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Role of Geoenergy in Meeting Sustainable Development Goals

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Abstract

Geoenergy engineering, which includes the use of geothermal energy and other forms of energy stored inside the Earth, is of key importance for the transition to renewable energy sources in the global energy mix. The article discusses the role of geoenergy science and engineering in meeting Sustainable Development Goals (SDGs), with particular attention to SDG 6 (access to clean water), SDG 7 (clean energy), SDG 9 (innovativeness), SDG 11 (sustainable cities), and SDG 13 (climate-related actions). The article also describes the role of the life-cycle assessment (LCA) of geothermal projects in pursuing Sustainable Development Goals. The analyses and reviews presented in the article indicate that geoenergy engineering will have a significant role in the meeting of Sustainable Development Goals by the energy sector. Energy production in geothermal power plants is expected to increase, reducing the demand for energy from conventional sources. The article also lists the most significant challenges faced by the geoenergy industry, such as high initial costs, demand for highly specialized workers and for adequate financing, as well as for LCA-based research regarding the general environmental impact of new geoenergy facilities.

Keywords: geoenergy; sustainable development; environmental aspects; life-cycle assessment

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1. Introduction

The goal of sustainable development is to act in such a way that the needs of modern societies are not fulfilled at the cost of future generations. From the energy-supply perspective, such actions require the transition to renewable energy sources (RES) [1]. According to the Euroelectric 2024 report [2], RES accounts for almost 48% of energy production in the European Union. The share of nuclear energy was 24%, and the fastest growth rate was observed for solar energy. The use of fossil fuels thus declined to 28%. The report also forecasts the share of RES to reach 77% by 2050. One of the energy sources in the energy mix is geoenergy, which uses the Earth's natural heat to produce electricity, heat, and cooling, as well as energy storage and water flow potential in post-mining excavations. The International Energy Agency report (2024) [3] observes this source to have great potential and indicates that, owing to technological progress, its share in the energy mix may be increased by several hundred percent. The current use of geothermal energy is not significant at only 0.8% of the global energy demand in 2023 [3,4]. In the case of the European Union, this indicator is at 0.27% for electricity generation and at 26.03% for heat generation [5]. Importantly, as compared to other RES generation technologies, only photovoltaics has the technical potential for electricity production that is higher than geothermal solutions. Its power-generation potential is threefold higher than that of onshore wind energy and more than fivefold higher

than that of offshore wind energy. According to the IEA (2024) report [3], the annual electricity-generation potential in geoenergy is 150 times higher than the current annual global demand. Also, the by-product of electricity generation in geothermal power plants is waste heat, which can be used for district heating, industrial processes, or recreational purposes, e.g., for heating water in swimming pools, spas, or in balneotherapy.

Until recently, the development of geothermal energy solutions was limited to the operation of ground-source heat pumps, which may use shallow geothermal heating and cooling resources at low temperatures in any location or at higher temperatures in specific locations. Currently, the decades-long development of geothermal systems has enabled the industry to overcome geological limitations and introduce such technologies as enhanced geothermal systems (EGSs) or advanced geothermal systems (AGSs), which allow access to significant amounts of geothermal energy regardless of the location and only on the condition of sufficient well depth.

The energy and heat stored inside the Earth is thus an interesting area of research and has significant potential as the main source of energy in the transition towards clean electricity, heat, and cooling production. Moreover, it supports economic development, as it allows for the security of electricity and heat supplies and thus has an important role in achieving Sustainable Development Goals. Therefore, the aim of this article is to present and discuss the potential of geoenergy engineering for accomplishing selected Sustainable Development Goals, in particular, what the key areas of synergy and interdependence between the implementation of the EGSs/AGSs and specific SDGs are.

