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Differences in Direct Geothermal Energy Utilization for Heating and Cooling in Central and Northern European Countries

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Abstract: Geothermal energy has emerged as an alternative heating source that can replace fossil energy. This mature technology is already in use all over Europe, but there are significant differences in its use between European countries. One possible explanation for this phenomenon concerns societal differences directly related to geothermal energy, the topic that is investigated in this study. The present work proposes using the societal embeddedness level (SEL) method to analyze and compare the status of non-technical factors affecting geothermal energy use in Hungary, Iceland, Norway, Poland, and Slovakia. The method considers four dimensions: environment, stakeholder involvement, policy and regulations, and markets and financial resources. Only Iceland fully covers the four dimensions by reaching all the milestones in the SEL framework. Iceland has the advantage of a long history of active use of geothermal energy for domestic use. The other countries face challenges within several of the dimensions, while the form and cause of these challenges are specific to each country. The findings illustrate that to mitigate climate change and drive the energy transition forward, both technical and societal factors related to various renewable energy sources must be assessed.

Keywords: geothermal energy; societal embeddedness level (SEL); environment; stakeholders; policy; regulations; market

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1. Introduction

In a time of energy transition due to accelerating climate changes and the insecurity of the energy supply, all kinds of energy usage must be analyzed to look for improvements. In 2021, almost 50% of the energy used globally was used for heat production, which accounts for 40% of energy-related greenhouse gas emissions and intense levels of air pollution that affect the environment and public health [1,2].

In the EU, the main use of energy in residential houses in 2020 was for space heating, accounting for 63% of the total energy used in this sector [3]. About 38% came from natural gas, 27% from renewable sources, 16% from oil products, 10% from derived heat, and 5% and 4% from electricity and solid fuels, respectively. On the other hand, home-space cooling is 100% covered by electricity in the EU.

Geothermal energy represents an alternative heating source that can replace fossil energy. This is a mature technology already in worldwide use, and a detailed description of the different technologies used is given by Lund and Toth [4]. The optimal technology to exploit this energy depends strongly on resource parameters. In the case of resources below 120 °C, direct energy use dominates. Above 150 °C, electricity is often produced. The temperature range between 120 and 150 °C is typical for geothermal binary power plants. The local nature of geothermal energy enables energy autonomy for heating and cooling, both for planned autonomy and as a possible means of mitigating infrastructure damage. This is a topic of wide current interest, as seen in the increase in published work within this field in recent years.

Based on data from Lund and Toth [4], the world leader in terms of the installed capacity in installations of the direct use of geothermal energy is Asia (installed capacity over 49 GW, energy production approx. 545 PJ/year, capacity factor 0.352), Europe is second (32.4 GW, 265 PJ/year, 0.259), North and South America are third (23.3 GW, 180 PJ/year, 0.245), Oceania is fourth (613 MW, ~11 PJ/year, 0.586), while Africa comes last (198 MW, 3.7 PJ/year, 0.597). The world-leading country in terms of direct energy production based on geothermal energy, relative to population, is Iceland (99.1 TJ/1000 citizens) [4]. The primary means of direct energy utilization in 2020 utilized heat pumps [4]. In terms of renewable electricity production, geothermal ranks fifth (with an installed capacity of 16 GW worldwide), following hydropower (1023 GW), solar energy (~850 GW), wind energy (~825 GW), and bioenergy (~143 GW) [5].

The main advantage of geothermal energy compared to other renewable energy sources, e.g., solar or wind energy, is its constant and stable availability. The available power is independent of the season and the time of the day. This reduces the planning problems that must be solved, e.g., photovoltaic power production [6]. As discussed by Williamson et al. [7], the Earth's crust can be seen as a vast natural energy storage. The magnitude of this storage is even larger when direct use is considered, not only electricity production. The ground can also conveniently be used for controllable seasonal energy storage [8]. Biomass and biofuels also have similar features; however, they have the disadvantage of emitting pollutants from the combustion. Geothermal energy also faces several challenges:

- High levels of geographical variation in terms of access to resources, dependent on the geological structure.
- There must be available ground area and subsurface volume for geothermal utilization.
- Corrosion and clogging.
- Emission of non-condensable gases.
- Utilization of cooled geothermal waters and brines.
- The buildings' heating system must suit the utilization of geothermal energy, e.g., having waterborne heat.
- Most district heating in Central Europe was designed for fossil fuels in the second half of the 20th century. This was a result of low energy costs and the prioritization of reducing financial expenditures, even if it resulted in lower efficiency.

Technical solutions to these challenges are known to a large degree. Still, there are differences with respect to how much geothermal heating is employed in different parts of Europe. This may be partly explained by societal differences directly related to geothermal energy. These are the topics investigated in the present study, where the focus is on differences specific to geothermal energy.

The User4GeoEnergy project (full title: Improving the energy efficiency of geothermal energy utilization by adjusting the user characteristics) is funded by the EEA and Norway Grants Fund for Regional Cooperation [9]. The participants are five European countries: Hungary, Iceland, Norway, Poland, and Slovakia.

The conditions in these countries differ, both in terms of the existing energy sources and in the status of and possibilities for utilizing geothermal heat as an energy source. Hungary, Poland, and Slovakia all have extensive district heating systems (DHSs), which are mainly designed for fossil fuel use. The goal of the User4GeoEnergy project is to harmonize these district heating systems with geothermal energy as the heating source. The project seeks to achieve this by adjusting the system characteristics, mainly by lowering temperature and flow rate demands.

Some key facts about the countries are summarized in Table 1.

Table 1. Key facts regarding the countries participating in the User4GeoEnergy project.

Country	Population 2023 [Million] [10]	The Main Energy Source for Space Heating	Geothermal Gradient [°C/km]
Hungary	9.7	Natural gas [11]	45 [12]
Iceland	0.4	Geothermal [13]	<150 [14]
Norway	5.6	Electricity [11]	13–24 [15,16]
Poland	38.0	Coal, biofuels, and waste [11]	10–50 [17,18]
Slovakia	5.4	Natural gas [11]	30 [19]

The main energy sources for space heating are visualized in Figure 1. Less energy is used for water heating, and the energy mix is somewhat different.

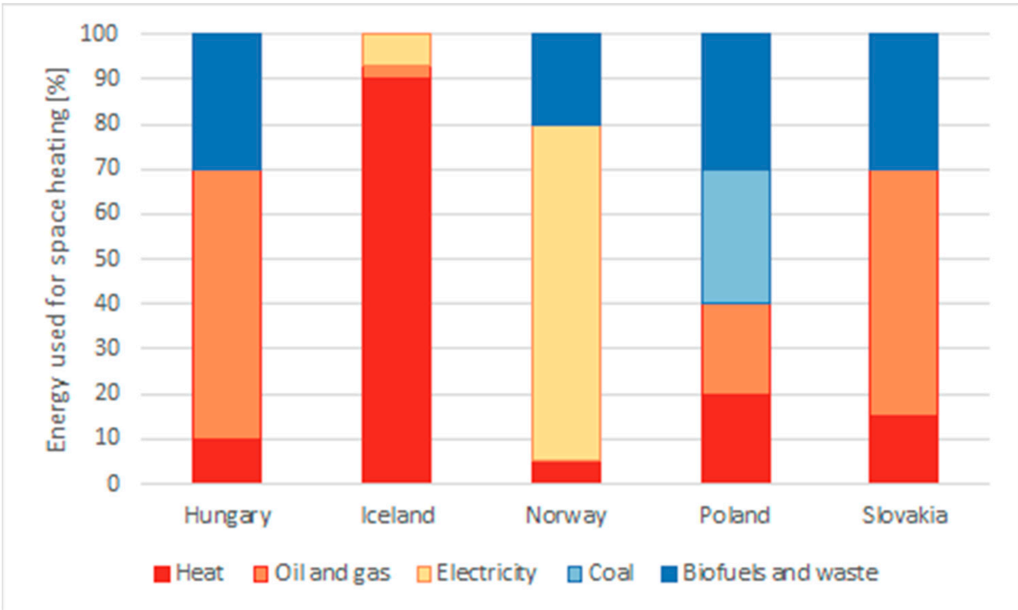

Figure 1. Energy used for residential space heating by source (rounded) [11,13].

In Figure 1, heat is the sum of the geothermal heat and all heat produced by main activity producer CHP and heat plants, as well as heat sold by autoproducer CHP and heat plants to third parties.

The potential for geothermal energy usage is typically coupled with the geothermal gradient, as given in the rightmost column of Table 1. An alternative to considering the geothermal gradient is considering the surface heat flow rate, as demonstrated by Chamorro et al. [20].

The main technologies used for exploiting geothermal energy in the five investigated countries are shown in Table 2.

Table 2. Main technologies used for exploiting geothermal energy in the countries participating in the User4GeoEnergy project [4].

Country	Main Geothermal Energy Technologies
Hungary	Direct use
Iceland	Direct use and electricity production
Norway	Ground-source heat pumps (GSHP) and borehole thermal energy storage (BTES)
Poland	Direct use and ground-source heat pumps
Slovakia	Direct use

Though there are pronounced local variations within each country, the data presented in Tables 1 and 2, and Figure 1 show that the countries investigated can be categorized into three groups:

(1) Iceland is a country with a high geothermal gradient and a high heat flow rate, where geothermal energy is the main heating source. The usage of geothermal energy is dominated by direct use and electricity production.

(2) Hungary, Slovakia, and Poland have medium geothermal gradients and heat flow rates. Natural gas or coal are the main energy sources for space heating in these countries, and direct use is the main technology used for exploiting geothermal energy.

(3) Norway has a low geothermal gradient and heat flow; here, electricity is the main heating source. Heat pumps, in the form of GSHP or BTES, are the main technology used to exploit geothermal energy.

This study therefore represents a wide range of energy situations, and it can therefore be expected to have relevance for several European countries.

