TCCS-11 - Trondheim Conference on CO_2 Capture, Transport and Storage
Trondheim, Norway - June 21-23, 2021

CO_2-ENHANCED GEOTHERMAL SYSTEMS FOR CLIMATE NEUTRAL ENERGY SUPPLY

Anna Sowiżdżał[1*], Paweł Gładysz[1], Trond Andresen[2], Maciej Miecznik[3], Bjørn S. Frengstad[4], Marcin Liszka[5], Anna Chmielowska[1], Marcel Gawron[5], Sigurd W. Løvseth[2], Leszek Pająk[1], Lars A. Stenvik[4], Barbara Tomaszewska[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

[5] EXERGON Sp. z o.o, Gliwice, Poland

* Corresponding author e-mail: anna.sowizdzal@agh.edu.pl

Abstract

The main objective of the research carried out by the Polish-Norwegian scientific team is to analyze the potential for implementation and efficiency of enhanced geothermal systems (EGS) using CO_2 as a working fluid (CO_2-EGS). This technology has attracted much interest of the scientific community in the last two decades due to the additional benefit of CO_2 geological storage that is occurring during the power generation process. The purpose of this technology is to mitigate climate change by producing clean geothermal energy and simultaneously reduce carbon dioxide emissions to the atmosphere coming from the combustion of fossil fuels. Within the paper, the scope of the EnerGizerS project is indicated. Moreover, the preliminary results of case study locations for the CO_2-EGS in both Poland and Norway are presented.

Keywords: *enhanced geothermal system, CO_2 utilization, CO_2 storage, techno-economic assessment, environmental assessment*

1. Introduction

Geothermal energy is a renewable source of heat and power, which unlike some other renewable sources can be used for baseload supply without additional energy storage. Although conventional (hydrothermal) geothermal resources have been used for over 100 years, and energy systems based on them are considered as mature, they do not develop at a rate that would significantly reduce greenhouse gases emissions globally due to the limited access to favorable geological conditions worldwide. Compared to conventional hydrothermal resources, enhanced geothermal systems (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 [1-3], the use of these energy reserves is gaining the growing attention of scientists in many parts of the world. Since the 1970s, over a dozen EGS reservoirs have been created by artificial stimulation of naturally impermeable rocks at depths exceeding 5 km. Numerous reports and publications of leading research centers [3] predict that the use of enhanced geothermal systems will develop at a much faster rate than geothermal energy based on hydrothermal reservoirs. Current EGS reservoirs use injected water as a heat carrier. However, due to the beneficial properties of carbon dioxide as a working fluid, research on the use of this greenhouse gas has been ongoing for nearly two decades [4-6].

The first EGS project 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. The Fenton Hill is an installation that uses water as a working fluid, like all EGS installations currently operating around the globe.

The utilization of CO_2 as a working fluid in geothermal systems has not been implemented commercially so far but is under research due to potential benefits compared with water. For instance, an EGS experiment and CO_2 sequestration test were carried out at the Ogachi EGS site (Japan) [1]. A considerable number of issues regarding the functioning of CO_2-EGS still remain unresolved. One important aspect is to understand the behavior of CO_2, both regarding its interaction with the reservoir rocks and in the operation of the subsurface installation.

Another important issue is to render the reservoir available, which is done by fracturing. Hydraulic fracturing technology has been known since the 1920s, and its first successful commercial application took place in 1949. The technology has developed rapidly since then due to the increasing scope of its application

[7]. Initially, it was used in conventional oil wells, now it is used on unconventional reservoirs and enhanced geothermal systems.

