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Research on the Effective Use of Enhanced Geothermal Systems in Poland to Achieve Environmental Effects

Anna Sowiżdżał, Barbara Tomaszewska, Michał Kaczmarczyk, Maciej Szymanek and Magdalena Starczewska

AGH University of Krakow, Mickiewicza Av. 30, 30-059 Kraków, Poland

ansow@agh.edu.pl, bts@agh.edu.pl, mkz@agh.edu.pl, maszyman@agh.edu.pl, magdalena.starczewska@agh.edu.pl

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ABSTRACT

Poland has low-temperature geothermal resources, which have been used in hydrogeothermal systems to produce thermal energy since the 1990s. Geothermal heat plants currently operate in only 7 towns, and although the current system of government support gives hope for the construction of new geothermal heat plants in the coming years, the use of this renewable and environmentally friendly energy source is still at a low level in Poland. In order to increase the share of geothermal energy in the country's energy balance, numerous research works are being carried out to develop this sector in Poland. In recent years, research related to the recognition of the potential use of hot dry rocks in Enhanced Geothermal Systems (EGS) has become increasingly important. These systems allow the production of both thermal and electrical energy under conditions of low-permeability and porosity of rocks, which definitely is not suitable for hydrogeothermal systems. In Poland, locations suitable for the construction of EGS have been selected. EGS mostly use water as a medium, but following the example of other countries, the effectiveness of using carbon dioxide, was also analyzed. This was possible due to Polish-Norwegian cooperation under the EnerGizerS project, aimed at identifying and characterizing in detail the geological structures for locating CO_2-EGS in Poland and Norway, combining the requirements of Enhanced Geothermal System technology and geological storage of carbon dioxide.

The development of innovative geothermal technologies, including Enhanced Geothermal Systems using supercritical carbon dioxide as the working medium, is of particular importance wherever there are resource limitations to the wider use of geothermal energy in classical hydrogeothermal systems. Many Polish cities still face the problem of air pollution, especially during the winter months. The problem of smog and low emissions resulting from the burning of solid fuels is significant. For this reason, it is necessary to look for solutions to produce energy in an environmentally friendly way, which is possible due to the efficient use of geothermal energy. This paper presents the results of research on the effectiveness of using EGS in Poland. Legal and environmental aspects are indicated for the construction of a pilot EGS in Poland located in the region of western Poland (Gorzów Block) using a petrothermal reservoir built from Lower Permian volcanic and sedimentary rocks with temperatures of 145°C at a depth of about 4.3 km bgl.

1. INTRODUCTION

Geothermal research has been carried out in Poland since the 1980s. Originally, they focused primarily on recognizing the resource potential for the construction of geothermal heating plants using geothermal waters accumulated in hydrogeothermal reservoirs. The result of this research was the launch of the first geothermal heat plant in Poland in the Podhale region in the 1990s. The next years brought the start of more geothermal heat plants, but also work on the recognition of the hydrogeothermal potential of our country. These resulted in a series of Geothermal Atlases (Górecki (ed.) et al., 2006 a, b; 2011, 2012, 2013; Górecki et al., 2015), which provides a solid foundation for the construction of further geothermal heat plants in Poland.

However, although hydrogeothermal resources are relatively well recognized in Poland (e.g., Górecki et al., 2015, Sowiżdżał, 2018), the work on recognizing the petrogeothermal potential for Enhanced Geothermal Systems (EGS) using the heat of hot dry rocks started much later and is currently in the pre-implementation stage. Since 2010 research work has been carried out in this field (Wójcicki et al. (eds.), 2013; Sowiżdżał and Kaczmarczyk, 2016; Sowiżdżał et al., 2013; Sowiżdżał et al., 2021; Gładysz et al., 2020a, b), although no installations of this type in Poland are in operation so far.

In 2024, the Polish-Norwegian EnerGizerS project: CO_2-Enhanced Geothermal Systems for Climate Neutral Energy Supply (http://www.energizers.agh.edu.pl/en/) was completed, which provided interesting results in the context of the possibility of using EGS technology for simultaneous energy production and CO_2 sequestration (Sowiżdżał et al., 2022a). It was assumed that the working medium in an EGS would be CO_2 (CO_2-EGS), instead of water, which commonly serves as the working medium in such plants operating worldwide (Sowiżdżał et al., 2022b) (Fig.1).

