m. In the KWK Budryk mine the depth is 129m below ground level

Most of the mines located in the north of the USCB are potentially hydraulically interconnected, either directly or indirectly, by drifts, roadways, boreholes, goaf, or intact coal barriers of limited thickness. Dewatering of mine allow to maintain the level of water in the abandoned mine under the level of the ''over-spill'' connection to the adjacent working mine. This criterion is codified in Polish geological and mining law.

The discharge of mine water into the environment poses a threat to water surface quality due to the high salinity of mine water (after Janson et al., 2009).

In Poland, for management of mine water and dewatering operations in abandoned mines in the USCB is responsible the Central Department of Mine Dewatering (*Centralny Zakład Odwadniania Kopalń* or "CZOK"). CZOK Department was formed in 2001 and is also engaged in the monitoring of mine water levels, the management of discharge water chemistry, and the rationalisation of mine dewatering systems. **Two main systems are used to dewater abandoned mines** (Figure 4-6):

- **SUB – submersible pumping system** – the pumps are installed in flooded shafts. SUB system is automatically monitoring and measured by transducers and recorded by data-loggers.
- **SAT – stationery pumping system** – the pumps are located in an underground plant room in a partially dewatered mine. SAT system is low cost-effectiveness because requires continued ventilation, staffing, and mechanical infrastructure in the shaft and mine.

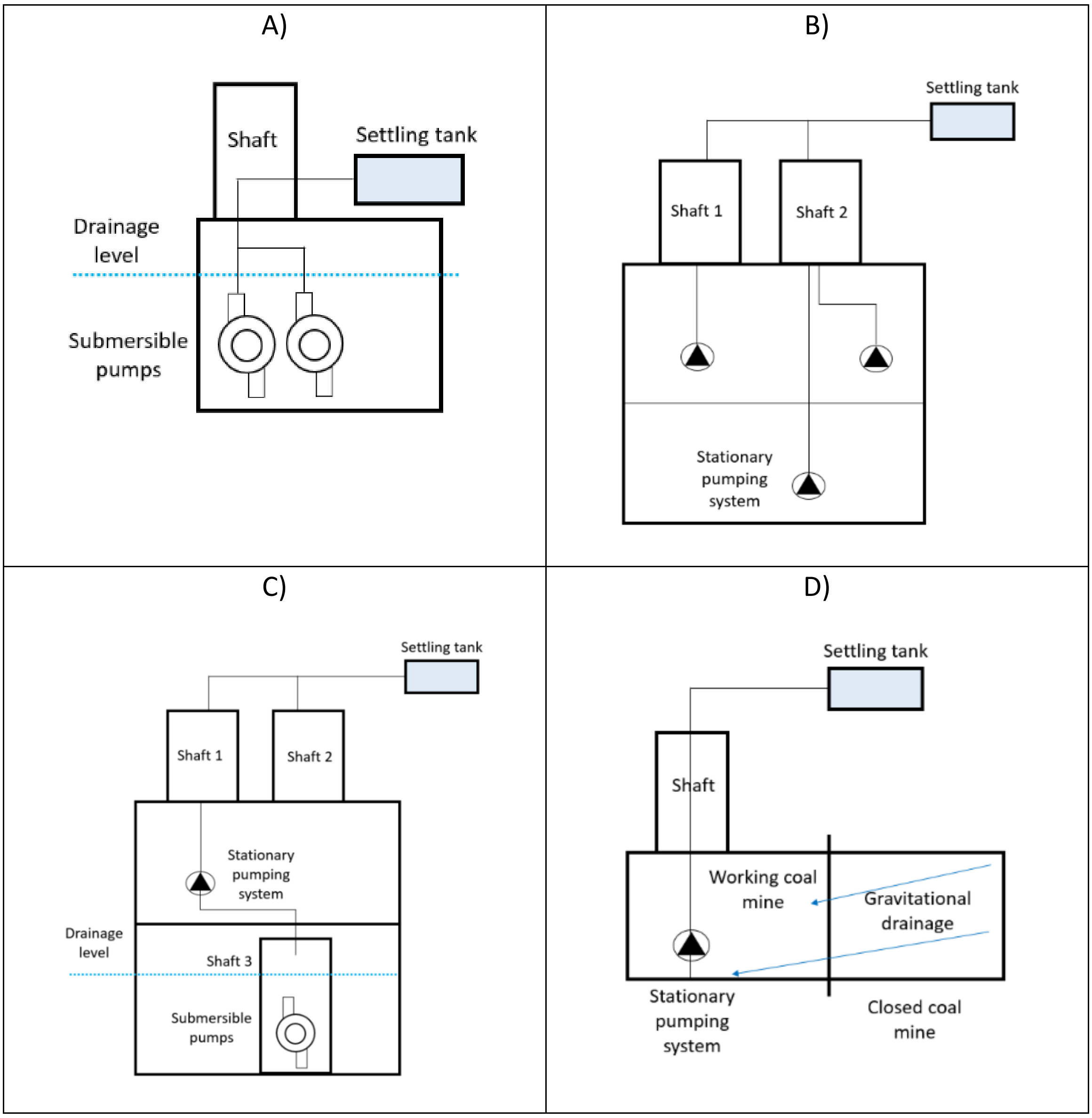


Figure 4-6. Scheme of dewatering systems in abandoned mines A) submersible pumping system (SUB), B) stationary pumping system (SAT), C) mixed, stationary, submersible pumping system (MIX), D) gravitational drainage (GD)

Source: based on (Kropka et al. 2005; Janson et al. 2009)

The depth of coal mines drainages by the CZOK Department varies between 360 – 1160m below ground level (bgl) (Table 4).

Table 4. Characteristics of dewatered coal mines in Upper Silesia Coal Basin: STA stationary pumping station; SUB submersible pumping station; MIX mixed pumping system (submersible & stationary) (Janson et al. 2009; Konsek and Czapnik 2020)

Mine	Mining area	Deepest working	Max. Permissible water level	Water volume in flooded mine	Pumping system	Water pumped from mine			Water inflow	flooding level/ designed flooding level	Temperature °C
Unit	(km^2)	(m bgl/ m asl)	(m asl)	(mln m^3)		(mln m^3/year)			m^3/min	m asl	
						2005	2006	2007	2019	2019	
Saturn	29	700/-430	69	7.5	MIX	9.05	10.63	12.36	25.0	+90	12.2 *(210m level)* 14.4 *(shaft Andrzej)*
Sosnowiec	20.4	450/-200	90	10.2	SUB	2.51	3.45	2.95	14.0 (~12 to Saturn)	liquidated	14.5
Paryż	27	510/-240	50	8.1	SUB	5.48	5.34	5.63		+107/ +140	13.5
Porąbka Klimontów	17.4	550/-270	-190	5.4 *(under water level 200.0 m ASL)*	SUB	2.7	2.53	2.45	4.00	-137/ +180/ liquidated	17.6
Grodziec	33.9	800/-540	90	11.6	SUB	0.03	1.29	0.51	1.85	+90	14.8
Niwka Modrzejów	29.1	910/-660	-145	5.8	SUB	5.52	5.3	4.53	10.00	-145/+136.0	18.5
						2.82	3.02	3.06	4.30	-177.5	
Katowice	8.7	780/-500	-177.5	7.2	SUB		2.54		4.30	340/-294	19.5
Kleofas	15.8	700/-524	-294	0.9	SUB	3.12	3.08	3.17	4.40	-261/-143	18.5
Gliwice	101.7	520/-270	-261.3	0.6	SUB	7.46	7.87	8.69	15.10	-555.0	20.2
Pstrowski	34	1160/-860	-555	1.9 *(under water level 559.0 m ASL)*	STA	1.54	1.57	1.53	8.2 (water inflow	-489.0	18.8

									from KWK Rozbark)		
Szombierki	10.3	950/-690	-498	0.1	STA	1.54	1.57	1.53	2.70	-467.5	24.5
Powstańców Śl. - Bytom I	17.7	650/-470	-467.5	0.5	STA	12.45	12.49	13.27	21.70	-327.0	18 *(500m level)* 26.5 (*760m level)*
Siemianowice	45.9	780/-450	-327	2.5	STA	16.86	17.26	15.34	21.10	+11.9/+30	16.2 *(shaft SIII 321m level)* 23.1 *(shaft Kolejowy 630m level)*
Jan Kanty	30.9	360/-90	11.9	1.3	STA	6	5.62	5.09	9.20	-460.0	11.3 (270m level)
Dębieńsko	46.6	850/-600	-460	0.15 (under water level 506.8 m ASL)	STA						12.3 *(270m level)* 15.7 (*410 m level)* 29.2 *(690 m level)*

The depth of the coal mine affects the temperature of the discharged water (a tendency which is readily observed in mines with stationary pumping systems at discrete levels). The USCB has an annual mean air temperature of around 6.9°C, while monthly 24 h means range from −3.9°C (in January) to 17.5°C (in July). Pumped mine water temperatures range from 11.3 to 29.2°C, generally increasing with depth. For example, in the KWK Dębieńsko, the temperature of water pumped from the level of 270 m is 12.3°C, and from the level of 690m has a temperature 29.2°C (Table 4). The coal mines in the USCB are located in urban areas (where there is a demand for space-heating and cooling), so the mine waters have a high potential for ground source heating and cooling via the use of heat pumps.

In Poland 3 methods of dewatering are used in liquidated mines:

- **Submersible drainage system (SUB)**: This is used in mines where they were hydrogeological conditions for damming up water to a certain depth. Down dewatering uses a single shaft with one or more pumps,
- **Stationary drainage system (STA)**: Its operation requires maintaining underground and surface technical infrastructure, at least one or two shafts and roadways on one or more levels,
- **Gravitational drainage (GD)**: It consists gravitational flow of water from a flooded mine to a surface watercourse or an adjacent mine or the CZOK pumping station. For example: from KWK Jowisz to ZG Piekary, from ZG Bytom II and KWK Rozbark V to PS Szombierki (Konsek and Czapnik 2020).

In the last 10-20 years, the drainage systems of liquidated or closed mines have changed. The gravitational transfer of water from one mine to neighbouring mines has reduced the total quantity to be pumped (Konsek and Czapnik 2020). For example, in 2015, the amount of water pumped by submersible drainage system was about 32.8 mln m^3, while in 2019 it was about 26.2 mln m^3. In the stationary drainage system, approximately 39.1 mln m^3 were pumped in 2015 and approximately 40.1 mln m^3 in 2019. In 2015-2019, the amount of water pumped by submersible pumping and stationary system decreased by about 5.7 mln m^3.

The volume of water flowing into the mines in Poland is ca. 412 m^3/min and the annual volume of pumped mine water is ca. 217 m^3/year (Table 5).

Table 5. Amount of water inflow and pumped water in active and abandoned mines in Poland (Philpott 2002; Lubelski Węgiel Bogdanka 2016; Konsek and Czapnik 2020)

Company	Number of mines	Water inflow (m^3/min)	Amount of pumped water (mln m^3/year)
ACTIVE MINES			
Polska Grupa Górnicza Sp. z o.o. (PGG)	8	134.3	70.58
Tauron Wydobycie S.A. (TW S.A.)	3	86.0	45.22
Jastrzębska Spółka Węglowa S.A. (JSW S.A.)	5	8.8	4.63
PG Silesia	1	4.1	2.14
ZG EKO-Plus	1	0.3	0.16
ZG Siltech	1	0.5	0.27
Lubelski Węgiel Bogdanka S.A.	1	3.0*	2.0**
Total active mines	**20**	**~235**	**~125**
ABANDONED MINES			
SRK S.A.	9	48	24.60
CZOK	13	128	66.4
Total abandoned mines	**22**	**168**	**91.0**
TOTAL	**42**	**~412**	**~217**

Heat recovery from mine water is based on a heat pump system. The cost-effectiveness of installing heating systems increases in areas with high ecological requirements.

Mining areas of hard coal mines affect the catchment area of watercourses in the USCB, including in particular the basins of the Upper Oder and the Lesser Vistula. 15%

of surface water bodies in Little Wisla and Upper Odra water region have a bad status due to the mine water discharges (Gzyl et al. 2017).

Implementation of a geothermal system based on mine water can be a solution to both environmental problems related to the discharge of mine water into the environment and play an important role in the development of geothermal energy in Poland.

However, effective implementation of geothermal systems for mine water requires a thorough re-modelling of the mine drainage system.

The drainage model of mines in Poland was developed in the 1990s. This model is based on direct and indirect hydraulic connections between mines. The lowest so far direct connections, determine the permissible level of flooding and dewatering in several submersible water pumping stations (SUB) CZOK. Often because direct connections, a stationary system was left in the liquidated mine dewatering (STA). The new developed model assumes that the method of dewatering a liquidated mine should be chosen after the analysis of:

- the possibility of directing water to the neighboring dewatered mine,
- existence of active excavations connecting the liquidated mine with the neighboring one dewatered,
- cost of construction and operation of SUB, STA,
- period of necessary mine dewatering (Konsek and Czapnik 2020).

A new plan for dewatering of mines has been developed by the CZOK Department to reduce of the amount of water pumped, cost of pumping mine water and for implementation of the geothermal methods based on the central pumping stations.

It was done a preliminary study for determination of possibility to use mine water for heating of houses and public utility buildings. The mines with the greatest potential for geothermal implementation were identified, taking into account both technical aspects (water volume, water temperature) and the geothermal heat demand in the surrounding area (public buildings, schools, houses). The selected mines are as follow:

- Pumping Station Saturn - extension of the heating system to the municipal buildings in Czeladź.
- Jan Kanty pumping station in Jaworzno - residential, commercial and public utility buildings, public buildings.
- Pumping Station Kleofas in Katowice - buildings located in the vicinity of the pumping station pumping station.
- Siemianowice pumping station - on the premises of the Mining and Metallurgy Tradition Park in Siemianowice Silesian Pumping Station.

- Dębieńsko pumping station in Czerwionka-Leszczyny - heating of houses and public utility buildings heating of houses and public utility buildings.
- Niwka - Modrzejów pumping station - residential buildings and public utility buildings public buildings.
- KWK Nowa Ruda - in the area of the Nowa Ruda Industrial Park, commercial and public utility premises, commercial and public utility buildings using water from the CZOK Pumping Station.

A model system for mine drainage was implemented at KWK Saturn as part of the REMINING - LOWEX (Revitalisation of European Mine Areas). It was build the first pilot central heating system using the lower source of heat from pumped mine water in KWK Saturn mine, which is extracted by pumping. In 2011, the dewatering system was upgraded from a stationary system to a submersible system. As a result two main drainage pumping stations and one pumping station were removed, approximately 6.0 km of excavations and two shafts were closed down. For the first time, the shaft was completely decommissioned by backfilling with dry concrete. The waters are pumped to the surface via the Paweł shaft. In 2012, 7.94 million m^3 of water were pumped out, i.e. approximately 15.1 m^3/min. The annual temperature of pumped water is ~13°C. The mine water is characterised by mineralisation of less than 2.0 g/l, sulphate ion content of less than 0.4 g/l and chloride ion content of less than 0.2 g/l, while maintaining a constant water table. The heat energy from pumped water is used to heat the building of the Department CZOK in Czeladź, located near the Paweł shaft (Tokarz and Mucha 2013).

In the case of implementation of a similar project using mine waters from deeper pumping stations, where the temperature of pumped water often reaches 26°C, the energy gain and environmental effect will be greater.

The new mine drainage plan for Poland envisages the creation of nine drainage districts and equipping each of them with a central mine water pumping station. The following table (Table 6) shows the planned water transfer from the individual active and abandoned mines to the central pumping stations.