2. Improved Geothermal Systems

Conventional geoenergy engineering uses various technologies, such as deep wells, heat pumps, or closed-loop systems, depending on the temperature and the depth of the geothermal resource. The conventional use of geothermal energy is based on four general technologies [6]:

- Direct dry steam power stations—use condensing turbines and steam at temperatures of 150 °C or higher;
- Flash steam power stations—the steam is separated from the water in the so-called flash process. Such power stations operate optimally at water temperatures above 180 °C;
- Binary cycle power stations—geothermal water is passed through heat exchangers for heating the secondary fluid in a closed loop. This type of power station is used when the geothermal water has a temperature from 100 °C to 170 °C;
- Combined cycle or hybrid power stations—the traditional Rankine cycle is added for electricity generation with the use of waste heat from the binary cycle [7].

A large part of the geothermal potential is heat accumulated at significant depths where the ground becomes less porous and, therefore, the water flow is limited. Solutions to this problem include enhanced geothermal systems (EGSs) and advanced geothermal systems (AGSs).

An EGS is a system in which the geothermal water is pumped from reservoirs formed in low-permeability rock by means of hydraulic, chemical, and thermal stimulation (Figure 1). It is a fracturing technique, i.e., a process in which cracks already present in the rock and filled with water are increased in size or new fractures are formed in order to increase the permeability of the rock. For this purpose, water containing chemical substances is injected under high pressures into the deposit. With an adequate pressure value, it is possible to open fractures, forming cracks in the rock. The water mixture also contains some solid particles which partially fill the fractures and allow them to remain open. The system includes two sub-types: deep sedimentary basin EGSs and shallow

(<3 km) low-temperature EGSs. Deep sedimentary basins do not store water and/or are not permeable. On the other hand, a shallow-type EGS uses low-permeability bedrock located at a depth of 3 km or less and commonly found in any location, on the condition of sufficient reservoir depth and stimulation. A deep EGS is typically considered in the context of electricity production, and a shallow EGS is considered in the context of heat generation [8–10].

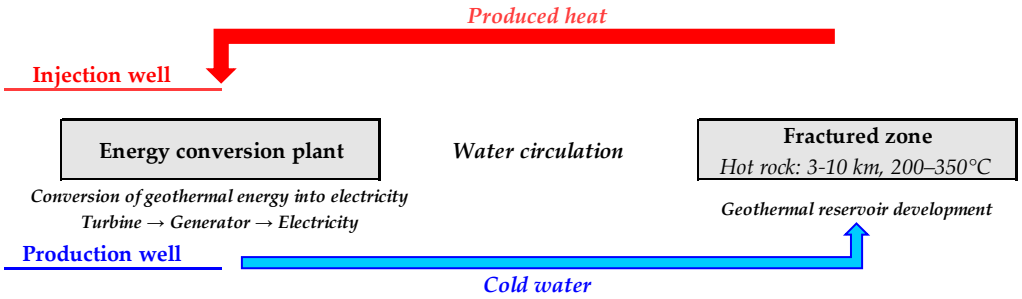


Figure 1. Enhanced geothermal systems (EGS) (based on [8–10]).

AGS, also referred to as a closed-loop geothermal system (Figure 2), employs a system of pipes forming a closed-circuit in hot rock formations. The advantage of the system lies in the fact that the rock does not need to be permeable or contain water, as the fluid is injected into the system from the surface and continuously circulates in the closed loop. Therefore, the system is not affected by problems related to sub-surface operations. Moreover, the system does not require the location to have specific conditions and can thus be installed in any location on the condition that the well is completed in both the horizontal and vertical direction [11]. Such a system generates energy only as a product of the pipes contacting the hot dry rock. The technology is low emission (mainly in the preparatory phase and pre-production phase), and the system can work using natural convection based on temperature differences.

