Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

Possibilities of Using Geothermal Energy in CO_2-EGS Systems in Poland and Norway - the EnerGizerS Project

Anna Sowiżdżał[1], Trond Andresen[2], Maciej Miecznik[3], Bjørn S. Frengstad[4], Paweł Gładysz[1], Leszek Pająk[1], Anna Chmielowska[1], Barbara Tomaszewska[1], Lars A. Stenvik[4], Maciej Szymanek[1]

[1]AGH University of Science and Technology, Kraków, Poland

[2]SINTEF Energy Research, Trondheim, Norway

[3]Mineral and Energy Economy Research Institute, Polish Academy of Sciences, Kraków, Poland

[4]Norwegian University of Science and Technology, Trondheim, Norway

E-mail address (contact person e-mail): ansow@agh.edu.pl

Keywords: Enhanced Geothermal System, CO_2-EGS, Poland, Norway.

ABSTRACT

The paper presents preliminary results of the work on the operational efficiency of unconventional geothermal systems using carbon dioxide as the working medium, carried out since Oct. 2020, when the EnerGizerS project (CO_2-Enhanced Geothermal Systems for Climate Neutral Energy Supply) started. Within the EnerGizerS project, an international consortium of scientists is conducting studies aimed at the identification and detailed characterization of geological structures for the localization of CO_2-EGS systems in Poland and Norway, combining the requirements of enhanced geothermal systems (EGS) technology and geological storage of carbon dioxide. The project includes six work packages focused on selecting suitable sites for CO_2-EGS, conducting laboratory tests of drill cores, running an experimental campaign aimed at the evaluation of supercritical carbon dioxide parameters, as well as doing advanced mathematical modeling of the reservoir performance and CO_2-based topside systems for heat and energy production. These activities will be followed by techno-economic and environmental assessments of the considered technology.

Due to advantageous thermodynamic properties of CO_2 (i.e. low viscosity, high compressibility & expansivity, thermosiphon effect) and the need to reduce CO_2 emissions to the atmosphere, an EGS that uses CO_2 instead of water as the working fluid seems extremely attractive. An important aspect of the system is an additional environmental benefit resulting from the geological storage of a fraction of CO_2 used during the power generation process.

Closing the first stage of the project resulted in the indication of important parameters for the localization of CO_2-EGS facilities onshore (Poland) and offshore (Norway). The most important parameters in the case of the CO_2-EGS location appear to be: existing wells and other infrastructure, good level of geological recognition, high reservoir temperature, favorable physical parameters of reservoir rocks, petrogeothermal parameters as well as availability of the CO_2 sources. The analysis of key parameters together with the analysis of geothermal conditions in both countries made it possible to indicate geological structures suitable for CO_2-EGS technology. In Poland, the area of the Gorzów Block and the region of Mogilno-Łódź Basin were pointed out as the most promising for such systems, while in Norway, the Åre formation in the Norwegian Sea as well as the Ula formation and the Skagerrak formation in the North Sea were pointed out.

The progress of ongoing activities can be followed on the project website (www.energizers.agh.edu.pl).

1. INTRODUCTION

In October 2020, five institutions from Poland and Norway joined scientific forces and launched a project entitled *CO_2-Enhanced Geothermal Systems for Climate Neutral Energy Supply*, acronym EnerGizerS. For three years, this international consortium of researchers from AGH University of Science and Technology in Krakow (Project Promoter; Krakow, Poland), Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (Krakow, Poland), SINTEF Energi AS (Trondheim, Norway), Norwegian University of Science and Technology (Trondheim, Norway) and EXERGON LLC (Gliwice, Poland), will progress the technology of enhanced geothermal systems using supercritical carbon dioxide as a working fluid (CO_2-EGS) closer to the industrial deployment.

Enhanced Geothermal System (EGS) enables the extraction of energy from dry rocks that do not contain water or contain water in small amounts by artificially increasing the hydraulic capacity of a geothermal reservoir (Figure 1). Compared to conventional hydrothermal resources, EGS have the advantage of accessing much more abundant heat that is available in most parts of the world. As the heat content in the upper crust is several orders of magnitude higher than annual global energy consumption (Lu, 2018, Tester, 2006), the use of these energy reserves is gaining the growing attention of scientists in many parts of the world.