It is also very important to consider the effect of impurities in CO_2 working fluids, where the inclusion of components other than CO_2 will influence thermodynamic fluid properties such as phase transition curves, density, and viscosity. Zhang et al. [8] investigated thermodynamic impacts of using impure CO_2 as a working fluid in CO_2-EGS, and a slightly altered behavior and lower efficiency with increased impurity content were reported. Further, in order to correctly model the CO_2-EGS working fluids, access to experimental data of thermodynamic properties of the specific fluid mixture at system-relevant conditions is important to ensure model accuracy and reliability. Relevant impurity components would greatly depend on the composition of the CO_2 injected into the reservoir to be used as a working fluid, but also on the native chemistry of the geological reservoir, which is determined by location and well depth. One important impurity is naturally H_2O, where a survey performed by NTNU and SINTEF [9] showed a significant lack of data in the CO_2-rich liquid and supercritical phase. There is even less data if salts are present. Furthermore, although the ratio of density to viscosity is proportional to the mass flow through the geothermal reservoir, there are large gaps in experimental data on viscosity and density of CO_2 and CO_2-rich mixtures at relevant processing temperatures and pressures [10-11]. SINTEF has an extended track-record in measuring phase equilibrium of CO_2-rich fluids, where accurate measurements of binary and ternary systems of CO_2 with impurities such as CO, N_2, O_2, CH_4 and Ar have been performed using a custom-made phase equilibrium cell [12-17].

Norwegian leading research organizations spearheaded the resurgence of CO_2 as a working fluid in the early 1990s, and they have since had research and technology development on aspects related to CO_2 heat pumping and power cycles as the main focus area. Rankine cycles with CO_2 are actively investigated on a global scale. In addition to concentrated solar and nuclear power, the technology is still highly relevant in specific waste heat applications, for example, offshore gas turbine exhaust. There have been considerable research activities on CO_2 transcritical power cycles, including constructing and operating a laboratory-scale CO_2 Rankine cycle, through projects such as ROMA (2007-2013) and CREATIV (2009-2013), funded by the Research Council of Norway. Later projects continued technology development towards specific applications such as offshore gas turbine bottoming cycles (EFFORT 2010-2014) and industrial waste heat (COPRO 2016-2019), in addition to confidential demonstration projects with the industry. Internationally, a few companies have developed such technology into larger prototypes and arguably even to commercial maturity.

The idea of merging CO_2-EGS systems with other energy systems has also been investigated in the literature. As an example for Polish conditions, results of an investigation of a biomass-fired combined heat and power plant with CO_2 capture integrated with a CO_2 enhanced geothermal system [18-20] indicated the need to study the behavior of CO_2 as a working fluid. Further, it was concluded that the real possibilities of implementing such a solution in other countries should be assessed. From an economic point of view, only CO_2-EGS systems were proven competitive to conventional storage of captured CO_2 [19].

Geothermal conditions in Poland are relatively well recognized and have been studied since the 1980s [21]. Comprehensive information about Poland's geothermal resources is provided by a series of Geothermal Atlases, covering the areas of the Polish Lowland, Carpathians, and the Carpathian Foredeep. These works indicate the possibilities of using hydrogeothermal resources gathered in groundwater for various purposes, mainly heating, but also balneotherapy, recreation and the like. In recent years, research was conducted also to evaluate the energy potential of using petrogeothermal reservoir potential EGS systems [22-24].

Mainland Norway consists with few exceptions of Precambrian and Paleozoic crystalline rocks with low porosity and permeability. Temperature logging of boreholes down to 500-1600 m has revealed moderate geothermal gradients between 13.0 and 21.7 K/km [25-28]. Offshore Norway in the North Sea and the Norwegian Sea, there are many deep boreholes for oil exploration and extraction. Baird [29] describes thermal gradients between 33.0 and 42.2 K/km for Norwegian North Sea reservoirs, which might make them interesting for extraction of geothermal heat. The Arctic archipelago of Svalbard might be another candidate for geothermal heat with general gradients of 30 K/km and some measurements in the range of 40-50 K/km [30].

2. Planned research with EnerGizerS project

On October 1st, 2020, a joint Polish-Norwegian research and development project was launched. The main objective of this project, entitled "CO_2-Enhanced Geothermal Systems for Climate Neutral Energy Supply" (EnerGizerS), is to progress the technology of enhanced geothermal systems (EGS) using CO_2 as a working fluid closer to industrial deployment. The project consortium, constituted of AGH University of Science and Technology (Poland), SINTEF Energy Research (Norway), Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (Poland), Norwegian University of Science and Technology (Norway) and EXERGON (Poland), will pursue the goals of the project through 36 months of extensive theoretical and experimental research activities.