The CO_2-EGS solution is being studied in many regions of the world (Di Pippo, 2016), but due to its peculiarities and a number of difficulties arising from it, it is not currently used on a commercial scale. The peculiarity of this solution is the significant environmental effect of geological storage of CO_2 (CCS - Carbon Capture and Storage) during the power generation process, as part of the carbon dioxide injected into the reservoir remains permanently stored. Such a solution can bring many benefits in terms of energy production while reducing greenhouse gas emissions. This is of particular importance in countries such as Poland, which face the problem of environmental pollution resulting from fossil fuel energy extraction. Carbon capture and storage is a technology to reduce large-scale greenhouse gas emissions from fossil fuel-based energy and industrial sectors in the near future (e.g. Zhang et al., 2017) . Combining this aspect with the production of clean and renewable energy seems to be an ideal environmental solution. CO_2 -Enhanced Geothermal System is a system that extract energy from rock formations (dry or not containing a sufficient amount of water) by artificially increasing the hydraulic capacity of the geothermal reservoir, introducing an energy-carrying working fluid into the reservoir, and then bringing it to the surface (to the power plant) for energy purposes. The working fluid in CO_2-EGS systems is carbon dioxide. The purpose of this type of installation is primarily related to the energy aspect, i.e., acquiring energy accumulated in hot, dry rocks located at great depths, secondary -an increase in the pro-environmental effects through the geological storage of CO_2 during the energy generation process.

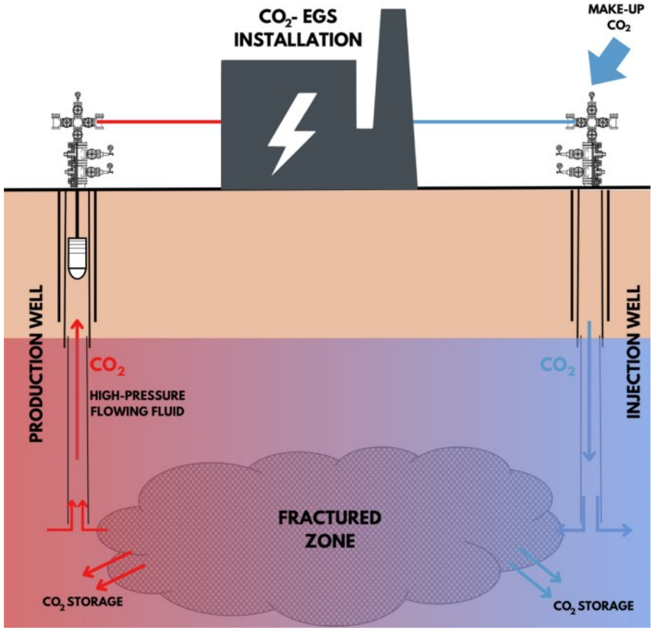

Figure 1: CO_2-EGS scheme.

The paper considers the possibility of implementing CO_2-EGS in Polish conditions, with particular attention to the environmental aspects of its use.

2. GEOTHERMAL ENERGY UTILIZATION ON THE BACKGROUND OF GEOLOGICAL CONDITIONS IN POLAND

Increasing the use of geothermal energy in Poland has, for years, been one of the Polish government's priority tasks, as part of the implementation of international commitments to increase the share of renewable energy sources (RES) and reduce pollution emitted into the atmosphere (Galos, 2024). Currently, the applications of geothermal energy and geothermal waters in Poland mainly include district heating, balneotherapy, and recreation. At the end of 2022, the total installed geothermal thermal capacity of these systems was approximately 129 MW, with the largest and oldest geothermal system located in the Podhale region. In 2022, this system had a geothermal capacity of 70 MW, which has now increased to over 100 MW due to the connection of new facilities to the district heating network. Geothermal heat production in 2022 amounted to about 1122 TJ (Kępińska, Hajto, 2023), which represents a small share of Poland's total final energy consumption (less than 1%).

In 2023, there were 7 geothermal heat plants in Poland (marked in green in Fig. 2), but the number of installations is expected to grow in the coming years. Three new heat plants (marked in purple in Fig. 2) in Kole, Sieradz, and Konin are currently at various stages of implementation, signaling the possibility of supplying heat to consumers in the next heating season. The development of new investments is also supported by new geothermal boreholes subsidized by government funds from 2017 to 2023. Thanks to priority programs, there is a real opportunity to drill 56 new geothermal boreholes and document new thermal water deposits in Poland (Galos, 2024).