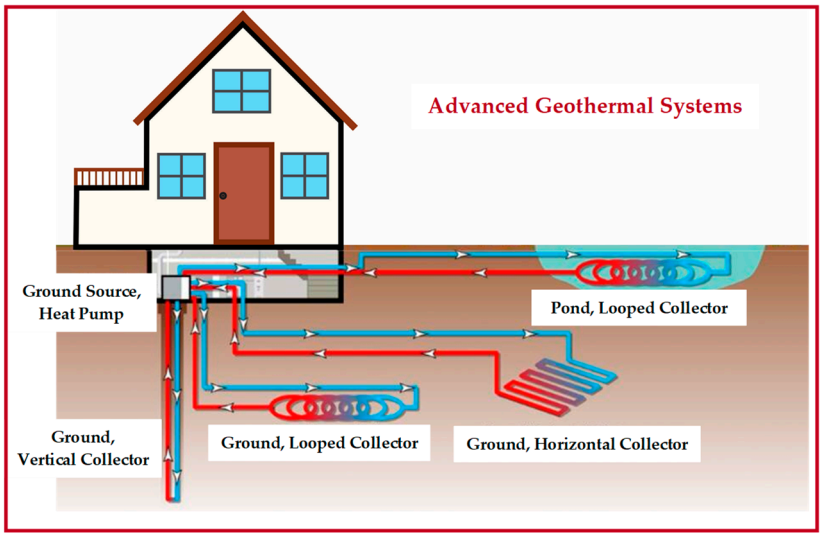


Figure 2. Advanced geothermal systems (AGS) (changed, based on [12]).

Advanced geothermal systems have two basic configurations:

- A simple, single-well coaxial closed loop;
- A multi-leg circular closed loop resembling underground ribbed "radiators" comprising a number of wells connected at various levels [11,12].

In terms of environmental impact, the systems presented may have a minimal impact on land use or the landscape. What is important is that this is a low-emission solution. A

review of geothermal geotechnologies conducted in the US indicates that existing technologies can achieve life-cycle emissions of less than 50 kg CO_2/MWh, which means that these systems are very competitive, especially in relation to conventional energy sources [13].

3. Geoenergy Engineering and Sustainable Development Goals

Sustainable development is a concept intended to integrate the social and economic aspects with natural resource consumption in order to meet the present and future needs of the society and environment [14]. The concept is expected to be implemented through so-called Sustainable Development Goals (SDGs). The goals have been adopted in the document Agenda 2030 [15], during the UN General Assembly in September 2015, as a general plan for the 2030 perspective. The document sets 17 Sustainable Development Goals intended as global directions, comprising 169 related tasks in the areas of key importance for humanity (Figure 3). These goals are aimed at stopping negative phenomena related to the development of civilization, and their implementation depends on the engagement of governments, businesses, and non-government organizations. Moreover, each of the 169 tasks is globally monitored with the use of defined indicators [16]. It is worth adding here that many countries have committed themselves to achieving Sustainable Development Goals, as well as net-zero emissions goals. Introducing such aspects as national policy directions may mitigate, for example, the effects of global warming [17]. According to CAT (2023) [18], China's implement to achieve net-zero emissions by 2060 could contribute to limiting the temperature increase by approximately 0.2–0.3 °C.

Geoenergy engineering has great potential in supporting the SDGs outlined in Agenda 2030. Of these, particular importance is placed on the five goals related to energy, climate, industry and infrastructure, clean water, innovation, sustainable cities, and economic growth. Within each of these goals, geoenergy engineering offers solutions based on modern technologies for supplying clean and stable electricity, heat, and cooling. Figure 3 highlights the sustainable development goals which are particularly relevant in the context of the future development of geothermal engineering.



Figure 3. Sustainable Development Goals in the context of geoenergy engineering (based on [16]).

3.1. Sustainable Development Goal No. 6: Clean Water and Sanitation

Geothermal energy can also be used in water desalination processes, particularly in the context of supplying drinking water. The technology includes using geothermal energy, e.g., in water distillation or pre-heating prior to other desalination processes. In such applications, geothermal energy allows for the reduced consumption of energy from other sources. The energy intensity of desalination ranges from 2 to 27 kWh/m^3 depending on the type of technology used for this process [19].