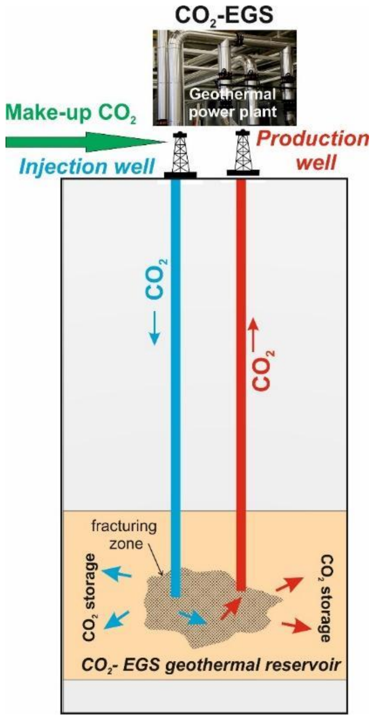

Figure 1: CO_2- EGS scheme.

Since the 1970s, over a dozen EGS reservoirs have been created by artificial stimulation of naturally impermeable rocks at depths exceeding 5 km. The first EGS project (1974) was developed in Los Alamos National Laboratory, USA, utilizing the Earth's heat at Fenton Hill in closed geothermal systems by an artificial increase of the hydraulic flow rate of a geothermal reservoir (Brown, 2000).

Results from global research work (Brown, 2000, Prues, 2006, Olasolo and, 2016, Dickson and, 2004; Lu, 2018, Tester, 2006) indicate that the use of enhanced geothermal systems will develop at a much faster rate than geothermal energy based on hydrothermal reservoirs. Standard medium used in EGS is water (Moeck, 2014). However, due to the beneficial properties of carbon dioxide as a working fluid (i.e. low viscosity, high compressibility and expansivity), research into the use of this greenhouse gas has been ongoing for nearly two decades. This idea was proposed by Brown (2000) and since then research has been conducted into the behaviour of CO_2 as a working fluid.

Because of excellent thermodynamic, transport properties and low chemical activity (Pruess et al, 2006; Olosolo et al, 2016; Aminu et al, 2017) and the need to reduce greenhouse gas emissions into the atmosphere (Brown, 2000) Enhanced Geothermal Systems using CO_2 instead of water as the working fluid becomes of great interest for scientists and industrial sector worldwide. Significant benefits arise from the possibility of geological storage of CO_2 during the power and/or heat generation process.

Among the worldwide EGS installations, currently none use carbon dioxide as the working medium (Lu, 2018, Sowiżdżał et al., 2022b). Experimental operation of CO_2-EGS was carried out more than a decade ago at the Ogachi EGS plant (Japan), resulting in a model for injecting carbon dioxide into a reservoir (Lu, 2018). Due to the additional environmental and economic benefits of being able to geologically store CO_2 in the process of converting Earth's heat into a usable form, CO_2-EGS systems have attracted considerable interest, but there are still significant unresolved issues arising from the use of CO_2 as a working medium in EGS. The major challenges seem to be the behaviour of carbon dioxide in contact with rock, possible contamination of the working fluid with other substances or the operation of underground and surface installations.

The analysis of CO_2-EGS operations is the main objective of the EnerGizerS project. The project activities are aimed at identification and comprehensive characteristics of geological structures in Poland and Norway that simultaneously meet the requirements for Enhanced Geothermal Systems (EGS) and carbon sequestration (CCS) technologies. In addition, they will also help determine the viability of combining EGS and CCS technologies for sustainable energy generation and mitigation of anthropogenic climate change. An extremely important aspect of the EnerGizerS project is also the exchange of knowledge and valuable experience in the fields of geothermal energy and CO_2 geological storage, along with the intensification of international cooperation. The realization of the project opens by developing a methodology for searching the geological structure suitable for potential CO_2-EGS system location followed by petrophysical, thermal and mechanical laboratory tests of chosen drill core samples. These results will be used for advanced mathematical modelling, including structural modelling of the geological reservoir, modelling of the fracturing process and 3D modelling for multi-variant simulations of CO_2 injection and exploitation along with forecasts of reservoir behavior over time. Moreover, novel laboratory research on CO_2 mixtures with reservoir fluids will be performed to enhance the 3D geothermal simulations. The pinnacle of the EnerGizerS project will be a high-performance system concept for heat and/or electricity production along with professional techno-economic and environmental assessments.

This paper primarily presents results of the first two tasks already completed, which enabled identification of appropriate locations for CO_2-EGS potential installations in Poland and Norway as well as detailed laboratory tests on drill cores taken from selected locations. Full methodology of the carried work is presented in separate publications (Pająk et al., 2021, Sowiżdżał et al., 2022a).