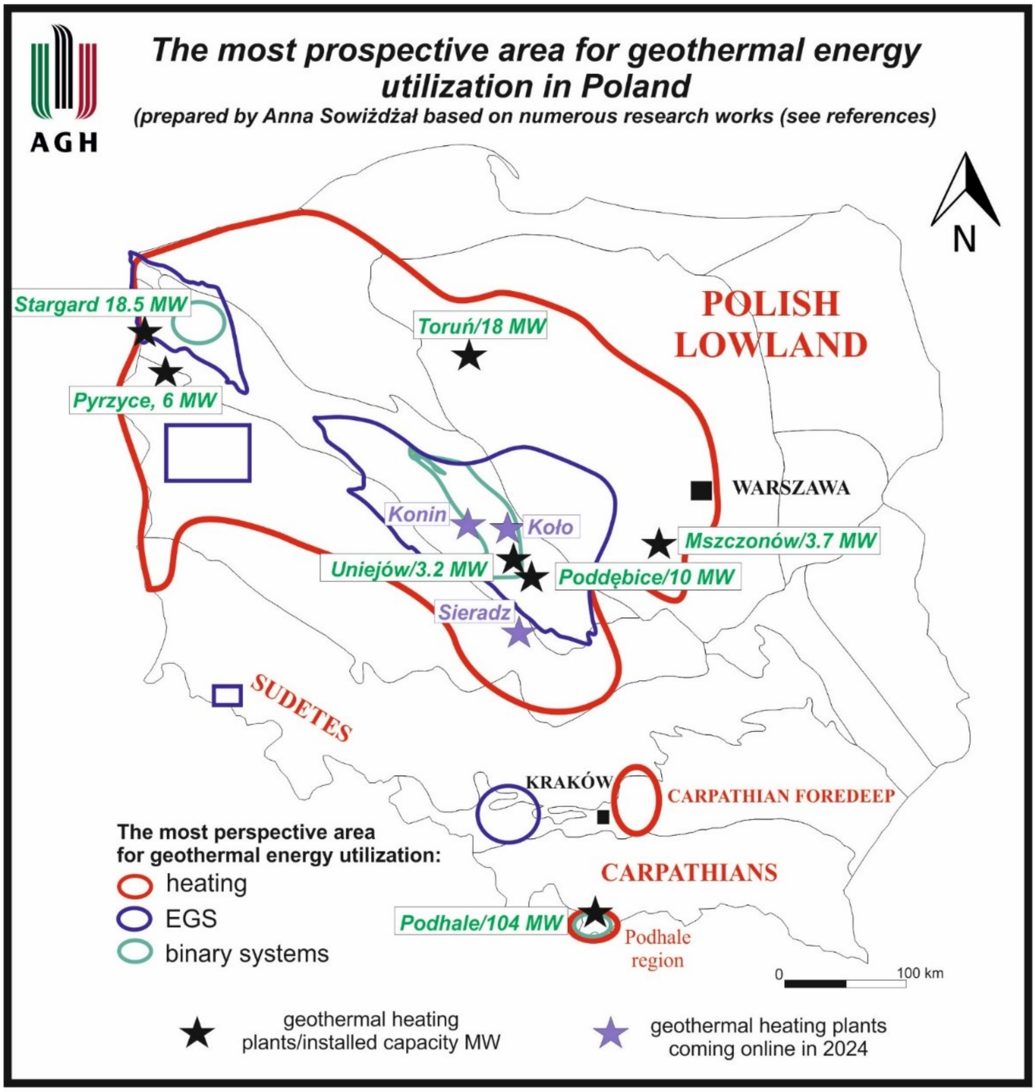

Figure 2: The most prospective area for geothermal energy utilization in Poland with the location of geothermal facilities (based on results of research works realized in Poland since 2004: Górecki ed, et al. 2006a, b, 2011, 2012, 2013; Górecki et al., 2015; Wójcicki, et al. eds. 2013, (Bujakowski, Tomaszewska (eds.) et al. 2014).

Poland is characterized by low-temperature geothermal resources, not exceeding 100°C. The occurrence of geothermal resources in Poland is associated with four major hydrogeothermal provinces: The Polish Lowlands, the Carpathian Mountains, the Carpathian Foredeep and the Sudeten Mountains, characterized by different geological conditions. Among the most promising regions for the crystallisation of hydrogeothermal resources in district heating systems, several areas should be identified (Fig.2): Podhale, central part of the Polish Lowlands, and locally Carpathians Foredeep and Sudetes Region. One of the most prospective regions for geothermal energy development in Poland are connected with Polish Lowlands. Water in these areas are characterized by favourable temperatures (even above 90°C) and relevant value of discharges of wells (to several hundred m^3/h). The principal resources of geothermal waters in the Polish Lowlands are accumulated in the Mesozoic groundwater horizons. Geothermal waters are accumulated first of all in the Lower Jurassic and Lower Cretaceous formations. Another perspective area for the use of hydrothermal resources is the Inner Carpathian – Podhale (southern part of Poland), represented by favorable reservoir parameters and lithology, usually high yields and regional extent of the aquifer as well as recent recharge and low TDS (Górecki et al, 2015; Sowiżdżał et al, 2020, Sowiżdżał , 2018). Due to the fact that these are the most favorable areas in Poland, they have also been identified as potential for the construction of binary installations (Bujakowski, Tomaszewska, (eds.) et al., 2014).