Table 6. Projected regionalization of mine drainage in the USCB based on data from 2019. Adapted by (Konsek and Czapnik 2020)

No. of district	Active, abandoned or flooded mines	Central pumping station (CPS) (SAT/SUB)	Estimated inflow to CPS [m^3/min]
1	CZOP: SAT Jan Kanty TW S.A.: ZG Sobieski	Sobieski (SUB)	~81
2	CZOP: Saturn, Paryż, Sosnowiec (GD), Porąbka-Klimontów (GD) SRK S.A.: Kzimierz Juliusz (GD)	Saturn (SAT)	~40
3	CZOP: Siemianowice	Chorzów (SUB)	~22
4	CZOK: Grodziec, Szombierki, Powstańców Śl.-Bytom I, Pstrwoski, Jowisz (GD) SRK S.A.: Centrum, Rozbark, Piekary I, Bobrek-Piekary (GD)	Centrum (SAT/SUB)	~45
5	CZOK: Gliwice, Kleofas SRK S.A.: Makoszowy, Pokój I Śląsk PGG S.A.: Sośnica, Wujek, Ruda	Halemba (SAT)	~40
6	CZOK: Katowice, Niwka-Modrzejów SRK S.A.: Dary-Boże-Mysłowice-Wesoła I, Wieczorek II PGG S.A.: Mysłowice-Wesoła, Murcki-Staszic	Wesoła (SAT)	~45
7	PGG S.A.: Piast-Ziemowit TW S.A.: Janina	Piast (SAT)	~71
8	CZOK: Dębieńsko PGG S.A.: Bolesław Śmiały JSW S.A.: Knurów, Budryk	Budryk (SAT/SUB)	~33
9	SRK S.A.: Jas-Mos-Rydułtowy I JSW S.A.: Borynia-Zofiówka-Jastrzębie PGG S.A.: ROW, Pniówek	Jankowice (SAT)	~11

Methods of generating thermal energy from mine water are based on the use of heat pumps employment of subcritical cycles heat pumps in conjunction with open or closed geothermal loops. In most cases, the choice of design of geothermal loop systems depends on the quality of the mine water (suspended solids, pH or hardness). In the case of low-quality mine water, it is recommended to install a heat exchanger inside the underground reservoir in a closed loop system. Once the thermal exchange has been carried out, the clean water circuit enters the heat pump to transfer the thermal energy. If the mine water quality is good, it is preferable to install an open-loop system.

In the dewatered area of the USCB, there is a general tendency for increased ground water mineralisation with depth. The concentration of anions changes in the following order HCO_3^- → SO_4^{2-} → Cl^-. Down to a depth of 650 m, both fresh and brackish groundwater is present, with mineralisation up to 4.5 g/L (Różkowski 2006; Janson et al. 2009). During the process of closing mine, accumulated sulphide oxidation products (mainly pyrite) are leached into the mine water, usually causing a large increase in iron and sulphate concentrations (Janson et al., 2009). Total iron in unfiltered, acidified mine water sampled from the USCB coal mines ranges from 0.18 to 39 mg/L (Gzyl and Banks 2007). Often during the post-flooding period it could be observed the increasing concentrations of Zn, Pb, Cu, (e.g. zinc concentrations increased from <0.3 to 17.8 mg/L during the flooding of the Porąbka Klimontów mine). Zinc concentrations was typically between <10 and 300 µg/L in the mine waters pumped by CZOK in 2007-2008. Lead concentrations ranged from <10 to 4.68 mg/L, copper from <10 to 350 µg/L, and nickel from <10 to 920 µg/L. Chromium was consistently <10 µg/L (Janson et al. 2009).

5 Demosite Installation. Main economic/technical characteristics

5.1 Demosite installation

Resource assessment is the first step in any project. The projects we will discuss here are designed to be carried out in closed and flooded mines. In the specific cases of HUNOSA, which we will discuss later, we will see that in the developments carried out to date. It is necessary to pump the water that floods an already closed mine to maintain a sure water table to avoid causing problems for the nearby population.

The first step in assessing the resource is to know the amount of water available, its variability over the year and its variation over several years. Usually, a mine has historical pumping records that allow this to be known. The search for customers is conditioned by knowing how much flow and in which periods it is available for a geothermal project. It is also interesting to see the flexibility of the system to estimate the maximum power available, i.e. to determine to what extent we can concentrate pumping at a given time without compromising the mining aquifer, neither in the volume of accumulated water nor in temperature or quality.

In situations like the one mentioned in the HUNOSA projects (compulsory pumping to maintain a stable water table), there may be a loss of resources, as it may be necessary to pump to keep that level without the corresponding amount of energy being demanded at that time. These situations should be assessed with all historical pumping data and estimated energy demand data from customers.

Temperature and flow rate are other important aspects when designing the installation (mainly heat exchangers and coolers). Its value should be recorded once the mine is flooded, and it is advisable to make measurements over a whole year to see the seasonal variation. If possible, it is also advisable to monitor over several years.

It is also essential to know the connections between the different mining operations and the suspected communications with other water tables that may contribute (or withdraw) water from the system. Water inputs can increase capacity, but in return, if there are inputs from surface levels, this can lead to decreases in temperature. Therefore, a hydrogeological study is essential.

Water quality is another aspect to consider, especially if we have water with substances that can damage pumps, pipes or exchangers.

Survey of potential customers

Potential customers should be sought in the immediate vicinity of the mine. There is no critical distance; it all depends on the type of customer and the business plan results concerning that customer. So, if we have a large consumer of heat and cold, we can afford to go to more distant places if the economic numbers are favourable.

The distance factor also involves other aspects, such as impediments to crossing streets, roads, railways, rivers, etc., and the relevant permits from the different administrations involved. All of these can contribute to making access difficult for some customers.

As far as customers are concerned, it is imperative to know their total consumption, whether this consumption is only heat or heating and cooling, and the distribution over time, not only annually but also weekly and daily, being crucial for sizing and optimising the installation.

So, for example, we can have one customer who consumes heat from Monday to Friday in the mornings (e.g., a secondary school) and another customer who consumes heat preferably in the evenings from Monday to Friday and at the weekend for most of the days (e.g., a residential building). If both installations require a power of 0.5 MW, our facility does not need to have 1 MW, as there will be hardly any simultaneous consumption. Therefore 0.5 MW would be sufficient, thus saving money on the equipment of our installation.

Therefore, it is interesting to find customers that compensate for the consumption, following the previous example.

It should be taken into account that the previous installation of the building (usually natural gas), which existed before the implementation of geothermal energy, is generally maintained. This installation will act as a backup in case anomalous consumption peaks or a breakdown of the geothermal system.

Technology to be used

Below we will describe the elements involved in a geothermal energy installation according to the experience of the projects developed by HUNOSA in recent years.

Pipelines

There are two types:

- High-density polyethylene (PE100).

The PE100/PE100RC high-density polyethylene pipes are designed under different Standard Dimension Ratios (SDRs), offering a wide range of installations thanks to their high performance.

Their most common applications are:

- Transfer of drinking water and industrial fluids.
- Air conditioning.

- Buried fire-fighting networks.
- Industrial refrigeration.

They are very competitive pipes due to their chemical and mechanical characteristics. Their main advantages are:

- High durability.
- Less surface roughness.
- High corrosion resistance.
- High resistance to the chemical products of industrial wastewater.
- Available in a wide range of thicknesses and pressures with accessories and equipment to create a complete system.
- Lightweight and flexible for easy and cost-effective transport, handling, and installation.
- Carbon black additive for UV resistance.

As with polypropylene pipes (PPR), it can be joined using various welding systems, such as socket welding, electro-welding and butt welding, and mechanical and threaded joints.

As with PPR, diameters up to 160 mm are standard, although larger diameters are available on request. The recommended working temperature range for polyethylene is from -40°C to 60°C. It is a very low temperature-resistant material, which makes it very versatile.

- Polypropylene random (PP-R)

They offer many advantages and are currently used, for example, in installing boilers, radiator connections and solar heating systems. They are increasingly used in private homes and buildings such as hospitals, schools, hotels, factories, etc., as they are ideal for transporting hot and cold water. Some of their most essential characteristics are:

- Excellent thermal insulation and low thermal dispersion.
- High resistance to high temperatures.
- High support rates at high pressure.
- They are suitable for transporting both hot and cold water.
- Long service life at total capacity, estimated at more than 50 years.
- High elasticity and enormous impact resistance.
- Acoustic and thermal insulation.
- Low-temperature loss during liquid transport.
- They have a completely smooth interior, favouring a low load loss.
- Commercial diameters up to DN160. Larger diameters on request.
- They guarantee non-toxicity.

- They prevent the growth of micro-organisms that could compromise the potability or healthiness of the water.
- They do not form corrosion. The corrosion barrier prevents water from retaining its properties even when transporting alkaline or acidic liquids and substances or those with a high level of chlorine or iron.
- They also do not conduct electricity, so they cannot be affected by stray electrical currents.
- Installation is clean, simple and cheap, as the pipes weigh little and it is not necessary to spend much money, neither on transport nor on the number of workers needed to handle them.

o Types of welding of plastic materials (PE and PP-R).

Three types can be distinguished: butt welding, socket welding and electrofusion welding.

- Butt welding consists of welding the pipes (face to face) and does not require additional fittings to make this joint. This type of welding is most commonly used for large diameters, from 140 or 160 mm and above.
- Socket welding is possibly the most widely used, especially up to 125 mm diameter, as the fittings used are not too expensive and the welding is quicker and easier to perform.
- Electrofusion welding is the type of welding that is perhaps the least used nowadays, but it is still a welding method with all the guarantees. For this type of welding, we need electrofusion sockets and accessories.

The main problem of welding with this type of pipe is that the welding procedures have to be carried out with great care and meticulousness, as the welds have to be very precise in order not to have leaks in the future.

If the welds are well done, and all the parameters and standards indicated in each one has been respected, we can be sure that any of the offers meet all the guarantees for long-lasting installations.

o Pre-insulated rigid tubes:

These are manufactured from St37 carbon steel. This range of pre-insulated pipes is supplied for typical district heating and cooling applications in lengths of 6 or 12m and is characterised by

- The wide range of sizes from DN20 to DN1200.
- The variety of fittings to realise any routing.

- The thermal insulation of high-density PUR foam with a lambda of 0.027 W/mK, firmly bonded to the service pipe and the enclosure forming a composite material giving mechanical strength and, simultaneously, minimal heat loss.
- The service temperature is up to 120°C.
- The leak detection system with an accuracy of +/- 1m.
- The joint kit for insulating and sealing the joints. The joints are made by conventional carbon steel welding.
- The range of tubes with one or two under the same housing.
- The possibility to adapt to industrial applications requiring unique fabrication.
- The complete system that provides a professional and reliable solution.

<u>Heat exchangers</u>

There are two main types:

- Plate heat exchangers.

The plate heat exchanger consists of a series of parallel-arranged corrugated metal plates fixed in a steel casing and separated by gaskets. These grooves create turbulent flows in the heat transfer fluid, even when the fluid's velocity is low. A different fluid (to which the heat is transferred) must flow in parallel or countercurrent on each side of the plate. However, some manufacturers recommend countercurrent so that thermal stresses are not generated in particular areas. The plate heat exchanger can be "compact", designed to facilitate a larger heat transfer surface area, and "regenerative", a type characterised by passing a cold fluid that removes the heat accumulated in the solids before thermal equilibrium is reached. This is achieved by modifying the flow rates. The plate heat exchanger can be installed when NH_3, CO_2 or glycols are used as refrigerants. Its main characteristics are

- Low initial purchase cost.
- There are many configurations to choose from, being adaptable to the power conditions of the installation by adding or reducing the number of plates.
- Higher heat transfer efficiency.
- Reduced fouling due to the high turbulence of the heat exchanger.
- Significant temperature crossover can be achieved.
- Reduced size.
- Narrower allowable pressure and temperature ranges.
- Narrow flow paths are prone to clogging or fouling.
- Units with gaskets require special opening and closing procedures.
- Due to the thin tube wall, the choice of material is critical.

- Tubular heat exchangers.

Also known as shell and tube heat exchanger or tubular heat exchanger. It is widespread in industry and often goes hand in hand with NH3-oil systems, for example. It consists of a large capsule (shell) containing a variable number of tubes, which are put in place by a perforated baffle plate. However, this has another function: to cause a turbulent cross-flow of the fluid flowing through the casing to improve convection. If the fluids have very different pressures, the fluid with higher pressure flows through the inside of the tubes, while the fluid with lower pressure flows through the casing. The reason for this arrangement is that the tubes can withstand higher pressures. The tubes can be arranged in squares (easier to clean and lower pressure drop on the casing side), in turned squares (same advantages) and in triangles (larger contact surface, but more difficult to clean). In addition, they can be single-pass or multi-pass, depending on the specific needs of the installation. Evaporators (horizontal or vertical tube evaporators) are, in reality, a tubular heat exchanger, as they have a heating chamber and an evaporation chamber divided by the surface of the tubes where the heat exchange takes place. Designed for pressures above 30 bar and temperatures above 260°C, they are used for high-pressure applications. Their main characteristics are:

- Widely known and understood.
- High resistance to fouling and fines accumulation.
- The most common type of heat exchanger service.
- Extensive pressure and temperature range.
- Robust mechanical structure.
- Heat exchange efficiency is lower than other types of heat exchangers.
- Subject to flow-induced vibrations.
- Not suitable for crossover temperature conditions.
- Contains stagnation zones on the shell side which can lead to corrosion.
- Uneven flow distribution.

An important concept when choosing and sizing a heat exchanger is power, the amount of thermal energy per unit of time the heat exchanger can transfer.

<u>Chillers/heat pumps</u>

Heat pumps are electrically driven machines characterised by extracting heat from the environment (air or water) and transporting it to a warmer space by means of a thermodynamic process, displacing the thermal energy in the opposite direction. There are three types of heat pumps:

- Air-to-air heat pump.
- Water-to-water heat pump.
- Air-to-water heat pump.

The choice of the appropriate heat pump for the installation will depend on the primary and secondary circuit fluid (air or water), the type of refrigerant to be used, the thermal power of the facility and the operating temperatures, both in the evaporation and condensation circuits. Heat pumps can operate up to temperatures of 85°C, although the best performance is obtained at lower temperatures.

Water-to-water heat pumps are most commonly used in geothermal installations with mine water. However, they are often referred to as coolers instead of heat pumps. The fundamental difference is that a cooler cannot reverse the circuit from heat to cold internally. Any change must be made externally in the circuits connected to the cooler. Coolers are usually also higher power machines.

Mine water extraction pumps

The main selection criteria that will define the characteristics of the pump are:

- The quality of the pumped water, which can be clean (impurities ≤ 5 mm), loaded (impurities ≤ 20 mm) or heavily loaded (≥ 20 mm).
- The discharge head, i.e. the head between the submerged pump and the discharge point.
- The geometric head represents the head between the water level and the discharge point.
- The length of the discharge pipe connecting the pump to the discharge point.
- The immersion depth corresponds to the maximum water level (m) that the pump can handle.
- The minimum water level, measured in millimetres (mm), mainly for dewatering pumps.
- The desired outlet pressure.
- The desired flow rate, expressed in litres/second (l/s);
- The temperature of the pumped liquid, expressed in degrees Celsius (°C);
- The head losses concerning the length of the discharge hose and the various elements.

Therefore, to determine the head, i.e. the total resistance to be overcome by the pump for a given flow rate, the geometric head, the total head loss and the desired outlet pressure shall be added together.

In the presence of abrasives (sand), it is recommended that the pump be jacketed, limiting the suction of abrasives. The most common types of stainless steel are 304 and 316. The main difference is the addition of molybdenum (316 steel), an alloy that significantly improves corrosion resistance, especially in more saline environments or those exposed to chlorides.

In HUNOSA's installations, the number of pumps is doubled so that there is always a backup pump in case of failure.

Most common types of breakdowns in mine water pumps

The most common failures affecting submersible pumps are those related to insulation and sealing and those related to temperature rise (overload).

