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Potential, Challenges, and Opportunities in the Development of Geothermal Energy Projects

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Abstract: Geothermal energy is an important yet insufficiently explored renewable source. Known for its supply stability and low environmental impact, it offers significant potential, however, broader adoption faces notable technical, economic, and regulatory challenges. This paper first examines the origin of geothermal energy and its historical use, followed by the technological evolution of systems for both direct thermal use and electricity generation. It also reviews global trends and statistical indicators, providing context for current utilization patterns. The analysis places special emphasis on the Republic of Croatia, highlighting existing projects, available geological data, and strategic development plans. Key barriers to wider deployment are identified, and potential solutions are discussed, including legislative adjustments, investment incentives, and stronger institutional support. The paper concludes by emphasizing the need for a systematic approach to integrate geothermal energy into Croatia's energy transition, thereby enhancing energy independence and reducing greenhouse gas emissions.

Keywords: Croatia; energy independence; energy transition; geothermal energy; geothermal power plants; renewable energy

1 INTRODUCTION

The increasing energy demands of modern society require innovative energy solutions. In this context, renewable energy sources will play a key role. In addition to the inherent limitations of fossil and nuclear fuels as global resources and their actual and potential harmful environmental impacts, energy supply chains are under growing pressure due to the current unstable geopolitical situation. Therefore, new energy solutions are being sought that, in addition to reducing greenhouse gas emissions and the exploitation of finite natural resources, must also ensure energy independence through local energy production. Geothermal energy naturally emerges as an attractive alternative. Compared to renewable sources such as solar or wind energy, this form of energy enables energy production both day and night, regardless of weather conditions and throughout the year, which makes its supply stable and predictable. Geothermal energy is a virtually inexhaustible, clean, and renewable energy source, but it faces numerous challenges, and its utilization is currently rather limited.

2 ORIGIN OF GEOTHERMAL ENERGY

Geothermal energy is the thermal energy present within the Earth's interior that is, in the Earth's crust, mantle, and core. There are two main sources of this heat: primordial or accretion heat, i.e., the heat remaining from the formation of the Earth, and the heat released due to the decay of radioactive elements in the Earth's interior [1]. In [2] another important mechanism of heat source within the Earth is proposed, namely, a gravitational heat source generated by viscous friction in the upward flows of material deep from the mantle towards the surface. These flows occur because mantle material gradually loses iron over time. The denser iron sinks towards the core, while the remaining, lighter material rises, bringing additional heat closer to the surface. The heat released by these mechanisms drives further processes that enhance local heat transfer within the Earth's interior all the way to the surface. Therefore, in addition to pure heat conduction, convective heat transfer occurs due to the movement of viscous mantle material, which consequently causes shearing, subduction, overthrusting, collision and uplifting of tectonic plates, processes that also release large amounts of energy. As a result, geothermal energy manifests at the Earth's surface in the form of volcanoes, geysers, hot springs, and similar phenomena.

3 HISTORICAL AND PRESENT-DAY USES OF GEOTHERMAL SOURCES

Humans have always been aware of the existence of geothermal energy because they witnessed the previously mentioned surface manifestations. There is evidence that people used hot springs for bathing and cooking more than ten thousand years ago. The oldest known bathhouses that used geothermal water were built in China during the Qin dynasty in the 3rd century BC. Many bathhouses from the time of the Roman Empire are also well known, and the Romans used geothermal springs for medicinal purposes also, particularly for treating skin and eye diseases, as they believed that the minerals in geothermal water had healing properties. The Romans also used geothermal sources for underfloor heating in buildings, such as in Pompeii. The oldest centralized heating system was built in France in the 14th century. In addition to bathing, healing, and building heating, geothermal water is also valuable as a resource. For example, in the early 20th century in Tuscany, Italy, it was used to produce boric acid [3]. On that same geothermal field, Larderello, the first geothermal power plant was commissioned in 1904. Today, the Larderello field is one of the largest geothermal fields in the world with a total installed capacity for electricity generation of 800 MW [4]. Today, geothermal sources are used for a wide range of purposes. They are used both as an energy source and as a source of raw materials. As an energy source, the most common use is the direct use of geothermal heat. Some of the applications of this heat include district heating of urban areas, heating of large facilities such as industrial plants or warehouses, heating of greenhouses for growing fruits, vegetables, and