Petrogeothermal energy resources in Poland have been recognized in three different geological conditions - sedimentary, volcanic and crystalline rocks. Based on international experiences (Brown et al., 2012; Tester et al., 2006; Tenzer, 2001; Sausse et al., 2007), requirements for development of petrogeothermal energy have been specified. Critical requirements for the EGS or/and HDR location comprise: thermal parameters of the rocks (temperatures >150°C), thickness of the reservoir (minimum 300 m), porosity and permeability of the reservoir rocks (as the lowest) and the depth of the reservoir (3-6 km) (Wójcicki et al., eds. 2013). In Poland, outcrops of igneous rocks, interesting in terms of the application of EGS technology, with relatively large areas and volumes, occur in the south (Sudetes and Fore-Sudetic Block), continuing in the Czech Republic. The most interesting area for the application of EGS technology in crystalline rocks was identified in Karkonosze pluton (part of Sudetes). This area is characterized by favorable thermal conditions - geothermal gradient is approx. 4°C/100 m, temperature reaches 165°C at a depth of 4,000 m bsl. Due to the elevated temperature on a regional scale and the high thickness of volcanic deposits, a particularly attractive region in the context of the use of unconventional geothermal resources is the north-west and west part of the Gorzów Block (Permian volcanics, Dębno region).

Based on the comprehensive geological analysis (Sowiżdżał et al, 2022a, Pająk et al, 2021), the Lower Permian reservoir in Gorzów Block (Fig. 3) was indicated as the most interesting for CO_2-EGS systems in Poland. Several factors influencing such selection were considered, and the Cross-Impact Structured Data Analysis method was selected as a tool to assist in the selection process. The key parameters in the analysis were the thermal and petrophysical parameters of the reservoir rocks, the availability of CO_2 sources, the existing wells and other infrastructure, and the level of geological recognition. The Gorzów Block region, located in the NW part of Poland, seems to be the most optimal for this area. The additional reason for choosing the site was the analogy of the EGS Groß Schönebeck in Germany, where Lower Permian sandstones and volcanic rocks at a depth of about 4000 m bgl form a petrogeothermal reservoir. For the three wells positively verified for the core region of the Gorzów Block, there is a high heat flow (even above 80 mW/m^2 in the Ośno IG-2 well - the highest in Poland) and the temperature at a depth of 3 km bgl exceeds 100 °C. Therefore, based on the comprehensive geological analysis, the Lower Permian profile was selected for testing in the Ośno IG-2 well, including sedimentary rocks and effusive rocks. The Ośno IG-2 well is located in the northwest part of Poland (Gorzów Block) (Sowiżdżał et al, 2022a). This paper focuses on the environmental aspects of the operation of a potential Enhanced Geothermal System using CO_2 as the working medium in Poland.

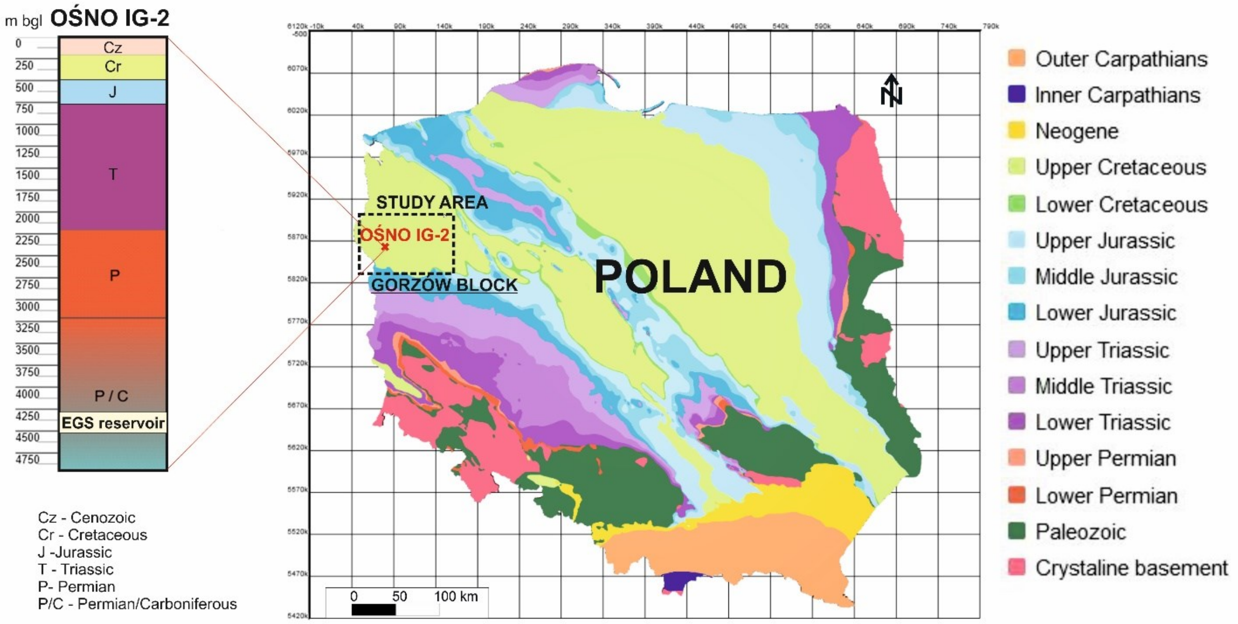

Figure 3: Location of the study area on the background of Bedrock Geology of Poland 2005 based on Małolepszy et al., 2023.