To achieve the project objectives, the consortium partners will conduct research aimed at detailed identification of potential geological structures for the location of CO_2-EGS systems, combining the requirements for both EGS and carbon capture and storage (CCS) systems both in Poland and Norway. 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 analysis.

2.1. Work Package 1

Work Package 1 consists of analytical tasks, where the Cross Impact method will be used to select a list of factors that are key for the indication of optimal locations suitable for CO_2-EGS systems. The results, in combination with CO_2 sources and other energy systems assessments, will be used to select locations and technologies related to CO_2-EGS installation, thus defining the case studies to be investigated in detail both in Norway and Poland. For the selected geological structures, core samples will be gathered for further research activities.

2.2. Work Package 2

In Work Package 2, core samples gathered in Work Package 1 will be subjected to laboratory tests. Petrophysical, thermal and mechanical tests will be performed on drill-core samples taken from appropriate geological structures. Based on the results, the database containing archival petrophysical and mechanical data as well as new laboratory measurements of rocks will be developed.

2.3. Work Package 3

The goal of Work Package 3 is to provide high quality experimental data on phase behavior and viscosity and density properties of CO_2-EGS to cover the most critical knowledge gaps identified so far, thus allowing to improve existing fluid models of CO_2-EGS relevant working fluids based on generated fluid property data. New data will be produced using state-of-the-art ECCEL ERIC infrastructure [12-17,31-33]. The fluid systems, properties, and conditions of the experimental investigations will be selected based on the knowledge of reservoir fluids and available CO_2 of the EGS locations selected in WP1, combined with a survey of existing data on relevant systems.

2.4. Work Package 4

Work Package 4 will be dedicated to the assessment of possible scenarios of the fracturing process for geological structures specified in WP1, the nature of possible fractures, their orientation and the resulting increase in permeability. Further on, the injection pressure required to circulate the CO_2 in the reservoir while maintaining the thermosiphon effect will be assessed. The optimum well separation distance in order to minimize pressure drop in the reservoir, while avoiding thermal drawdown at the production well, will be estimated. Assessment of possible CO_2 reaction with rock-forming minerals and reservoir brine and consequences on EGS behavior over time (i.e. CO_2 amount permanently stored, increase or decrease in permeability through dissolution or precipitation of minerals) will be carried out. Finally, the heat quantity and quality (temperature, enthalpy) produced from the EGS reservoir under various scenarios will be estimated.

2.5. Work Package 5

Within Work Package 5, the high-performance topside system concepts for producing heat and/or electric power from geothermal energy, using CO_2 circulating in the EGS reservoir as the direct working fluid, will be developed. Mathematical modeling will be carried out using existing and demonstrated frameworks [34]. The heat exchanger models [35-36] use geometry data as input to calculate parameters such as hydraulic diameters, perimeters and cross-sectional areas for each fluid stream and pass. Based on the geometry specification and the fluid inlet conditions, the outlet conditions are found through the integration of the fluid passes (with a 4th order Runge Kutta routine) and iteration on the wall temperature profile (with DNSQE from SLATEC). Geometry-specific, state-of-the-art models for heat transfer and pressure drop will be applied. For a set of operating conditions, these models will be used to optimize the geometry within given operational and physical constraints. A similar framework will be developed for system-level analyses, which will enable connecting heat exchangers and other component models such as pumps, turbines, valves, and reactors in any type of arrangement to evaluate and optimize complex processes and systems.

2.6. Work Package 6

In Work Package 6, the techno-economic framework and guidelines will be developed, following some of the best practices used in research and industry. Most of the technical-oriented costs will be gathered based on extended literature review, and the experience of the project partners, and will be expressed as “power functions”, “unit costs” or “cost functions”. For the geographical-oriented costs and prices, a literature review will be performed, including governmental reference documents. Similarly, an environmental assessment framework will be developed, which in general will follow the ISO standards (ISO 14040:2006 and ISO 14044:2006) for the environmental management - Life Cycle Assessment (LCA). Due to the early stage of research, the comprehensive LCA analysis will not be performed. Best practices from LCA studies, together with the environmental assessment methods based on saved production of electricity and heat (and associated environmental effect) will be combined to formulate an adequate framework.