flowers, heating of fish farms, heating of pools, spas, and wellness centers, de-icing of roads, drying of wood, fruits, vegetables, and similar products, food processing such as milk pasteurization, salt production, textile washing and dyeing, and so on. It is also important to mention the use of heat pumps for households and geothermal cooling [5]. In addition to the direct use of heat, power plants that utilize geothermal sources for electricity production are gaining increasing importance. Finally, geothermal sources are also used to produce raw materials such as lithium, boron, silicon, and others [6].

4 CRITERIA FOR SELECTING OPTIMAL LOCATION AND TYPE OF GEOTHERMAL SYSTEM

Not all geothermal systems are suitable for all locations. For example, systems for direct use of heat can be constructed in areas where the geothermal reservoir has a significantly lower temperature than what would be required for the construction of a geothermal power plant. In this context, the concept of the geothermal gradient is of primary importance. It is a measure that describes how much the subsurface temperature increases with depth. It is usually expressed in °C/km. In the continental crust, it typically amounts to about 25 °C/km down to depths of approximately 3 to 5 km [7]. In addition to the fact that the geothermal gradient is not constant at a given location, that is, it varies with different geological layers and with increasing depth, there are also large differences in geothermal gradients between different regions. Fig. 1 shows a map of Europe with temperatures at the depth of 4500 m. It is evident that the highest subsurface temperatures are found in countries such as Iceland and Turkey, while regions such as the Pannonian Basin, parts of Italy, Germany, and France also exhibit a higher geothermal gradient than the European average.

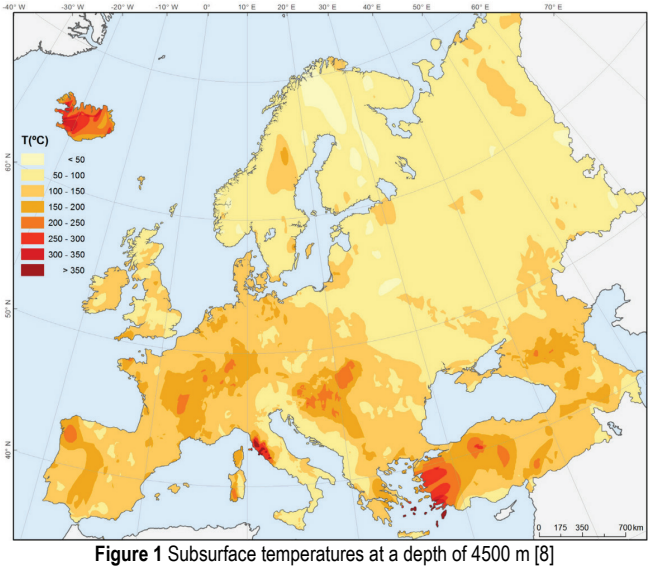


Figure 1 Subsurface temperatures at a depth of 4500 m [8]

Regardless of the type of geothermal system, the selection of a location requires the consideration of a wide range of different criteria. This is a multidisciplinary process that involves evaluating numerous factors. Primarily, these include locational criteria such as geographical and geological characteristics, but other aspects must also be considered, such as economic, regulatory, and social factors, in order to assess the need, feasibility, profitability, and acceptability of a geothermal project. For example, the construction of a geothermal system will be unfavorable or impossible on inaccessible terrain, in populated areas or natural protected areas, on remote mountains, or on bodies of water.