- Insulation faults occur when live parts of the pump's electrical circuit that should not be in contact with the fluid come into contact with the fluid. This is due to a deterioration of the pump's power supply cables or pump seals. To avoid this type of failure, extreme care must be taken when introducing the pump into the wells so as not to damage the cable or any seals. It is recommended that when carrying out maintenance operations on the pumps, the state of the seals should be observed, changing them at the slightest sign of deterioration, as they are usually inexpensive spare parts.
- Failures due to temperature rise, which are detected by thermal probes installed in the pump's electric motor, can have several causes:
    - Wear of the impeller elements: wear of the pump impellers leads to a decrease in the pump's evacuation power, which leads to a decrease in the flow rate and, thus, in the pump's cooling, resulting in overheating.
    - Blockage of the pump suction: this leads to a decrease in the flow of water entering the pump, which reduces its cooling and therefore causes an increase in the working temperature. To avoid this type of failure, the casing is essential.
    - Accumulation of overloads: poor sizing of the pump can lead to periodic overloads. These overloads will cause the pump's electric motor to overheat, progressively deteriorating until total failure occurs.

Flexible pipelines in mine water extraction pumps

The self-supporting flexible piping dramatically simplifies the installation of the pumps while facilitating their removal.

- The flexible piping system allows considerable savings in transport and storage costs, and its manoeuvrability and ease of installation reduce the time and labour required for assembly and disassembly.
- Its flexibility and light weight facilitate packaging, transport and storage. It is quick to install and retrieve and does not require pump support cables, making assembly and disassembly difficult.
- Thanks to its expansion, the pipe absorbs the water hammer produced by sudden pressure changes.
- High durability and low wear
- It has a low head loss, which results in lower energy consumption for each desired flow rate.

- It is manufactured in a continuous section and can be installed in deep and narrow wells without joints, allowing the total diameter of the well to be used.
- It has centring devices, allowing it to be installed in inclined wells.
- Exposure to aggressive water, salt water, hydrocarbons, oils, and grease does not affect the hose's performance.
- It is limited to a depth of 250m for the conventional type and can reach 350m in unique mining models.

For its installation, it is necessary to use support rollers to avoid contact with the pipe with sharp edges that can deteriorate the most superficial layers and reduce its useful life. It is also possible to use special winches that allow the pipe to be wound onto the drum, but they are pretty bulky and expensive, as they are concrete equipment.

5.2 Main economic/technical characteristics

To establish the main economic characteristics, we will use the data from Hulleras del Norte, S.A. (HUNOSA), the only coal mining company in which it was possible to collect financial information.

Two district heating were developed by HUNOSA for the geothermal use of mine water. Both are linked to urban wells in Langreo and Mieres, two towns of about 40,000 inhabitants in the Central Asturian Coal Basin.

5.2.1 District Heating Fondón

It uses water from the Fondón well, located in Langreo (Figure 5-1), connected to the Candín well. Together, some 1.7 hm^3 are pumped annually. The water has a temperature of 23°C, which is constant throughout the year. The district heating of Fondón came into operation this year, 2022.

Figure 5-1. A photograph of Fondón pit

The water is pumped by four submersible pumps of 30 kW (180 m3/h) located between 95 and 100 m depth, connected to the outside with a flexible pipe. The water level to be maintained for safety reasons is 45 m below the surface.

Once the water has been extracted, we pass it through a 1 MW SARCOME tube exchanger, consisting of two 6m long units arranged in series. This exchanger transfers the heat to a secondary clean water circuit called the evaporator (Figure 5-2).

All the pipes connecting these circuits in the generating room are made of St37 carbon steel.

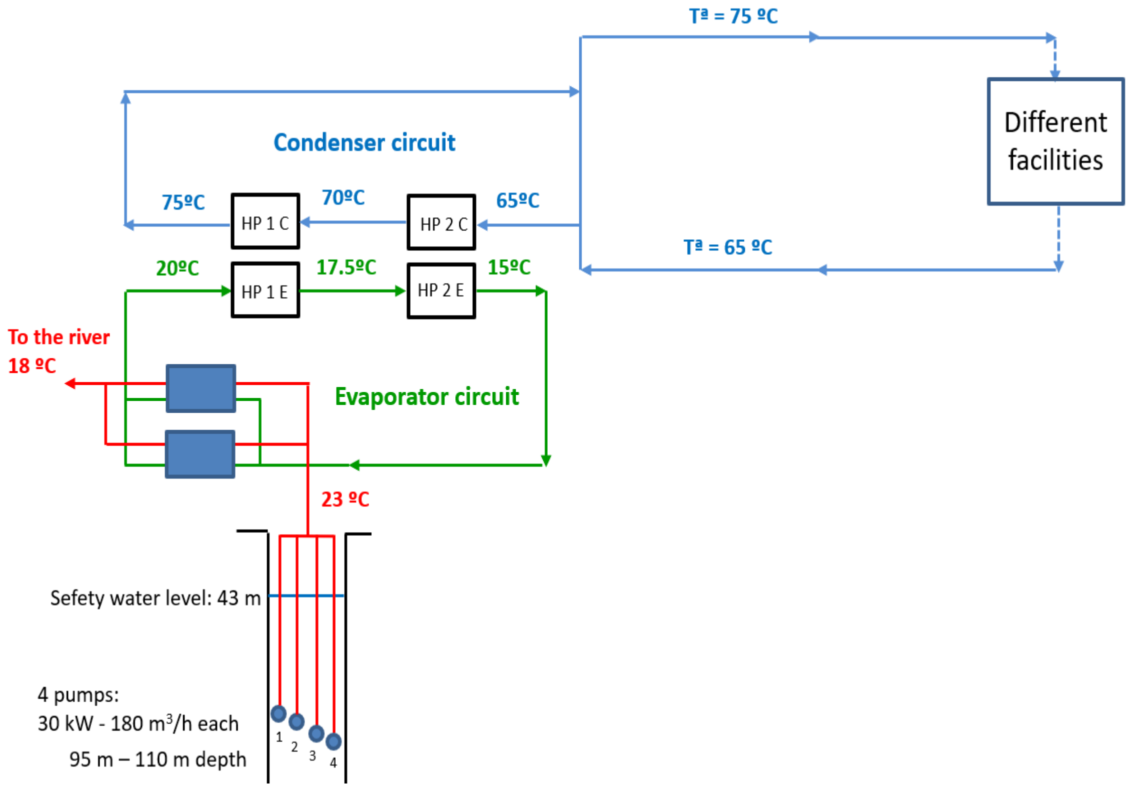


Figure 5-2. Conceptual scheme of the geothermal system. Power and energy supply (estimated data for 2022)

The evaporator circuit is connected to two chillers connected in series and countercurrent. This type of connection optimises operation and provides better equipment performance. The chillers raise the temperature of the condenser circuit to the setpoint temperature required by the customers. The coolers are water-to-water, CARRIER brand. One has a single 484 kW compressor, and the other has two 484 kW compressors. Each compressor can be modulated in power, starting from a minimum of 193 kW. In total, we have an available capacity of 1.45 MW.

The district heating system in Fondón supplies heating and domestic hot water to several customers (Figure 5-3): a sports centre, a hotel, an older people's home, a health centre and a block of flats. The demand is always high temperature, as the customers have high-temperature heating systems installed. The production set point (approx. 75°C) is determined by the hotel and the nursing home, which require the highest and most constant temperature all year round. The heat is supplied via a pre-insulated carbon steel DN200 return pipe. The connections to the various customers are made via DN65 pipes, except in the residential block, which is DN50. We use carbon steel pipe instead of PE or PP-R because the system is prepared to supply at high temperatures (more than 80°C), so it is much more convenient to use this type of pipe, although it is more expensive. This pipe also allows the coupling of a leak detection system.

In each customer's building, there is a substation consisting mainly of the following:

- Incoming flow control valve (in the primary circuit).
- Temperature probes (in the primary and secondary circuits).
- Heat meter (in the primary circuit).
- Plate heat exchanger. Heat transfer from district heating (primary circuit) to the building's pre-existing thermal installations (secondary circuit).
- Booster pumps (in the secondary circuit).

Figure 5-3. Map of customer locations

The total cost of District Heating Fondón was 2,235,360 €, from which 1,136,215 € corresponded to a FEDER subvention.

As said before, the heating generation plant was of 1.45 MW, with a total installed power (heating) of 2.5 MW to provide heating to a sports centre, a hotel, an older people's home, a health centre and a block of flats. The investment was relatively high because complex infrastructures were needed to heat these buildings.

Figure 5-4 presents the detailed installed power (kW) and thermal energy supplied (MWh) for the different buildings. The thermal energy provided (total heating) in 2022 was 3,448 MWh. The reduction of emissions was estimated at 887 t CO_2.

		Installed power (kW)	**Thermal energy supplied (MWh)**
Sport Centre	heating (generation plant) 1.45 MW	1,000	1,715
Health Centre		500	299
Hotel and Geriatric Centre		800	1,302
Residential building		200	132
Total heating		**2,500**	**3,448**

Figure 5-4. District Heating Fondón installed power and thermal energy supplied in 2022.

5.2.2 District heating Barredo

It uses water from the Barredo well, located in Mieres (Figure 5-4), which is connected to a series of wells found upstream in the Turón valley (Figaredo well, San José and Santa Bárbara well). Together they pump about 4 Hm^3 per year. As in El Fondón, the water has a temperature of 23°C, constant throughout the year. The Barredo district heating system came into operation in 2020.

However, as previously described, several earlier geothermal installations are also linked to the Barredo well but are not part of this district heating system. These installations supply heat and cold to the Álvarez Buylla Hospital, the Asturian Energy Foundation and the Research Building of the University of Oviedo (Mieres Campus).

Barredo mine is connected hydraulically with other mines and was in operation from 1937 till 1995. The depth of the mine is 355 m with five levels. The annual pumped water from Barredo Colliery is approximately 4 Hm^3, while the total pumped water in HUNOSA is 35 Hm^3.

Figure 5-5 presents the Barredo pit.

Figure 5-5. Photograph of the Barredo pit.

5.2.2.1 Barredo Colliery. The first phase (2014-2016)

The geothermal installation developed during the first phase in the District Heating Barredo Colliery had an investment cost of 1,452,157 €, corresponding to a heating generation plant of 3.8 MW.

It was designed to provide heating and cooling to three emblematic buildings in the village of Mieres (Asturias, Spain):

1. Mieres Hospital.
2. Research building of the University of Oviedo.
3. Asturian Energy Foundation (FAEN), which is also a partner of GreenJOBS.

Figure 5-6 presents the first phase of the geothermal installation of Barredo Colliery. It uses four submersible pumps of 75 kW – 215 m^3/h each. Three pumps are located at 85-100 m depth, and the fourth is 130 m deep. The water level to be maintained for safety reasons is 35m below the surface. The water temperature in the mine is 23 ºC. The water returned to the river temperature is at 18 ºC; the water sent to the heat pumps temperature is at 20 ºC, and the water returned to the heat pumps temperature is at 15 ºC

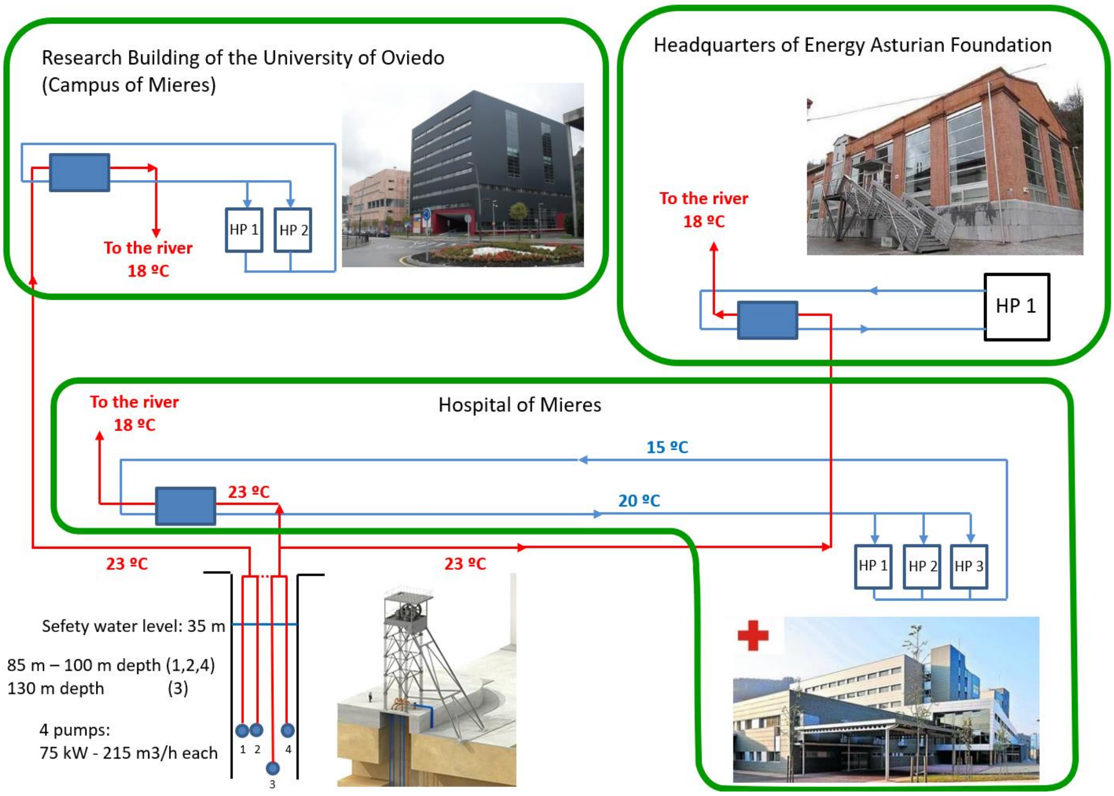


Figure 5-6. Geothermal energy. First phase.Barredo Colliery

The installed power was divided into 4,650 kW for heating and 3,630 kW for cooling.

For 2021, as presented in Figure 5-7, the total energy supplied for heating was 5,058 MWh, and for cooling was 2,063 MWh. The estimated reduction of CO_2 emissions was 1,567 t.

		Installed power (kW)	**Thermal energy supplied (MWh)**
Hospital of Mieres	heating	3,800	4,797
	cooling	3,000	2,063
Research building UO	heating	725	241
	cooling	530	0
Asturian Energy Foundation	heating	125	20
	cooling	100	1
Total heating		**4,650**	**5,058**
Total cooling		**2,500**	**3,448**

Figure 5-7. Installed power and thermal energy supplied (2021) in the first phases of District heating Barredo

5.2.2.2 Barredo District Heating. The second phase (2020)

In the District, the water is pumped by two submersible pumps of 90 kW (330 m^3/h) located at a depth of 85 and 95m, connected to the outside with a flexible pipe. The water level to be maintained for safety reasons is 35m below the surface.

Once the water has been extracted, we pass it through a 2 MW tube heat exchanger, CEYMAR ENERGY WORLD brand, consisting of three 6-metre long units in series. This heat exchanger transfers the heat to a secondary clean water circuit called the evaporator (Figure 5-9).