3. LEGAL ASPECTS FOR EGS IN POLAND

The key formal and legal regulations related to the location of CO_2-EGS are regulated in three Polish acts: *Geological and Mining Law*, *Act on the provision of information on the environment and its protection, public participation in environmental protection and environmental impact assessments and Energy Law*. In the geological context, it is necessary to process a concession to search for an appropriate geological structure for the construction of the CO_2-EGS system. At this stage, it is considered essential to recognize the hydrogeological and geological engineering conditions related to the injection of carbon dioxide. It is also necessary to identify all environmental limitations to reduce the negative impact of the investment on the environment.

The concession is also required for the exploration or recognition of an underground carbon dioxide storage complex. Granting a concession by the Ministry of Environment must be preceded by a decision on environmental conditions. The legal basis here is the Act of 3 October 2008 on the provision of information on the environment and its protection, public participation in environmental protection, and on environmental impact assessments. The essence of the procedure to decide on environmental conditions is to understand the problem and the environmental nuisance of a project. Only on this basis, the impact of the planned conditions on the environment is determined, and then the liquidation or minimization of the identified conditions. After obtaining the concession for the construction of the CO_2-EGS system, it is also necessary to meet the requirements resulting from the energy regulation. A carbon dioxide transport network is a network for the transmission of carbon dioxide, together with accompanying compressor or reduction stations, the network traffic of which is the responsibility of the operator of the carbon dioxide transport network. Therefore, it is necessary to regulate these issues in consultation respected regulatory office. The operator of the carbon dioxide transport network is an energy company engaged in the transmission of carbon dioxide, and the operator is responsible for the network traffic of the carbon dioxide transport network, the current and long-term safety of the operation of this network, its operation, maintenance, repairs and the necessary expansion. The main role here plays energy company from which it follows that it is an entity that conducts - apart from processing, storing, distributing fuels or energy or trading in them - also activities in the field of carbon dioxide transmission. Underground carbon dioxide storage facility is a part of a rock mass with a specific capacity used for the permanent storage of carbon dioxide, connected to a surface injection installation. The operator of the carbon dioxide transport network is responsible for ensuring equal and open access to the carbon dioxide transport network. The task required energy regulatory office is to ensure equal and open access to the carbon dioxide transport network.

One of the important elements of the correct application of CCS technology is the reduction of the composition of the carbon dioxide stream, consistent with the primary purpose of geological storage, i.e., the separation of carbon dioxide emissions from the atmosphere, based on the risk that pollution may pose to the safety and security of transport and storage networks and the environment and human health. That is why, the entrepreneur is obliged to accept the composition of the carbon dioxide stream after carrying out the risk assessment. The risk assessment consists in showing that the content of other gases and substances in the composition of the carbon dioxide stream that will be injected into the underground storage site does not pose a threat to the environment or human health and life and is below levels that could adversely affect the integrity of the underground storage site and the network of carbon dioxide transport. The statutory criteria for the acceptance of the composition of the carbon dioxide stream are the percentage composition, taking into account the minimum level of carbon dioxide content and the permissible content of other gases and substances and the physical parameters of carbon dioxide, including temperature and pressure.

The operator should accept and inject carbon dioxide streams only when an analysis of the composition of the streams, including corrosive substances, and a risk assessment have been carried out, and if this assessment has shown that the contamination levels of the carbon dioxide streams comply with the composition criteria. The above aspect is particularly important for the risk assessment that the concentration of all accidental and added substances is below levels that would adversely affect the integrity of the landfill or the relevant transport infrastructure, constitute a significant risk to the environment or human health, or contravene the requirements of applicable community legislation.

The concession serves as an instrument of state supervision over the performance of activities consisting mainly in the extraction of minerals from deposits, underground nonreservoir storage of substances, underground waste storage, and underground carbon dioxide storage. The concession is also a practical instrument for the protection of other elements of the environment.

4. ENVIRONMENTAL ASPECTS FOR EGS IN POLAND

Analysis of the environmental aspects of geothermal energy, especially in the context of EGS, requires comprehensive assessment tools, the most important of which is the life cycle assessment (LCA). This methodology allows for a systematic assessment of the environmental impact at every stage of the functioning of geothermal systems, from the extraction of raw materials to the production of installation components through the operation stage to their liquidation and recycling. LCA analysis is very important in the case of EGS, which requires intensive drilling work and large material inputs (Kaczmarczyk et al., 2024).