3. CO_2-EGS system case study definition

3.1. Cross Impact method results

Structural analysis is, first of all, a tool for structuring ideas. It gives the possibility to describe a system with the help of a matrix connecting all its components. By studying these relations, this method provides an opportunity to reveal variables essential to the system's evolution. It is possible to use it alone (as a support for reflection and/or decision making), or as part of a more complex forecasting activity (scenarios).

Within the analysis, the Micmac Forecasting method was used [37]. During the study, a group of 20 experts pointed out 193 variables important for the CO_2-EGS system and its location. As a result of variables' aggregation, their number was reduced to 49 and assumed as important for the CO_2-EGS systems development and exploitation. The experts were asked to assess the strength of interconnections among all variables. Results of the analysis indicated groups of factors, that are: key factors, targets, results, auxiliary factors, determinants, motors and breakers, regulating factors and autonomous. For an onshore system location as the most important variables were identified, viz.

- existing wells and other infrastructure;
- geological recognition level;
- reservoir temperature;
- depth of the EGS system;
- physical and petrogeothermal parameters of reservoir rocks;
- availability of the CO_2 sources;
- formal constraints related to local nature protected area;
- distance of CO_2-EGS site to thermal energy users and electricity grid.

3.2. Case study definition

For both Norway and Poland, all relevant CO_2 sources were identified, assessed and categorized in terms of potential CO_2 capacity from the capture process, as well as other relevant factors like CO_2 purity, time perspective of availability (especially important for Poland due to the forthcoming decarbonization of the energy system) and type of CO_2 source (power generation, industry). In addition, all existing wells in Norway and Poland suitable for the EGS system development were identified and assessed, taking into account, for example, the depth of the reservoir, expected temperatures, and permeability. Moreover, the local heat demand in selected areas was also identified, as the CO_2-EGS system's operation could potentially be a source of decarbonized heat supply for district heating systems. All these data were put on an interactive map, as an aid in the selection procedure (ranking) of potential CO_2-EGS locations in both Poland and Norway.

3.3. Selection procedure

Taking into account the identified key factors related to location, identified by means of the Cross Impact method, as well as the gathered data on the CO_2 sources and promising geological structures, the appropriate procedure was defined to allow selection of the most suitable locations for the CO_2-EGS system and definition of the case study, which include for example the subsurface installation design.

3.4. Preliminary results

3.4.1. Poland

Taking into account geological criteria, including first of all thermal and petrophysical parameters of rocks, 5 potential regions for CO_2-EGS were indicated. Preliminary analyzes were conducted of the various types of rocks: crystalline, volcanic and sedimentary. The results of the analyzes indicate the following areas as those in which further works aimed at selecting this prospective location should be concentrated: Karkonosze area, Gorzów Block, Szczecin Trough, Mogilno-Łódź Trough, Upper Silesian. These are areas with a varied geological structure, but also with a different degree of geological recognition

An assessment of environmental issues that may limit the implementation of proposed solutions was also carried out for these zones. Following key factors were used for the environmental assessment:

- existence of mining areas - licensed/concession areas designated for the exploitation of minerals;
- existence of licensed/concession areas related to the exploration and recognition of mineral resources (in particular for crude oil, natural gas, healing and geothermal waters, etc.);
- existence of Natura 2000 protected areas;
- the presence of other forms of nature protection - National Parks, National Park buffer zones;
- limitations in accordance to hydrogeological condition - groundwater protection zones, main groundwater reservoirs, groundwater bodies;
- limitation in accordance to hydrological condition - especially as flood hazard zones.

