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Opportunities and Challenges of Geothermal Energy: A Comparative Analysis of Three European Cases—Belgium, Iceland, and Italy

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Abstract: Geothermal energy is a unique energy source in the energy policy mix that would help the clean energy transition and energy independence, supporting the energy needs in heating and electricity. Although there have been studies on the opportunities and challenges of renewable energy, this paper is the first paper that concentrates on geothermal energy for three distinct countries, Italy, Belgium, and Iceland, for the first time. Using semi-structured interviews that will cover the stakeholders representing the quadruple helix (academia, citizens, policymakers, and industry), this paper aims to find the unique and common opportunities and barriers the geothermal sector has. Shared challenges include financial barriers, regulatory complexities, environmental issues, and the need for improvement in the social acceptability of geothermal energy. Despite these challenges, geothermal energy, a promising energy source for clean transition, could create opportunities like improved household welfare through combined uses in district heating and electricity and have the potential to generate employment opportunities.

Keywords: geothermal energy; semi-structured interviews; market development; geothermal policy; opportunities; barriers; energy flexibility

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1. Introduction

Geothermal energy, an essential player in the energy mix for a successful green energy transition, gained even more interest with its unique position of providing a consistent and reliable power and heat source, energy efficiency, dual uses, high-capacity factor, and competitiveness [1]. Life Cycle Assessment studies on geothermal power plants identified environmental impacts of these technologies as in line with other renewable energy sources and generally lower than national energy mixes [2]. For example, Basosi et al. [3] benchmarked a flash technology geothermal power plant in Italy with the national energy mix, wind energy, and large photovoltaic plants with similar capacity. The authors concluded that despite that the geothermal scenario has slightly lower environmental performances than the other renewables considered (but much higher than the national energy mix), its high productivity compared to wind and solar confirms that geothermal energy is a good option for sustainable development.

This paper aims to explore the opportunities and challenges in Italy, Belgium, and Iceland and provide the first comprehensive results for these three countries. The unique and shared challenges and opportunities are outlined using semi-structured interviews in these three European countries with critical stakeholders from the quadruple helix (academia, government, industry, and society). Face-to-face and online interviews with 44 stakeholders sketch the opportunities and barriers in the context of countries' geothermal potential and regulatory context.

Applying interviews for qualitative research purposes gives room to collect data and gather information from the perceptions of important players. This method lets us learn about the important prior information that will give us the reasons for the behaviours and perceptions of significant actors in the field [4]. Semi-structured interviews as a method have been used in this study with open-ended questions that provide relevant and comprehensive information even beyond the scope of the interviewer.

This study has been performed in line with the Horizon 2020 GeoSmart project; we employed semi-structured interviews in various markets from 2021 to 2023 to find out the opportunities and challenges of geothermal energy. This is the first paper in that sense to cover three markets, Iceland, Belgium, and Italy, for the first time. A detailed stakeholder mapping has been performed and using a snowball sampling, more participants have been added to the interviews. Interviews stopped when we did not obtain any added information from participants. During the interviews, common questionnaires of 15 questions have been asked to uncover the interviewees' perceptions on geothermal energy with an emphasis of importance of geothermal energy resources and important tools to extract the potential. Potential incentives have also been outlined to improve flexibility on geothermal plants. Interviewees have received the questionnaire before, and interviews have been conducted face to face and online. Interviews have been recorded with the consent of the interviewees and have been transcribed. Following the GeoSmart project classifications, the stakeholders have been classified under categories with ultimate end users and beneficiaries (e.g., geothermal power operators), optimal end users, manufacturers, primary influential bodies, investors, academia, and public and grid operators. Interviews have been held by stakeholders in these categories that also include all quadruple helix participants.