When evaluating geological criteria, it is first important to pay attention to surface manifestations. Clearly visible geothermal activity, such as the proximity of hot water springs, volcanic activity, and geysers, are clear indicators of favorable geological conditions. Additionally, gas and steam emissions from the ground may signal geothermal activity. Further indicators include craters, calderas, and other similar formations. These structures often occur alongside extrusive igneous rocks such as trachyte, rhyolite, and basalt, which further indicate favorable geothermal characteristics of the area. In addition to surface indicators, possible signs also include faults and fracture zones that allow geothermal fluids to flow through the rocks, acting as high-permeability channels [9].

In addition to surface indicators, valuable data is provided by surface geophysical measurements. These include multispectral and hyperspectral imaging, InSAR, LiDAR data, and similar sources. Subsurface data is obtained through methods such as seismographic, magnetotelluric, and gravimetric surveys. These exploration methods are useful for detecting large geological structures, rock composition, subsurface layer thickness, and general characteristics of a potential geothermal reservoir. Geophysical survey methods are typically used to analyze parameters such as density and to identify anomalies [10].

However, by far the highest quality and most reliable data comes from actual wells. The drilling of exploratory wells is the most expensive method of obtaining subsurface data, but it provides the most accurate information about the geothermal reservoir, including lithological data, permeability, porosity, and the overall quality of the reservoir. It also yields detailed data on the geothermal fluid (water) such as its composition, salinity, the quantity and type of dissolved minerals and gases, and similar characteristics. Naturally, it also provides information about reservoir temperature (of both water and rock) and geothermal gradients.

By using all this data, a precise 3D representation of the subsurface structure can be made. Such models can help assess the profitability of the project and allow engineers to plan drilling locations more efficiently, define well trajectories to maximize thermal output, and carry out economic analysis to select the most favorable design variant of the geothermal system [10]. A large amount of data is often already available, so it is always necessary to thoroughly examine existing archive data. In the Republic of Croatia, around 4500 wells have been drilled so far [11], which is, relative to the country's territory and the fact that Croatia is not a particularly significant producer of oil and

gas, a very large number. Therefore, there is a great deal of data on the Croatian subsurface, and it is considered well explored. Such a situation represents a major advantage, as it enables a much better assessment of geothermal potential and reduces the costs of data collection and exploration. In addition, old wells that were considered negative in terms of hydrocarbon production can be repurposed into geothermal wells, which significantly reduces costs.

Based on data on earthquakes, heat flow, sediment thickness, groundwater, tectonic data, elevation, and other factors, Coro and Trumpy [12] created a map shown in Fig. 2. The map shows the most promising areas on Earth for the development of geothermal systems, primarily located along the Pacific Ring of Fire, in China, the Middle East, parts of Africa at the boundary between the Nubian and Somali plates, Hawaii, New Zealand, Iceland, the Azores, and parts of Europe from Turkey towards southeastern and central Europe and Italy. Although geothermal systems can be constructed almost anywhere, these areas are significantly more suitable for their construction.

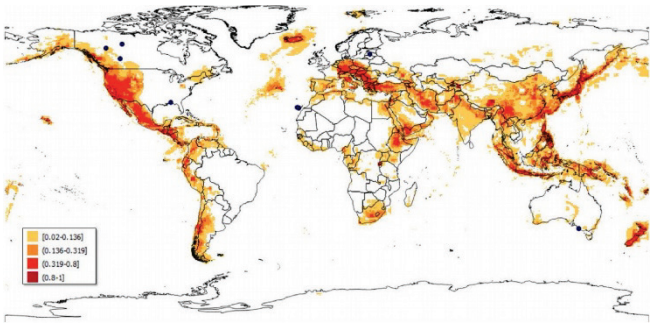


Figure 2 The most promising areas for the development of geothermal systems on Earth [12]

5 TYPES OF GEOTHERMAL SYSTEMS

Today, there are various types of systems for direct heat use. Direct heat systems range from simple, shallow pipe setups used for household heating and cooling, such as heat pumps, to large-scale systems with deep wells designed for heating urban districts or agricultural facilities like greenhouses.