The importance of understanding conditions beyond the purely technical for exploiting geothermal energy has been discussed for many years [21]. The focuses of scientific investigations include reduced social acceptance resulting from adverse environmental influences on Iceland [22], and if and how the exploitation of geothermal energy influences tourism in Iceland [23]. Suggested measures to increase social acceptance include advertising campaigns to raise public awareness of heat pumps in Norway [24] and activities to increase the attractiveness of spa towns in Poland, sites that are often based on thermal springs [25].

The importance of financial support or subsidies has been emphasized by several authors, e.g., [26–29]. Additionally, bidirectional influences have been investigated, e.g., from economic and financial development towards the increased use of geothermal energy and from the use of geothermal energy towards economic and financial development [30].

Some studies point to the combination of public awareness, financial support, and regulation and laws as essential for further developing geothermal energy [31]. However, a systematic analysis comparing these non-technical influences for countries with highly different preconditions is lacking. The present work proposes using the societal embeddedness level (SEL) method to analyze and compare the status of non-technical factors affecting the use of geothermal energy in Hungary, Iceland, Norway, Poland, and Slovakia.

The SEL method was developed by the Dutch research institute TNO [32]. It provides insight into non-technical elements that are important for the successful deployment of technological innovation. The four dimensions considered are the environment, stakeholder involvement, policy and regulations, and market and financial resources. Recently, the method was used to assess and compare the SEL of carbon storage projects in four different European countries [33]. In the present work, the method is applied to geothermal energy as a source for heating in the five countries participating in the User4GeoEnergy project.

The SEL method has some similarities to the Social License to Operate (SLO), which has also been applied to geothermal energy [34]. However, SLO is related to specific projects, while SEL relates to the status of technology within a country or region.

The present article first describes the method of the societal embeddedness level in detail, before the geothermal energy SEL status is presented for each country (in alphabetical order). Each of the four dimensions is discussed separately before the overall SEL for each country is summarized. The final part of the article is devoted to a discussion, a comparison of the countries, and a conclusion.

2. Materials and Methods

2.1. Societal Embeddedness Level

Each dimension is given a level between 1 and 4: SEL 1—exploration, SEL 2—development, SEL 3—demonstration, or SEL 4—deployment.

The method identifies a set of milestones corresponding to each dimension and level [33]. For instance, one of six milestones for SEL 1 in the dimension Environment is the "Identification of natural environment of the innovation concept", and one of four milestones for SEL 4 of the same dimension is "Harm to the natural environment is as low as possible within the limits of the project/technology". Several questions are specified to aid in determining whether a milestone is reached.

The result can be presented visually, as shown in Table 3, where colors are used to indicate whether a specific SEL is reached or not.

Table 3. Sample visualization of SEL levels for a specific application in two countries. Green indicates that all milestones for that level are reached, yellow indicates that some milestones are reached, and red indicates that no milestones for that SEL are reached.

		SEL 1	**SEL 2**	**SEL 3**	**SEL 4**
Country A	Environment				
	Stakeholders				
	Policy and Regulations				
	Market and Resources				
Country B	Environment				
	Stakeholders				
	Policy and Regulations				
	Market and Resources				

In this example, it is clear that country A should focus its efforts on policy and regulations and on market and resources. Country B has made more progress regarding policy and regulations, so some of their experience there may be helpful to country A. On the other hand, country B should focus their efforts primarily on environmental issues and next on market and resources.

SEL is linked with the technology readiness level (TRL) [35], in that the successful deployment of new technologies requires a high score on both the TRL and SEL scales. A low SEL is sufficient for low TRLs, while a higher SEL is required for higher TRLs. In other words, environment, stakeholder involvement, policy, regulations, markets, and resources must all be addressed for a technology to be successfully deployed. This relationship is summarized in Table 4.

Considering Tables 3 and 4 together, country A being ranked SEL 1 for the technology considered may be perfectly fine if the TRL for this technology is currently 1, 2, or 3. On the other hand, if the current TRL is 8, significant problems may be expected when deploying this technology.

The TRL of geothermal energy in all the countries studied in the present work is considered to be 9, requiring an SEL of geothermal energy at "SEL 4: deployment".

Table 4. Relationship between TRL and SEL [36].

Basic principles observed Technology concept formulated Experimental proof of concept	TRL 1 TRL 2 TRL 3	SEL 1: Exploration	Societal aspects explored
Technology validated in a lab Technology validated in relevant environment Technology demonstrated in relevant environment	TRL 4 TRL 5 TRL 6	SEL 2: Development	Societal aspects assessed
System prototype demonstration in an operational environment System completed and qualified	TRL 7 TRL 8	SEL 3: Demonstration	Societal aspects included in the system
Actual system proven in operational environment	TRL 9	SEL 4: Deployment	Innovation proven in the societal environment

From the brief method description above, it is clear that a combination of several kinds of expertise is required to perform the SEL assessment. In the present work, the method is applied in interdisciplinary collaboration, i.e., integrating and synthesizing various types of knowledge and contributions [37].

2.2. Gathering of Information and Data

For this analysis, experienced researchers and experts on geothermal energy were consulted, in addition to analyzing official documents and webpages, and other available relevant sources, such as media coverage. Information not supported by references comes from the authors of the article and is the result of their observations and many years of experience.

3. Results

This section describes the societal development status for geothermal energy in the five European countries considered. The technical status is given as background, followed by a discussion of each of the four SEL dimensions. Finally, a summary of the societal embeddedness level is given for each country, considering all four SEL dimensions together.

3.1. Geothermal Energy in Hungary

3.1.1. Status

Hungary is situated in the Pannonian Basin in Central-Eastern Europe, in an area with a well-known positive geothermal anomaly. Here, geothermal resources have been utilized for a long time. The outstanding geothermal potential of the Pannonian Basin manifests as a higher-than-average heat flow density (50–130 mW/m^2, with a mean value of 90–100 mW/m^2) and a geothermal gradient of about 45 °C/km.

Geothermal district-heating- and thermal-water-heating-based cascaded systems represent a major part of direct use in Hungary. Such systems operate in 23 locations, accounting for about 223 MW$_{th}$ for installed capacity and 636 GWh$_{th}$/year for annual production. Major projects have recently been established in Győr and Szeged, the latter serving 27,000 end users with geothermal-based heating and domestic hot water. Space heating (mostly associated with spas) is available at nearly 40 locations in Hungary, representing an installed capacity of about 77 MW$_{th}$ and production of 83 GWh$_{th}$/year. The agricultural sector is still an important player in direct use and has the largest share of geothermal usage, at 47%. This is especially true for the southern part of Hungary, where the geothermal heating of greenhouses is widespread and rooted in long-standing traditions. Agricultural uses there account for about ~358 MW$_{th}$ installed capacity and ~803 GWh$_{th}$/year production. Balneology also has long-standing traditions in Hungary. More than 250 wells yield thermal water, sometimes medicinal waters, which represent a total installed capacity of 249.5 MW$_{th}$ with an annual use of 745.5 GWh$_{th}$/year accounting for 30% of total geothermal heat use.

The first (and so far, only) Hungarian geothermal power plant is situated in Tura, with a 3 MW_e capacity. Actual gross electricity production is, however, only 2.3 MW_e, of which nearly 1 MW_e comprises the electricity demand of the power plant. The shallow geothermal sector is lagging behind in terms of the pace of development compared to other European markets, but equally importantly, due to the lack of registers, it is hard to assess the exact number of GSHP-s. Air-based heat pumps have nevertheless become dominant in the family house market and in other official and industrial applications, with the majority of the new applications installed in new office buildings.

The first geothermal well in Hungary was drilled by Vilmos Zsigmondy in 1868 in Budapest: the well reached 970 m, making it the deepest borehole in Europe at that time. Since then, more than 1100 geothermal wells have been drilled in Hungary, tapping reservoirs between a few hundred and 2500 m, producing water at around 30–90 °C.

3.1.2. Environment

With the exception of one low-capacity pilot power plant, all of the geothermal wells in Hungary are used to provide direct heat energy (and in the case of balneological operations, water for spas). Such direct-use geothermal energy systems produce 8.5 TWh total heat energy, equivalent to a 74,000 t oil equivalent of fossil fuel use, from local renewable sources every year. Therefore, the effects of these operations on the natural, built, and social environments should be considered to be very positive. Nevertheless, drilling, the laying of pipelines during the implementation phase, and water extraction and discharge during operations all affect the environment too. While surface pollution, noise, and the increased use of urban green areas are all risks that are mitigated by laws and the regulation-based management of the reservoirs, the monitoring of water levels, well interference, and other subsurface effects, the impacts of which are less evident in the short term, should be given more consideration. This is evident in the way that regulations regarding the compulsory injection of used thermal water have been postponed, and most agricultural operators still discharge thermal waters on the surface.

All in all, the harm caused by the implementation and operation of the direct use of geothermal energy systems on natural, built, and social environments is mitigated, and the potential harm is as low as possible within the limits of the technology. However, risks or uncertainties that may harm the natural environment in the future are not entirely mitigated.

3.1.3. Stakeholder Involvement

Besides balneological and agricultural uses, several municipalities utilize geothermal energy in their district heating systems. Based on favorable medium-enthalpy resources, most rely on the doublet or triplet concept (one production well and one or two injection wells) of heat extraction, with some utilizing the thermal water for heating and for bathing too. Such projects require a high level of stakeholder involvement with investors, local municipalities, the managing authorities responsible for central (usually EU) fund distribution, drilling companies, district heating system operators, etc., who all participate in the process.

All projects are different, but recent examples from how Szeged, Miskolc, Makó, Csongrád, and other small or medium-sized cities have switched their district heating to geothermal sources might provide valuable insight into how stakeholder involvement contributes to a common goal.