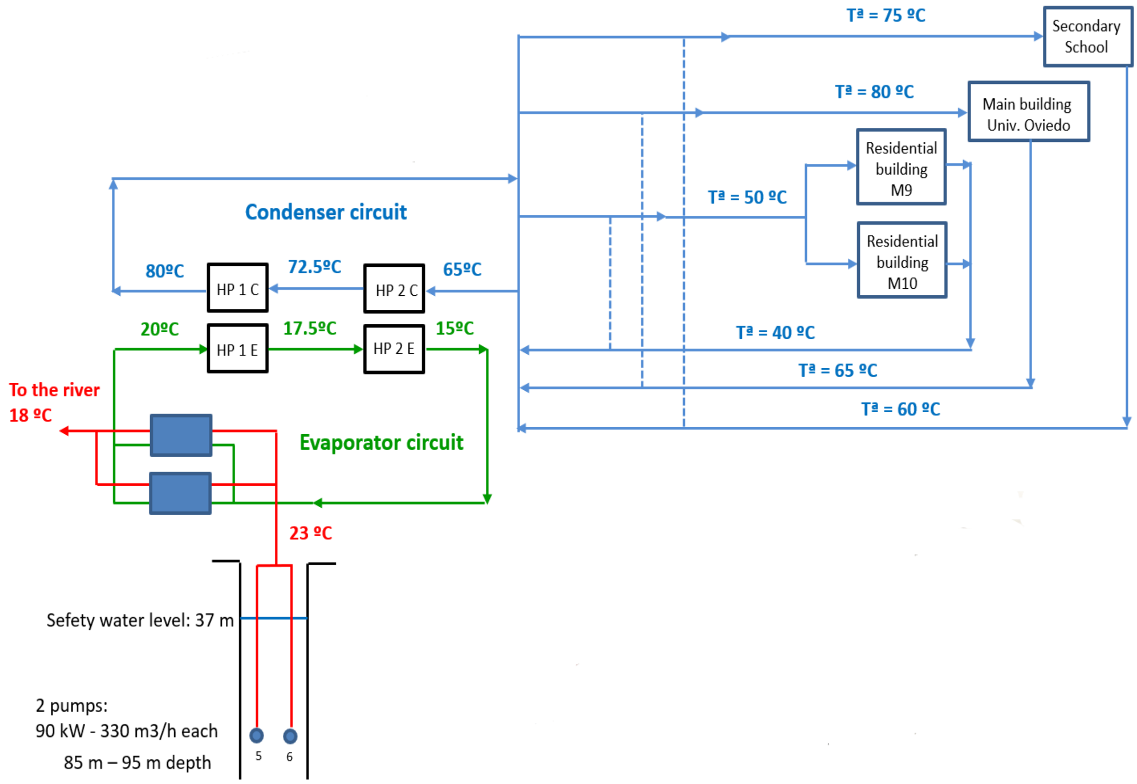


Figure 5-8. Conceptual scheme of the geothermal system. Power and energy supply (2021 data)

All the pipes connecting these circuits in the generator room are made of St37 carbon steel.

The evaporator circuit connects two coolers connected in series and counter current. This type of connection optimises operation and provides better equipment performance. The coolers raise the temperature of the condenser circuit to the setpoint temperature required by the customers. The coolers are water-to-water, TRANE brand. Each cooler has four 250 kW compressors capable of modulating power from a minimum of 125 kW. In total, we have an available capacity of 2 MW.

The Barredo district heating system provides heating for several customers (Figure 5-6): the main building of the Polytechnic School of Mieres (University of Oviedo), a secondary school and two blocks of flats. Unlike the district heating system in Fondón, the district heating system in Barredo has two types of supply depending on the temperature demand. A high-temperature line for customers with high-temperature heating systems installed (Mieres Polytechnic School Building and Secondary School) and a low-temperature line for two blocks of flats with low-temperature heating systems.

The heat is supplied employing a PP-R supply pipe and a return pipe with variable diameters depending on the client. DN160 was used for the main building of the University and the residential blocks, while DN90 was used for the Secondary School.

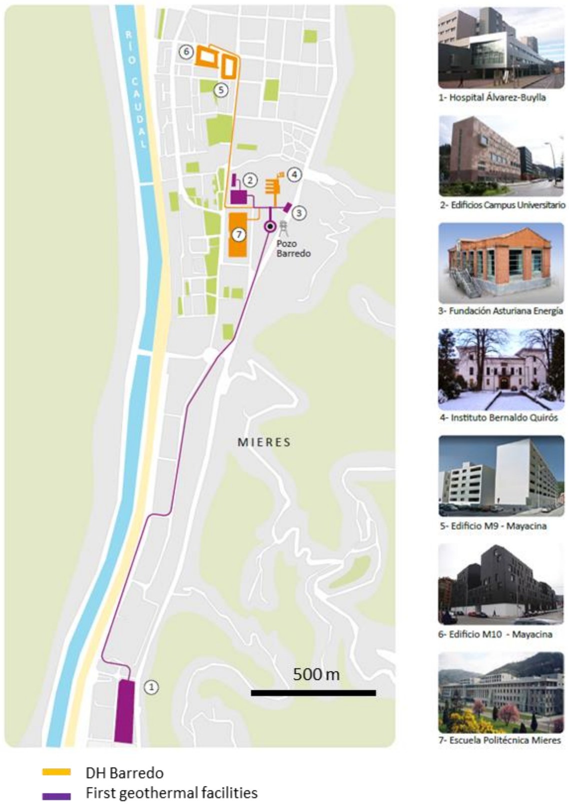


Figure 5-9. Map of customer locations

Each customer's building has a substation consisting of the same elements as described in the case of district heating in Fondón. Thus, we have:

- Incoming flow control valve (in the primary circuit).
- Temperature probes (in the primary and secondary circuits).
- Heat meter (in the primary circuit).
- Plate heat exchanger. Heat transfer from district heating (primary circuit) to the building's pre-existing thermal installations (secondary circuit).
- Booster pumps (in the secondary circuit).

The total cost of District Heating Barredo, the second phase (2020), was 1,421,541 €.

The heating generation plant was 2 MW, with a total installed power (heating) plus domestic hot water of 4,060 kW to provide heating to the main building of the Polytechnic School of Mieres (University of Oviedo), a secondary school and two blocks of flats (M9 and M10).

Figure 5-10 presents the detailed installed power (kW) and thermal energy supplied (MWh) for the different buildings. The thermal energy provided (total heating and domestic hot water) in 2021 was 1,789 MWh. The reduction of emissions was estimated at 451 t CO_2.

		Installed power (kW)	**Thermal energy supplied (MWh)**
Main building UO	heating (generation plant) 2 MW	2,000	1,008
Secundary School		500	0
Residential building M9		720	407
Residential building M10		840	374
Total heating		**4,060**	**1,789**

Figure 5-10. Installed power and thermal energy supplied (2021) in the District Heating Barredo (second phase)

5.2.3 Capital expenditure (CAPEX)

5.2.3.1 Total investment versus installed power (kW)

To develop an economic assessment of a generic geothermal installation, first, we will compare the investment amounts with the installed power in kWh.

In the case of District Heating Fondón, we will not consider the FEDER subvention, as it was given regarding the infrastructure difficulties that this project had to overcome due to the location of the buildings.

Figure 5-11 presents the different ratios of total investment versus installed power in kW. The cooling supply was not included in this comparison, as the two cases have no installed cooling power. Taking into consideration that Fondón figures may be distorted due to the specific constructing difficulties as well as because of the FEDER subvention, we can establish an average ratio of total investment versus installed power in kW of around:

$$\boldsymbol{Total\ investment/Installed\ power}\ \textbf{(kW) = 331 €/kW}$$

Figure 5-11. Total investment versus installed power (kW) ratio

5.2.3.2 Total investment versus Thermal energy supplied (MWh)

In the case of comparing the investment amounts with the thermal energy provided in MWh, again, in the case of District Heating Fondón, we will not consider the FEDER subvention, as it was given regarding the infrastructure difficulties that this project had to overcome due to the location of the buildings.

Figure 5-12 presents the different ratios of total investment versus thermal energy supplied in MWh. The cooling supply was not included in this comparison, as the two cases have no installed cooling power. Taking into consideration that Barredo second phase figures may be distorted due to the low amount of energy supplied, we can establish an average ratio of total investment versus installed power in kW of around:

$$\boldsymbol{Total\ investment/Thermal\ energy\ supplied}\ \textbf{(MWh) = 303 €/MWh}$$

5.2.3.3 Total investment

The total investment we will use for the calculations will be that of Barredo Colliery – First phase. The first phase, estimated at 1,452,157 €, corresponds to a heating generation plant of 3.8 MW.

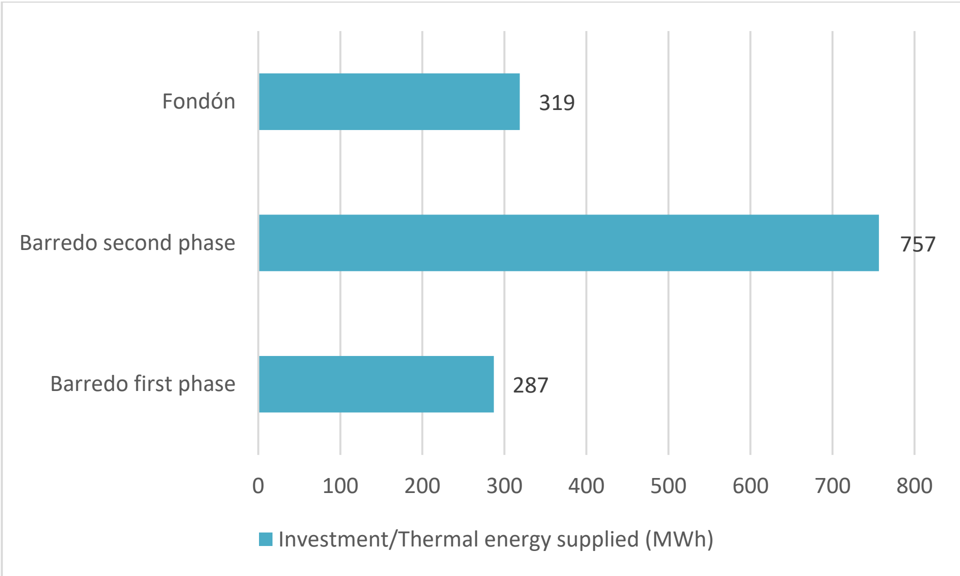


Figure 5-12. Total investment versus thermal energy supplied (MWh) ratio

5.2.4 Operational expenditure (OPEX)

As it is easy to understand, HUNOSA does not want to disclose the operational expenditures of its geothermal installations. That is why we will have to undergo an estimation of them.

The example that we will use to estimate the operational expenditure (OPEX) will be the Barredo Colliery – First phase, as it is the case where the thermal energy supplied is the highest, providing also cooling energy to the customers. Of course, the energy cost of pumping water from the pit will not be considered, as it is a sunk cost for the coal mining company.

Four are the main components of the OPEX:

1. Salaries.
2. General expenses.
3. Maintenance costs.
4. Energy costs (electricity).

Salaries correspond to the wages of the people in charge of the installation. Considering that the full salary costs of a specialized worker can be at 55,000 €/year and that one worker will be enough to take care of two of these installations, it is possible to estimate the salaries at:

$$Salaries = 27{,}500 \text{ €/year}$$

Maintenance costs, corresponding mainly to subcontracting, can usually be estimated at approximately 15% of the total operating expenses of the installation. According to the Maintenance Costs Industry Standards of the Association of Asset Management Professionals, an alternative calculation method is using the 2-3% annual capital replacement value. Both approaches give very similar figures.

General and administrative expenses, including overheads and municipal taxes, can usually be estimated at 10% of the total operating costs or 4% of the total revenues, according to Levin & Watson (2016) from McKinsey & Company.

Finally, considering that Barredo Colliery – First phase produces 5,058 MWh of heating and 2,063 MWh of cooling per year, the electricity consumed by the geothermal installation can be estimated as 1 kWh per 4.5 kWh of heating (dandelionenergy.com). Using an energy price of 70 €/MWh that HUNOSA can achieve through a Power Purchase Agreement PPA, we obtain:

$$\textit{Thermal energy supplied (heating + cooling)} = \textbf{7,121 MWh/year}$$

$$\textit{Electricity consumption} = \textbf{7,121 MWh/year : 4.5 = 1,582 MWh/year}$$

$$\textit{Electricity costs} = \textbf{1,582 MWh/year x 70 €/MWh = 110,740 €/year}$$

Thus, we obtain the following equation to calculate the OPEX:

OPEX = 27,500 + 110,740 + OPEX x 0.15 + OPEX x 0.10

OPEX = 184,320 €/year

So maintenance costs and general expenses can be estimated at:

$$\textit{Maintenance costs} = \textbf{\textit{184,320} € x 0.15 = 27,648 €/year}$$

$$\textit{General expenses} = \textbf{\textit{184,320} × 0.10 = 18,432 €/year}$$

5.2.5 Revenues

According to The National Renewable Energy Laboratory (NREL), the terms for public geothermal power purchase agreements signed from November 2019 through September 2020 in the USA are around 70 \$/MWh (Robins et al., 2021), precisely:

- Hell's Kitchen, California: 74 \$/MWh.
- Whitegrass, Nevada: 67.50 \$/MWh.
- Star Peak, Nevada: 70.25 \$/MWh.

- Casa Diablo, California: 68 $/MWh.
- Puna, Hawaii: 70 $/MWh.

These figures are given only to have an approximate idea of what we can expect in our case.

According to HUNOSA, the prices in 2021 considering both the unitary price (€/kWh) plus the fixed costs were (expressed in €/kWh):

Heating (2021) = 0.03287 €/kWh + fixed costs = 0.03912 €/kWh

Cooling (2021) = 0.0208 €/kW + fixed costs = 0.02704 €/kWh

Thus, as the prices are indexed to that of gas, and in 2022 prices were 88.3% more expensive than in 2021, prices in 2022 can be estimated at:

Heating (2022) = 0.07366 €/kWh

Cooling (2022) = 0.05092 €/kWh

These figures are not so different from the ones obtained in the USA for public geothermal power purchase agreements.

Considering again that Barredo Colliery – First phase produced 5,058 MWh of heating, and 2,063 MWh of cooling per year, the revenues can be estimated at:

Revenues = 5,058 MWh x 0.07366 €/kWh + 2,063 MWh x 0.05092 €/kWh = 477,620 €/year

5.2.6 Financial outcomes

First, and to benchmark the discount rate, Scheule & Jortzik (2020) provided alternative discount rates using historical bank data.

The average risk premium from 2008 was around 6.0%, while the risk-free rate given by global credit data (GCD) from 2009 was around 1.0%, corresponding to the European Interbank Offered Rate (EURIBOR).

The Capital asset pricing model (CAPM) states that the shareholder discount rate will be the one presented hereafter:

$$\boldsymbol{r = riskfree\ rate + average\ risk\ premium\ rate = 1.0\% + 6.0\% = 7.0\%}$$

Second, financial outcomes will be calculated using a period of 20 years, with residual values of the geothermal plant after these years valued at 0. This value of 20 years is between the 25 years usually considered for a photovoltac plant and the 15 years for a green hydrogen plant.

Using real values instead of nominal ones, mainly forced by the extreme variations of inflation in the current context, we obtain the cash flows presented in Table 8, considering a working capital of 10% of the CAPEX.

Table 8. Cash flows calculations (k€)

Item	2022	2023	2024
Capital expenditure (CAPEX)	(1,452)		
Working capital	(145)		
Operating revenues		478	478
Operating expenses		(184)	(184)
Depreciation (20 years)		(73)	(73)
EARNINGS BEFORE INTEREST AND TAXES		220	220
Taxes (25%)		(55)	(55)
NET INCOME		165	165
CASH FLOW (Net income + Depreciation)	(1,597)	238	238

Thus, the expected NPV for 20 years will be:

$$\boldsymbol{Net\ Present\ Value\ (NPV) = -1,597 + \frac{238}{(1+0,07)} + \ldots + \frac{238}{(1+0,07)^{20}} = \ 927\ k€}$$

$$\boldsymbol{Internal\ rate\ of\ return\ (IRR) = \ 14\%}$$

$$\boldsymbol{Payback\ Period\ (PP) = \ 10\ years}$$

These figures confirm the project's commercial viability and show an economic added value of 927,183 €. However, special attention should be given to the payback period, which is high, although not enough to discourage undertaking the investment.

5.2.7 Sensitivity analysis

Figure 5-13 presents the Spider graph. As it was easy to foresee, the heating price is the most sensitive variable of this analysis.