The scientific literature emphasises the importance of life cycle assessment in the context of greenhouse gas emissions, water consumption, impact on biodiversity and degradation of the local environment (Bayer et al., 2013; Kaczmarczyk 2019; Stranddorf et al., 2005). In the case of EGS systems, special attention should be paid to emissions related to the construction of infrastructure (e.g. drilling rigs), the consumption of process water in reservoir stimulation processes and the possibility of reinjection of working fluids to minimize the impact on water resources. In addition, EGS systems offer the possibility of reducing emissions of non-condensable gases such as CO_2 or H_2S, which constitutes an additional environmental potential of this technology.

This chapter focuses on the environmental aspects of EGS systems, particularly emphasising the results of LCA analyses as a tool supporting the sustainable development of the geothermal sector. The analysis includes the leading environmental indicators, key challenges, and opportunities for optimising technological processes to maximize the environmental benefits resulting from the development of EGS systems. The conclusions presented in this chapter are intended to support further research and strategic decisions in shaping energy policy based on sustainable solutions

4.1 Life Cycle and Water Footprint Assessment for EGS

Due to its stability, low emissions and renewable nature, geothermal energy is an important element of the global energy transformation. In particular, the Enhanced Geothermal Systems (EGS) technology enables the use of thermal resources in regions where previous geothermal methods were impossible due to low rock permeability or lack of natural reservoirs. By hydraulically stimulating rock formations at great depths, EGS create artificial reservoirs that allow the extraction of thermal energy and its use for producing electricity and heat. This advanced technology opens up new perspectives for geothermal energy, but its development requires a thorough understanding of the environmental impacts at each stage of the system's life cycle (Strojny et al., 2024). The assessment of the environmental impact of EGS is based on the Life Cycle Assessment (LCA) method, which allows for the analysis of impacts from the construction stage through operation to the dismantling of the installation. A key aspect of EGS systems is the management of the construction and operation processes, which have the largest share of their environmental footprint. Particular attention should be paid to greenhouse gas emissions, water consumption and the possibility of microseismicity, which are the most significant environmental factors.

The construction of EGS systems generates significant emissions related to the drilling processes and the construction of ground infrastructure. Drilling to a depth of several kilometers requires significant energy and material inputs, which burdens the environmental balance. Studies indicate that construction-related emissions can constitute over 80% of the system's total carbon footprint (Sigurjonsson et al., 2021). Using alternative materials and more efficient construction methods could contribute to reducing this impact.

The operation of EGS systems is characterised by low greenhouse gas emissions compared to fossil fuel technologies. For example, CO_2 emissions from EGS systems range from 42 to 62 kg CO_2/MWh_{el}, making them competitive with other renewable energy sources (Frick et al., 2010). One of the solutions to reduce emissions is the reinjection of gases such as CO_2, which further reduces their impact on the environment. Another important operation element is the management of working fluids, which can be reinjected into the reservoir in a closed circuit, minimising the impact on water resources.

Water consumption in EGS systems is a significant challenge, especially in regions with limited resource availability. Hydraulic stimulation processes require significant amounts of water, which can lead to local shortages. The solution to this problem is implementing closed-water circulation technology and optimising its use during operation (Gurbuz et al., 2022). Thanks to this, it is possible to reduce the negative impact on water resources and minimise the risk of their degradation.

One of the challenges of EGS technology is microseismicity, which can occur due to hydraulic stimulation. This phenomenon is usually local and low magnitude, but requires constant monitoring and appropriate countermeasures to minimise potential effects. The implementation of advanced monitoring systems and strict risk management regulations allow for the effective reduction of the impact of microseismicity on the environment and local communities (Sigurjonsson et al., 2021). The LCA methodology enables the identification of key areas with the greatest environmental impact in EGS systems and the implementation of optimization measures. For example, the use of ORC (Organic Rankine Cycle) technology with low GWP (Global Warming Potential) working fluids allows for further reduction of the environmental impact (Heberle et al., 2016). Integrating EGS with other technologies, such as energy storage or multi-generational energy systems, can increase the efficiency of systems and reduce their negative impact on the environment.

Studies on EGS systems in Reykjanes, Iceland and Vendenheim, France confirm their low greenhouse gas emissions of 1.6–17.4 g CO_2eq/kWhel and 6.9–13.9 g CO_2eq/kWhel, respectively (Sigurjonsson et al., 2021). Pratiwi et al. (2018) conducted a comprehensive analysis of greenhouse gas (GHG) emissions over the life cycle in five scenarios, encompassing heat production, electricity generation, and cogeneration systems. Using real project data and applying the LCA methodology, the study found that the Rittershoffen plant had emissions ranging from 6.97 to 9.15 g CO_2/kWh during its 25-year operation. In contrast, the Illkirch-Graffenstaden plant, still under development, was projected to emit between 2.69 and 4.39 g CO_2/kWh for heat and 29.53 to 54.2 g CO_2eq/kWh for electricity.