This paper includes countries with different geothermal backgrounds, namely Italy, Belgium, and Iceland. Italy has a long history of geothermal energy since the 1900s. The world's first geothermal plant was built in the Larderello region in Tuscany. Although geothermal energy has been increased through the years, the rise was small with a rise in installed capacity from 2002 to 2017 of 10%. Originally as an alternative to coal-fired engines, steam coming from geothermal wells has been used but this practise has evolved to converting heat to electric energy through time. Belgium on the other hand is a small country that has lots of differences in geology. Unlike the neighbouring European countries, geothermal energy in Belgium focuses on shallow applications. For several decades in terms of deep geothermal energy, only three projects have been implemented around Mons, Hainau [5]. Iceland is the third country that we will use in this study and is one of the world leaders in geothermal energy. For years, Iceland used geothermal energy to harness district heating and the production of electricity. Supplying 100% of its electrical energy from renewable energy, Iceland has been a special example with government incentives and financial schemes to support geothermal energy. This paper will exploit the three district country cases to find the main barriers and opportunities in geothermal energy.

According to the interview results, the findings could be summarised as follows: Although mature and industrialised since the 20th century, Italy's geothermal sector is hindered by complex authorisation processes, insufficient lobbying efforts, and social resistance (several of the listed issues are or could be important for other countries as well but they have been emphasised in the interviews and therefore are listed here as country-specific cases). Stakeholders highlight the necessity for a cohesive national energy strategy emphasising geothermal energy alongside innovative plant schemes and capacity-building initiatives. Belgium, reliant on energy imports due to limited geothermal potential, focuses on heating applications. Challenges here include a lack of subsurface data and induced seismicity. Stakeholders advocate for technological innovations, effective communication, and public engagement to enhance social acceptance. In contrast, Iceland's advanced geothermal sector, which contributes significantly to its energy mix, benefits from environmentally solid sustainability practises and comprehensive planning. Challenges in Iceland revolve around sustainable exploitation and technical issues, with stakeholders emphasising innovation in utilisation techniques and better environmental management.

From the policy standpoint, this paper suggests several policy changes that could direct each country in a different direction in need of country specifics like simplifying regulatory frameworks, improving incentives, and increasing capacity-building efforts and public awareness. Technological innovation and integration could be given a first stance with country-specific needs, such as Italy's technical standards, Belgium's heat production and thermal storage innovations, and Iceland's resource efficiency. Lastly, promoting social acceptability through public engagement seems to be an essential step for all three countries. Targeted policy actions could aim to help the improvement in geothermal energy sectors in these diverse contexts.

Following the introduction, the Section 2 of this paper concentrates on the geothermal outlook for the three European countries separately. The geothermal landscape and its properties are summarised. In the Section 3, methodology, the semi-structured interviews are summarised. The Section 4 includes the interview results from Italy, Belgium, and Iceland, and the Section 5 concludes with a comparative evaluation and policy suggestions.

2. Geothermal Outlook of Italy, Iceland, and Belgium

2.1. Italian Case

Geothermal resources are abundant in Italy, thanks to its favourable geological context in a tectonically active region and hydrothermal circulation in volcanic, sedimentary, and crystalline rocks, including faults and lateral discontinuities allowing the local rise in hot water from deeper formations up to produce hot springs [6]. Underground temperatures range from >90 °C to >150 °C temperatures at depths accessible only by wells, usually within 3–4 km [7]. Della Vedova et al. [8] reported that the potential for power generation in Italy is mainly concentrated in Tyrrhenian regions and islands, as also reported in Figure 1. Higher temperatures are in conjunction with crustal thinning areas, where the mantle is closer to the earth's surface and many magmatic and volcanic activities are the consequence. However, the geothermal potential in these areas is favoured by frequent permeable structures, below shallower impermeable caprocks [9].

Low- to medium-temperature deep resources are also available in northern and southern regions and islands, where the infiltrated rainwater is heated by deeper formations in some areas and rise through convective circulation, to origin geothermal reservoirs, or continue rising to the surface through faults and gush out in thermal springs, according to the local geology. This may occur through heating by the conduction of water circulating within a fractured metamorphic basement and rapidly rising through a fault, as described for the Acqui Terme's thermal springs in the Piedmont region, northwest Italy [10], or by convection, as in the eastern part of the Po Plain [11]. Here, Pasquale et al. [12] suggested that the deep groundwater flow is favoured by the deep carbonate aquifer and fracturing and faults further increase permeability (e.g., in Ferrara, high, and its surroundings). Similarly, carbonate complexes host a middle-enthalpy geothermal resource in some areas of Sicily, as in the western part of the island [13,14]. Other areas potentially interesting for medium-enthalpy geothermal development are the Sardinian Rift-Campidano Graben, which probably host a 2.000 m deep carbonate reservoir [15], and the volcanic island of Pantelleria, hosting high-temperature hydrothermal systems at less than 1.000 m, potentially suitable for power production [16]. In addition to what is reported above, carbonate reservoirs up to 5 km in southern Italy can guarantee a technical potential of 2.082 GWth, 2.168 GWth, or 77 GWe for district heating, district heating and cooling, and electrical power production, respectively [17].