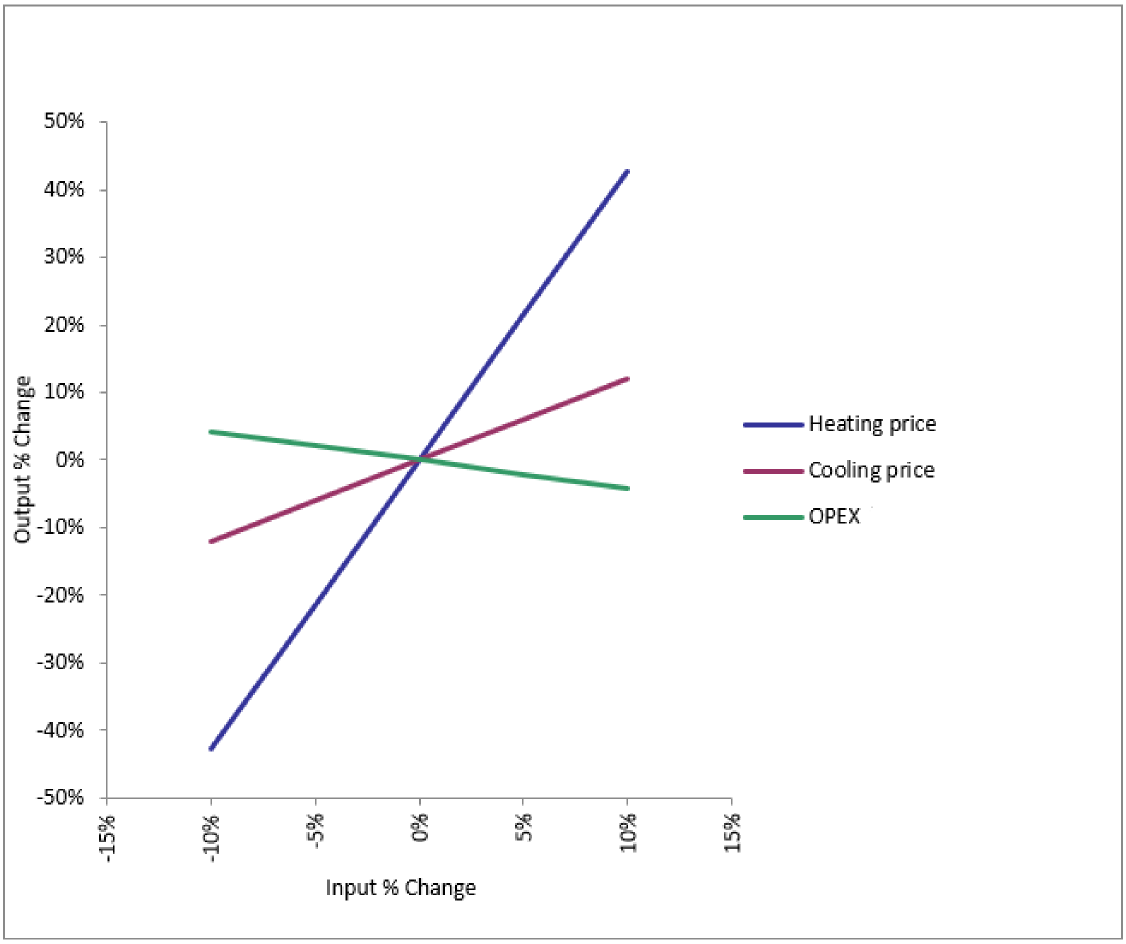


Figure 5-13. Spider graph of the sensitivity analysis

5.2.8 Uncertainty analysis

Uncertainty analysis will be developed for each specific case study of the project.

5.3 Business plans

The most suitable contract to enter with customers is the energy services contract or a similar one based on this model.

Usually, a district heating network involves several essential elements that would make up the initial investment the company would undertake.

- Mine water pumping (pumps, pipes, etc.)
- Heat exchangers
- Coolers/heat pumps
- Connecting pipes for all these elements
- Booster pumps
- Distribution of piping to customers
- The substation at the customer's premises
- Control and programming

In a conventional energy services contract, the company would make the initial investment, and the customer would pay, over several years, the investment cost. The complete installation would be handed over to the customer at the end of the period. However, in a district heating network of the characteristics we are considering, the company always keeps that initial investment (that installation). It does not make sense for a customer to take over that installation linked to the mine, in addition to how costly it would be.

Therefore, in these district heating systems, the customer would pay for the energy consumed and the preventive and corrective maintenance of the installation.

To make joining the geothermal grid attractive to customers, they must be offered certain advantages compared to the energy system they consume. Typically, customers are offered a reduction in the price of energy, depending on the outcome of the business plan and negotiations between the customer and the company. Typical values are in the order of 10% to 15%. These savings have to be indexed to the fuel they use, so the customer is always guaranteed a price reduction. On the other hand, complete installation maintenance should also be offered at competitive prices, ensuring the customer that they do not have to worry about anything else from the moment they join the network.

Once the main aspects to be taken into account in the business plan have been established, such as the initial investment, energy consumption, the price of energy with the savings offered, the cost of maintenance, the duration of the contract, as well as an estimate of the future prices of electricity, gas (or other fuel used by the customer) and inflation, we can now develop a business plan that allows us to know the profitability of our installation.

It is vital to bear in mind that the costs associated with pumping mine water alone are often very high. As mentioned in previous sections, there is an obligation to pump the water that floods a closed mine to maintain a sure water table to avoid causing problems for the nearby population. This entails eternal costs associated with the cessation of mining activity, which will depend on many factors (level of pumping, flow of water pumped and electricity prices) but, in any case, will be a very significant expense for the company. This cost has to be incurred whether or not a geothermal project linked to the mine is developed. Therefore, it is perfectly logical not to include these costs in the business plan not to compromise the project's profitability.

A project of this type is eligible for development aid because we are investing in renewable energies to develop district heating networks, thus increasing energy efficiency and mitigating CO_2 emissions while contributing to energy sovereignty. Moreover, these are projects linked to mining areas undergoing challenging reconversion processes and the need to create new activities and, therefore, new skilled jobs. Finally, we are also taking advantage of old mining facilities that would otherwise be in ruins in a few years and benefiting from a resource (heat from mine water) that would otherwise be wasted. All these arguments, and others that could be derived from them, are essential when looking for funding, highlighting the appropriate aspect depending on the particular call we select. Multiple European, national and local funds can finance a geothermal mine water project.

Obtaining a grant, which can be up to 50% in many programmes, significantly helps improve the business plan and create incentives for companies to carry out such projects. Subsidies can turn unprofitable or borderline unprofitable projects into economically viable and attractive projects for implementation in mining areas and breathe new life into mines.

Permitting

The permits required to develop a geothermal mine water project can vary greatly depending on the country in which it is implemented and the particular characteristics of the project. In this section, we will focus on the permits necessary for the geothermal mine water projects developed by HUNOSA in Asturias, as these are projects that have already been in operation for a long time and, therefore, there is an experience in this respect.

We will divide the permits into three groups:

- Pre-project
- For the execution of the works
- Post-construction: legalisation of the installations.

<u>Pre-project permitting</u>

As this project was linked to an old closed mine, the procedure we followed was stipulated in the Mining Law and the General Regulations for the Mining Regime.

These establish several groups of resources and an administrative route for their exploitation. Geothermal resources associated with mine water heat belong to the so-called "Section D" according to Law 54/1980 of 5 November (amendment of the Mining Law - Law 22/73). This section includes, in addition to geothermal resources, minerals and energy resources such as coal, radioactive minerals, bituminous rocks and any other type of mineral deposits or geological resources of energy interest.

To secure the rights to geothermal use of mine water during the preliminary stages of studying the resource, "exploration permits" were applied for one year. Subsequently, these permits were converted into "Research Permits", held for three years, extendable for a further three years, and an extraordinary extension of another three years was requested until the maximum possible term was reached. The "Exploitation Concessions" were then asked for the specific areas where the projects were to be carried out. However, in some of these areas, the "Concesiones de Explotación" were applied well before the end of the "Permisos de Investigación" term because sufficient data had already been collected to develop the project.

An "Exploitation Concession" is a permit granted by the administration to exploit a resource, geothermal. It delimits the surface over which the entire deep extension of the mine (galleries and exploited areas) is projected, representing the whole artificial aquifer created by the underground mining activity (the aquifer to be exploited).

Many connected mines can be problematic concerning the latter, as the exploited aquifer may be more extensive than indicated. In this case, the delimitation of the exploitation concession may be arbitrary and ambiguous and must be resolved on a case-by-case basis with the competent Mining Authority.

Once the exploitation concession has been obtained, the project to be carried out is submitted to the Mining Authority.

Permits for the implementation of the project

In Spain, if you want to exploit an aquifer for geothermal purposes, you need a permit from the competent Confederación Hidrográfica, which are the state bodies that manage Spain's water resources and are divided by large hydrographic basins. However, the peculiarity of mine water means that geothermal projects in Asturias do not require this procedure. What does need to be obtained from these bodies is a discharge authorisation, i.e. permission to discharge the pumped mine water into the river. Usually, these authorisations already existed before the development of the geothermal project, as these are mining operations that have been in operation for many years and where water continues to be pumped due to the need to maintain the water table. Therefore, no additional procedures are carried out before the Hydrographic Confederation, and the exploitation is fully validated with the exploitation concession granted by the Mining Authority.

Once the area to be exploited has been selected and the execution project has been drawn up, all the necessary permits to carry out the works are applied. All this can take a long time, and it is required to think beforehand about the execution of a project that minimises these bureaucratic aspects, for example, by designing a distribution network that affects as few administrations as possible or that affects the most agile administrations.

The examples developed in Asturias have involved:

1. Autonomous Administration (Government of Asturias): affecting roads under autonomous competence.
2. Railways (RENFE, state body): affecting railways.
3. Hydrographic Confederation (State body): crossing bridges over rivers.
4. Local administration (town councils): application for building permits.

It saves time in the processing if, together with the project submitted for the application for the building permit, the permits (already approved) from each of the administrations concerned are attached, as mentioned in points 1, 2 and 3.

Once the building permit has been obtained, including the permits from all the administrations involved, construction work on the facility can begin.

Post-construction permits: legalisation of installations and commissioning

Once the project is completed, a certificate of good execution is obtained from the site management, and all the necessary documentation is submitted to the Mining Authority for approval. Once this has been obtained, the Mining Authority requires an annual work plan to be submitted, including what has been done during the year and what is planned for the following year in terms of water pumped, energy supplied, investments, changes to the installation, operating costs, environmental effects, prevention and control systems, etc.

Parallel to the project's approval by the Mining Authority and before the start-up of the installation, it is necessary to register it with the Industrial Authority, which depends on the Government of Asturias. Registration must be done in two ways:

- It is an air conditioning installation registered in the RITE (Reglamento de Instalaciones Térmicas en los Edificios).
- On the other hand, it is also necessary to register the electrical installation.

Both registrations are necessary for the district heating generation room and each substation located at each customer. Each customer's part of the geothermal installation (pumps, heat exchangers, etc.) must also be registered with the Industrial Authority.

Finally, the completion documents are submitted to the municipality, and the municipality grants us the "license to operate".

5.4 Demosite job creation potential

According to the previous OPEX calculations, the calculated employment for operation and maintenance (O&M) can be estimated at 0.5 permanent job per approximately 1,500,000 € of investment on a 3.8 MW geothermal plant.

This corresponds to the same figures used by Ortega et al. (2020) addressing photovoltaic installations: 0.12 direct jobs/MW as the calculated employment for operation and maintenance (O&M), so 0.09 indirect jobs /MW should be also considered an adequate:

0.12 jobs/MW x 3.8 MW = 0.456 jobs

6 Best practices

The good practices included information on implemented in the RFCS project Low-Carbon After-Life (LoCAL): sustainable use of flooded coal mine voids as a thermal energy source - a baseline activity for minimising post-closure environmental risks) pilot located in Bytom on post mining area. The proximity of mine water discharge from abandoned but still dewatered Szombierki mine was the reason for using renewable energy as the main source for heating at the planned residential area. Szombierki mine continues dewatering of abandoned mine workings to protect interconnected active mines, like Bobrek and Centrum coal mines against water hazard. Szombierki mine is now a part of Polish Mine Restructuring Company, with one of department (CZOK) which is responsible for dewatering abandoned hard coal mines in Upper Silesia. Szombierki is one of CZOK's 15 pumping stations with continuous dewatering. Polish Mine Restructuring Company is the owner of technical infrastructure and shaft "Ewa" (source of water for heat pump installation). The amount of the water pumped from Szombierki mine is around 5 m^3/min (83 L/s), while the temperature varies from 24 to 28 degrees. Szombierki mine has been closed down for several years, but the Armada Development (one of the project partners) company is conducting regeneration works at the site. Land reclamation includes the construction of a sports area (golf course) and housing development. The proximity of the mine water discharge from the former Szombierki was an argument for using renewable energy as the main source for heating and cooling at the planned residential area.

GIG has conducted analysis (Figure 6-1, figure 6-2) that shown that water temperature at discharge point to pond Ws65/5 is stable (23-25^{o}C). Analysis at the receiver pond has shown that temperature of water decreases in relation to the part of the year, and decreases below 10^{o}C, so this source will not be taken into account for pilot plant construction. It was a part of technical research for possibilities of pilot implementation. As a result, only water from the discharge point or directly from the CZOK mine water pipeline was recommended as a source for Armada mine water heating installation.

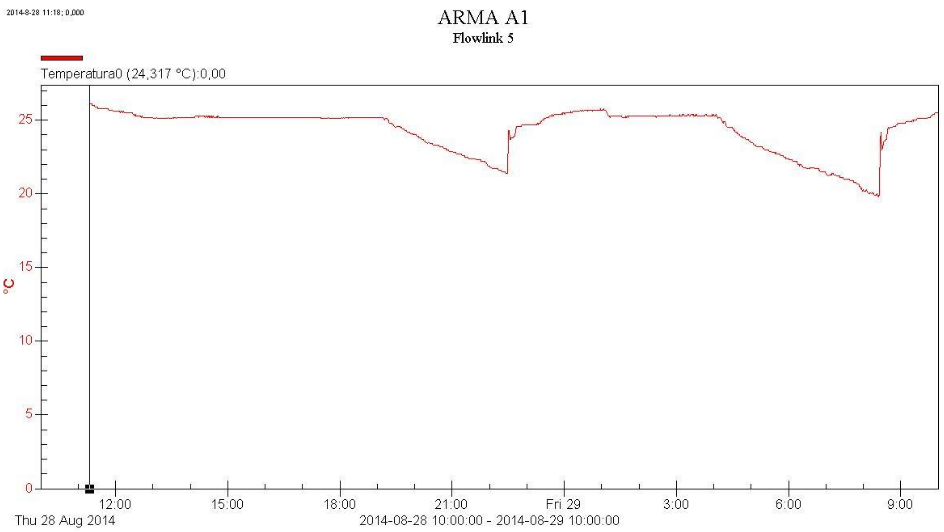


Figure 6-1. Temperature at the discharge point – on line measurements

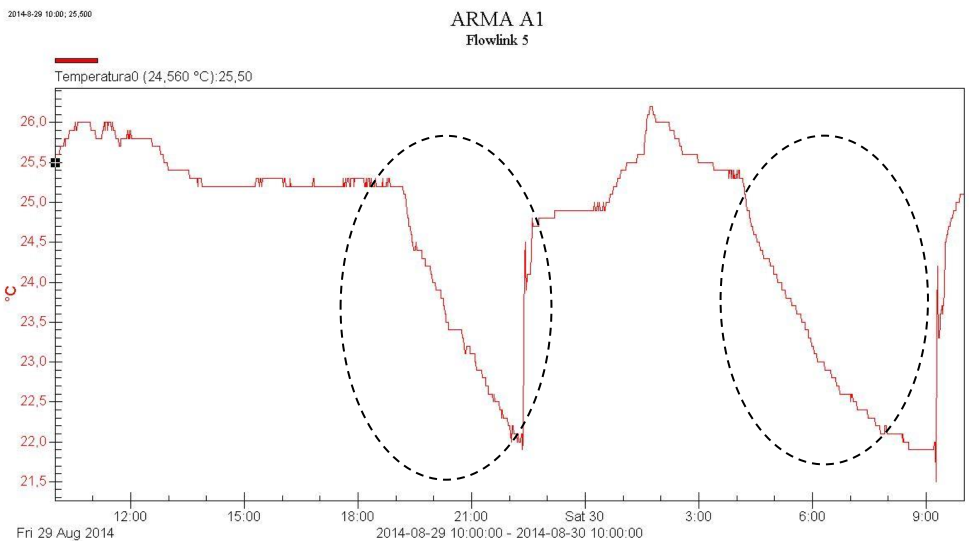


Figure 6-2. Temperature at the discharge point – on line measurements (intervals in pumping catched)

During the first stage of pilot implementation GIG conducted a technical study on the basis of STEEP analysis to evaluate the technical and economical options for implementation. Within the technical evaluation of ARMADA pilot site implementation also interactive tool were used and showed possibilities of its implementation.