In all of the towns listed above, the aim was to reduce the emissions of the gas-powered heating plants and to improve the economy of the heating system with the help of renewables. The projects differ in terms of the origins of this idea, but the decision regarding the level of participation of the stakeholders was, in all cases, inevitably taken during the design phase of the developments. The city halls participated in (or started) the day-to-day communications with local, regional, and national organizations, seeking professionals to take part in the project development. In all of the cities listed, the municipality, the district heating company, and specialized firms with geologists and hydrogeologists onboard were the main drivers of the projects, and they were involved in all decision-making throughout the developments. On a national scale, the Association of Hungarian District Heating Enterprises, the Southern Great Plain Thermal Energy Cluster, and the Hungarian Thermal Energy Association provide cooperation and a platform for knowledge sharing. The two-way communication of best practices, bottlenecks, etc., with these organizations greatly enhanced the capacities of the experts on the ground in Szeged, Miskolc, Makó, Csongrád, and elsewhere: to this day, this cooperation provides opportunities for stakeholders from other cities to familiarize themselves with the projects. As the municipality owns the district heating company, the involvement of the city is a given. With the city halls and specialist companies actively participating in the projects, it may be concluded that the relevant stakeholders are indeed included in the deployment process, and that the technology is supported by the relevant stakeholders. Notably, missing in almost all cases is the active representation of end users and local advocacy groups. It is likely that, with the exception of Szeged, end users may argue that they have not been sufficiently involved in decisions about the technology and its systems. This is definitely an area that requires more attention from future project developers.

3.1.4. Policy and Regulations

There has been a delay in the implementation of the National Renewable Energy Action Plan targets in the case of shallow and deep geothermal capacity and production, as well as in power production. The Hungarian government has expressed many times its strong intention to support geothermal energy. This support is, however, (1) totally dependent on the availability of EU funding and (2) not sufficiently backed by the necessary policies and regulations. Regulatory barriers are hard to overcome, the relevant laws and regulations do not provide a level playing field for geothermal developments, conditions for obtaining permits are hard to navigate and are ever-changing, permitting procedures are long and not transparent, and recognized experts, established NGOs, and relevant stakeholders are rarely in the position to provide input to policymaking. All in all, national policies and regulations are among the factors hindering the deployment of geothermal technology and its systems, a situation that presumably will change in the near future.

3.1.5. Market and Financial Resources

Hungary depends on energy imports: 83% of its hydrocarbon and about 20 billion m^3/year of natural gas are imported, mainly from Russia. This constitutes a threat to the country's energy security, especially in the heating sector.

Geothermal energy is almost independent from fossil fuel prices. However, fossil fuel prices have a significant indirect effect on spreading renewable energy utilization, as energy production from fossil fuels forms a benchmark for payback period calculations. High oil prices help the spread of renewables. This would imply that geothermal energy is bound to experience a huge boom in Hungary, but due to the lack of supporting policies and legislation, as well as a general lack of funding, progress is very slow. The few notable exceptions are projects realized because of EU funding and private investment. Being capital-intensive, the availability of EU funds is a prerequisite, but even when they are available, the scarcity of potential private investors can rather swiftly limit what otherwise would be an industry experiencing exponential growth.

With the district heating market largely centralized and market drivers taken out of the equation by state subsidies on household energy expenses, the market position of investors regarding geothermal district heating is hard to comprehend. Long-term gains may be calculated, but financial models and business plans are all too easily nullified by new legislation, taxes, or other changes in the economic context.

3.1.6. Societal Embeddedness Level

Overarching support from and the involvement of relevant stakeholders are prerequisites for the success of any large-scale project, with geothermal energy being no exception.

However, the baselines of what is considered good communication, desirable level of societal involvement, or the sufficient engagement of the public vary significantly between different regions of Europe. It would stretch the scope of the present paper to discuss such differences in detail; suffice to say that it would be unfair to set the same criteria of the success of stakeholder involvement in geothermal investments in well-established democracies and in less open societies. Prospectors, drilling companies, system operators, investors, district heating companies, municipalities, and the consortiums of these countries do have certain levels of understanding of why good communication is important; moreover, as they are participating in the deployment process, it could be concluded that stakeholder involvement reaches the relevant milestones. However, involving the public in the planning, deployment, and operation phases is not generally seen as important (or even feasible), and this is an area of geothermal SEL in Hungary that needs to be worked on in the future.

The findings for Hungary are summarized in Table 5.

Table 5. Societal embeddedness level in Hungary. Green indicates that all milestones for that level are reached and yellow indicates that some milestones for that SEL are reached.

Hungary	SEL 1	SEL 2	SEL 3	SEL 4
Environment				
Stakeholders				
Policy and Regulations				
Market and Resources				

3.2. Geothermal Energy in Iceland

3.2.1. Status

Iceland is one of the most volcanically active countries in the world, with over 200 volcanoes located within the active volcanic zone that stretches through the country from the southwest to the northeast. At least 30 of them have erupted since the country was settled. This is due to Iceland's position on the mid-Atlantic ridge and the hot spot with increased magma production. In total, over 600 hot spring areas, defined as having temperatures above 20 °C, are found. Of these, the temperature reaches 200 °C within a depth of 1000 m in at least 20 areas in the volcanic zone. Near the active zones, about 250 areas with underground temperatures 20–150 °C above a depth of 1000 m are found [38].

There are over 20 companies operating district heating systems under a monopoly license in Iceland, and dozens more systems are privately run. The district heating networks are mainly located in or close to urban areas where there is geothermal energy, mainly low-temperature areas, which are located close by. Around 92% of the Icelandic population has access to district heating and 89.7% of all space heating in 2019 was produced through geothermal district heating [39]. The estimated installed capacity for geothermal heat is around 2500 MW.

There are currently eight geothermal power plants in Iceland, with an installed capacity ranging from 2 MW electric to 303 MW; they are mainly located in the high-temperature areas and use steam in a flash cycle to produce electricity. Most of these plants also produce heat, which increases the efficiency of the transformation. In total, geothermal energy accounts for around 30% of the total electricity produced in Iceland and over 90% of the heat [13].

Heat pumps are not utilized to a significant degree in Iceland, as the geothermal water used for space heating is generally available and inexpensive. Subsidies of electrical and oil heating have also caused a reluctance to invest in heat pumps. However, recent legislation allows users of subsidized electrical heating to receive a contribution to improve or convert their heating system. It is likely that heat pumps will become competitive in areas where water with temperatures above 50 °C is not found. In those areas, heat pumps can be used to replace the use of direct electrical heating [40].

As described in a recent report from the Nordic Council of Ministers [41], "The Icelandic government has encouraged the utilization of geothermal energy as far back as the 1940s. An Icelandic National Energy Fund has since the 1960s offered loans to fund the initial cost of drilling and exploration of geothermal energy. If the initial drilling turns out to be unsuccessful, the loan defaults to the state. This policy promoted the expansion of geothermal energy.

In more recent years, space heating in residential buildings has been subsidized by the state in areas where district heating is not reachable. End users living in areas where district heating is not available are encouraged (through subsidies) to invest in heat pumps".

3.2.2. Environment

Geothermal utilization is a mature technology in Iceland, and so many of the initial problems that emerged have been mitigated, either through regulation or through methods developed by the producers. Resource management is governed by Act no. 57/1998 on resources, which stipulates that a utilization permit must be acquired, and the utilization should be sustainable. Emissions, noise, and other forms of pollution are regulated by various health regulations and monitored by the Environmental Agency and the local health authorities, which also issue operation licenses for operators, where applicable. Projects that are expected to produce more than 10 MW electric or/and 50 MW thermal energy must be submitted to the Master Plan [42] and must undergo an environmental impact assessment (EIA). Smaller projects may also be required to undergo an EIA. The Resource Act also stipulates requirements for the drilling and reporting of boreholes; issues related to induced seismicity have also been regulated. Wastewater is generally considered pollution and is not allowed to be released to the surface. Geothermal production is generally situated outside of urban environments, so the impact on buildings, structures, and communities is minimal. Currently, drilling is generally achieved using electricity, which decreases pollution. The workers involved in the construction and operation are members of Icelandic unions, and there are no known instances of any problematic practices in that regard.

3.2.3. Stakeholder Involvement

When a new geothermal plant is in preparation, there are several levels where stakeholders are invited to participate in the process. The municipality is generally involved very early on due to planning and construction permits, and the licensing process involves several rounds of consultations with legally mandated stakeholders such as the Environmental Agency, the Institute of Natural History, and landowners. Furthermore, the planning and EIA processes are advertised, giving the public opportunities to offer their input. Once the licensing process is concluded, stakeholders have a month to appeal the decision to an appeals committee. The Resource Act states that the landowner, who is the owner of the resource, must be compensated for the utilization, which essentially gives the landowner the power to decide if and who uses the resource. Geothermal projects are generally highly beneficial to the local community, providing cheap and dependable heating, swimming pools, jobs in an industry that uses the energy, and tourist attractions such as spas, which increases public acceptance. Geothermal projects are generally uncontroversial compared to other energy projects, but experience has shown that involving the municipalities, landowners, and other important stakeholders early in the process is important to avoid controversies and promote public acceptance.

3.2.4. Policy and Regulations

The geothermal sector in Iceland is mature and the legal framework has, in many ways, been designed to overcome and regulate problems that have already been identified. The Resource Act no. 57/1998 [43] governs the exploration and utilization of ground resources, including geothermal resources, and the Energy Act no. 58/1967 [43] governs the operation of district heating systems. Power plants must obtain a license according to the Electricity

Act no. 65/2003 [43]. Furthermore, publicly operated district heating systems can apply for a monopoly license, in which case a regulation for the system is issued, defining the duties of the operator. Historically, the policy in Iceland has been to facilitate the use of geothermal for socially important ventures, such as district heating and industry that creates jobs in rural areas. According to the Resource Act, municipalities have priority for utilization licenses for the purposes of space heating within the municipality. There have also been substantial grant schemes to subsidize and mitigate the risk of geothermal exploration for municipalities in recent decades, which proved to be highly effective in facilitating the current widespread use of geothermal for space heating.