Agriculture commonly employs such RESs as solar energy or biomass. Farms need energy to heat greenhouses and other farm buildings, as well as to irrigate fields or dry crops. Ahmed et al. (2016) [20] demonstrate that desalinated water can be successfully used for irrigation without affecting the nutritional quality of the crops and can thus aid the production of fresh food in the Gulf Cooperation Council countries. Spain is the global leader in water desalination projects. It uses 22% (14×10^6 m^3/day) of desalinated water in field irrigation [21].

According to the International Food Policy Research Institute (IFPRI), by 2050, more than half of the global population will face shortages of drinking water. Moreover, the World Bank Annual Report indicates that electricity produced from solar energy is more expensive than electricity from the grid by threefold [22]. Importantly, desalination plants need to operate continuously day and night, and they therefore must rely on expensive batteries which supply electricity at night [23]. Viewed from this perspective, geothermal energy offers constant availability of energy supply and a number of other advantages. The first advantage lies in the reduced costs of purchasing energy from external sources. The fact that geothermal energy is the cheapest source of energy can be considered an additional advantage [13]. Also, the excess energy can be sold to the grid and translate into additional income. Another advantage results from the reduction in greenhouse gas emissions, which is obviously a contribution to the fight against climate change [24].

3.2. Sustainable Development Goal No. 7: Affordable and Clean Energy

This goal describes the need to ensure common access to clean fuels and energy, popularize RESs, and improve energy efficiency. It additionally recommends increasing the share of RESs in the energy mix and emphasizes the role of regulatory frameworks and innovations in the transformation of existing energy systems.

Geoenergy engineering offers successful solutions for this goal, as it plays an important role in supplying clean and stable energy. This energy is available throughout the year, across all seasons, regardless of weather conditions, and is thus a reliable renewable energy source. Globally, the geoenergy available to the current engineering technologies at a depth down to 8 km is approx. 300,000 EJ. This value corresponds to 600 TW of geothermal power available for 20 years. This value is also 2000 times greater than the technical potential of conventional geothermal energy. As compared to other geothermal generation technologies, only photovoltaics has the technical potential for an electricity production higher than geoenergy engineering solutions. Moreover, geoenergy has a power-generation potential threefold greater than onshore wind energy and a fivefold greater potential than offshore wind energy [3].

Importantly, geoenergy engineering can also be used in heating and cooling systems. The amount of heat extractable globally from sedimentary water-bearing layers at a depth of 0.5–5 km and at temperatures higher than 90 °C is estimated at above 250,000 EJ. This value corresponds to a mean heat flow of 320 TW for 25 years. The 90 °C threshold reflects the requirements of modern district heating utilities, which rely on fossil fuels, but which can be decarbonized in the process of the transition to geothermal energy without affecting the existing network infrastructure. However, the potential of hot sedimentary water-

bearing layers is even greater in the case of modern, highly efficient district heating plants, which operate at temperatures below 70 °C, and of plants employing geothermal heat pumps. In the case of an assumed minimum temperature threshold of 60 °C, the potential of geothermal energy is estimated to be four times greater (one million EJ) than in the case of the 90 °C threshold. Also, although geothermal sources above 200 °C are less commonly available, with an adequate technical potential, they still account for approx. 15,000 EJ, which is sufficient to cover almost 500 years of the global industrial demand for heat below 200 °C [3].

Almost 90% of the heat-generation potential of hot sedimentary water-bearing layers is concentrated at a depth smaller than 3 km, as only several regions have deeper sediment layers. At greater depths, enhanced and closed-loop geothermal systems remain as a technically available option for district heating regardless of the presence of sedimentary water-bearing layers [3].

3.3. Sustainable Development Goal No. 9: Industry, Innovation, and Infrastructure

Geoenergy engineering offers access to great amounts of thermal energy. Until recently, geothermal energy solutions were limited to the operation of either ground-heat pumps using low-temperature resources or high-temperature systems specific to a particular location. However, in recent decades, increasingly intensive research and innovations have provided solutions to geological limitations, and the currently used drilling technologies (EGSs and AGSs) allow access to sources at greater depths. For this potential to be fully used, further research and development works are needed, which would increase the effectiveness of drilling processes (drills, drill strings, construction materials, casings and cement channels, etc.) and their efficiency in specific geothermal conditions. Therefore, although geoenergy engineering is a solution based on innovation, it is still being developed. These developments and innovations improve drilling indicators and efficiency, reducing the drilling time and cost [25].