These results indicate the potential of EGS technology as a solution consistent with the principles of sustainable development. The use of integrated analysis methods, such as Life Cycle Costing (LCC), additionally allows for the assessment of the economic environmental costs and the identification of the most effective design strategies. In summary, EGS systems are a technology with great environmental potential that can play a key role in energy transformation. Thanks to life cycle assessment methods, it is possible to precisely identify the challenges and opportunities related to their implementation, which supports the development of sustainable geothermal energy. The implementation of innovative technological solutions, efficient resource management and integration with other energy systems will allow for maximising the environmental benefits offered by this advanced technology.

4.2 Results of Life Cycle Assessment of Enhanced Geothermal Systems in the Polish conditions

LCA analysis was carried out for CO_2-EGS installation under Polish conditions (Strojny et al., 2024). The main objective of the analysis was to determine the environmental impact of an EGS installation using supercritical carbon dioxide as the working medium. The Gorzów Block was selected as a potential location under Polish conditions, a regional geological unit in north-western Poland. The studies included the Ośno IG-2 borehole (depth 4950 m). power generation only within hybrid cycle. The results of process modeling and optimization of supercritical carbon dioxide-Enhanced Geothermal Systems in Poland (Gładysz et al., 2024) indicate that it is possible to build CO_2-EGS systems with powers from 0.4 MWel to 9MWel in case of combined heat and power within the direct sCO2 cycle and 1.7MWel if only hybrid cycle power generation is considered.

The main assumptions for the calculations:

- Project lifetime: 33 years
- Functional unit:1 MWh
- Operating hours: 7884 (90% of the year)
- Injection well: 1
- Production well: 1
- Well length:4200 m
- Working fluid mass flow: 100 kg/s
- Fractured zone volume: 0.096 km^3,
- Fractured zone permeability: 425.57 mD,
- Temperature: 145.31 °C,

- Fractured zone porosity: 0.03.

Two plant configurations were assessed:

- Case 1 - combined heat and power with direct sCO_2 cycle,
- Case 2 - electric power generation with indirect sCO_2 cycle with ORC (Organic Rankin Cycle).

In addition, simultaneous CO_2 sequestration was taken into account in both cases.

The calculations covered three phases of the installation's life:

1. The construction phase - included geophysical surveys, borehole drilling, energy consumption and reservoir stimulation. In addition, the authors focused on the materials used for construction and the necessary equipment. Input and output data were adopted from GEOENVI guidelines.
2. The operational phase - includes the plant's energy production and service maintenance (materials such as corrosion inhibitors and oil used for equipment maintenance). Leakage of the working medium CO_2 was also included.
3. End of life phase - included the procedure for shutting down the well and managing the waste generated in the previous phases. Recycling of equipment and plant components was not included in the calculations.

The calculations were carried out using SimaPro with the Ecoinvent 3.10 database, and the ReCiPe (H) method was used. For details of the calculations, see the paper by Strojny et al., 2024. Table 1 summarises the results of the calculations for both cases.

Table 1: Result of LCA analysis (Strojny et al., 2024).

Impact categories	Unit	Case 1 - combined heat and power with direct sCO_2 cycle	Case 2 - electric power generation with indirect sCO_2 cycle with ORC
Global warming	kg CO_2 eq	38.682	54.148
Stratospheric ozone depletion	kg CFC11 eq	0.000	0.000
Ionizing radiation	kBq Co-60 eq	2.871	3.996
Ozone formation, Human health	kg NO_x eq	0.051	0.072
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.052	0.069
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.054	0.076
Terrestrial acidification	kg SO_2 eq	0.084	0.112
Freshwater eutrophication	kg P eq	0.012	0.016
Marine eutrophication	kg N eq	0.001	0.001
Terrestrial ecotoxicity	kg 1,4-DCB	415.091	542.357
Freshwater ecotoxicity	kg 1,4-DCB	2.314	2.773
Marine ecotoxicity	kg 1,4-DCB	3.137	3.794
Human carcinogenic toxicity	kg 1,4-DCB	17.772	24.013
Human non-carcinogenic toxicity	kg 1,4-DCB	39.411	48.943
Land use	m^2a crop eq	0.843	1.177
Mineral resource scarcity	kg Cu eq	1.028	1.377
Fossil resource scarcity	kg oil eq	6.173	8.681
Water consumption	m^3	1.702	17.114

In both cases, the construction phase is dominant, with the most significant impact in this phase being the drilling of wells. The lowest impact is recorded during the plant closure phase. The lower value of the global warming category was obtained in the first case (38.7 kg CO_2 eq) due to the additional heat production within the installation. This solution maximises energy utilisation through the simultaneous production of heat and electricity; heat can be supplied to local consumers, minimising transmission losses and generating savings in the construction of industrial infrastructure.