2.1 Identification of appropriate locations for CO_2-EGS potential installations in Poland and Norway

The first stage of the work undertaken made it possible to identify parameters relevant to the location of CO_2-EGS systems in onshore (Poland) and offshore (Norway) conditions. Applying the cross-impact structural data analysis method, groups of significant and less important parameters for the development of CO_2-EGS technology were identified (Pająk et al., 2021). Strong attention was paid to the parameters important from the point of view of the location of such a system. The research was divided into three main stages, opening with the formation of a group of 20 experts representing various specializations related to the subject of the project. Then experts developed a list of variables on which, in their opinion, the development of CO_2-EGS technology depends, with particular emphasis on the variables limiting/influencing the location of the system. The initial result was a list of 193 parameters that were considered important by experts in the context of site selection for the CO_2-EGS system. The list was subjected to the procedure of eliminating similar factors by unifying them. Some factors were merged, eventually forming a single factor. The goal of this stage was to reduce the list of factors to an amount that would allow the third stage, so-called Matrix of Influences (MOI), to be done. Finally, the list of variables that seem to be crucial included 48 factors. Then, each expert filled MOI individually by assigning weights (from 0 - meaning "no-influence" to 3 - meaning "strong influence") to how one variable impacts others. Each expert provided a completed matrix. On this basis, a final matrix was formed from experts' individual inputs (arithmetic mean, rounded to an integer number). In the last part of the work, the result matrix was subjected to a statistical processing using the Cross Impact method, using the MICMAC opensource software. Results of the analysis indicated groups of following factors: key factors, targets, results, auxiliary factors, determinants, motors and breakers, regulating factors and autonomous. In the end, eight parameters were considered to be crucial for an onshore system location, viz.: (1) existing wells and other infrastructure; (2) geological recognition level; (3) reservoir temperature; (4) depth of the EGS system; (5) physical and petrogeothermal parameters of reservoir rocks; (6) availability of the CO_2 sources; (7) formal constraints related to local nature protected area; (8) distance of CO_2-EGS site to thermal energy users and electricity grid. Analyses of key parameters (Pajak et al., 2021) together with local geological and geothermal conditions made it possible to identify geological structures convenient for the location of potential CO_2-EGS facilities in Poland and Norway (Sowiżdżał et al., 2021). The Gorzów block (Fig. 2) has been selected as the most prospective area in Poland, pointing out the volcanic rocks of the Rotliegend as a potential petrogeothermal reservoir, and highlighting a possible analogy with the neighboring EGS installation operating in Groß Schönebeck (Germany). The second area of interest in the context of the prospective location of a CO_2-EGS installation is the Krosniewice-Kutno region (the Mogilno-Łódź Trough; Fig. 2), which has been previously considered as a potential location for a water-based EGS system (Wojcicki et al. (ed.), 2013). In this case, Lower Triassic sedimentary rocks are being considered as a potential petrogeothermal reservoir. In Norway, three Mesozoic formations: the Åre in the Norwegian Sea, and the Ula and Skagerrak in the North Sea, were selected as optimal for the lactation of a potential CO_2-EGS system in Norway. In the end, the Åre formation (the Norwegian Sea area) was identified as the most promising for conducting further studies (Fig. 2).

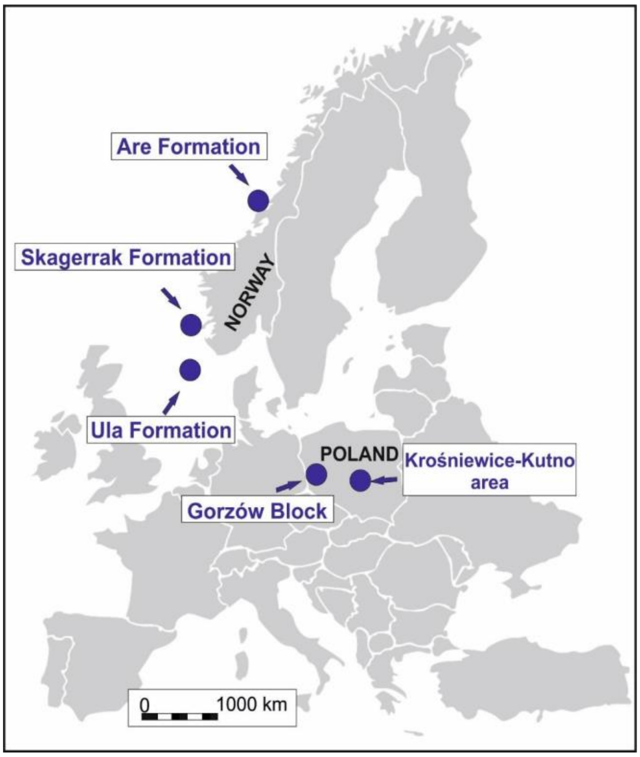

Figure 2: Selected locations for potential CO_2-EGS systems in Poland and Norway.