Ecotechnologies are also becoming increasingly popular in civil engineering. Such technologies not only allow for reduced energy consumption but also energy generation, making buildings energetically self-sufficient. Best practices in building design include the use of geothermal heat pumps. This solution has many advantages, from lower operating costs to the improved reliability of geothermal systems. Such systems require minimum maintenance and thus offer lower long-term operating costs. They are also silent and do not emit greenhouse gases into the atmosphere. Importantly, the water pulled from the ground can also be used to cool air in buildings. In effect, external air conditioning is not required, further lowering the investment costs.

3.4. Sustainable Development Goal No. 11: Sustainable Cities and Communities

Geothermal sources are available locally and can be easily developed in the vicinity of the locations in which they are used, saving costs related to energy transfer. In addition, local geothermal systems reduce the dependency on fossil fuels and are inexhaustible [26–28]. Therefore, geothermal systems will be able to provide heat for many years. Moreover, geothermal technologies provide a regular supply of energy, which translates into comfort for society and lower energy costs. Geothermal power plants are independent of weather conditions.

Also, they do not interfere with the environment and do not modify it as much as wind farms or hydroelectric plants do. Another advantage is that geothermal energy may positively influence local economies by creating workplaces in construction and technical maintenance. The construction process, operation, and maintenance of geothermal power plants creates demand for qualified workers such as engineers and technicians,

renewable energy experts, on-site personnel, and workers involved in the construction of the infrastructure for the plant.

3.5. Sustainable Development Goal No. 13: Climate Action

The reduction in greenhouse gas emissions requires concrete actions. One of them may be to invest in renewable energy, including in geoenergy. Geoenergy is based on renewable geothermal resources, and as it does not use fossil fuels, it significantly contributes to reducing greenhouse gas emissions. It also reduces the dependency on and the demand for fossil fuels, thus reducing the emissions related to fossil fuel extraction, transport, and combustion [29].

The GeoVision analysis [25] focused, among other things, on the influence of energy consumption on emissions into air. The research was performed for greenhouse gas (GHG) emissions, as well as for sulfur dioxide SO_2, nitrogen oxides NO_x, and particulate matter $PM_{2.5}$, for both electricity and non-electricity sectors. The results indicate that, by 2050, the use of geothermal energy could prevent the GHG emissions equivalent to removing a total of approximately 26 million cars from roads in the USA. The report also indicates that the emissions of SO_2, NO_x, and $PM_{2.5}$ are negligible in such a case. On the other hand, the IEA 2024 analysis [3] indicates that, in comparison to fossil fuel-fired plants of a similar size, geothermal power plants emit 99% less CO_2 and 97% less sulfur compounds related to acidic rains. A conclusion can thus be made that geothermal systems or ground-heat systems do not generate CO_2 or other GHGs, which are mainly responsible for climate change.

4. Challenges and Perspectives

Despite its numerous advantages, geoenergy engineering also faces challenges, including high initial investment costs or the limited accessibility of geothermal resources in some regions. Another problem is the limited supply of qualified personnel. The technology requires investments in research and development, as well as policies supporting RESs [30]. Investments in the development of geoenergy engineering may bring benefits in the future as it becomes a zero-emission energy production technology. Obviously, the EU financially supports geothermal technologies, e.g., as part of programs for the development of emission-free energy sources. However, the majority of such financial projects focus on research and innovation.

The IEA 2024 report [3] observes that including geoenergy engineering in national energy plans could aid new investments. According to the report, such an approach could improve the cost competitiveness, financial security, and predictiveness of geothermal projects which—owing to appropriate regulations—may reduce the costs of electricity generation by as much as 80%. In such a case, geoenergy would become one of the cheapest sources of renewable energy.