Geothermal power plants can be divided into conventional and unconventional types. Conventional geothermal power plants are further classified into three main types: dry steam systems, flash steam systems, and binary cycle systems. In dry steam systems, steam from underground reservoirs is used directly to drive a turbine and generate electricity. These systems require high reservoir temperatures (150 °C or above) where dry steam is present. This system is also the first and simplest type of geothermal power plant ever developed. The flash steam system uses geothermal water in liquid form at a temperature of around 180 °C under very high pressure. The water is brought to the surface through a well into high-pressure tanks (separators). When the pressure drops in the tank (in one or more stages), the water flashes into steam, which is then directed to the turbine. The binary cycle differs from the previous two types in that geothermal water is not used directly to generate electricity. Instead, in a heat exchanger, the geothermal water transfers its heat to another working fluid. This working fluid, vaporized by the heat, drives the turbine. The working fluid is typically a fluid with a lower boiling point than water. This approach enables the system to operate with geothermal water at temperatures as low as 100 °C or even lower, making it suitable for lower-temperature geothermal reservoirs [13].

The second type includes unconventional geothermal systems. These are divided into two main groups: enhanced geothermal systems (EGS) and closed-loop geothermal systems (CLGS). In enhanced geothermal systems, a geothermal reservoir is not required, although it can still be used if present. What is needed are hot rocks, either dry (HDR) or wet (HWR). These systems artificially improve or create rock permeability between production and injection wells by hydraulic fracturing, allowing water to circulate and transfer heat [14]. In closed-loop geothermal systems, there is no geothermal water present in the system. Instead, closed pipe circuits are used to circulate a working fluid through underground formations, where it absorbs heat from hot rocks [15]. There are different designs of closed systems, such as U-tubes, multilateral wells, coaxial systems, and others. The types of conventional geothermal power plants are shown in Fig. 3, while the types of unconventional geothermal power plants are shown in Fig. 4.

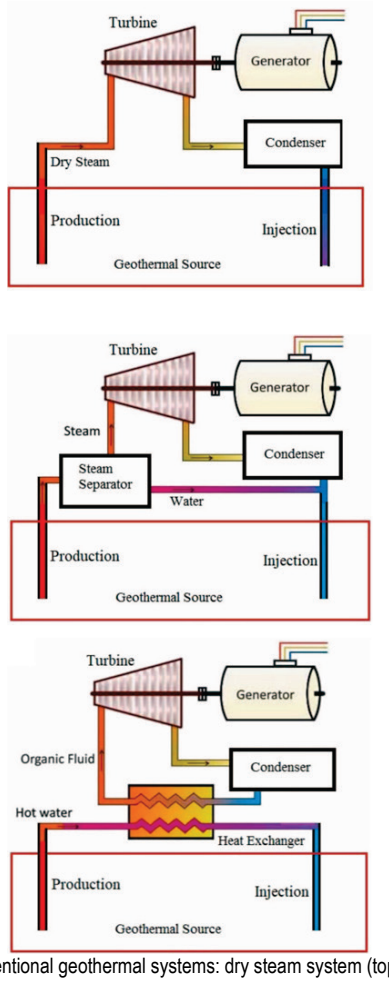


Figure 3 Conventional geothermal systems: dry steam system (top), flash steam system (center), and binary cycle (bottom) [13]

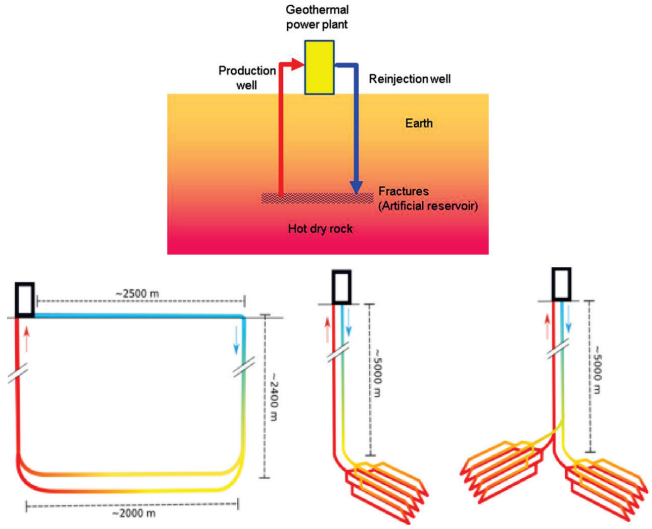


Figure 4 Unconventional geothermal systems: EGS (top) [14] and CLGSs (bottom) [15]