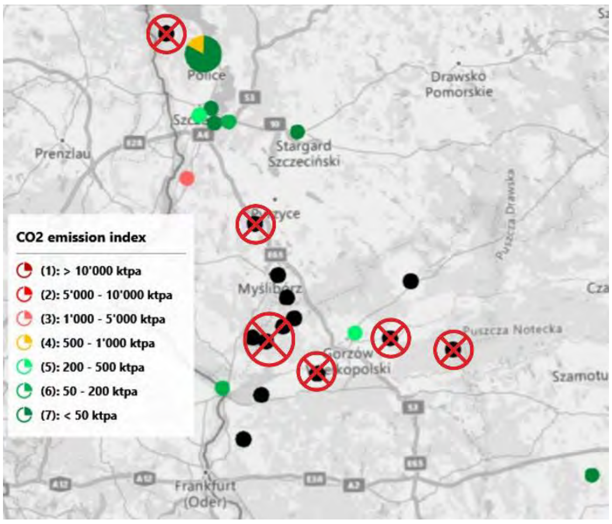

Figure 1: Map showing existing deep wells in the Gorzów Block. Wells not suitable for the CO_2-EGS system due to formal and environmental restrictions were crossed in red.

Although the granite massifs of the Karkonosze Mountains (SW Poland) were also interesting due to potentially high temperatures and presumably homogenous lithology of reservoir rocks, the complete lack of drilling data for depths exceeding 2 km and numerous environmental limitations resulted in the rejection of this region for further analyzes. In the case of Gorzów Block, it should be mentioned that not all of the existing wells are suitable for the development of the CO_2-EGS system due to the aforementioned environmental constraints (marked red in Figure 1).

For Mogilno-Łódź Trough (Kutno area), a detailed analysis regarding the potential CO_2 sources, as well as nearby (from 2 to 15 km) heat demand in district heating systems, was done. As presented in Figure 2, the area has potentially favorable temperatures between 160 and 190 °C at depths of 5000 to 6000 meters below sea level. In the near vicinity, significant perspective industrial CO_2 sources were identified, associated with the refineries and their power generation plants. Other nearby CO_2 sources, mainly the lignite-fired power plant in Pątnów, are rather not suitable long-term sources of carbon dioxide, due to the planned decommissioning in the coming years.

Figure 2: Map showing the Kutno area, three district heating systems in nearby municipalities and potential (perspective and not perspective) CO_2 sources.

Further on, more detailed studies are planned to investigate options for long-term CO_2 supply and heat demand in regions considered as possible for the CO_2-EGS systems development as the feasibility of such systems must be determined.

4.3.2. Norway

Wellbore logs accessed from the Norwegian Petroleum Directorate [38] have revealed six favorable formations (fm) offshore Norway, see Figure 3. These are the Are fm in the Norwegian Sea, and Devonian rocks (no formation defined), Lunde fm, Skagerrak fm, Tor fm and Ula fm in the North Sea.

The formations display temperatures between 100 and 170 °C, depths between 2400-4700 meters below seafloor, and seawater depths ranging from 60 to 380 meters. The most realistic CO_2 source and energy user would be offshore oil and gas installations, since all formations locate far from the coastline. However, all formations are located within 15 km from oil and gas platforms already in place. Still, further analysis must be conducted to assess the feasibility of such a fully offshore CO_2-EGS system.