Technical Project of the pilot site infrastructure with all necessary site compounds (buffer tank and pipeline) was prepared for Armada company.

Work in construction of pilot site undertaken during the project lifetime undertaken by Armada consisted of:

- January 2015: inquiry for construction project of pilot site in Bytom.
- April 2015: final version of construction project
- May 2015: application for a building permit from local government.
- June 2015: obtaining of preliminary permission from Central Mine Dewatering Department (CZOK - owner of mine water) for uptake of heat from mine waters. Getting acceptation from CZOK of construction project for pilot site.
- June 2015: obtaining of building permit from local government.
- October 2015: start of construction of pilot site. Construction works included: installation of pumps with equipment, electrical installation, central heating installation, installation of the container at the pumps.

During the project activities in relation to pilot installation in Armada the main problem occurred when the permission for use of water generally resulted in delay of construction works. In June 2015 it was possible to obtain the preliminary permission from Central Mine Dewatering Department (CZOK - owner of mine water) for uptake of heat from mine water with the note that final legal and financial terms for future water use will be designed. Armada Development got also from CZOK an acceptation of construction project for pilot site. After a lengthy period of seeking to resolve mine water ownership and access the matter was resolved in February 2016, when finally Armada received permission for use the water for free. Collection and transfer pipeline was installed and the 9KW compacted heat pump system was constructed during the second half of 2016. Final installation of the heating systems in the buildings utilizing fan coil units was carried out in early 2017 with the system now being operational.

Armada works resulted in construction of the container (building for installation of pumps with equipment) and connection of CZOK pipeline with buffer tank. Effects are presented on photos below.

Figure 6-3. Construction of the container

Source: Project LoCAL - Armada Development archive

Figure 6-4. CZOK drain with mine water (to be connected with buffer tank)

Source: Project LoCAL - Armada Development archive

Figure 6-5. Excavation for a pipeline (connection between buffer tank and container)

Source: Project LoCAL - Armada Development archive

Figure 6-6. Pilot installation of heat pump in Armada Development

Source: Project LoCAL - Armada Development archive

Figure 6-7. Final look over installation container

Source: Project LoCAL

Figure 6-8. Central heating installation (fan coil unit)

Source: Project LoCAL - Armada Development archive

Whole system is fully operational, and was tested in low ambient temperature conditions. The results were satisfying, by reaching the proper indoor house temperature.

Option of implementation an open-loop heat pump solution, with prophylactic heat exchangers transferring heat from the mine water flux to the heat pumps, together with appropriate pipework was the best technical solution in ARMADA pilot site. The technical implementation and technical solution for the pilot site resulted from preliminary analysis and were a basis for conducting feasibility study for implementation of such solutions. The pilot site was also equipped with monitoring instrumentation to provide information about the mine water temperature evolution, process efficiency and heat loads delivered. Based on analysis of the pilot site, a report summarizing the results of system implementation and recommendations for future expansion has been prepared.

Installation at Armada site have been equipped with measuring devices for testing its efficiency. Main parameters that have been measured are: circuit temperature, energy consumed from grid and heat energy introduced into heating system. Below a block scheme shows the localization of measuring devices at pilot installation.

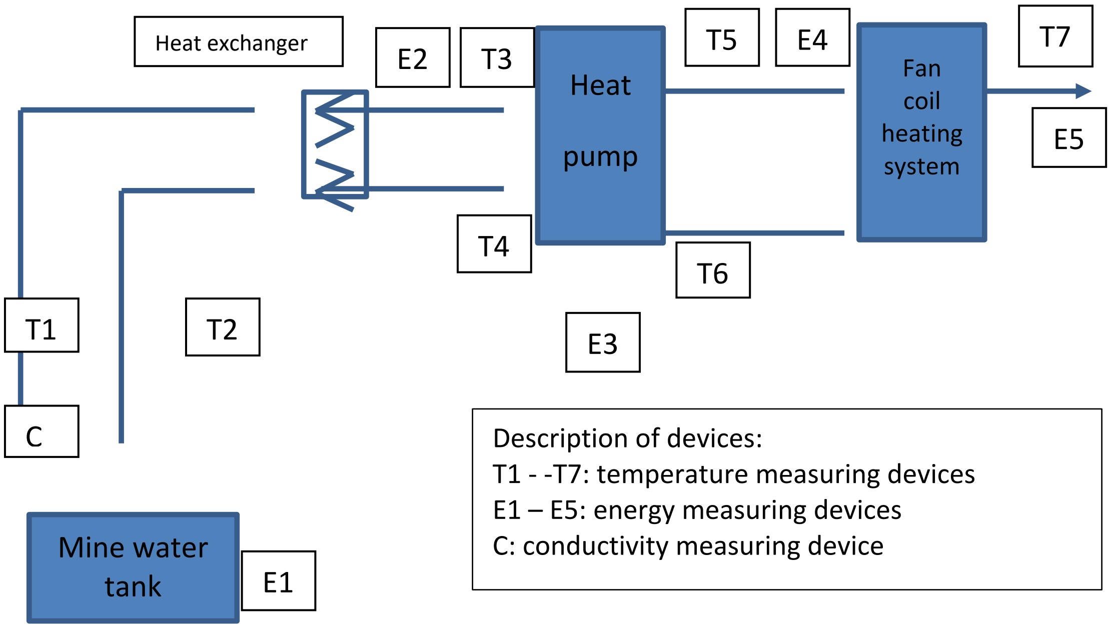


Figure 6-9. Block scheme of pilot installation with localization of measuring devices

As shown on Figure 6-9, mine water is taken from mine water tank, then it circulates through heat exchanger: it is the first circuit. Second circuit runs on glycol and runs into the heat pump where heat condensates both with grid energy uptake. Then system heat goes on the third circuit that is located in building rooms and powers the system of fan coils with the heat. Such system allows for efficient heat uptake from mine waters with avoiding the risk of internal heat pump installation damage caused by mine water reactive properties. As the COP of this system is calculated on value 3, it shows that it is possible to uptake 2 times more heat than cost of electricity. On the graph below (Figure 6-10) the difference between energy consumed from grid and energy putted into the heating system can be easily noticed. Such example proves the success of use mine waters for heating purposes as well as gives a proper field for multiplication of LoCAL project results.

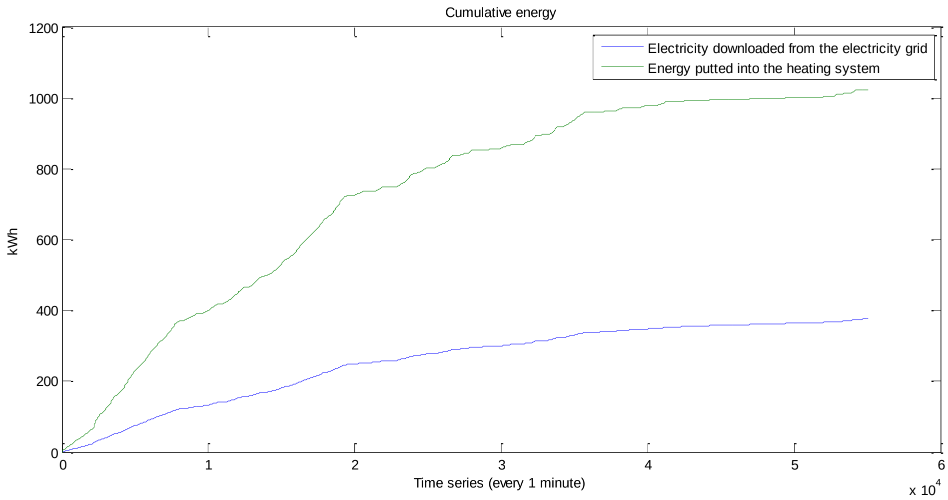


Figure 6-10. Cumulative energy plot

Figure 6-10 shows the cumulative energy over time. Time step is 1 minute. These curves present the sum of energy putted into heating system and the sum of electricity downloaded from the electricity grid. First measurement was 2017-04-16 00:01:00 and the last 2017-05-26 00:00:00. there was a break in measurements from 2017-05-10 00:00:00 till 2017-05-11 17:11:00.

As a conclusion it was determined that there is a little thermal difference between mine water temperature at the inlet and outlet from heat exchanger (Figure 6-11). The difference is ca 1 Celsius degree so it shows how little heat is extracted and how big thermal potential stands behind such heat source. The temperature at the heating system is about 20 degrees higher than the temperature at the output from heat pump heat exchanger (Table 7). Such difference proves that via correctly designed system good household heating conditions can be reached. To use a scientific background for such phenomena it need to be said that whole geological structure, and mine water works as a one huge heat exchanger (rock/water) underground. Despite all technological issues it is necessary to do as much as possible in order to avoid this natural resource being wasted.

Table 7. Average temperatures from heating system

Temperature at various points of the installation	Output from the heat exchanger to the mine water reservoir	Input from the heat exchanger from the mine water reservoir	Input from the heat exchanger from the heat pump	Output from the heat exchanger to the heat pump	Output from the heat pump to the buffer (heating system)	Input from the heat pump from the buffer (heating system)
average temperature	23,04	24,19	15,01	18,77	32,72	27,96

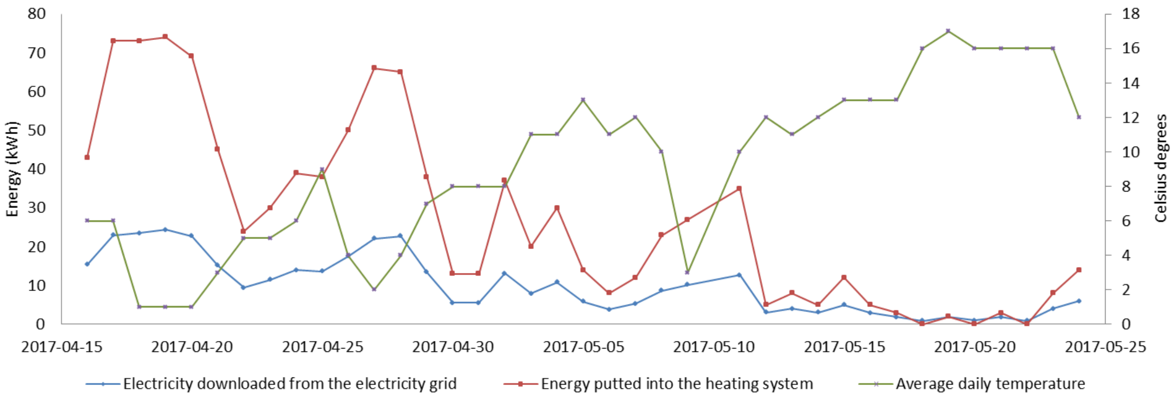


Figure 6-11. Plot showing daily averaged energy taken from the grid vs daily averaged energy transferred into the system correlated with average daily temperatures of the ambient air measured by nearby meteorological station at Katowice airport.

Figure 6-12 shows an important correlation between daily temperature and the operation parameters of the heating system. It can be noticed that during the days with relatively low temperature the systems works very efficient. During such days electric energy consumption raises to 20-30 kWh, and the heat energy of the system raises to 70-80 kWh. This situation changes when the daily temperature raises, then the need for system heating goes down and the system distributes very little amount of heat with lower effectiveness.

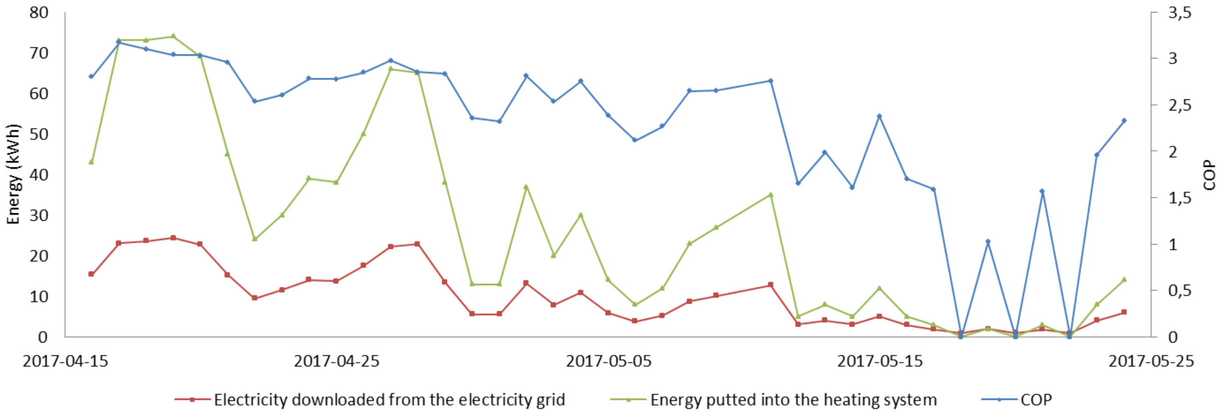


Figure 6-12. Plot showing energy taken from the grid vs energy transferred into the system correlated with resulting system COP

Similarly like in the previous plot, the correlation between energy taken and energy produced is compiled with heat pump COP (coefficient of performance). During the days with low ambient temperatures, the COP values are about 3 which shows good operating parameters of the system. COP value decreases when the heating system works on minimal electric energy consumption.

Due to the proximity of the pipeline with mine water, the company is considering the possibility of using heat from the mine water to heat buildings (CO) and water (CWU) in planned multi-family buildings in future housing estates. The planned multi-family housing estate will consist of 29 multi-family buildings, where 685 flats will be built, with a total usable area of 36,479 m^2.

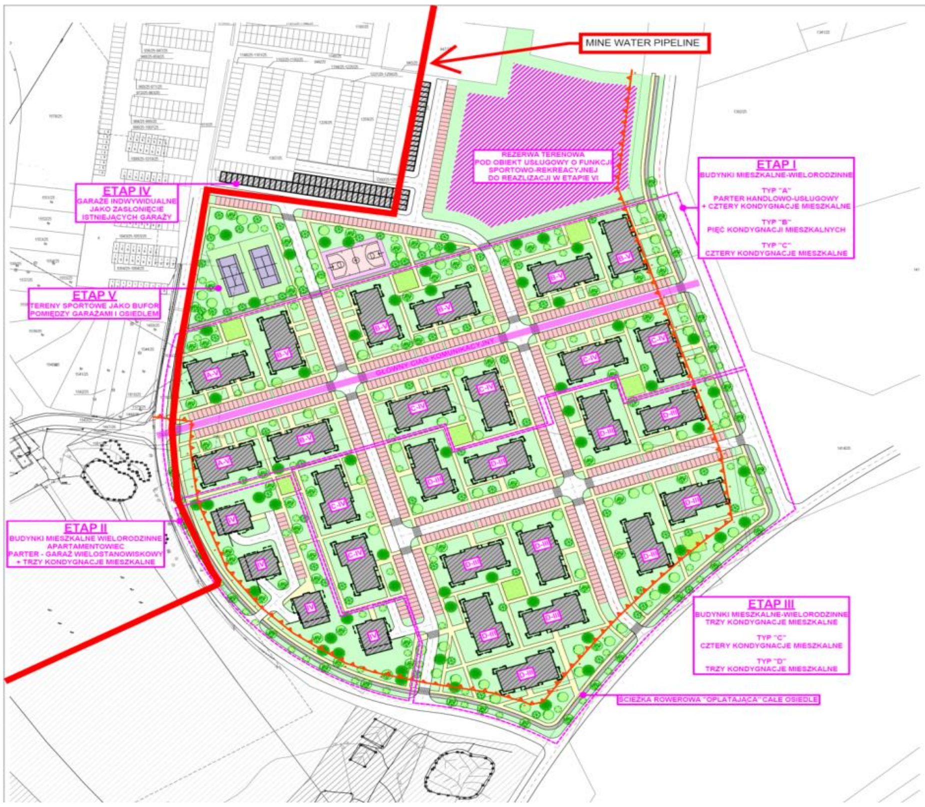


Figure 6-13. Pilot installation of heat pump in Armada Development

Source: Project LoCAL - Armada Development archive

The source of heat from mine water is considered as an alternative solution for heating of water and living spaces. Originally estimated source of heat was form gas. Operating costs of heating the building and heating are on average between 2.94 PLN / m^2 (1,43 Eur/m2) and 5.24 PLN / m^2 / month (1,24 Eur/m^2/month). It should be noted that the savings per month is PLN 107,248.26 (25,474.64 Eur) for heating and PLN 191,149.96 (45,403.79 Eur) for water heating per month, assuming that all flats have been built and used.