Another challenge for geoenergy engineering is to understand the complex influence of new geoenergy facilities on the environment. On the one hand, the use of geoenergy to produce heat, cooling, and electric energy has an important role in reducing GHG emissions and in meeting carbon emission goals. On the other hand, it is also a source of growing environmental concerns [31]. The literature points to the significant benefits of using RESs, which are frequently balanced by high environmental costs related to drilling and facility construction processes, as well as to the consumption of water (the water footprint). Importantly, however, geothermal energy typically has a smaller water footprint than in the cases of other energy sources (e.g., fossil fuels or nuclear energy), with the potential influence depending strongly on the particular project and on the employed exploitation method [32]. Analyzing such a complex influence of new geothermal objects is possible

with the use of the full life-cycle assessment (LCA) [32,33]. It is a very good tool, as it allows for a comprehensive evaluation of the sustainable development of the electricity, heat, and cooling production capacity of geothermal energy from the perspective of its impact on the natural environment, as well as on the economic and social aspects over the entire life-cycle of a project, from the exploitation of geothermal resources, through the construction of the infrastructure, until the use and reclamation of the area after exploitation has finished [34]. LCA also allows an objective comparative evaluation of the advantages and limitations of geothermal energy production relative to energy production not only from traditional sources, such as coal-fired power plants, but also from RESs, such as wind turbines or hydroelectric plants. The use of LCA in the management of energy production, in the context of decision-making processes aimed at defining and prioritizing solutions in accordance with the sustainable development criteria, allows for the accelerated transition to sustainable energy production [35,36].

The principle and structure of LCA are defined in ISO 14040 and ISO 14044 [37–39]. The initial stage of LCA involves defining the goal and scope of the research, as well as the complexity level of the project. The life-cycle of a project is a system of unit processes combined with the flows of intermediate products and waste. The division of the system into components facilitates the identification of inputs and outputs. The limits of unit processes are defined by the complexity level of the model required for accomplishing the research goal [33]. The first stage of performing a life-cycle assessment is to define the purpose and scope of the study. The next stage is to define the set of inputs and outputs. On the input side, raw materials and energy are analyzed, and on the output side, products, waste, and emissions into the environment are analyzed. Next, a Life-Cycle Impact Analysis (LCIA) is performed. This involves assigning appropriate environmental impact categories to individual items. The final stage of the LCA is the interpretation of the life-cycle, which determines conclusions and guidelines to reduce the negative environmental impact of the analyzed project [33,37]. In the case of geothermal energy, a life-cycle assessment requires the precise knowledge of numerous variables, such as analyses of land use, geological structures and the related threats, emissions into the air, water consumption, or the impact on biodiversity [40].

In fact, LCA is a standardized methodology describing the potential influence of a system on the natural environment, the society, or the economy over its entire life-cycle. LCA is an important tool for assessing the influence of technological systems on their functional environment by investigating their advantages and disadvantages within the entire sequence of technological processes [37,41]. An LCA analysis may confirm the positive influence of geothermal energy on the environment and allow for other factors, such as water consumption, gas emissions, or the impact on local communities. On the other hand, by identifying the negative ecological, economic, and social consequences, the LCA enables the development of strategies for minimizing the impact of geothermal energy projects on the natural environment and society [32].

The use of an LCA in evaluating the effectiveness of geothermal projects is not a common approach. This fact is due to the great complexity of investment processes in geothermal energy projects and to considerable differences between individual systems. The consequence is the significant variability of the data describing such systems and the problematic comparison of LCA results, particularly relative to the different actual environmental impact of each project [40]. On the other hand, it is the only assessment of such breadth that allows for a multidimensional factor analysis of the economic and environmental performance of geoenergy projects throughout their entire life-cycle. According to the authors, this is particularly important when comparing the LCA to assessments based

solely on environmental analyses of individual elements, such as water or carbon footprints, or analyses over a selected time period, such as environmental impact assessments.