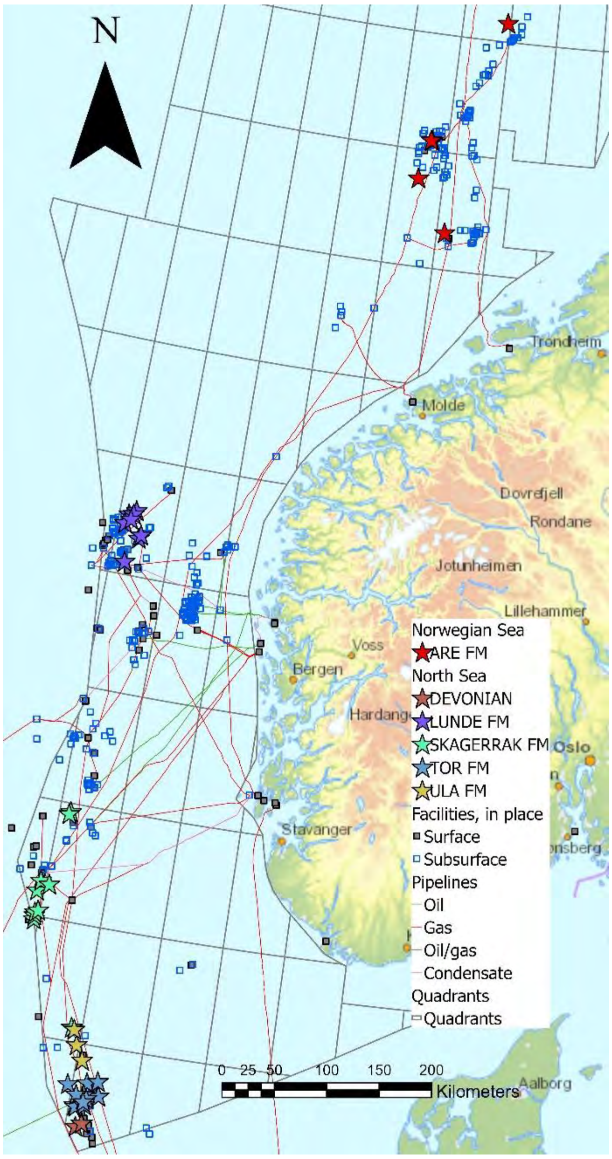

Figure 3: Map showing the location of six promising formations for CO_2-EGS utilization offshore Norway. In place, infrastructure is also indicated.

4. Conclusions and further studies

Hot dry rocks characterized by high temperatures are reservoirs of geothermal energy with great potential for application in many regions of the world. This potential can be exploited with enhanced geothermal systems, which is a forward-looking, yet immature technology. Therefore, numerous research is underway to develop this technology. One of them is the EnerGizerS project, carried out by a Polish-Norwegian consortium. The main purpose of the project is to analyze the effectiveness of the operation of unconventional geothermal systems using CO_2 as a working fluid. Due to the excellent thermodynamic properties of CO_2 and the need to reduce its emissions to the atmosphere, the EGS system, which uses CO_2 instead of water as a working fluid, is of great interest. 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.

Researchers from Poland and Norway will cooperate to analyze the effectiveness of CO_2-EGS systems in their respective countries. Six work packages will be completed during the project, under which a number of analytical and laboratory research will be performed, including laboratory tests on drill-core samples taken from appropriate geological structures, mathematical modeling, including structural modeling of the geological reservoir, modeling of the fracturing process of solid rocks and 3D modeling for multi-variant simulations of CO_2 injection and exploitation with forecasts of reservoir behavior over time, experimental determination of properties and behavior of CO_2-EGS working fluids as well as mathematical modeling of CO_2-based topside systems for heat and power production. All performed tests and analyzes will form the basis for conducting techno-economic and environmental assessments of the proposed technology. The current progress in the implementation of the EnerGizerS project allows us to initially indicate the most convenient locations for the first CO_2-EGS installations in both 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.

References

[1] Shyi-Min, L. A global review of enhanced geothermal system (EGS). Renewable and Sustainable Energy Reviews 2018; 81:2902-2921.

[2] Dickson, M. H., & Fanelli, M. (2004). What is geothermal energy? International Geothermal Association, Bochum.

[3] Tester, J., et al. (2006). The Future of Geothermal Energy. Impact of Enhanced Geothermal Systems (EGS) on the Unites States in the 21st Century. Massachusetts Institute of Technology. Report no. INL/EXT-06-11746. MIT. Cambridge, MA, USA.

[4] Brown, D. W. (2000). A Hot Dry Rock Geothermal Energy Concept Utilizing Supercritical CO_2 Instead of Water. Proceedings, Twenty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, January 2000.

[5] Pruess, K. Enhanced geothermal systems (EGS) using CO_2 as working fluid — A novel approach for generating renewable energy with simultaneous sequestration of carbon. Geothermics 2006; 25:351-367.

[6] Olasolo, P., Juárez, M. C., Morales, M. P., D`Amico, S., & Liarte, I. A. Enhanced geothermal systems (EGS): A review. Renewable and Sustainable Energy Reviews 2016; 56:133-144.