There are also hybrid systems that combine features of two or more systems, as well as so-called cascade systems, in which geothermal water is used at multiple levels (e.g., first for electricity production, and then the remaining warm water, before reinjection into the reservoir, is used for heating greenhouses).

6 USE OF GEOTHERMAL ENERGY WORLDWIDE

The International Geothermal Association (IGA) regularly updates its database on the use of geothermal energy around the world. Data on installed geothermal energy capacity is shown in the charts in Fig. 5.

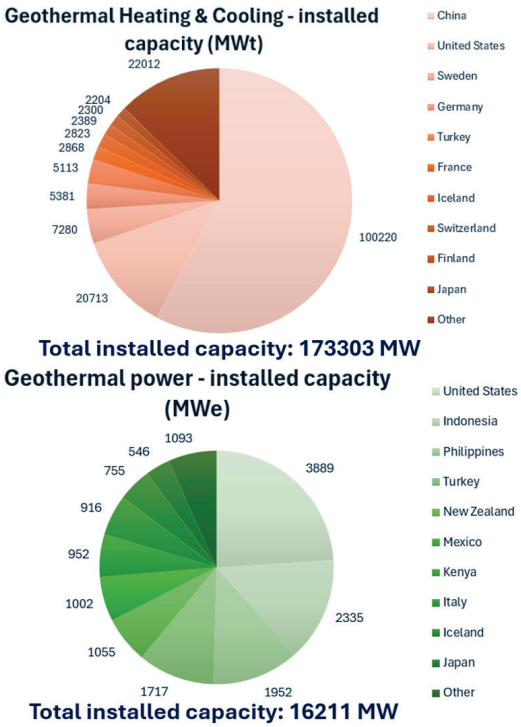


Figure 5 Installed geothermal capacities worldwide [16]

From the chart in Fig. 5, it is evident that, when it comes to direct use of heat, China accounts for more than half of the world's capacity, and the top five countries alone account for over 80%. In the case of electricity production, the capacities are distributed somewhat more evenly among the top ten countries. It is interesting to note that most of the electricity generation capacity is located in countries along the Pacific Ring of Fire (USA, Indonesia, the Philippines, New Zealand, Mexico, Japan). A large share of the remaining installed capacity is found in Turkey, Italy, and Iceland, as well as in Kenya, a significant representative of geothermal energy in Africa. Also, although the capacities for direct heat use and for electricity generation are not easily directly comparable, it is still evident that geothermal energy today is far more commonly used as a direct source of heat than for electricity production. The reason for this lies in the already mentioned fact that much more prominent geothermal reservoir characteristics are required for electricity production. When this data is compared with the map in Fig. 2, a significant correlation can be observed. This fact confirms the great importance of geographical location, i.e., geological conditions, for the potential of geothermal energy use.

Taking into account the estimate that just within ten kilometers below the Earth's surface lies a geothermal energy potential 50 thousand times greater than the energy potential of all oil and gas reserves in the world [17], and that geothermal energy accounts for only 0.34% of global electricity production [18], it can be concluded that geothermal energy is still significantly underutilized as an energy source and that there is an enormous room for growth.

7 GEOTHERMAL ENERGY IN CROATIA

The favorable position of Croatia in regard to geothermal energy is already visible from Fig. 1 and Fig. 2. The Pannonian region of Croatia exhibits a geothermal gradient up to 60% higher than the European average [19]. Using temperature data from 154 wells and by preforming interpolation, Macenić et al. [20] produced a detailed geothermal gradient map. Fig. 6 presents this gradient map, while Fig. 7 shows the geothermal fields in Croatia, including granted permits, projects in the exploration phase, and projects in the production phase.