In 2020, the government formulated a new energy policy [44]: a proposal for a long-term Energy Policy for Iceland until 2050. In the policy introduction, it is stated that access to energy is vital both for quality of life in Iceland and for the Icelandic economy. This includes energy security as well as the necessary transition to renewable energy sources.

3.2.5. Market and Financial Resources

In 1967, the Energy Fund was established, and over the next two decades, it funded geothermal exploration throughout the country with grants and loans. The fund made a vital contribution to the rapid development of geothermal district heating in Iceland. Once the geothermal producers were established and operating, they generally self-financed further exploration and drilling. Geothermal operators are, for the most part, publicly owned, so the municipalities that own them have also financed these explorations. Geothermal exploration in areas that do not yet have geothermal heating has received continued support, either via the energy fund or with specific schemes aimed at reducing the public subsidies granted to residents in these areas for electric heating. Producers of electricity compete in an open market in Iceland and are therefore generally not supported with public funds. In the case of CHP power plants that also produce heat for monopoly district heating systems, they are obliged to keep separate accounts for heat and power production to prevent the cross-subsidization of electricity.

3.2.6. Societal Embeddedness Level

Considering the SEL framework, all milestones are reached in Iceland due to its long experience (100 years) in this field, with corresponding lessons learned, development, and improvements, leading to structures and regulations that mitigate most risks related to geothermal energy.

The findings for Iceland are summarized in Table 6.

Table 6. Societal embeddedness level in Iceland. Green indicates that all milestones for that SEL are reached.

Iceland	**SEL 1**	**SEL 2**	**SEL 3**	**SEL 4**
Environment				
Stakeholders				
Policy and Regulations				
Market and Resources				

3.3. Geothermal Energy in Norway

3.3.1. Status

Coastal Norway has a temperate climate due to the prevalent wind directions and the Gulf Stream. In the mountainous and northernmost regions, the climate is polar. The bedrock in Norway consists of Precambrian rocks, with late Precambrian sediments and Cambro-Silurian deposits [45]. The geothermal gradients in Norway, based on existing measurements, are in the range of 13–24 °C/km (personal communication, Y. Maystrenko).

About half the households in Norway live in single-family homes, which generally require more energy than flats, due to there being more exterior walls [46]. Norway also has a higher average number of rooms per household member than the other countries involved in this project [47]. Nonetheless, the total energy consumption per person in Norway is at the same level as in comparable countries, i.e., the Nordic countries, Canada, and the US [46]. The dominant position of electricity as a heating source is caused by its prices, which are historically very low [46].

There is no geothermal power production, i.e., production of electricity from water at 90 °C or above, installed in Norway [48]. Geothermal energy is therefore used exclusively for heating and cooling. The first geothermal installations in Norway were drilled in the 1980s. As of now, there are approximately 75,000 geothermal boreholes in Norway. The total installed power of geothermal energy storage is about 1200 MW, and the systems produce 3.5–4.0 TWh per year [49]. The most common usage type of geothermal energy is low-temperature (<25 °C) GSHP. Medium-temperature (<60 °C) BTES is used for storing solar heat seasonally and high-temperature (<100 °C) BTES is investigated as a means of storing surplus heat from waste incineration plants [48]. The NGU (Geological Survey of Norway) maintains a database of boreholes in Norway [50]. Most projects are found in the capital, Oslo, and in the surrounding, largely urban, and heavily populated county of Viken.

3.3.2. Environment

Few negative impacts on the natural environment are identified, but those that are identified as potential risks are pollution during drilling and operations, the leakage of antifreeze during operations, underground temperature changes during the operation phase, and in some geographical areas, permafrost. Settling damage in areas with quaternary sediments may affect buildings and infrastructure in the neighborhood, thus posing a risk to the built environment. In terms of harm to the social environment, the drilling itself may cause a mess due to mud. Drilling companies have been notified of runoff of muddy water into rivers. In addition, the drilling may be noisy for neighbors. Social dumping is also a recurring risk in the construction industry. The potential harm to the natural, built, and social environments that are mentioned here are considered to be of low probability, as these risks can be mitigated through laws and regulations, e.g., the Neighbor law (Grannelova §§2 [51]) concerning noise and the Pollution law (Forurensningsloven [52]). However, the mapping of potential environmental impacts is so far limited; hence, there are some uncertainties with regard to future harm to the environment.

In sum, the negative impacts of geothermal energy technology and systems, including those on natural, built, and social environments, are considered to be low in light of the high-reward outcomes, yet there are some uncertainties with regard to future harm to the environment and some instances where action should be taken to avoid, e.g., runoff.

3.3.3. Stakeholder Involvement

When it comes to stakeholders that are relevant to geothermal energy in Norway, they include those who use (or those who are close to the usage of) geothermal energy for heating and cooling, professionals who are involved in building and operations, and stakeholders with the formal and informal power to influence development.

The first category are stakeholders who live in or use buildings, such as residential buildings, office buildings, and public buildings, or who are neighbors of these buildings. There have been some cases where neighbors have experienced settling damage in buildings due to the establishment of boreholes; however, these cases most often lead to no or low levels of conflict, unlike, e.g., many cases of onshore wind turbines. It has also been found that some potential users are prevented from becoming users due to regulatory restraints where permissions are not given. This has mainly been an issue in the Oslo area for larger buildings, where drilling is more thoroughly regulated than in other places (see Section 3.3.4). There are generally few stakeholders in the user segment compared to other forms of energy production, as the drilling of boreholes involves small local installations with little visual and noise pollution near users.

Other relevant stakeholders are those who are involved in the establishment and operation of geothermal energy, such as equipment producers and suppliers, drilling companies, and service providers. In this stakeholder segment, there have been some cases of dissatisfaction with the tendering processes, as well as conservative regulation in some regions. Beyond this, little is heard from this group. Furthermore, some stakeholders have the official authority to make decisions and uphold or develop laws and regulations, such as national directorates and departments and regional and local authorities, while others have less formal power, but are in a position to draw attention to geothermal energy as an alternative energy source and thus influence public perception. Examples of the latter group are interest organizations, media, marketers, and researchers. Some stakeholders question the low prevalence of geothermal energy in Norway and seek to draw attention to this as a long-term, stable, environmentally friendly alternative that generates little sound and visual noise. These voices, mainly comprising researchers and interest organizations, have so far received moderate attention, yet they are far from mute.

To sum up, in Norway, no significant controversies have been identified regarding the establishment and use of geothermal energy, and there are no hard pro- or anti-geothermal movements. It is found that some stakeholders are dissatisfied with processes related to geothermal energy; however, no stakeholders (to the authors' knowledge) express opposition to the technology itself.

3.3.4. Policy and Regulations

There are generally few regulatory barriers to geothermal energy and its systems in Norway. There is no requirement to receive drilling permission from local authorities, except in the Oslo municipality, where installations with two or more borehole heat exchangers require permission. However, technical installations or intervention in the terrain may trigger the obligation to apply before drilling. This is also the case when affecting buildings' firewalls and for the establishment of so-called borehole fields, which consist of more than two boreholes, as stated in the Planning and Building Act §20-1. When drilling geothermal boreholes, the drillers are responsible for maintaining a safe distance from public water and sewerage, tunnels, parking garages, and other possible underground establishments. The drillers are also responsible for not spreading polluted drilling mud during the drilling phase. According to §46 in the Norwegian Water Resources Act [53], new boreholes and wells shall be reported to the water authorities, in practice to the NGU, within three months of drilling.

Regional differences occur in terms of regulations and public attention. The majority of geothermal borehole heat exchangers in Norway are located around the capital, Oslo, where there are more regulations than elsewhere. For instance, in the Oslo municipality, an application must be filed before a borehole is made to ensure safe distances from the pipes for the water supply and sewerage. Also in Oslo, geotechnical investigations are routinely required to safeguard against settling damages [54]. On the one hand, such investigations are intended to reduce the risk of settling damage. On the other hand, they add to the total cost, which has made it less attractive for some operators to establish borehole heat exchangers in the Oslo area [55]. To reduce local differences, the industry has requested national regulations be put in place. Such regulations are allegedly under development. Moreover, public attention toward geothermal energy varies significantly from region to region, as seen in regional energy plans. For instance, one county, Viken, illustrates their official web page on local energy initiatives with a picture of geothermal boreholes, while others, such as Agder, do not mention this possibility at all when listing possible renewable energy sources. This is an example of regional variation concerning governmental preparation for geothermal energy in Norway.

In the most recent energy commission report "Mer av alt—raskere" (more of everything—faster) (NOU 2023:3), the energy commission mapped national energy needs and suggested increased energy production. In the report, geothermal energy is not examined, but is mentioned as a future option, along with wave energy and airborne wind energy. The report mentions that recent techno-economic studies of these technologies are lacking. However, the establishment of geothermal energy is included in Norwegian energy strategies through a national financial support system (Enova).

3.3.5. Market and Financial Resources

The cost of establishing a borehole heat exchanger depends on factors such as the depth of the borehole, the efficiency of the heat pump, and the contractor's profits. A liquid-to-water heat pump in Norway costs upwards of NOK 120,000 [56]. Additional costs include installation and drilling. The total cost for establishing a borehole heat exchanger and purchasing a liquid-to-water heat pump is estimated to be from NOK 200,000 to 300,000 for a single household. It is possible to receive financial subsidies of up to NOK 10,000 from Norwegian authorities through Enova. For new buildings or buildings without water-borne heating, there will be additional costs. In these cases, it is also possible to apply to Enova for funding up to NOK 10,000. In sum, it is possible to be funded up to NOK 40,000 when geothermal energy is established from scratch, and the purchase of equipment and installation is carried out within a short timeframe. Hence, there are financial funds available for establishing geothermal energy in Norway; however, they are only modest for house owners compared to the large upfront cost.