5. CHARACTERISTICS OF WORKING FLUIDS IN EGS SYSTEMS

The most common working fluid used in EGS is water (Moeck, 2014). Experience in this area is more extensive than the use of CO_2, but CO_2 as a working fluid instead of water is a very interesting alternative (CO_2-EGS). This solution was first proposed by Brown in 2000. The advantages of using CO_2 as a working fluid, including its favorable transport properties, low chemical activity or excellent thermodynamic properties, may make this working fluid also used in the future (Pruess et al, 2006; Olasolo et al, 2016a, b; Brown, 2000; Aminu et al, 2017). A comparison of the properties of CO_2 and water is being worked on by the team for a better understanding of the characteristics of working fluids in EGS systems (Szymanek et al., 2024)

The main factors determining the advantage of CO_2 over water are lower risk of scaling and precipitation, higher mobility for a given pressure gradient, thermal expansivity providing buoyancy force that enables lower power consumption of the circulation pumps, and geological sequestration of this greenhouse gas (Olasolo et al. 2018).

Taking into account the reservoir parameters for the system located in the Gorzow Block area (temperature of 145°C at a depth of 4,300 m bgl), a possible way to use energy in the proposed geothermal power plant is to use the Organic Rankine Cycle (Jasmi et al. 2023; Loni et al. 2021). A mathematical model was used to calculate the parameters of the working medium, such as temperature and pressure at the wellhead (Miecznik et al., 2024).

The assumptions were made that the flowrate and the injection temperature were set to 50 kg/s and 40°C, respectively, both for CO_2 and water. For the ORC system, a pentane and R134a working mediums were selected. Parameters of these fluids were calculated using REFPROP software and determined to the results of the reservoir model output temperature and pressure on the wellhead, which are assumed to be the same as the input values to the heat exchanger. The analysis of the EGS system was performed using the IPSEpro software, where a simple model of EGS was developed. To the analysis, the following assumptions were made:

- Temperature difference between geothermal working medium and ORC fluid: 5°C
- Condensation temperature: 22°C
- Subcooling: 2°C
- Turbine efficiency: 90%
- Pump efficiency: 70%

The analysis was applied to: water-pentane, water-R134a, CO_2-pentane, CO_2-R134a. The working medium in the geothermal cycle is water/CO_2, in the ORC – pentane/R134a, cooling medium – water – in both cases. The results of the analysis are presented in Table 2.

Table 2: Results of the analysis conducted in IPSEpro.

	Water-pentane	Water-R134a	CO_2-pentane	CO_2-R134a
ORC efficiency [%]	17.95	14.7	17.4	14.78
EGS efficiency [%]	8.91	3.83	16.82	12.79
Backwork ratio of ORC [%]	3.11	12.88	2.86	12.84
Backwork ratio of EGS [%]	53.68	73.97	3.35	13.45
Generated power [kW]	3,815.57	3,156.71	1,574	1,336.82

The EGS efficiency is higher for CO_2 system rather than for water, also the backwork ratio is significantly lower for CO_2 systems. The backwork ratio describes the percentage of energy produced in the generator that is needed to be consumed by injection and circulation pumps in the system. These results can be reached due to thermosiphon effect, which is induced by buoyancy force resulted as a higher density difference between injection and production well. Water system can produce much more energy than CO_2-EGS, however, the energy loses for self-consumption, reduce the affordability of the system. Due to the energy extraction and geological sequestration of CO_2 and at the same time, CO_2-EGS could be considered as a more preferable alternative than conventional water EGS.

6. CONCLUSIONS

Geothermal energy, as a renewable and low-emission source, plays a vital role in global strategies aimed at reducing the environmental impact of energy production. Enhanced Geothermal Systems (EGS) technology, which enables the exploitation of deep and dry thermal resources, offers promising opportunities to expand geothermal applications in regions with limited access to conventional geothermal resources. Despite technological challenges, EGS systems hold the potential to significantly reduce greenhouse gas emissions and minimize land-use impacts compared to other energy technologies, aligning with the general advantages of geothermal energy.

In Poland, research initiatives such as the EnerGizerS project (www.energizers.agh.edu.pl) or AGH project "Multi-criteria life cycle analysis of geothermal installations" are advancing the development of the first pilot EGS installations. A prospective CO_2-EGS installation could be situated in western Poland (Gorzów Block), utilizing a petrothermal reservoir of Lower Permian volcanic and sedimentary rocks with temperatures of approximately 145°C at a depth of around 4.3 km below sea level.

Young researchers, particularly doctoral candidates, are actively contributing to these studies, focusing on the environmental and thermodynamic aspects of such installations. Life Cycle Assessment (LCA) analyses indicate that the construction phase, especially well drilling, has the highest environmental impact. Based on reservoir modeling and the thermodynamic properties of Organic Rankine Cycle (ORC) fluids, a comparative analysis of EGS systems has been conducted, highlighting the differences between CO_2 and water as working fluids. Results suggest that CO_2-EGS systems offer superior sustainability compared to water-based EGS systems, making them a compelling option for future geothermal energy solutions.

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