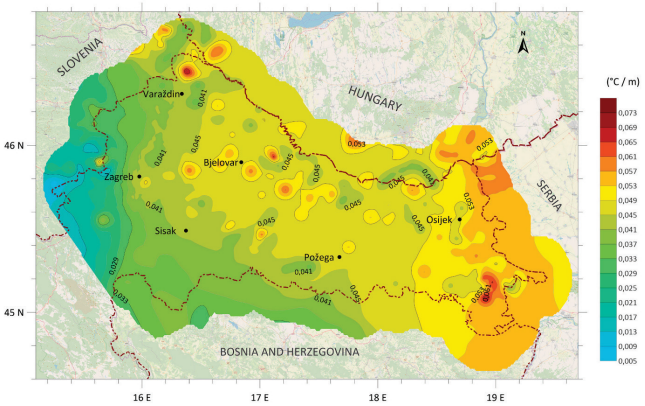


Figure 6 Geothermal gradient map of Croatia [20]

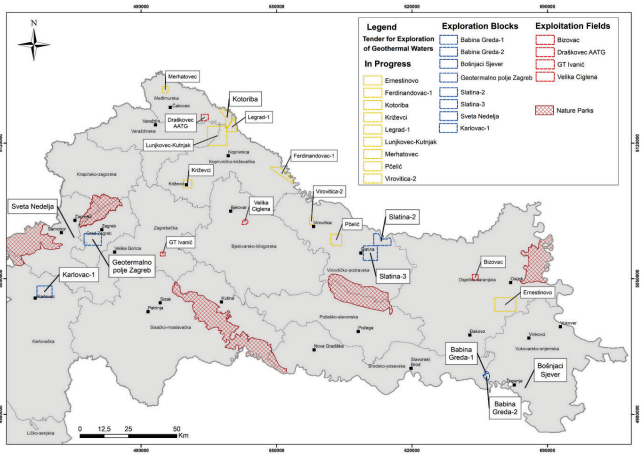


Figure 7 Geothermal fields in Croatia [20]

Croatia currently has 75 MW of installed capacity for thermal energy and 16.5 MW of installed capacity for electricity production [16]. It is estimated that the total geothermal potential in Croatia ranges between 750 and 1300 MW for thermal energy and about 500 MW for electricity production [21], with more recent estimates suggesting that the potential for electricity production could reach up to 1000 MW [22]. The 16.5 MW actually come from just one location, Velika 1 geothermal power plant, the only geothermal power plant in Croatia, operational since 2019, and the largest binary cycle geothermal power plant in mainland EU [23]. According to data from 2023, only around 0.21% of gross electricity production in Croatia comes from geothermal sources [24]. Based on the above, it can be concluded that Croatia utilizes only about 6 to 10% of its total potential for direct use of geothermal heat and only around 1.7 to 3.3% of its total potential for geothermal electricity production. Therefore, it is expected that installed capacities in Croatia will increase. This claim is supported by the fact that there are currently 24 active exploration areas in Croatia, 12 production fields are already in the production phase, and six preliminary exploration areas are focused on the development of district heating systems [25].

8 CHALLENGES IN THE DEVELOPMENT OF GEOTHERMAL PROJECTS AND POSSIBLE SOLUTIONS

When examining the challenges in developing geothermal projects, it is useful to categorize them broadly into technical, economic, regulatory, social, and other challenges.