Moreover, buildings in Norway have traditionally been heated with cheap and renewable electricity from hydropower; thus, there has been low interest in and demand for alternative energy sources such as geothermal energy. However, a large interest in and willingness to invest in solar and wind energy has been seen during the past decade due to energy transitions from fossil fuels to renewables, yet these energy sources use the same infrastructure as hydropower, making it easier to connect them to the existing power grid. Geothermal energy does not produce electricity in Norway due to the low geothermal gradients, but is suitable for heating and cooling buildings. To use geothermal energy for heating and cooling, water-borne systems are required. Since water-borne systems have been used to a small extent in Norway compared to other Nordic and European countries where district heating is more widely used, transitioning from heating buildings with electricity to geothermal energy is extensive and expensive due to the lack of infrastructure in buildings.

The previous years' sudden rise in electricity prices and increased media attention toward energy efficiency have boosted the prevalence of solar panels and, in particular, air-to-air heat pumps (e.g., [46,57]). The installation cost for air-to-air heat pumps is relatively low, and distributors have provided consumers with various payment solutions, such as low-interest down-payment methods. There have also been local political initiatives in several municipalities to subsidize the purchase and installation of air-to-air heat pumps. However, in many cases, the added value of air-to-air heat pumps is found in increased comfort rather than net energy savings [46]. Distributors of solar panels have made efforts to offer customers opportunities for direct purchase, leasing, and buyouts, making solar panels more accessible for more consumers, even though the total cost is high. Such alternative funding options are yet not available for those seeking to access geothermal energy. Because electricity prices have traditionally been low in Norway and geothermal investment costs are high, geothermal energy has primarily been recommended for large-scale users and high-demand households (above 30,000 kWh per year), either in new buildings or as part of building renovations.

High investment costs are considered to be one of the largest barriers to the increased prevalence of geothermal energy. Additionally, the moderate financial subsidization available, the lack of various funding options, and a dearth of progressive marketing are holding back geothermal energy's position in the commercial market. However, as the energy situation is changing and electricity prices increase and become less predictable for consumers, there is the potential for geothermal energy to gain a better market position.

3.3.6. Societal Embeddedness Level

In light of the SEL framework, most milestones are reached in Norway; however, there are some milestones that are not reached or about which there are uncertainties. This leaves three of the four dimensions in the SEL framework marked as yellow, which indicates that not all milestones have been reached (see Table 7).

Table 7. Societal embeddedness level in Norway. Green indicates that all milestones for that level are reached and yellow indicates that some milestones for that SEL are reached.

Norway	SEL 1	SEL 2	SEL 3	SEL 4
Environment				
Stakeholders				
Policy and Regulations				
Market and Resources				

In the first dimension, Environment, it is found that the majority of harm to natural, social, and built environments can be mitigated by Norwegian laws and regulations. However, there are some uncertainties with regard to future harm, particularly for the natural and built environments, as there are regional differences when it comes to the requirements for geotechnical investigations to safeguard against damages. In the second dimension, Stakeholders, all milestones are met, which is indicated by the green blocks in the table. The third dimension, Policy and Regulations, is marked as yellow for reasons linked to the existence of few regulations at the national level, despite general regulations being requested by the industry itself. There is also the potential to embed geothermal energy more heavily in national energy strategies. The fourth dimension, Market and Resources, is also marked yellow, as there is potential for geothermal energy projects to receive more financial support and gain a better market position in light of energy transitions and increasing energy costs. Additionally, the high cost, lack of various leasing/payment options, and moderate level of marketing makes geothermal energy less readily available for the broader public.

The findings for Norway are summarized in Table 7.

3.4. Geothermal Energy in Poland

3.4.1. Status

Poland's geothermal energy resources are relatively well recognized thanks to the existence of over 9000 boreholes with a depth of at least 1 km drilled between the Second World War and now. These wells were mainly drilled by the oil and gas industry to search for hydrocarbons, but over 1200 wells were drilled as research wells, mainly with the aim of exploring the geological structure of the country. A few dozen deep wells were drilled strictly in order to exploit geothermal waters [58]. Datasets from these wells, supported by geophysical surveys, were the basis for the preparation of a series of geothermal atlases in Poland, first published in 1990 and continuing until 2014 [59–62]. Each of these elaborations is a printed atlas of a few hundred pages with numerous maps containing detailed information on geothermal resources, arranged according to the age of the resources. Geothermal development in Poland is also widely described in scientific articles [63,64].

The most likely regions for geothermal usage are the Inner Carpathians in southern Poland (especially the Podhale region), the Mogilno-Łódź Trough in central Poland, and the Szczecin Trough in northwestern Poland. The Eocene and Middle Triassic carbonates forming reservoir rocks in the Podhale region accumulate low-mineralized (up to 3 g/L only), high-temperature (up to 90 °C) and high-flow-rate (up to 550 m^3/h from a single well) geothermal waters. On the other hand, the most potential resources in the Mogilno-Łódź Trough and in the Szczecin Trough can be found in Lower Cretaceous and Lower Jurassic formations, with the local flow rate exceeding 250 m^3/h and temperatures above 90 °C, and potentially even higher. Unlike the Podhale region, geothermal waters there can be highly mineralized (even more than 200 g/L), especially in the Lower Jurassic and older formations. The geothermal gradient in Poland ranges from 10 to 50 °C/km [17,18].

Geothermal resources used for heating are highly diverse in terms of temperature, flow rate, and the mineralization of reservoir fluids. In the case of seven currently operating geothermal district heating systems in Poland, the temperature of the geothermal resources ranges from 42 to 87 °C, mineralization ranges from 0.4 to 150 g/L, and the flow rate of geothermal fluid varies from 60 to 1070 m^3/h in total. The total installed geothermal capacity (without peak boilers) is 137.5 MW, while the annual geothermal heat production is around 281.5 GWh (1013 TJ). Some of these DHSs work in a single-well mode, while some use both production and reinjection wells.

The first (launched in 1993) and the biggest geothermal DHS is located in the Podhale region, southern Poland. The total installed geothermal heating power is 74.6 MW (peak boilers excluded), while the annual heat production is 146.5 GWh (527.4 TJ). Highly importantly, the use of gas peak boilers throughout the year is marginal, being around 5% in 2022 [65].

Until now (the first half of 2023), geothermal resources in Poland have not been used to produce electricity. However, fairly extensive studies were conducted in recent years aiming to identify geothermal fields in Poland that are potentially suitable for that purpose [62]. Studies were carried out and are ongoing on the non-standard methods of obtaining geothermal energy, such as heat from hot dry rocks (HDR) [66] or the utilization of CO_2 as a working fluid in enhanced geothermal systems (CO_2-EGS), the second of which is the subject of the EnerGizerS project [67].

There are no cooling systems that utilize geothermal as the driving energy in Poland, excluding one example. The office building of PEC Geotermia Podhalańska is equipped with an absorption chiller driven by geothermal heat. The cooling power of that unit is small, and it is supported by compressor heat pumps. However, this small installation indicates the possibility of the future utilization of geothermal resources with high-enough temperatures.

3.4.2. Environment

There are a few concerns regarding the exploitation of geothermal waters from deep boreholes in Poland. Two major concerns are as follows.

- The utilization of brine water after heat exchange: this is a serious problem for geothermal installations with highly mineralized waters. Currently, the only method to get rid of that water is to reinject it back to the reservoir, although in many cases, this is problematic due to scaling on casings and clogged filters. Therefore, the capacity of reinjection wells is usually much smaller than that of production wells, so in some cases, more reinjection than production wells are needed. Additionally, in order to push that brine water back into the formation, more electrical power is needed, which in Poland is mainly generated from coal.
- Reinjection is not compulsory, at least for reservoirs of waters with low or very low mineralization. This in turn may cause pressure drawdown to increase over time and make production from reservoirs with limited recharge unsustainable. Moreover, when reinjection is not undertaken, geothermal waters are discharged to surface waters after heat removal. Care must be taken to ensure that the discharged water is sufficiently cooled and does not contain too much saline so as not to harm the biosphere.

However, these procedures are regulated by law in Poland (i.e., the Geological and Mining Law, Water Law act) and the need for reinjection is an increasingly frequent prerequisite for issuing concessions for the exploitation of geothermal resources. Reservoir monitoring is a standard procedure and is beneficial to reservoir operators in maintaining stable heat production. Drilling geothermal wells with depths exceeding 1000 m is preceded by an environmental impact assessment.

With regard to the built and social environments, drilling for geothermal waters and their further utilization does not pose any serious threats in Poland. Poland is a low-seismicity country, so damage to buildings caused by induced seismicity is very unlikely to occur. Additionally, noise made during drilling is something that people can or have to deal with. In this regard, it should be noted that geothermal energy has high public acceptance in Poland [68,69].

In the case of Poland, one positive effect of using geothermal energy is the elimination of fossil fuels with renewable energy. The effect is associated, among other things, with significantly improving air quality. Of course, the share of geothermal energy in the final amount of energy depends on the users' requirements and reservoir parameters. Heat pumps allow the temperature requirements of the user to be met using low-temperature resources. They are commonly perceived in Europe and around the world as clean energy sources. Unfortunately, the positive effect is partially offset in Poland, where driving electricity is mainly produced from conventional fuels. Fortunately, the share of RES in the energy mix is growing, but traditional carriers still dominate here.