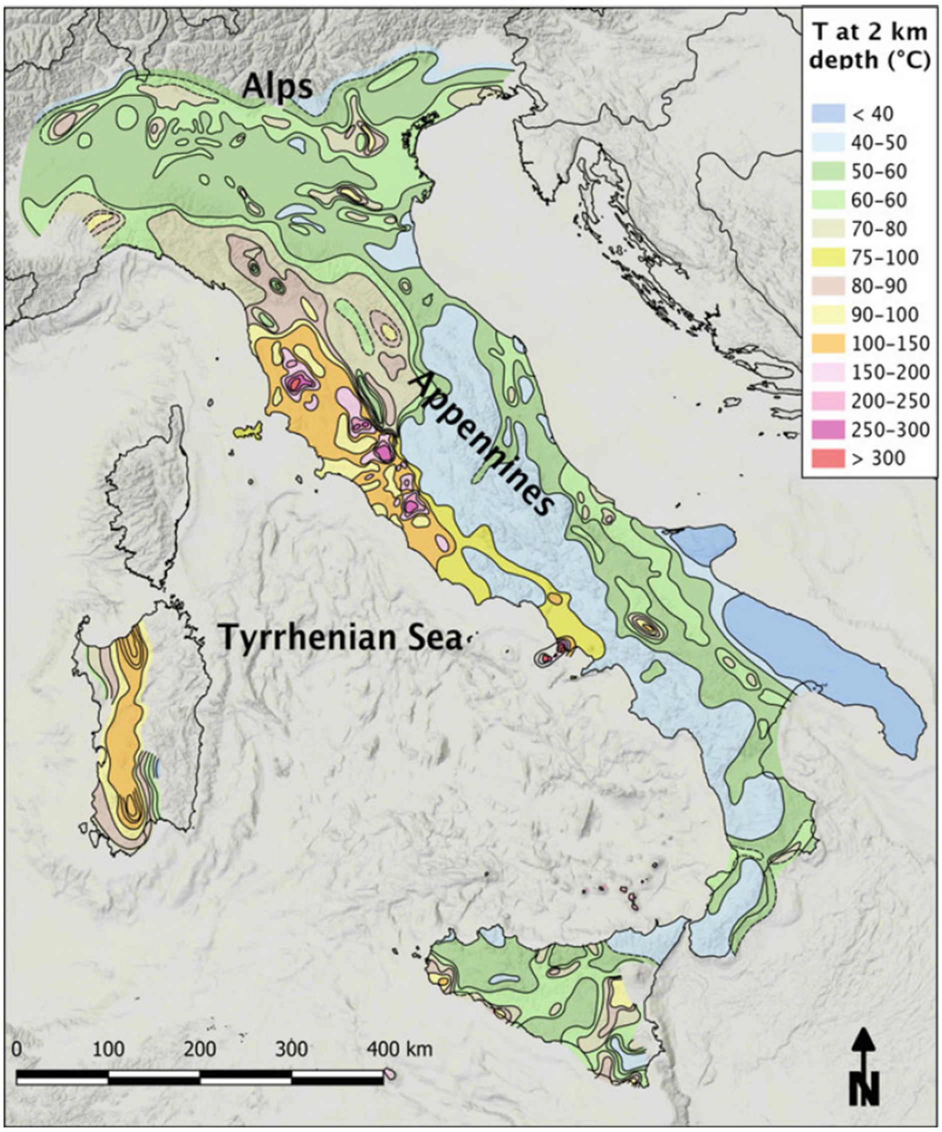

Figure 1. Temperature distribution at 2 km depth in Italy (map from Pellizzone et al. [6], with data source from Cataldi et al. [18]). (Since this article mainly addresses non-technical topics, the aim of this map is to only support and facilitate the reading of the paragraphs describing the geothermal potential in Italy).