8.1 Technical Challenges

Drilling technology is a proven technology whose modern development began in the 19th century when large-scale drilling started in search of oil. Although the drilling process for hydrocarbon exploration and for geothermal project development is very similar, there are certain differences. These primarily relate to the temperatures encountered during drilling and the type and characteristics of the rocks. High temperatures limit the performance and lifespan of drilling tools and reduce the effectiveness of drilling fluids. Drilling fluids easily degrade, lose functionality, and the accuracy of measurement instruments during drilling decreases. Rubber parts have difficulty achieving proper sealing, and controlling the drilling trajectory is more challenging. Additionally, high temperatures affect the stability of cement slurry and the quality of cementing, which complicates later reservoir development. Since the goal is often to find fractured rocks, circulation losses of drilling fluids frequently occur as fluids enter the fractures. Favorable geothermal reservoirs are also often located in hard rocks, which further complicates drilling [26]. Moreover, geothermal wells are usually of somewhat larger diameter than oil wells because, especially for lower temperature reservoirs, a higher water flow rate is required for electricity production [27]. Also, during the construction of geothermal wells, it is often necessary to install casing along the entire length of the well, which is not always required in oil production.

The problems mentioned, although solvable, make geothermal projects much more expensive. Solutions include the development of temperature resistant fluids, instruments and tools, advanced cementing methods, and innovative drilling technologies (gas or foam instead of drilling mud, PDC bits, etc.), but further research and development of drilling technology for even higher temperatures and depths are needed [26].

However, the biggest technical challenges actually relate to the unreliability of surface measurements. No matter how good the data obtained from these measurements are, they can never be completely reliable. Before a reservoir is reached by drilling, the quality of the reservoir cannot be determined with certainty. Data such as permeability, porosity, reservoir fluid pressure, temperature, composition of reservoir fluids, etc., can only be reliably obtained by sampling rocks and fluids directly from the reservoir. It is a great advantage when well data from old wells exist in an area. Furthermore, if old wells have not been abandoned (liquidated), they can often be re-entered with measuring equipment and sampling tools, allowing reliable data about the subsurface to be obtained. This is a great opportunity for Croatian geothermal projects as many old wells can be revitalized and reused.

8.2 Economic Challenges

It is estimated that, in Croatia, the costs for the surface part of a geothermal power plant amount to around 1.5 million euros per MW. However, due to the high drilling costs and the aforementioned technical challenges involved in drilling such wells, costs can multiply, in some cases reaching up to 6 million euros per MW of installed capacity. For this reason, innovation centers, companies, and universities are developing new technologies aimed at accelerating and reducing the cost of the drilling process [28].

However, the biggest problem is precisely the unreliability of surface geological and geophysical data. This fact causes significant scepticism toward investing in the early exploratory phase of geothermal projects. As for the costs of above-ground (surface) equipment and infrastructure, these are usually comparable to those of similar projects [29], so they do not cause as much uncertainty. Therefore, the extremely high initial, i.e., capital

investment costs and the long payback period represent a challenge for the development of such projects. Banks are generally conservative investors and are usually willing to participate only in the production phase of a project, so such projects are often, at least at the early stage, financed from other sources, often own funds [28].

The profitability of investment in geothermal power plants could largely depend on the level of the premium price set by the Croatian Energy Market Operator (HROTE). With appropriate support, the investment payback period could be reduced to eight to ten years [28], which could motivate investors to invest in such projects. Alongside considering the price premium, it would be beneficial to review clear quotas for promoting production from geothermal sources, which could contribute to creating a more favorable investment environment and further strengthen the sense of regulatory predictability and security among investors [28]. Likewise, the development of risk-sharing schemes in the exploration phase (e.g., government guarantees or funds to cover unsuccessful drilling) could stimulate investments in the risky phases of projects [30]. Also worth mentioning are the 75 million euros that have been secured for the development of geothermal projects in Croatia through the European Regional Development Fund and the Recovery and Resilience Plan [25].