3.4.3. Stakeholder Involvement

The interest in geothermal energy in Poland has recently increased due to active governmental support. The National Fund for Environmental Protection and Water Management (NFEP&WM) is a state-owned body responsible for financing ecological investments in Poland, and the development of geothermal district heating systems is currently at the top of its list of priorities. In the years 1995–2022, NFEP&WM subsidized the drilling of 46 geothermal wells for the total amount of PLN 583.5 million (1 PLN = ~EUR 0.215), of which 11 wells were financed in the years 2016–2022 for the total amount of PLN 268.3 million. Another prioritized program to boost geothermal development in Poland was launched in 2020. The program, which is called "Providing access to thermal waters in Poland", has a total budget of PLN 530 million, of which PLN 480 million comprises 100% grants and the remaining PLN 50 million comprises low-interest loans. The current call expires in 2026, but the investment can be financed until 2028. The main recipients of this type of public support are local governments, which can receive grants of up to 100% of the investment costs for the drilling and testing of the first well.

Other forms of public support are subsidies and low-interest loans for enterprises that are willing to build, expand, or modernize geothermal heating plants. The program is called "Polish Geothermal Plus" and has a total budget of PLN 600 million (PLN 300 million equally distributed for grants and loans). The program can be used to finance the reconstruction of geothermal wells, as well as finance the drilling of new wells, except for the first exploratory well.

All seven geothermal heating plants in operation in Poland were donated to some extent (sometimes a significant one) by the government or from international funds. However, many facilities utilizing geothermal heat for recreation, bathing, and individual heating are private entities. They are also entitled to support, but usually in the form of loans.

The prices of geothermal well drilling in Poland follow worldwide standards. A few drilling companies originating within the oil industry can drill wells deep enough to obtain geothermal resources at sufficient temperatures. However, when economics is considered, geothermal energy utilization in Poland means cooperation with an existing district heating system that supplies heat to enough users to cover capital expenditures. Constructing from scratch a new heat distribution system would probably be the most capital-intensive part of the project, often rendering it financially inviable.

Due to the substantial allocation of public and EEA funds, a keen interest among stakeholders has been observed in recent years. The stakeholders interested in geothermal development in Poland are local governments and their unions, drilling companies, district heating operators, and energy producers and users. Currently, a Polish–Icelandic project financed by EEA grants, called "Capacity building of key stakeholders in the area of geothermal energy", acronym KeyGeothermal (www.keygeothermal.pl/en (accessed on

4 September 2023)), is organizing a series of workshops and study visits dedicated to key stakeholders with a real impact on the development of geothermal energy in Poland [70]. Two rounds of three-day training organized in Poland in 2022 and 2023 attracted over 120 people. Most of the participants are representatives of local governments and private companies that have already applied or plan to apply for public support for geothermal investments. In light of this, it should be noted that in 2023, two new geothermal district heating plants are expected to be launched in central Poland (Konin, Koło), and representatives actively participated in workshops and study visits as part of the Key-Geothermal project.

There is a lack of promotional activities for systemic solutions that would result in the widespread use of low-temperature heating systems better suited to the specificity of Polish geothermal resources. Energy consumers are still unaware that their requirements affect the final price of energy, especially in geothermal installations.

Some danger can also be seen in the decentralization trend, the assumptions of which are generally justified. However, the effective use of geothermal energy requires the cooperation of the source with a sufficiently large recipient; in practice, it is a district heating system. The trend in the gradual reduction in district heating is not conducive to the development of the use of geothermal energy.

Geothermal energy is widely accepted in Poland, mainly thanks to the popularity of geothermal spas. The cost of geothermal energy in Poland is highly dependent on the resource parameters and the requirements a user sets. The final energy price for end users can be fully competitive with gas heating, as was proven by PEC Geotermia Podhalańska.

3.4.4. Policy and Regulations

The values of ambient design temperature are defined by the Polish Standard PN-EN 12831-1:2017 [71], which is applicable to designers of heating systems and installations. The lower ambient air temperature ranges from −16 to −24 °C during winter. Legal regulations define the energy consumption standards applicable to newly built objects. They define, among other elements, the heat transfer coefficient of external walls, ceilings, and floors [72] required for new buildings (values not higher than $W/(m^2\ K)$: 0.2 in the case of outside walls, 0.15 in the case of roofs, and 0.3 for floors on the ground). New buildings must also meet the demand for primary energy specified in the aforementioned legal requirement, depending on the type of building.

Unfortunately, the system of determining energy prices discourages the use of innovative solutions that allow for earnings on the energy sold. All heating companies with a capacity higher than 5 MW have state-controlled tariffs. Revenues from the sale of energy may cover eligible costs only. On the one hand, this allows for users to be protected against unfair practices on the part of the energy supplier. On the other hand, it discourages actions that could provide profit for the entrepreneur and cheaper energy for the user at the same time. Despite the profit that the energy producer would earn, there are also no mechanisms that would make the price of energy dependent on its quality, which could be measured, for example, by temperature.

All energy sources with installed power higher than 20 MW have to participate in the market of allowance of carbon dioxide emission. The cost of CO_2 emissions plays a significant role in the final energy price.

3.4.5. Market and Financial Resources

Nowadays, dynamic growth in heat pump sales is observed in Poland. According to data from the European Heat Pump Association, the growth rate of sales of heat pumps in 2022 compared to 2021 was among the highest in Europe and amounted to 112% [73]. Air-to-water heat pumps have dominated the heat pump market in recent years; they are characterized by lower investment expenditures and simple installation. Of the total number of heat pump units installed in 2022, 73% were air-to-water heat pumps for heating, and only 3.5% were brine-to-water heat pumps [74]. The economics of the use of heat pumps is strongly influenced by the price of electricity and the supply temperature parameters set by recipients, as is the case for geothermal energy. While the requirements set by the recipient have become obvious and most recipients of this type of installation are satisfied with very low supply temperatures (35–38 °C), in the case of geothermal energy, it is still a rarity. Matching users' needs to the capabilities of heat pumps proves the effectiveness with which the price appeals to the energy user. The structure of the consumption of primary energy carriers in households in Poland is as follows [26]: 18.2% natural gas, 12.2% electric energy (53% hard coal and 26% lignite in 2021), 23.0% biomass, hard coal 25.5%, LPG 2.4%, and other energy carriers 1.1%. The maintenance of households constitutes a significant portion of the citizens' budget, at about 20% of total expenses [28].

3.4.6. Societal Embeddedness Level

Referring to the SEL methodology and the conditions for achieving defined milestones in the four dimensions, the development of geothermal energy in Poland met the criteria at the SEL 3 level and, at the same time, the level of technological readiness is the highest possible (TRL 9) for the widespread deployment of geothermal heating in Poland.

The negative impact of well drilling and geothermal water exploitation on the environment can be considered negligible in Poland. There are no obvious concerns regarding the built and social environments, although there are still some issues regarding the protection of the natural environment that should be addressed. The issue of reinjection could probably be addressed to a greater extent, but it should be borne in mind that the current regulations already partially regulate this issue, and the obligatory injection in each case is a difficult compromise between the protection of natural resources and increased investment costs.

The involvement of public stakeholders in applying for governmental support to receive financing for geothermal investments can be considered high. However, private investors are much less well supported, and more incentives are needed to engage this group. One possible solution is the introduction of geological risk insurance mechanisms, which resulted in a marked acceleration of the development of geothermal heating in France and the Netherlands.

Still, nothing is being done to encourage final energy users to reduce their required supply and return water temperatures in a district heating loop. In principle, all geothermal installations adjust the operating parameters of the energy source to the requirements of the user, thus allowing them to choose a faster, simpler, but less effective solution. This is partly due to loopholes in the legislation, which do not allow for the possibility of setting energy prices depending on temperature requirements. Partly, this situation occurs because the energy user bears the costs of energy generation and transmission anyway, often without being aware of it.

The system of financial support for the use of geothermal energy can be considered fairly good. Preferential treatment was given in particular to the use of geothermal energy in the district heating sector and to support the recognition of local geological conditions by financing the drilling of the first well. Unfortunately, some entities were not able to bear the financial burden of further work and there are known cases in which the investment was suspended after drilling.

It was found that the market, including users, has a positive attitude towards geothermal energy. Most of the key stakeholders in Poland are aware of the weaknesses of geothermal exploration and utilization. Unfortunately, very little is said about the impact of customer requirements on the costs of generating energy from geothermal energy.

The findings for Poland are summarized in Table 8.

Table 8. Societal embeddedness level in Poland. Green indicates that all milestones for that level are reached and yellow indicates that some milestones for that SEL are reached.

Poland	SEL 1	SEL 2	SEL 3	SEL 4
Environment	Green	Green	Green	Yellow
Stakeholders	Green	Green	Green	Yellow
Policy and Regulations	Green	Green	Green	Yellow
Market and Resources	Green	Green	Green	Green

3.5. Geothermal Energy in Slovakia

3.5.1. Status

As part of the Western Carpathians region, which is partially consolidated and does not exhibit any recent volcanic activity, the territory of Slovakia has moderate geothermic activity: its mean geothermal gradient is approximately 30 °C/km and its mean surface heat flow density reaches 82.1 mW/m^2. Low-to-moderate enthalpy (up to 150 °C) resources have been successfully sampled, prevailing with a water phase at a reservoir or a wellhead. The thermodynamic quality of the sampled resources is, however, low to moderately low [19]. The most promising geothermal water resources are tied to sedimentary basins with Mesozoic carbonates (e.g., the Kosicka Kotlina Basin) and Neogene sands and sandstones (e.g., the Danube basin) [75]. Previous national assessments reported 6233 MW$_{th}$ of probable geothermal potential, with 436 MW$_{th}$ already proven by 282 wells, including those producing geothermal waters for curative purposes in spas. Nowadays, 121 wells are in active service at 76 localities. The nameplate online capacity is 230 MW$_{th}$. According to the available data (as of 2020), the yearly production reached 470 GWh of geothermal heat [19]. Recreation (heating outdoor and/or indoor pools) prevails in terms of the utilization of geothermal energy in Slovakia, with 49 wells at 41 sites and an overall nameplate capacity of 102 MW$_{th}$. Agriculture covers both the heating of greenhouses and fish farming. The geothermal energy used for these purposes is produced by 12 wells at 11 sites. The total installed capacity is 45 MW$_{th}$. Balneotherapy is served through 46 wells at 11 sites, with an overall installed capacity of approximately 37 MW$_{th}$. In total, 10 wells at 10 sites provide heat from geothermal resources for the individual heating of administration buildings or resorts, with an overall installed capacity of 33.4 MW$_{th}$. Four geothermal district heating systems exist in Slovakia, and their number has not changed since 2016: the Sered', Šal'a, Vel'ký Meder, and Galanta. Their total installed capacity is 20.6 MW$_{th}$ [19]. There is no geothermal powerplant installed in Slovakia to date, but there are two powerplant projects in the preparation phase. A rapid acceleration in the utilization of shallow geothermal energy resources has occurred in Slovakia; however, official numbers are not available.