[7] Biagi, J., Agarwal, R., & Zhang, Z.. Simulation and optimization of enhanced geothermal systems using CO_2 as a working fluid. Energy 2015; 86(6):627–637.

[8] Zhang, F., et al. Thermodynamic analysis of enhanced geothermal systems using impure CO_2 as the geofluid. Applied Thermal Engineering 2016; 99:1277-1285.

[9] Aasen, A., et al. Thermodynamic models to accurately describe the PVTxy-behavior of water /carbon dioxide mixtures. Fluid Phase Equilibria 2017; 442:125-139.

[10] Li, H., et al. PVTxy properties of CO_2 mixtures relevant for CO_2 capture, transport and storage: Review of available experimental data and theoretical models. Applied Energy 2011; 88(11): 3567-3579.

[11] Munkejord, S. T., et al. CO_2 transport: Data and models – A review. Applied Energy 2016; 169:499-523.

[12] Westman, S. F., Stang, H. G. J., Løvseth, S. W., Austegard A., & Størset, S. Ø. Vapor-liquid equilibrium data for the carbon dioxide and nitrogen (CO_2 + N_2) system at the temperatures 223, 270, 298 and 303 K and pressures up to 18 Mpa. Fluid Phase Equilibria 2016; 409:207-241.

[13] Westman, S. F., Stang, H. G. J., Løvseth, S. W., Austegard, A., Snustad, I., & Ertesvåg I. S. Vapor-liquid equilibrium data for the carbon dioxide and oxygen (CO_2 + O_2) system at the temperatures 218, 233, 253, 273, 288 and 298 K and pressures up to 14 Mpa. Fluid Phase Equilibria 2016; 421:67-87.

[14] Løvseth, S. W., Austegard, A., Westman, S. F., Stang, H. G. J., Herrig, S., Neumann, T., & Span R. Thermodynamics of the carbon dioxide plus argon (CO_2 + Ar) system: An improved reference mixture model and measurements of vapor-liquid, vapor-solid, liquid-solid and vapor-liquid-solid phase equilibrium data at the temperatures 213–299 K and pressures up to 16 Mpa. Fluid Phase Equilibria 2018; 466:48-78.

[15] Petropoulou, E., Voutsas, E., Westman, S. F., Austegard, A., Stang, H. G. J., & Løvseth, S. W. Vapor - liquid equilibrium of the carbon dioxide/methane mixture at three isotherms. Fluid Phase Equilibria 2018; 462:44-58.

[16] Westman, S. F., Austegard, A., Stang, H. G. J., & Løvseth, S. W. Vapor-liquid equilibrium data for the carbon dioxide and carbon monoxide (CO_2 + CO) system at the temperatures 253, 273, 283 and 298 K and pressures up to 13 Mpa. Fluid Phase Equilibria 2018;.473:37-49.

[17] Ottøy, S., Neumann, T., Stang, H. G. J., Jakobsen, J. P., Austegard, A., & Løvseth, S. W. Thermodynamics of the carbon dioxide plus nitrogen plus methane (CO_2 + N_2 + CH_4) system: Measurements of vapor-liquid equilibrium data at temperatures from 223 to 298 K and verification of EOS-CG-2019 equation of state. Fluid Phase Equilibria 2020; 509:112444.

[18] Gładysz, P., Sowiżdżał, A., Miecznik, M., & Pająk, L. Carbon dioxide-enhanced geothermal systems for heat and electricity production: Energy and economic analyses for central Poland. Energy Conversion and Management 2020; 220: 113142. https://doi.org/10.1016/j.enconman.2020.113142.

[19] Gładysz, P., Sowiżdżał, A., Miecznik, M., Hacaga, M., & Pająk, L. Techno-Economic Assessment of a Combined Heat and Power Plant Integrated with Carbon Dioxide Removal Technology: A Case Study for Central Poland. Energies 2020; 13: 2841. https://doi.org/10.3390/en13112841.

[20] Sowiżdżał, A., Gładysz, P., & Pająk, L. Sustainable Use of Petrothermal Resources—A Review of the Geological Conditions in Poland. Resources 2021; 10(1):8. https://doi.org/10.3390/resources10010008.