8.3 Regulatory, Social, and Other Challenges

Geothermal projects, unlike other renewable energy sources, are subject not only to the usual legislation (such as the Renewable Energy Sources Act, the Electricity Market Act, and the Construction Act), but also to the Hydrocarbons Exploration and Exploitation Act. This additional law regulates the exploration, evaluation, and exploitation of geothermal reservoirs, as well as the design and construction of the plant. As a result, geothermal energy investors must navigate two parallel administrative processes: one for the exploitation of geothermal water and another for the construction of the power plant. Such a system is rather complex and time-consuming, so unifying the regulations under a dedicated geothermal energy law could significantly facilitate project development. Additionally, cooperation with investors in drafting new laws and regulations would be desirable at an early stage, not only during public consultations [28].

The development of a geothermal project is a complex and lengthy process involving public tenders for exploration permits, the preparation of technical studies and economic assessments, approvals from expert commissions, environmental impact assessments, and obtaining numerous permits and energy approvals. All these phases prolong project timelines and increase risks for investors. Therefore, it is necessary to further simplify and accelerate procedures for geothermal projects, for example, by limiting the entire process to a maximum of two years and to more clearly define national policy toward this type of energy, especially regarding electricity generation capacities and grid access. It would also be beneficial to ease administrative obstacles, particularly in spatial planning procedures before the public tender [30].

The National Plan for the Development of Geothermal Energy by 2030 foresees increasing the share of renewable energy sources to at least 36.6%, reducing emissions, and developing geothermal energy for electricity generation as well as for heating and cooling. By 2030, the plan aims to install 68 MW of geothermal power plants [19]. The plan includes strengthening exploration activities, encouraging investment, building infrastructure, improving the regulatory framework, and involving local governments, with an emphasis on sustainable resource use and environmental protection. With its above-average geothermal potential, Croatia aims to accelerate its energy transition and strengthen supply security and energy independence by 2030 [31].

However, other challenges also arise, such as public mistrust due to environmental concerns (e.g., contamination of groundwater or gas emissions) [32] and issues related to property rights (land ownership, leases, compensation, etc.). Solutions to these problems include transparency with the public and all stakeholders, educational campaigns, and presentations of successful projects.

9 NEW GEOTHERMAL TECHNOLOGIES

As mentioned before, several companies have emerged that, through their innovations, aim to significantly change the approach to geothermal energy. Two such interesting examples are Eavor and Quaise. The Canadian company Eavor Technologies Inc. is developing advanced closed-loop systems, commercially known as Eavor-Loop™, which utilize a network of multilateral wells with complex geometries to efficiently transfer heat from the subsurface to a working fluid, with the goal of making geothermal energy scalable and applicable in nearly any location [33]. The American company Quaise Energy Inc. is developing a technology that, instead of conventional drilling, uses microwaves to melt and vaporize rock, with the purpose of enabling drilling into deeper and harder layers and accessing virtually unlimited geothermal resources. This approach could overcome the current limitations in the availability and scalability of geothermal sources [34].

10 CONCLUSION

By its nature, geothermal energy represents practically inexhaustible, clean, and renewable source of energy. In just the first 10 kilometers of the Earth's crust, there is 50 thousand times more energy potential than in all hydrocarbon reserves combined. This type of energy has been used by humans since ancient times, and at the beginning of the 20th century, it was used for the first time to generate electricity. However, despite this enormous potential, geothermal energy contributes very little to electricity production, both globally and in the Republic of Croatia. The reasons for this lie in numerous technical, economic, regulatory, and other challenges faced by geothermal projects. Technical problems could be solved through the development of innovative technologies and new, more modern drilling methods, which are already being researched by certain companies and institutions. Economic challenges will have to be addressed through incentivized feed-in tariffs, risk-sharing, and subsidies. Regulatory challenges should be mitigated through

amendments to regulations aimed at simplifying and accelerating administrative processes, which would also help to further reduce the risks of investing in such projects. In addition to all of this, there is a need to strengthen institutional support and apply a systematic approach in promoting geothermal energy, which could play a very important role in the green transition and in achieving energy independence for Croatia and other countries. Lastly, it is important not to overlook the potential role of oil and gas companies, whose technical expertise, extensive experience, and substantial capital could prove invaluable for the future research, development, and deployment of geothermal energy.

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