Slovakia is among the countries with above-average geothermal energy potential within Europe. An intensive hydrocarbon and basic geological exploration took place in the second half of the 20th century, producing a great deal of data that are also usable in the field of geothermal energy utilization. Based on these data, the Atlas of Geothermal Energy of Slovakia was developed and compiled in 1995. The atlas can be downloaded for free from the State Geological Institute of Dionyz Stur website [76].

Responding to the Water Framework Directive No. 2000/60/EC of the EU Parliament and the Council, 31 geothermal water bodies have been delineated recently in Slovakia [19]. Geothermal resources have already been proven by 282 wells among 30 out of 31 geothermal water bodies, proving 436 MW$_{th}$ of reserves. Following global trends, heat pump installations and the use of shallow geothermal energy potential are growing rapidly in the country, with realistic capacity data being inaccessible [19].

The main energy carrier used as a source for the purposes of space heating in Slovakia is natural gas. Approximately 99% of its natural gas has to be imported; in previous years, it was mainly imported from Russia. Since an extensive natural gas distribution network has been built and operates in the country, the full replacement of natural gas usage can be hardly expected to occur in the next few years. However, due to the increase in natural gas prices, all kinds of renewable energy sources (RESs) are popular and desired. In general, due to its favorable properties as well as the existence of many district heating systems, geothermal energy appears to be one of the most advantageous forms of RESs in Slovakia.

3.5.2. Environment

Several possible negative impacts on the natural environment have been identified in relation to the direct use of geothermal energy. Most of them are tied only to the drilling phase and thus to a relatively short period of time. These impacts are:

- The risk of oil or diesel leakage during drilling works.
- The risk of the contamination of underground water by drilling fluids and possibly by geothermal fluids.
- High levels of noise during drilling works.
- High levels of transportation density and construction activities.
- The contamination of rivers by geothermal fluid due to the discharge of thermally utilized geothermal water into rivers during long-term operations.

The risk of oil and diesel leakage is suppressed by standard and commonly used measures such as double tank walls and sumps under the tanks. Workplaces are also mandatorily equipped with a sufficient quantity of absorbents. There have been no incidents related to oil or diesel leakage in recent years, and this risk is thus sufficiently mitigated.

The risk of underground water contamination is quite often mentioned by environmental activists and the general public, but this risk is principally mitigated by the technical construction of the wells. Conductor and surface casings are thoroughly cemented, and pressure tests are carried out afterwards. Thus, any contamination of the upper layers of underground water is fully suppressed. This is not only for environmental reasons, but, understandably, the leakage of geothermal fluid would be highly undesirable for an investor or operator of the well. This risk is thus sufficiently mitigated.

Since drilling works are ongoing 24 h a day and seven days a week, the noise level could be high and disturbing for the inhabitants of nearby households. However, modern drilling rigs are equipped with noise-reducing covers on all engines and noise-reducing measures have developed over the time. Additionally, noise-reducing protective walls can be applied in the case of short distances to the households. As mentioned before, this impact is related only to the drilling work itself, so its duration is relatively short. There are no excessive noise levels during the operation of the geothermal installations. Therefore, this impact can be considered sufficiently mitigated.

Of course, the drilling of deep geothermal wells requires heavy drilling rigs consisting of many parts and devices that have to be transported to the drilling site and then returned after the completion of the work. Moreover, a lot of material has to be delivered and drilling cuttings have to be transported away from the site. Thus, a certain increase in transportation density cannot be avoided. The transportation is mostly provided by ordinary road trucks in the daytime and the impact to the environment is negligible.

The most common method for disposing of used geothermal water in Slovakia is discharge into rivers. This is due to hydrogeothermal reservoirs with a natural inflow of waters and natural regeneration. The impact of the discharged geothermal fluid on the rivers has to be precisely evaluated before permissions are granted, and the situation must be monitored throughout the operation. Required water quality limits in the rivers cannot be exceeded. In cases of adverse chemical composition of geothermal waters or closed hydrogeothermal structures, the reinjection of the utilized geothermal fluids is the only acceptable solution. Thus, this impact can be considered sufficiently mitigated.

In general, there are no negative impacts on the built environment caused by direct geothermal energy utilization. Due to their large space requirements, drilling rigs cannot be situated close to any structures or houses. Several studies have focused on the estimation of vibration creation during the drilling process, but all of them concluded that this impact is negligible. Geothermal installations have only minimal space requirements, and they have vibration- and noise-free operations.

Certain negative impacts on the social environment can be observed during the drilling phase; these are mainly related to increased noise and traffic density. Technically, these impacts can be mitigated as described above, but it is very important to communicate with local residents before the start of the work and to inform people about the plans and about the benefits of the project and geothermal energy utilization in general. Most inhabitants accept a temporary reduction in comfort when they are informed about the benefits of the project for them, such as ecological heat production with stable and favorable prices.

As is the case for any other technological branch, the drilling industry and rigs are being developed and innovated over time, so improvement in drilling rig parameters and processes with reduced impacts on the environment can be expected in the future.

3.5.3. Stakeholder Involvement

The involvement of stakeholders is an important issue at the beginning of each new geothermal project in Slovakia. Since there are no more state-driven exploratory or research works in the field of geothermal energy utilization, new geothermal projects have to be fully prepared and developed by stakeholders, operators, and the owners of the district heating systems. All four existing geothermal district heating systems in Slovakia were built without obtaining any subsidy from the state or EU structural funds.

The current situation, with the high prices of fossil fuels and uncertainty about their future availability, encourages stakeholders to pay more attention to RES utilization and the preparation of such projects.

There are basically two models of stakeholder involvement in direct geothermal energy utilization projects in Slovakia:

- A project is fully prepared, developed, and implemented by the district heating system's owner/operator.
- A geothermal loop is prepared, developed, and implemented by a separate company (a geothermal developer). A contract between a geothermal developer and a district heating system operator for the delivery of geothermal heat has to be signed during the initial phase of project preparation.

In both of these cases, stakeholder involvement is determined at the beginning of a project. Stakeholders are well informed about the benefits and drawbacks of a project from the beginning of the development. The geological risk is usually mitigated after the drilling of the first geothermal well and an efficient risk-mitigation tool also proves helpful. There are no identified stakeholders who can have a negative impact on the geothermal project development. Special services, such as drilling works and construction works, are usually subcontracted separately.

Direct geothermal energy utilization projects are usually accepted and positively perceived by the public. Of course, before starting any project, an information campaign in the available media is recommended in order to achieve sufficient public awareness.

Therefore, it can be concluded that the relevant stakeholders are involved in projects related to direct geothermal energy utilization in Slovakia. They are well informed, and knowledge and experience sharing are ensured by consulting companies that are active in this field. However, an efficient risk-mitigation tool would improve investors' interest in new geothermal projects in Slovakia.

3.5.4. Policy and Regulations

The legal framework related to the geothermal project permissions process is quite broad and complicated. The permissions process itself is therefore unnecessarily long and features some special items, such as an extremely lengthy environmental impact assessment (EIA) process. Since several geothermal projects have already been implemented, the legislation process can be passed reliably, but lasts a long time. Geothermal energy utilization is, in general, a very popular topic among politicians, and it has almost no opponents. Increased interest on the part of the state can be noticed in this field, and several activities focused on the simplification of the permissions processes have been started.

Slovakia has recognized the potential of geothermal energy and has implemented policies and regulations to support its utilization. Here are some relevant policies that are currently in place:

- Renewable Energy Act: Slovakia has a Renewable Energy Act that provides a legal framework for the promotion and support of renewable energy sources, including geothermal energy. The act includes provisions for feed-in tariffs, investment incentives, and other support mechanisms to encourage the development of geothermal energy projects.
- State Energy Policy: the State Energy Policy of Slovakia aims to diversify the country's energy sources and reduce its dependence on fossil fuels. It recognizes geothermal energy as a valuable renewable resource and encourages its development through various policy measures.
- National Action Plan for Renewable Energy: Slovakia has developed a National Action Plan for Renewable Energy, which sets specific targets and measures for the deployment of renewable energy sources, including geothermal energy. The plan outlines strategies for increasing the share of renewable energy in the country's overall energy mix.
- European Union (EU) Directives: Slovakia is a member of the European Union and is subject to EU directives and regulations related to renewable energy. The EU Renewable Energy Directive sets binding targets for the share of renewable energy in the member states' final energy consumption. It provides a framework for the promotion and development of various renewable energy sources, including geothermal energy.

Several permits are required for each new project. These permits are issued according to geological law, environmental impact assessment law, water law, and building law. The permissions process is defined and standardized; however, it is also complicated and lengthy.

3.5.5. Market and Financial Resources

In the past, the absence of any kind of financial support from the state resulted in limited interest in geothermal energy utilization, mainly due to a certain level of risk related to new geothermal wells. As a result of pressure from the stakeholders and entities that are active in the field of RES, as well as the critical energy situation in Central Europe, the state has introduced a new mechanism for exploratory geothermal well subsidies within the new EU structural funds framework. Thus, significantly higher levels of interest among stakeholders have been noticed since then. There are further financial resources available for geothermal project subsidies that were introduced in recent times, such as the Just Transition Fund.