Geothermal energy has been used from prehistory in Italy. The first geothermal industry was born in the first half of the 19th century when geothermal heat was used to extract boric acid from geothermal fluids that rose to the surface of the Larderello area. In 1904, Prince Ginori Conti used geothermal steam to turn on four light bulbs and nine years later, the world's first geothermal power plant entered operation in Larderello. Electricity production from geothermal energy continuously grew in the second half of the 20th century, apart from a setback during the Second World War. Geothermal fluids are used today also in the Monte Amiata area, an extinct volcano in southern Tuscany.

Today, Enel Green Power operates all 34 power plants with a nominal capacity of 915.8 MWe. It generated nearly 6 TWh in 2021 in three geothermal fields within the Tuscany Region, as reported in Figure 2. This corresponds to nearly 33% of the regional electricity demand and around 2% nationally [8].

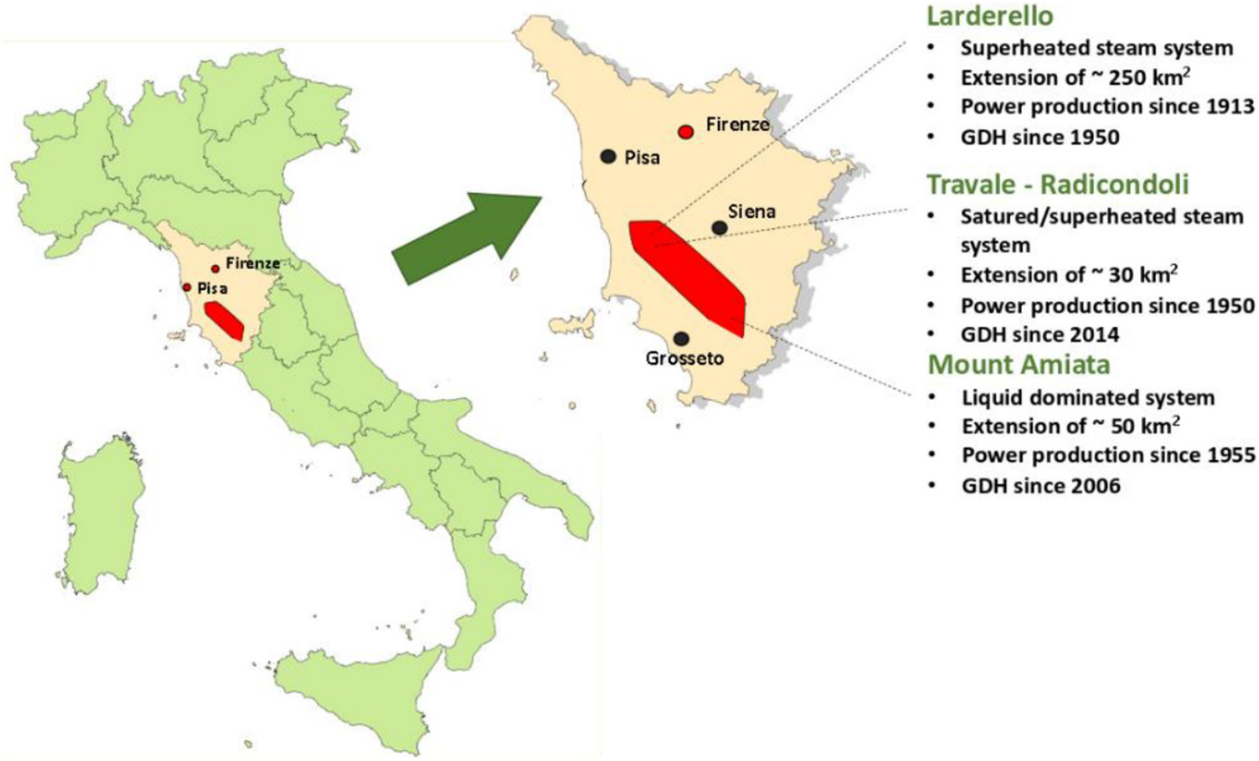

Figure 2. Location of geothermal fields in Italy [19].