2.2 Laboratory tests

In order to perform comprehensive characteristics of petrogeothermal reservoirs in Poland and Norway, detailed laboratory tests were conducted on drill cores taken from selected locations. The set of comprehensive studies included:

- analysis of rock mineral composition by X-ray diffraction (XRD);
- pore space analysis by mercury injection capillary pressure (MICP) and nuclear magnetic resonance (NMR);
- analysis of thermal properties of rocks - measurements of thermal conductivity using the FOX50 kit;
- analysis of mechanical properties of rocks - studies of elastic and mechanical parameters of rocks.

Sedimentary and volcanic Rotliegend rocks from the Ośno-IG2 well (Gorzow Block) and Mesozoic formations of the Skagerrak and Ula formations from the North Sea area as well as Åre formation (the Norwegian Sea) were selected for the study. A total of 10 samples of drill cores taken from a depth of 2804 - 5231 m b.s.l. from these three indicated Mesozoic formations located offshore were examined from the Norwegian area. Forty-two samples of drill cores from the depth range of 3212 to 3659 m b.s.l. representing three different rock types: sandstones, conglomerates and volcanites, were taken from the Ośno IG-2 well. Petrophysical characteristics of selected petrogeothermal reservoirs in Poland and Norway indicated that it is possible to combine two technologies, EGS and CCS, both to reduce carbon dioxide emissions and produce electricity and useful heat. The results of the pore space analyses made it possible to determine such rock parameters as effective porosity, permeability, bulk density and skeletal density, among others. Studies of the elastic and mechanical parameters of the rock are of particular importance in the context of hydraulic fracturing of the reservoir, and studies of the thermal properties of the rock provide information on the energy potential of the reservoir.

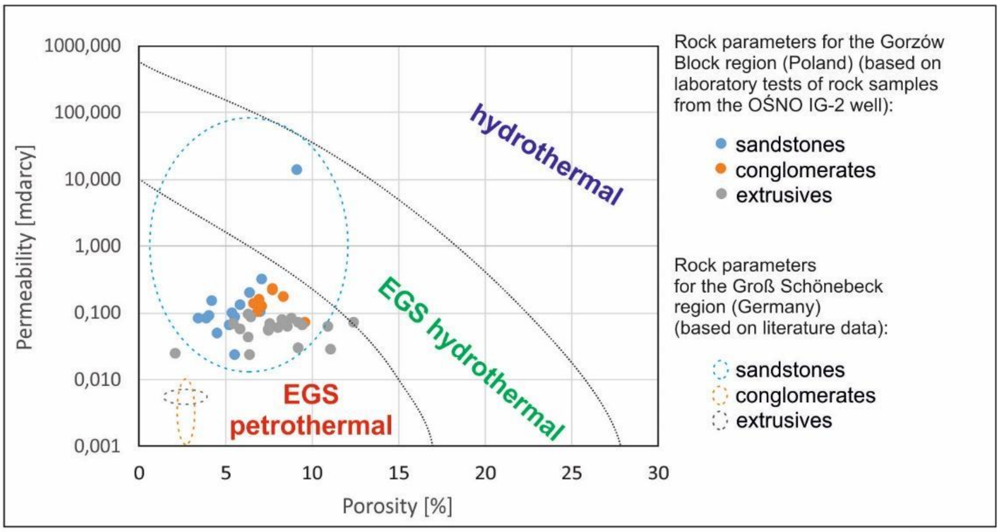

Figure 3: Porosity and permeability relation of different geothermal reservoir rocks. Application as EGS petrothermal, EGS hydrothermal or pure hydrothermal are presented (Sowiżdżał et al., 2022a based on Moeck, 2014).

The results indicate that the studied rocks have suitable parameters as a geothermal reservoir for CO_2-EGS. These parameters are similar to those of reservoir rocks for the EGS installation in Groß Schönebeck as well as all types of rocks are classified primarily as petrothermal EGS (Fig.3).