There is only one company capable of drilling geothermal wells with a maximal depth of approximately 2000 m in Slovakia, and this company's core business is the operation of underground gas storage. Therefore, foreign companies must be hired to drill new geothermal wells. This complicates the tendering processes and increases the price of new geothermal wells.

Geothermal projects have a good market position, because the utilization of geothermal energy leads to savings of natural gas or other types of fuel and consequently to the reduction in emissions released into the air. Geothermal energy utilization has advantages including an environmental impact of almost nothing, low space requirements, low operational costs, and independence from the import of fossil fuels. These factors make it one of the most advantageous kinds of RES. This results in a stable supply, and in long-term operations, also lowers the price of heat for the end-use customers.

The business case is unique for each new direct geothermal energy utilization project. A financial model and business plan are developed for each project individually, but there are several templates already implemented and verified in practice. Several private investors are already involved and are willing to participate in new geothermal projects.

In general, it can be concluded that direct geothermal energy utilization projects in Slovakia usually fulfill the needs of the market and of customers, as described above.

Significant increases in heat pump installations can be observed in Slovakia, both for shallow geothermal resources and ground sources, as well as air-based heat pumps. No statistical data are available so far.

3.5.6. Societal Embeddedness Level

In general, geothermal energy is rather popular among the wider public in Slovakia. This may be due to the historical existence of many thermal spas and aqua parks that are heated by geothermal energy. Additionally, the operational geothermal district heating systems are positively perceived and represent a good reference point for potential stakeholders interested in the development of new geothermal projects. One of the main advantages of geothermal energy is its low space requirements in comparison with the other RESs, as well as its negligible impact on the environment and the landscape. Thus, it can be concluded that the general acceptance of geothermal energy utilization is rather high.

The negative impacts of direct geothermal energy utilization projects on the natural environment, built environment, and social environment have been mitigated, and harm is as low as possible. Relevant stakeholders for such projects are identified and involved, schemes of participation have been introduced and verified in practice, and a risk-mitigation tool would help. Regulatory barriers for such projects are overcome, supporting legislation has been introduced, and all required permits can be issued using a standardized approach for each project separately. Both private and public funds are available, which can be used for the initiation of new geothermal projects in Slovakia. The market is ready for the adoption of such projects, and the results of such projects meet the needs of both the market and customers.

The findings for Slovakia are summarized in Table 9.

Table 9. Societal embeddedness level in Slovakia. Green indicates that all milestones for that level are reached and yellow indicates that some milestones for that SEL are reached.

Slovakia	SEL 1	SEL 2	SEL 3	SEL 4
Environment				
Stakeholders				
Policy and Regulations				
Market and Resources				

4. Concluding Remarks

This study explores the societal embeddedness of geothermal energy in Hungary, Iceland, Norway, Poland, and Slovakia. These countries have different traditions when it comes to the use of geothermal energy, even though geothermal energy is not new in any of these countries. The prevalence of geothermal energy in these countries varies, as it is affected by geological conditions, existing energy sources, and cultural and political contexts, among other factors. Thus, it is influenced by factors beyond purely technical components. When it comes to the countries' histories of using geothermal energy, some, such as Iceland, have used geothermal energy for over a century to a large extent, while others are less experienced. In general, geothermal energy stands out as an environmentally and climate-friendly energy source that can meet international climate goals and future demands for energy sources. Geothermal energy differs in terms of what kind of energy it replaces. For instance, in Norway, it is mainly a supplement to hydropower, but in the other countries, it replaces fossil fuels to a much larger extent. Some of the countries included in this study also have long traditions of spa and aqua cultures, in which geothermal heating plays a pivotal role. By studying the societal embeddedness of geothermal energy via the SEL framework, it is possible to identify non-technical features at work in the countries, particularly focusing on the four dimensions that make up the SEL framework: environments, stakeholder involvement, policy and regulations, and market and resources.

As indicated by the table, only Iceland reaches all the milestones in every dimension. Hungary, Norway, and Poland reach all milestones in one dimension, and some milestones in the other dimensions, while Slovakia reaches all milestones in two dimensions. In this part of the paper, some of the similarities and differences between the countries are emphasized, focusing on the milestones that are not met in the respective countries.

A summary of the findings for all the investigated countries is given in Table 10.

Table 10. Summary of the findings for all the investigated countries. Green indicates that all milestones for that level are reached and yellow indicates that some milestones for that SEL are reached.

Country	Dimension	SEL 1	SEL 2	SEL 3	SEL 4
Hungary	Environment				
	Stakeholder Involvement				
	Policy and Regulations				
	Market and Resources				
Iceland	Environment				
	Stakeholder Involvement				
	Policy and Regulations				
	Market and Resources				
Norway	Environment				
	Stakeholder Involvement				
	Policy and Regulations				
	Market and Resources				
Poland	Environment				
	Stakeholder Involvement				
	Policy and Regulations				
	Market and Resources				
Slovakia	Environment				
	Stakeholder Involvement				
	Policy and Regulations				
	Market and Resources				

4.1. Environment

In the first dimension, environment, there are only two countries, Poland and Norway, that do not meet all the milestones. In Poland, there are some concerns regarding the natural environment. Specifically, the concerns are related to the utilization of brine water from deep boreholes after heat exchanges, since reinjection is not mandatory. In Norway, there have been some instances of settling damage in buildings, runoff of muddy waters into rivers, and uncertainties linked to future risks of harm to the natural environment. However, compared to climate impacts from energy sources such as coal, oil, and gas, and environmental impacts from windmills and hydropower, the impacts of geothermal energy seem negligible. Moreover, geothermal energy does not cause political controversies.

4.2. Stakeholder Involvement

The second dimension deals with how stakeholders are involved in geothermal projects in the five countries, which is relevant for their uptake and reduction in potential conflict and opposition. In this dimension, Hungary, Poland, and Slovakia do not meet all of the milestones. In Poland, stakeholders are mainly involved in the process of applying for governmental financial support, even though private investors are less supported and thus less engaged in geothermal energy projects. In Slovakia, there are many processes in place for ensuring the active involvement of stakeholders in geothermal projects. However, to improve investors' interest in new projects and thus increase the use of geothermal energy, an efficient mitigation tool is called for. In contrast to Slovakia, in Hungary, the involvement of the public is generally considered neither important nor feasible. Thus, even though there are a variety of professional stakeholders involved in geothermal energy production processes and the technology is reported to have widespread acceptance among the general public, there is potential to improve stakeholder involvement in Hungary.

4.3. Policy and Regulations

All countries apart from Iceland report unmet milestones in the third dimension. In this dimension, it is interesting to note the difference in challenges that concern policy and regulations in the respective countries. In Poland, loopholes in legislation, resulting in faster but less efficient solutions, are considered an issue. In Hungary, regulatory barriers are hard to overcome, the relevant laws and regulations do not provide a level playing field for geothermal developments, conditions for obtaining permits are hard to navigate and are ever-changing, permissions procedures are long and not transparent, and recognized experts, established NGOs, and relevant stakeholders are not in a position to provide input to policymaking. In Slovakia, geothermal energy utilization is a popular topic among politicians, yet the legal framework is reported as being complicated and the permissions processes exceptionally long. In contrast, Norway faces a lack of general national regulations and a lack of political interest in geothermal energy compared to the interest in other RESs.

4.4. Market and Resources

In the fourth and final dimension, market and resources, Iceland, Poland, and Slovakia meet all the respective milestones. In Norway, the high upfront investment costs of geothermal installations weaken their market position compared to low-cost air-to-air heat pumps and hinder the wider public from making use of geothermal energy. In addition, compared to other RESs, there is a lack of alternative funding options and state subsidization. Increased energy prices and the improved efficiency of heat pumps may make geothermal energy systems more competitive. In Hungary, it is hard for geothermal actors to negotiate a market position for geothermal energy, as it is an unpredictable system and legislation and political leadership in the country are constantly changing.

5. Conclusions

This paper assessed the societal embeddedness of geothermal energy utilization in five European countries: Hungary, Iceland, Norway, Poland, and Slovakia. Geothermal technology is used—and has been for years—in all these countries and is at Technology Readiness Level 9. Despite all the countries being on the same technology readiness level, the prevalence of this energy source varies considerably between them. Through the lens of the social embeddedness level framework, societal factors that enable and hinder the prevalence of geothermal energy were studied.

This paper uncovered different societal challenges in the countries studied, and the comparative analysis demonstrates that Hungary, Norway, Poland, and Slovakia are at social embeddedness level 3, with considerable progress having been made towards level 4. To reach social embeddedness level 4, the countries should focus their efforts on the dimensions where they do not reach all milestones (see Table 9). Iceland is the only country included in this assessment where geothermal energy is fully societally embedded.

Hungary, Poland and Slovakia all use mainly non-renewable energy sources such as oil, gas, and coal for heating, which generates large emissions of CO_2. Increasing the utilization of geothermal energy in these countries can thus reduce the climate effect of their current energy mix. In Norway, an increased use of geothermal energy for heating could release valuable hydropower (electricity) for other purposes and reduce the need for construction of wind turbines, which is controversial. In all countries, the resulting energy autonomy for heating and cooling is also relevant.

This paper illustrates that in order to mitigate climate change and drive the energy transition forward, both the technical and the societal factors of various renewable energy sources must be assessed. The present paper considers geothermal energy, but this approach is equally valid for solar energy, wind energy, and other renewable energy forms. By addressing the shortcomings in terms of both technical and societal factors, the uptake of renewable energy sources in a societally acceptable manner within local contexts can be improved, and efforts can thus be directed toward where they are most needed.

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