The designed and implemented heating system in Armada Bytom powered by the heat of mine water works properly, and gives satisfying result. During the low daily temperatures it gives significant cost savings for heating purposes. With the COP of 3 it can be indicated that by the cost of 1 kW of electrical energy 3 kW of heat energy can be obtained. Gathered measurements data from the system indicates also a potential for its optimization. Implemented and tested system is fully multipliable, and will be hopefully implemented by Armada in the future for new house estates promoting the low carbon economy based on flooded coal mines.

7 Conclusions & lessons learnt

The lessons relevant to the Project from this deliverable can be summarised as follows:

1. End-of-life underground coal mines present a unique opportunity for geothermal energy production. These mines have already been excavated to great depths, and as a result, they have access to the earth's natural heat. By repurposing the existing infrastructure, it is possible to create a geothermal power plant that produces electricity and heat with minimal environmental impact, as far as the shaft is close to the potential clients.
2. This approach also creates new job opportunities for local communities. While underground coal mining jobs are often physically demanding and can be dangerous, geothermal energy production jobs are typically more skilled and involve fewer risks. This shift towards green energy production will create new, quality jobs that will contribute to the local economy in a sustainable way.
3. Geothermal energy is increasingly seen as an option that could assist in reaching the goal of the Paris Agreement to limit the atmospheric temperature increase to 2°C or less.
4. Moreover, geothermal energy is a reliable and constant source of energy that can power homes, businesses, and industries for decades. This makes it an attractive option for countries looking to reduce their reliance on fossil fuels and increase their energy security. Moreover, providing renewable energy, guaranteeing savings in energy costs and maintaining and replacing components, etc., may be attractive to potential consumers.
5. In Poland, coal mine geothermal energy has already been demonstrated to be a viable source of renewable energy. Several pilot projects have been carried out to extract heat from mine water, which is then used for district heating or electricity generation. The same is the case in other countries, especially Spain, where geothermal energy from closed mines is used more extensively.
6. The process of extracting geothermal energy from coal mines involves pumping water from the mines and using the heat to generate steam, which can then be used to power turbines and generate electricity. The need, in many cases, to pump water regardless of the presence of a geothermal installation helps increase the geothermal project's financial outcomes, as pump costs can be considered sunk costs.
7. There are also some challenges associated with coal mine geothermal energy, including the need for specialized equipment and the potential for water

contamination. It is important to ensure that the process is carried out in a safe and sustainable manner, with appropriate regulations and environmental monitoring in place.

8. Choosing a geothermal technology requires consideration of environmental aspects because the quality of surface waters to which loads of pollutants could be discharged together with industrial sewage or mine water is very low. For this reason, when choosing technologies based on an open-loop system, an environmental analysis should be carried out in order to limit the negative impact of mine water on the environment.
9. There are more advantages in a closed-loop system compared to an open-loop system, mostly in environmental terms. Given the technological progress, it is certainly possible to use pumps with equivalent efficiency as in the case of open systems. From an environmental point of view, a closed loop system with tube or shell-and-tube heat exchangers immersed in a flooded shaft or gallery is recommended. In this way, the need to use or even build large water reservoirs can be eliminated if the existing water pond is insufficient.
10. Due to variations in both the quantity of pumped water, its temperature and also its quality, a geothermal system mining areas should be selected after a feasibility study. In case of low-quality mine water, it is recommended to install a heat exchanger inside the underground reservoir in a closed loop system. If the mine water quality is good, it is preferable to install an open-loop system.
11. The development of a successful geothermal project will require a detailed study of the resource: mine aquifer, flow rate, temperature, etc., as well as the specific characteristics of the demand: temperature, timing, heating/cooling, etc. It is essential to explain to the potential clients the advantages of developing a development district heating instead of individual facilities: lack of space for geothermal equipment in the buildings, insufficient electrical power installed to use heat pumps, and efficiency.
12. Finally, the financial outcomes of the geothermal energy deployment are positive, with an Internal rate of return of 14%, although with a high payback period of around ten years.

Glossary

CAPEX – Capital expenditure

CAPM – Capital asset pricing model

COP – Coefficient of performance

DMT-THGA – DMT-Gesellschaft für Lehre und Bildung mbH

EURIBOR – European Interbank Offered Rate

FAEN – Fundación Asturiana de la Energía

GIG – Główny Instytut Górnictwa

HUNOSA – Hulleras del Norte. S.A.

ICP-AES – Inductively coupled plasma-atomic emission spectrometry

ICP-OES - Inductively coupled plasma-optical emission spectrometry

IRR – Internal rate of return

M&B – Magellan & Barents

NPV – Net present value

OPEX – Operational expenditure

O&M – Operation & maintenance

PP – Payback period

PV – Premogovnik Velenje d.o.o.

REA – Research Executive Agency

SWOT – Strengths. weaknesses. opportunities. and threats

TRL – Technology readiness level

UNIOVI – Universidad de Oviedo

WEGLO – Węglokoks S.A.

XRF – X-Ray Fluorescence

References

Abbas T, Ahmed Bazmi A, Waheed Bhutto A, Zahedi G (2014) Greener energy: Issues and challenges for Pakistan-geothermal energy prospective. Renewable and Sustainable Energy Reviews 31:258–269. https://doi.org/10.1016/j.rser.2013.11.043

Antics M, Sanner B (2007) Status of geothermal energy use and resources in Europe. Proceedings European Geothermal Congress :1–8

Augustine CR (2009) Hydrothermal Spallation Drilling and Advanced Energy Conversion Technologies for Engineered Geothermal Systems. Massachusetts Institute of Technology

Banks D (2009) Thermogeological assessment of open-loop well-doublet schemes: a review and synthesis of analytical approaches. Hydrogeology Journal 17(5)

Banks D, Athresh A, Al-Habaibeh A, Burnside N (2019) Water from abandoned mines as a heat source: practical experiences of open- and closed-loop strategies, United Kingdom. Sustain Water Resour Manag 5(1):29–50. https://doi.org/10.1007/s40899-017-0094-7

Bertani R (2012) Geothermal Power Generation in the World - 2005–2010 Update Report. Proceedings World Geothermal Congress

Blaschke W, Baic I, Wiesław S (2016) Coal Mining and Coal Preparation in Poland. Czasopismo Techniczne :40–45

Blázquez CS, Maté-González MÁ, Nieto IM, Martín AF, González-Aguilera D (2022) Assessment of the geothermal potential in the region of Ávila (Spain): An integrated and interactive thermal approach. Geothermics 98:102294. https://doi.org/10.1016/j.geothermics.2021.102294

Bondaruk J, Janson E, Wysocka M, Chałupnik S (2015) Identification of hazards for water environment in the Upper Silesian Coal Basin caused by the discharge of salt mine water containing particularly harmful substances and radionuclides. Journal of Sustainable Mining 14(4):179–187. https://doi.org/10.1016/j.jsm.2016.01.001

Bujakowski W (2015) Geologiczne, środowiskowe i techniczne uwarunkowania projektowania i funkcjonowania zakładów geotermalnych w Polsce. Wydawnictwo Instytutu Gospodarki Surowcami Mineralnymi i Energią Pan, Kraków

Bujakowski W, Tomaszewska B, Kepinska B, Balcer M (2010) Geothermal Water Desalination - Preliminary Studies. Geo-Heat Center Quarterly Bulletin 29(2)

Cátedra Hunosa (2023) Geothermal Gradient. https://www.unioviedo.es/catedrahunosa/index.php/geotermia/. Accessed 18 Jan 2023

Central Statistical Office (2020) Energy from renewable sources in 2020. https://stat.gov.pl/en/topics/environment-energy/energy/energy-from-renewable-sources-in-2020,3,13.html. Accessed 9 Nov 2022

Chamorro CR, Mondéjar ME, Ramos R, Segovia JJ, Martín MC, Villamañán MA (2012) World geothermal power production status: Energy, environmental and economic study of high enthalpy technologies. Energy 42(1):10–18. https://doi.org/10.1016/j.energy.2011.06.005

Chu Z, Dong K, Gao P, Wang Y, Sun Q (2021) Mine-oriented low-enthalpy geothermal exploitation: A review from spatio-temporal perspective. Energy Conversion and Management 237:114123. https://doi.org/10.1016/j.enconman.2021.114123

Chudy K (2022) Mine Water as Geothermal Resource in Nowa Ruda Region (SW Poland). Water 14(2):136. https://doi.org/10.3390/w14020136

Colmenar-Santos A, Folch-Calvo M, Rosales-Asensio E, Borge-Diez D (2016) The geothermal potential in Spain. Renewable and Sustainable Energy Reviews 56:865–886. https://doi.org/10.1016/j.rser.2015.11.070

Coro G, Trumpy E (2020) Predicting geographical suitability of geothermal power plants. Journal of Cleaner Production 267:121874. https://doi.org/10.1016/j.jclepro.2020.121874

Demollin-Schneiders E, Małolepszy Z, Bowers D (2005) Potential use of geothermal energy from mine water in Europe for cooling and heating. Santorini, Greece, pp 683–685

Dickson MH, Fanelli M (2003) Geothermal energy: utilization and technology. UNESCO Publisher

DiPippo R (2015) Geothermal Power Plants. Principles, Applications, Case Studies and Environmental Impact, 4 th. Elsevier Ltd.

Energy Education (2022) Geothermal heating. https://energyeducation.ca/encyclopedia/Geothermal_heating. Accessed 19 Jan 2023

EnergyCities (2023) Mine water as a renewable energy source. https://energy-cities.eu/best-practice/mine-water-as-a-renewable-energy-source/. Accessed 19 Jan 2023

ESMAP (2012) Geothermal Handbook: Planning and financing power generation, Technical Report. https://www.esmap.org/sites/esmap.org/files/DocumentLibrary/FINAL_Geothermal%20Handbook_TR002-12_Reduced.pdf. Accessed 20 Jan 2023

ESOLEO (2022) Types and use of geothermal energy in Poland. https://www.esoleo.pl/energia-geotermalna-i-jej-wykorzystanie-498/. Accessed 9 Nov 2022

EURACOAL (2022) Poland. The voice of coal in Europe. https://euracoal.eu/info/country-profiles/poland/. Accessed 20 Nov 2022

European Commission (2009) Research suggests mines could be a source of geothermal energy. https://cordis.europa.eu/article/id/31160-study-finds-mines-can-work-for-geothermal-power. Accessed 9 Nov 2022

EUROSTAT (2022) Coal production and consumption statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Coal_production_and_consumption_statistics. Accessed 20 Nov 2022

Franco A, Villani M (2009) Optimal design of binary cycle power plants for water-dominated, medium-temperature geothermal fields. Geothermics 38(4):379–391. https://doi.org/10.1016/j.geothermics.2009.08.001

Franza L, van der Linde C, Stapersma P (2018) Energy fundamentals. In: Clingendael Spectator. https://spectator.clingendael.org/pub/2018/2/energy-fundamentals/. Accessed 19 Jan 2023

Garabetian T (2020) Geothermal Lithium in Europe. An industrial strategy for the geothermal lithium battery value-chain. EGEC Report. Accessed 9 Nov 2022

Garabetian T, Dumas P, Serrano C, Kumar S (2022) 2021 EGEC Geothermal Market Report. Key Findings. https://www.egec.org/wp-content/uploads/2022/06/MR21_KF.pdf. Accessed 10 Nov 2022

Garabetian T, Dumas P, Serrano C, Mazzagatti V, Kumar S, Dimitrisina R, Erbanova H, Katechi S (2021) 2020 EGEC Geothermal Market Report. Key Findings. https://www.egec.org/wp-content/uploads/2021/06/MR20_KF_Final.pdf. Accessed 10 Nov 2022

Gerbelová H, Spisto A, Giaccaria S (2021) Regional Energy Transition: An Analytical Approach Applied to the Slovakian Coal Region. Energies 14(1):110. https://doi.org/10.3390/en14010110

Ghomshei MM (2007) Geothermal energy from Con mine for heating the city of Yellowknife, NWT: A Concept Study. Norman B. Keevil Institute of Mining Engineering, Vancouver

Ghomshei MM, Meech JA (2003) Usable heat from mine water: coproduction of energy and minerals, from "Mother Earth." In: Intelligence in a materials world: nanotechnology for the 21st century. CRC Press

Górecki W (1995) Atlas of geothermal resources in the Polish Lowland. Towarzystwo Geosynoptyków, Kraków

Gzyl G, Banks D (2007) Verification of the "first flush" phenomenon in mine water from coal mines in the Upper Silesian Coal Basin, Poland. Journal of Contaminant Hydrology 92(1):66–86. https://doi.org/10.1016/j.jconhyd.2006.12.001

Gzyl G, Janson E, Łabaj P (2017) Chapter 17 - Mine Water Discharges in Upper Silesian Coal Basin (Poland). In: Bech J, Bini C, Pashkevich MA (eds) Assessment, Restoration and Reclamation of Mining Influenced Soils. Academic Press, pp 463–486

Haehnlein S, Bayer P, Blum P (2010) International legal status of the use of shallow geothermal energy. Renewable and Sustainable Energy Reviews 14(9):2611–2625. https://doi.org/10.1016/j.rser.2010.07.069

Hajto M (2021) The state of geothermal energy utilization in Europe and the world as of 2020. Przegląd Geologiczny 69(9):566–577

Hajto M, Górecki W (2010a) Geological Analysis and Assessment of Geothermal Energy Resources in the Polish Lowlands. Proceedings World Geothermal Congress

Hajto M, Górecki W (2010b) THE MOST PROSPECTIVE AREAS OF USE OF THERMAL WATERS FOR HEATING PURPOSES IN THE POLISH LOWLANDS. Biuletyn Państwowego Instytutu Geologicznego 441(441):27–32

Hajto M, Gorecki W, Sowizdzal A (2005) Geological Analysis and Assessment of Geothermal Energy Resources in Selected Devonian, Carboniferous and Permian Reservoirs in the Polish Lowlands. Proceedings World Geothermal Congress

Hanbury O, Vasquez VR (2018) Life cycle analysis of geothermal energy for power and transportation: A stochastic approach. Renewable Energy 115:371–381. https://doi.org/10.1016/j.renene.2017.08.053

Huenges E, Ledru P (eds) (2011) Geothermal Energy Systems: Exploration, Development, and Utilization | Wiley. Wiley

Huttrer G (2021) Geothermal Power Generation in the World 2015-2020 Update Report

Igwe CI (2021) Geothermal Energy: A Review. International Journal of Engineering Research & Technology 10(3). https://doi.org/10.17577/IJERTV10IS030164

Iñigo A, Margarita DG, Cristina DS, Paloma P (2019) Geothermal Energy Use, Country Update for Spain

International Geothermal Association (2022) What is Geothermal. Quick geothermal power history. In: What is Geothermal. https://www.lovegeothermal.org/explore/what-is-geothermal/. Accessed 19 Jan 2023

Iorio M, Carotenuto A, Corniello A, Di Fraia S, Massarotti N, Mauro A, Somma R, Vanoli L (2020) Low Enthalpy Geothermal Systems in Structural Controlled Areas: A Sustainability Analysis of Geothermal Resource for Heating Plant (The Mondragone Case in Southern Appennines, Italy). Energies 13(5):1237. https://doi.org/10.3390/en13051237

IRENA (2022) Geothermal energy. In: Geothermal energy. https://www.irena.org/Energy-Transition/Technology/Geothermal-energy. Accessed 19 Jan 2023