[21] Sowiżdżał, A. Geothermal energy resources in Poland – Overview of the current state of knowledge, Renewable and Sustainable Energy Reviews 2018; 82(part 3):4020-4027.

[22] Sowiżdżał, A., Papiernik, B., Machowski, G., & Hajto, M. Characterization of petrophysical parameters of the Lower Triassic deposits in prospective location for

Enhanced Geothermal System (central Poland). Geological Quarterly 2013; 57(4):729–743.

[23] Sowiżdżał, A., & Kaczmarczyk, M. Analysis of thermal parameters of Triassic, Permian and Carboniferous sedimentary rocks in central Poland, Geological Journal 2016; 51(1):65-76.

[24] Sowiżdżał, A.. Possibilities of petrogeothermal energy resources utilization in central part of Poland, Applied Ecology and Environmental Research 2016; 14(2):555–574.

[25] Elvebakk, H. 2012a. Geofysisk logging av borehull ved Arnestad skole, Asker [In Norwegian]. NGU-report 2011.016. Trondheim: NGU.

[26] Elvebakk, H. 2012b. Geofysisk logging av tre borehull i Hurdal [In Norwegian]. NGU-report 2011.011. Trondheim: NGU.

[27] Elvebakk, H. 2018. Logging av dype energibrønner på Oslo Lufthavn, Gardermoen. [In Norwegian]. NGU-report 2018.020. Trondheim: NGU.

[28] Maystrenko, Y. P., Slagstad, T., Olesen, O., Elvebakk, H. K., Venvik, G., & Rønning, J. S. New heat flow data from three boreholes near Bergen, Stavanger and Moss, southern Norway. Geothermics 2015; 56:79-92.

[29] Baird, R. A. V. W. C. (1991). Relation between Liquid Hydrocarbon Reserves and Geothermal Gradients--Norwegian North Sea. Virginia Water Co. USA.

[30] Betlem, P., Midttømme, K., Jochmann, M., Senger, K., & Olaussen, S. (2018). Geothermal Gradients on Svalbard, Arctic Norway. Conference Proceedings, First EAGE/IGA/DGMK Joint Workshop on Deep Geothermal Energy, November 2018. https://doi.org/10.3997/2214-4609.201802945

[31] ECCSEL ERIC. 2021. Available at: http://www.eccsel.org/ (Accessed 20 January 2021).

[32] Stang, H. G. J., Løvseth, S. W., Størset, S. Ø., Malvik, B., & Rekstad, H. Accurate Measurements of CO_2 Rich Mixture Phase Equilibria Relevant for CCS Transport and Conditioning. Energy Procedia 2013; 37:2897-2903.

[33] Løvseth, S. W. Impact of impurities in the CO_2 on fluid density, viscosity and thermal conductivity, and CCS processes. Conference Proceedings. CLIMIT Digit, Round 1 - Transport & CO_2-EOR.. https://gyroconference.no/climit/#1-1, February 2021.

[34] Nikolaisen, M., & Andresen, T. System impact of heat exchanger pressure loss in ORCs for smelter off-gas waste heat recovery. Energy 2021; 215(part B):118956. https://doi.org/10.1016/j.energy.2020.118956.

[35] Skaugen, G., Kolsaker, K., Walnum, H. T., & Wilhelmsen, Ø. A flexible and robust modelling framework for multi-stream heat exchangers. Computers & Chemical Engineering 2013; 49:95-104. https://doi.org/10.1016/j.compchemeng.2012.10.006.

[36] Hagen, B. A. L., Nikolaisen, M., & Andresen, T. A novel methodology for Rankine cycle analysis with generic heat exchanger models. Applied Thermal Engineering 2020; 165:114566. https://doi.org/10.1016/j.applthermaleng.2019.114566.

[37] La prospective. 2021. MicMac Structural Analysis. Available at: http://en.laprospective.fr/methods-of-prospective/softwares/59-micmac.html (Accessed 21 January 2021).

[38] Norwegian Petroleum Directorate. 2020. Factpages. Available at: https://factpages.npd.no/nb-no (Accessed 14 December 2020).