The main data influencing environmental analyses for geothermal power plants include geological, geomorphological, topographic, and ecological conditions [42]. Therefore, in the case of geothermal power plants, the LCA requires an interdisciplinary approach and individual consideration for each case [40]. It also needs to allow for the fact that, in the case of geothermal energy, sustainable development and environmental protection reach far beyond the reduction in GHG emissions and include a number of other components of the environment [32,42,43]. The variability of geological (geothermal gradient, lithology of rock layers taking into account their temperature, permeability, and degree of fracturing), topographical (landform, mass movements occurring near the project), and ecological conditions (forms of nature conservation, fauna, and flora) is the main factor determining differences in impact effects and also forms the basis for decision-making in the creation of a geothermal project [32].

There are many examples in the literature of the use of an LCA to study the environmental impacts associated with energy production from various sources, both conventional and renewable [33]. The examples presented in the literature concern the life-cycle assessment, particularly in the context of greenhouse gas emissions [44] or environmental acidification by geothermal power plants [45], the environmental impact of the preparatory phase of geothermal projects, such as drilling and casing [45–47], or the possibility of using existing oil and gas wells for geothermal heating systems [33,46]. The results presented indicate that geothermal systems have one of the lowest CO_2 emissions of any energy system and that the environmental impact of future geothermal power plants can be further reduced through, for example, the electrification of drilling and sustainable cementing practices, especially in the context of existing oil and gas wells [33].

In conclusion, research on the LCA and water footprints in the geothermal sector is of key importance for the complex understanding and evaluation of all the aspects of geothermal energy production, from the extraction of the resource to its usage. The LCA applied in geothermal projects allows for a complex evaluation of the sustainable development of geothermal energy production, including the economic, social, and environmental results of such projects.

5. Conclusions

The IEA 2024 report points to the globally increasing investments in geoenergy. Governments are becoming interested in this source of energy. The reason is that geoenergy is a constantly available source of energy with no day–night intermittency. It is also a stable source, and geothermal plants may continuously operate at maximum capacity. For example, in 2023, the capacity factor for geothermal energy plants was above 75%.

Renewable energy sources have the potential to replace traditional energy systems based on fossil fuels and provide economic support for society [32,40,48]. Of all the renewable energy sources and technologies, geothermal energy currently (with the so-called new-generation EGS technology) offers the technical electric energy capacity potential exceeded only by photovoltaics.

The analysis showed that geoenergy includes key areas of synergy and interdependence, with specific Sustainable Development Goals, particularly in the areas of clean energy, environment protection, innovation, and sustainable cities. Reduction in GHG emissions due to the development of geoenergy science and technology may contribute to mitigating results of climate change such as droughts, floods, or rising sea levels and, in effect, reduce the long-term costs for society. This industry has significant potential and can become one of the most important elements for economies across the globe. With the use

of geothermal energy, it is possible to reach greater energy independence on the national level, reduce GHG emissions, create new jobs, and facilitate the development of geothermal regions. If its dynamic development is maintained, geoenergy engineering is expected to even generate a sixfold increase in the demand for specialists (up to approximately one million jobs).

Despite the fact that geoenergy may become a key element in the development of the energy economy, it is important to remember the challenges it faces. One of the key challenges, according to the authors, is the need for further technological and financial support, because, although there are certain difficulties (e.g., high investment costs or the need for specialist knowledge), the long-term benefits of geothermal energy development may prove to be very advantageous. Furthermore, including geoenergy projects in countries' energy plans would facilitate the release of funds for new investments.

Another important challenge involves the life-cycle assessment of energy projects, which is necessary, especially in the case of comparing different energy-production methods for both traditional and renewable energy technologies [32]. Such an approach will allow for an objective and global evaluation of the advantages and limitations of geothermal energy production, particularly in the context of energy transformation in accordance with Sustainable Development Goals, as will be explored by the authors in their next publication. The implementation of the LCA analysis in geoenergy projects may significantly influence decision-making regarding the development of these projects, both in financial and environmental terms, which, according to the authors, is one of the most important issues in the functioning and development of this energy sector.

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