Janson E, Gzyl G, Banks D (2009) The Occurrence and Quality of Mine Water in the Upper Silesian Coal Basin, Poland. Mine Water Environ 28(3):232–244. https://doi.org/10.1007/s10230-009-0079-3

Jurevicius O (2022) Value Chain Analysis: The Ultimate Guide. In: Strategic Management Insight. https://strategicmanagementinsight.com/tools/value-chain-analysis/. Accessed 19 Jan 2023

Kapuściński J, Nagy S, Długosz P, Biernat H, Bentkowski A, Zawisza L, Macuda J, Bujakowska K (1997) Zasady i metodyka dokumentowania zasobów wód termalnych i energii geotermalnej oraz sposoby odprowadzania wód zużytych. Poradnik metodyczny. MOŚZNiL, Warszawa

Karpiński M, Sowiżdżał A (2018) Coal mines heat source for heat pumps. https://www.rynekinstalacyjny.pl/artykul/pompy-ciepla/34295,kopalnie-wegla-kamiennego-zrodlem-ciepla-dla-pomp-ciepla. Accessed 9 Nov 2022

Kępińska B (2008) Geothermal energy use in Europe. Geothermal Training Programme :1–14

Konsek S, Czapnik A (2020) Target dewatering model liquidated coal mines, in the Upper Silesian Coal Basin. Systemy Wspomagania w Inżynierii Produkcji Vol.9, iss. 2

Kropka J, Janson E, Czapnik A (2005) Changes of hydrogeological conditions in the area of liquidated coal mines in the north—eastern part of Upper Silesia Coal Basin (southern Poland). In: Proceedings of 9th International Mine Water Congress. Oviedo, Spain, pp 209–215

Lapanje A, Rajver D, Székely E (2010) Review of geothermal energy utilization in north-eastern Slovenia and south-western Hungary in the scope of projet Screening of the geothermal utilization, evaluation of the thermal groundwater bodies and preparation of the joint aquifer management plan in the Mura-Zala basin T-JAM. https://geothermalcommunities.geonardo.com/assets/elearning/1.18.EN_geothermal_energy_utilization.pdf. Accessed 19 Jan 2023

Lara LM, Colinas IG, Mallada MT, Hernández-Battez AE, Viesca JL (2017) Geothermal use of mine water. In: European Geologist Journal 43. https://eurogeologists.eu/european-geologist-journal-43-viesca-geothermal-use-of-mine-water/. Accessed 22 Feb 2023

Lipták B (2020) 3 technologies to to capture geothermal energy. In: Control Global. https://www.controlglobal.com/measure/temperature/article/11295373/3-technologies-to-to-capture-geothermal-energy. Accessed 9 Nov 2022

Loredo C, Ordóñez A, Garcia-Ordiales E, Álvarez R, Roqueñi N, Cienfuegos P, Peña A, Burnside NM (2017) Hydrochemical characterization of a mine water geothermal energy resource in NW Spain. Science of The Total Environment 576:59–69. https://doi.org/10.1016/j.scitotenv.2016.10.084

Loredo C, Roqueñí N, Ordóñez A (2016) Modelling flow and heat transfer in flooded mines for geothermal energy use: A review. International Journal of Coal Geology 164:115–122. https://doi.org/10.1016/j.coal.2016.04.013

Lubelski Węgiel Bogdanka (2016) Integrated Report

Lund JW, Toth A (2021) Direct Utilization of Geothermal Energy 2020 Worldwide Review

Madhawa Hettiarachchi HD, Golubovic M, Worek WM, Ikegami Y (2007) The Performance of the Kalina Cycle System 11(KCS-11) With Low-Temperature Heat Sources. Journal of Energy Resources Technology 129(3):243–247. https://doi.org/10.1115/1.2748815

Małolepszy Z (2003) LOW TEMPERATURE, MAN-MADE GEOTHERMAL RESERVOIRS IN ABANDONED WORKINGS OF UNDERGROUND MINES. Stanford University, Stanford, California, pp 1–7

Mazovian Energy Agency (2022) Geothermal energy. In: Geothermal energy. https://www.mae.com.pl/oferta-mae/baza-wiedzy/odnawialne-zrodla-energii/energia-geotermalna. Accessed 9 Nov 2022

Mckinsey (2020) The mining value chain: A hidden gem. https://www.mckinsey.com/industries/metals-and-mining/our-insights/the-mine-to-market-value-chain-a-hidden-gem. Accessed 19 Jan 2023

Menéndez J, Ordóñez A, Álvarez R, Loredo J (2019) Energy from closed mines: Underground energy storage and geothermal applications. Renewable and Sustainable Energy Reviews 108:498–512. https://doi.org/10.1016/j.rser.2019.04.007

Menéndez J, Ordónez A, Fernández-Oro JM, Loredo J, Díaz-Aguado MB (2020) Feasibility analysis of using mine water from abandoned coal mines in Spain for heating and cooling of buildings. Renewable Energy 146:1166–1176. https://doi.org/10.1016/j.renene.2019.07.054

Miecznik M, Sowiżdżał A, Tomaszewska B, Pająk L (2015) Modelling geothermal conditions in part of the Szczecin Trough – the Chociwel area. Geologos 21. https://doi.org/10.1515/logos-2015-0013

Milenić D, Vasiljević P, Vranješ A (2010) Criteria for use of groundwater as renewable energy source in geothermal heat pump systems for building heating/cooling purposes. Energy and Buildings 42(5):649–657. https://doi.org/10.1016/j.enbuild.2009.11.002

Ministry of Climate and Environment Energy Policy of Poland until 2040 (EPP2040). In: Energy Policy of Poland until 2040 (EPP2040). https://www.gov.pl/web/climate/energy-policy-of-poland-until-2040-epp2040. Accessed 12 Nov 2022

Ministry of Infrastructure (2021) Comprehensive assessment of the potential for efficient heating and cooling in Slovenia. https://energy.ec.europa.eu/system/files/2022-01/SI%20CA%202020%20en.pdf. Accessed 19 Jan 2023

Mruk Ł (2004) Analiza możliwości wykorzystania niekonwencjonalnych źródeł energii w obiekcie budowlanym

Ni W, Wu S, Ren Q (2012) Preparation and Characterization of Silanized TiO2 Nanoparticles and Their Application in Toner. Ind Eng Chem Res 51(40):13157–13163. https://doi.org/10.1021/ie302249v

Nowak W, Sobański R, Kabat M, Kujawa T (2000) Systemy pozyskiwania i wykorzystania energii geotermicznej. Wydawnictwo uczelniane Politechniki Szczecińskiej, Szczecin

Office of energy efficiency & renewable energy (2022) Electricity Generation. https://www.energy.gov/eere/geothermal/electricity-generation. Accessed 9 Nov 2022

Ortega M, del Río P, Ruiz P, Nijs W & Politis S (2020) Analysing the influence of trade, technology learning and policy on the employment prospects of wind and solar energy deployment: The EU case. Renewable and Sustainable Energy Reviews 122: 109657. https://doi.org/10.1016/j.rser.2019.109657

OZE (2015) Heat pumps in a former coal mine in Zabrze. http://odnawialnezrodlaenergii.pl/energia-geotermalna-aktualnosci/item/1897-pompy-ciepla-w-dawnej-kopalni-wegla-w-zabrzu. Accessed 9 Nov 2022

Pająk L, Tomaszewska B, Bujakowski W, Bielec B, Dendys M (2020) Review of the Low-Enthalpy Lower Cretaceous Geothermal Energy Resources in Poland as an Environmentally Friendly Source of Heat for Urban District Heating Systems. Energies 13(6):1302. https://doi.org/10.3390/en13061302

Patsa E, Zarrouk SJ, Arianpoo N (2015) Geothermal Energy in Mining Developments: Synergies and Opportunities Throughout a Mine's Operational Life Cycle. In: Proceedings World Geothermal Congress 2015

Peralta Ramos E, Breede K, Falcone G (2015) Geothermal heat recovery from abandoned mines: a systematic review of projects implemented worldwide and a methodology for screening new projects. Environ Earth Sci 73(11):6783–6795. https://doi.org/10.1007/s12665-015-4285-y

PETA (2023) Heat Roadmap Europe. https://heatroadmap.eu/peta4/. Accessed 19 Jan 2023

Philpott KD (2002) Evaluation of the Bogdanka mine, Poland. In: Proceedings of the IV European Coal Conference. Polish Geological Institute Special Papers, pp 199–206

Plewa S (1994) Rozkład parametrów geotermalnych na obszarze Polski. Wyd. IGSMiE PAN, Kraków

Polish Geothermal Association (2022) Geothermal - general information. In: Geothermal - general information. http://www.pga.org.pl/geotermia-informacje-ogolne.html. Accessed 9 Nov 2022

Polish Geothermal Society (2022) Geothermy in Poland. https://energia-geotermalna.org.pl/geotermia-w-polsce/. Accessed 9 Nov 2022

Polish Geothermal Society (2017) Geothermal from (closed) mines. https://energia-geotermalna.org.pl/geotermia-z-zamykanych-kopalni/. Accessed 11 Sep 2022

Polska Grupa Górnicza (2020) W PGG S.A. podpisano porozumienie ze stroną społeczną - PGG.pl. https://www.pgg.pl/strefa-korporacyjna/aktualnosci/1057/PGG-podpisano-porozumienie. Accessed 20 Nov 2022

Porter ME (1985) Competitive Advantage. Creating and Sustaining Superior Performance. The Free Press, United States of America

Prananto LA, Juangsa FB, Iqbal RM, Aziz M, Soelaiman TAF (2018) Dry steam cycle application for excess steam utilization: Kamojang geothermal power plant case study. Renewable Energy 117:157–165. https://doi.org/10.1016/j.renene.2017.10.029

Preene M, Younger PL (2014) Can you take the heat? – Geothermal energy in mining. Mining Technology 123(2):107–118. https://doi.org/10.1179/1743286314Y.0000000058

Rajver D, Lapanje A, Rman N, Prestor J (2016) Geothermal Energy Use, Country Update for Slovenia. Strasbourg, France,

Rajver D, Lapanje A, Rman N, Prestor J (2019) Geothermal Energy Use, Country Update for Slovenia. Den Haag, The Netherlands, pp 1–16

Rajver D, Rman N, Lapanje A, Prestor J (2020) Geothermal Country Update Report for Slovenia, 2015-2019. In: Proceedings World Geothermal Congress 2020+1. Reykjavik, Iceland, pp 1–16

Levin R, Watson A (2016) Maximizing the value og G&A. McKinsey Quaterly: June 23, 2016. MacKinsey & Company. https://www.mckinsey.com/capabilities/operations/our-insights/maximizing-the-value-of-ga#/

Rman N, Markovic T, Brenčič M (eds) (2018) Geology, hydrogeology and geothermy of NE Slovenia and N Croatia. Geological Survey of Slovenia, Ljubljana

Robins J, Kolker A, Flores-Espino F, Pettitt W, Schmidt B, Beckers K F, Pauling H, Anderson B (2021) 2021 U.S. Geothermal Power Production and District Heating

Market Report. Technical Report. Golden, CO: National Renewable Energy Laboratory, July 2021. https://www.nrel.gov/docs/fy21osti/78291.pdf.

Roslin A, Esterle JS (2016) Electrofacies analysis for coal lithotype profiling based on high-resolution wireline log data. Computers & Geosciences 91:1–10. https://doi.org/10.1016/j.cageo.2016.03.006

Różkowski (2006) Czynniki kształtujące przeobrażenia środowiska hydrochemicznego strefy wymiany w utworach karbonu w północno—wschodniej części Górnośląskiego Zagłębia Węglowego (GZW). In: Mat. Konf. Hydrogeochemia '06. Złoty Potok, pp 95–98

Rudakov DV, Inkin OV (2022) A method to evaluate the performance of an open loop geothermal system for mine water heat recovery. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu (1):5–11. https://doi.org/10.33271/nvngu/2022-1/005

Sanchez-Guzman J (2005) Geothermal Energy Development in Spain - Country Update Report

Scheule H, Jortzik S (2020) Benchmarking loss given default discount rates. Journal of Risk Model Validation 14(3): 53-96. https://doi.org/10.21314/JRMV.2020.225

Shokati N, Ranjbar F, Yari M (2015) Exergoeconomic analysis and optimization of basic, dual-pressure and dual-fluid ORCs and Kalina geothermal power plants: A comparative study. Renewable Energy 83:527–542. https://doi.org/10.1016/j.renene.2015.04.069

Sokołowski J (1996) Definicje pojęć określających warunki występowania zasobów energii geotermicznej i geotermalnej. Mat. Kursu „Polska Szkoła Geotermalna", Kraków

Solik-Heliasz E, Małolepszy Z (2001) The possibilities of utilisation of geothermal energy from mine waters in the upper Silesian Coal Basin. In: Proceedings of International Scientific Conference. Ustroń

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

Sowiżdżał A (2010) Prospects of use of thermal water resources of lower Jurassic aquifer in the Szczecin trough (NW Poland) for space heating and balneology and recreation. Przegląd Geologiczny 58(7):613–621

Swiss Seismological Service (2022) Forms of Geothermal Energy. http://www.seismo.ethz.ch/en/knowledge/things-to-know/geothermal-energy-earthquakes/forms-of-geothermal-energy/. Accessed 9 Nov 2022

Tester J (2007) The Future of Geothermal Energy. In: Congressional Testimony for "Oversight hearing on Renewable Energy Opportunities and Issues on Federal Lands: Review of Title II, Subtitle B- Geothermal Energy of EPAct; and other renewable programs and proposal for public resources"

The Coal Authority (2022) Geothermal energy from abandoned coal mines. https://www2.groundstability.com/geothermal-energy-from-abandoned-coal-mines/. Accessed 9 Nov 2022

ThinkGeoEnergy (2020a) Global map to identify areas suitable for geothermal power plants. https://www.thinkgeoenergy.com/global-map-to-identify-areas-suitable-for-geothermal-power-plants/. Accessed 19 Jan 2023

ThinkGeoEnergy (2023) ThinkGeoEnergy's Top 10 Geothermal Countries 2022 – Power Generation Capacity (MW). https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2022-power-generation-capacity-mw/. Accessed 29 Jan 2023

ThinkGeoEnergy (2020b) Understanding the geothermal opportunity in mine waters. https://www.thinkgeoenergy.com/understanding-the-geothermal-opportunity-in-mine-waters/. Accessed 19 Jan 2022

Tokarz M, Mucha W (2013) Use of geothermal energy from mine's water in Spółka Restrukturyzacji Kopalń S.A. Zakład Centralny Zakład Odwadniania Kopalń (CZOK) in Czeladź Poland. Technika Poszukiwań Geologicznych R. 52, nr 1

U.S. Energy Information Administration (2022) Where geothermal energy is found. https://www.eia.gov/energyexplained/geothermal/where-geothermal-energy-is-found.php. Accessed 29 Jan 2023

Venegas R, Kuravi S, Kota K, Nguyen T, McCay M (2015) Review of Geothermal and Solar Thermal Power Plants and a Comparative Design Analysis. American Society of Mechanical Engineers Digital Collection

Wang M, Zhang S, Edwin GNJ (2017) Hydrothermal Spallation Drilling Technology: An Alternative Method of Geothermal Energy Development. Atlantis Press, pp 302–305

Wolfson R (2012) Energy from Earth and Moon, 2nd edn. W.W. Norton & Company, New York

Xevgenos D, Gzyl G, Panteleaki K, Skalny A, Bałazińska M, Sapoutzi D, Loizidou M (2020) LIFE BRINE MINING Policy Brief. Developing the 1st Circular Economy Action Plan on the coal mine sector in Poland. https://brinemining.eu/wp-content/uploads/2021/03/LIFE-BM-Policy-brief.pdf. Accessed 19 Jan 2023

Yari M (2010) Exergetic analysis of various types of geothermal power plants. Renewable Energy 35(1):112–121. https://doi.org/10.1016/j.renene.2009.07.023

Ziemia na rozdrożu (2017) A renewable energy source – geothermal. https://ziemianarozdrozu.pl/?p=156779. Accessed 9 Nov 2022