Detailed information about laboratory test is presented in work (Sowiżdżał et al., 2022a).

2.3 Other project activities

The results obtained as the effect of the laboratory work were afterwards used in the construction of structural-parametric models for the Gorzów Block and the Krośniewice-Kutno area. Structural-parametric modeling was carried out using Schlumberger's Petrel software, which allows a smooth transition from 2D maps to 3D models. Furthermore, an important part of the project is the development of a numerical model of the fractured zone. A simplified mathematical model of the reservoir part of the CO_2-EGS system has also been created, with particular emphasis on the performance of injection and production wells using CO_2 as the working fluid. The model takes into account various parameters in order to represent many possible variants of system operation. Running many scenarios made it possible to select those parameters that are critical to the operation of CO_2-EGS, in particular to maintain the thermosyphon effect between injection and production wells.

In addition to the modeling of the underground part, work is being carried out on the mathematical modeling of topside cogeneration power systems operating with carbon dioxide. For this purpose, a model concept was developed and analyses were carried out for CO_2-EGS power cycles: direct and ORC systems with different working fluids. A simplified model of heat flow and transfer in the well and reservoir made it possible to evaluate different solutions for topside systems to maximize net energy production.

As mentioned before, the most commonly used working fluid in EGS systems is water (Moeck, 2014). The use of carbon dioxide as a working fluid has many advantages, such as good thermodynamic and transport properties or low chemical activity (Olasolo et al, 2016; Brown, 2000; Aminu et al, 2017). However, to date, carbon dioxide has not been used as a working fluid at industrial-scale EGS plants. One of the sub-goals of the EnerGizerS project is to provide high-quality experimental data on the phase behavior and properties (mainly viscosity and density) of carbon dioxide as a working medium in unconventional geothermal systems. The experimental campaign is being conducted using the laboratory infrastructure located at SINTEF Energi AS (Trondheim, Norway), in cooperation with a young scientist from the AGH University of Science and Technology pursuing a research internship at the SINTEF unit. The experimental data obtained will not only enable direct verification of the operating states of the CO_2-EGS system, but will also be matched with existing working fluid models.

Implementation of all planned activities will culminate in the development of technical and economic frameworks and guidelines, in accordance with best practices in research and industry. In accordance with relevant ISO standards (i.e. ISO 14040:2006 and ISO 14044:2006), an environmental assessment framework will be developed, in terms of environmental management - life cycle assessment (LCA). The results of this work, especially the economic analyses, are extremely important in the context of the current rising energy prices and turbulence in the energy markets.

3. SUMMARY

The geothermal energy stored in the earth's interior is a huge and untapped energy potential. In many parts of the world, lack of thermal water reservoirs pose a limitation to the efficient use of geothermal energy. On the other hand, EGS allow the use of geothermal energy in areas where geothermal reservoirs do not contain sufficient water for hydrothermal systems. Fluid injected beneath the land surface (commonly water) circulates through the hot rock structure receiving heat from it and is then pumped to the surface and directed to a power plant. CO_2-EGS systems additionally provide an environmental effect by sequestering carbon dioxide in geological formations. This technology is currently not applied on a commercial scale anywhere in the world. The Polish-Norwegian EnerGzierS project is dedicated to the development of this technology. The proposed solution aims not only to meet energy needs, but also to protect the climate by limiting anthropogenic carbon dioxide emissions. After a number of analyses, perspective locations in Poland and Norway were selected. In Poland the Gorzów Block area and the Mogilno-Łódź Trough (Krośniewice-Kutno area) have been identified for further research work. In Norway Åre Formation in the Norwegian Sea, Skagerrak Formation and Ula Formation (North Sea) were indicated. In order to characterise petrogeothermal reservoirs in Poland and Norway, detailed laboratory studies were carried out on drill cores from selected locations. Laboratory results indicate that the studied rocks have adequate parameters for a CO2-EGS geothermal reservoir and are classified primarily as petrothermal EGS. After the completion of mathematical modelling of geological reservoir for CO_2-EGS exploitation as well as mathematical modeling of CO_2-based topside systems for heat and power production, a techno-economic and environmental analysis will be done for case studies in Poland and Norway.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the Norway Grants 2014-2021 via the National Centre for Research and Development. The results are part of the Polish-Norwegian project: CO_2-Enhanced Geothermal Systems for Climate Neutral Energy Supply, acronym EnerGizerS, registration number NOR/POLNOR/EnerGizerS/0036/2019.

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