In Tuscany, geothermal power plants produce enough electricity to meet over 30% of the region's electricity needs. Electricity is, however, fed into the national grid and so does not offer particularly advantageous conditions in the bills of local users, at least directly. Despite this, companies that directly use geothermal energy for space heating and production processes and citizens connected to the 21 district heating networks in the Tuscan geothermal areas can benefit from advantageous tariffs, thanks to agreements signed among Enel, municipalities, and the Tuscany Region.

Geothermal energy provides heat to towns near geothermal power plants and in a few other areas (e.g., Ferrara) through 25 district heating networks. The first plant was built in Larderello in 1955 [15], but most networks have been built since the 2000s [8]. Except in the case of one greenhouse complex in northern Italy, geothermal power plants provide heat to swimming pools, dairies, greenhouses, a cured meat factory, and a brewery in Tuscan geothermal areas.

Two projects are in development, representing a capacity of 25 MWe, and 43 projects, equating to an additional 372 MWe, are under investigation. Delays in issuing the new support scheme FER2, which will include measures for traditional "flash" geothermal plants with innovations and innovative binary systems [8] with the reinjection of non-condensable gases, and the long-lasting authorisation processes are slowing down the projects' developments. Indeed, the FER2 decree was expected in 2019 and was approved by the European Commission in early June 2024.

Historically, Legislative Decree Number 22, dated 11 February 2010, liberalised access to the geothermal market, allowing many new players to enter the geothermal sector and the opportunity to apply for an exploration lease to the regional authority. The main points of the measure concern the classification of geothermal energy as reported in Table 1 (based on temperature and depth) and plants (based on the installed capacity), a publicly available inventory of geothermal resources, regulation of exploration permits and geothermal leases, provisions for small local utilisations of geothermal resources, and licence fees. The law also provides that the authorities in charge of managing authorisations (research and use of resources) are the regions. In contrast, simplified authorisations are envisaged for zero-emission pilot plants, for which the relevant competent authority is the Ministry of Environment and Energy Security. The recent Law 181 of November 2023 reports measures that will act in business support, promotion of renewable energy, energy security, and decarbonisation and could help investments in geothermal production.

Table 1. Classification of geothermal resources in Italy.

Classification	Characteristics	Authority in Charge
Resources of national interest (considered as mining resources)	Fluids > 150 °C Deliverable power > 20 MWth	Regions or delegated authorities
	Geothermal resources in the sea	The State
	Fluids > 90 °C Used in < 5 MW zero-emission pilot plants	The State
Resources of local interest (considered as mining resources)	Fluids < 150 °C Deliverable power < 20 MWth	Regions or delegated authorities
Small local utilisations (not considered as mining resources)	Deliverable power < 2 MWth Resources from <400 m deep wells	Regions or delegated authorities

Concerning the policies as a promising development, the publication of the RePowerEU plan in 2022 resulted in great expectations regarding improved regulation and support measures for the geothermal sector. Additionally, the Italian Ministry of Environment and Energy Security (MASE) proposed to the EU to update the National Integrated Energy and Climate Plan (PNIEC) 2023 in July 2023. The national plan outlines how EU countries intend to address fundamental energy-related themes. Regarding geothermal energy, the installed capacity is expected to grow moderately by 183 MW (or 22%) by 2030. However, it focuses more on developing a geothermal supply chain and considers this energy source a priority for the Italian research system.

More than 100 players cover the whole deep geothermal supply chain. This mapping exercise was adapted and updated from previous research by [20]. Many of these companies are satellite activities of Enel Green Power. However, other relevant players, such as developers, consultancy companies, and turbine providers, operate outside the Tuscan geothermal district and abroad (e.g., Türkiye, Kenya, and the Philippines). Four of Europe's major turbine manufacturers for hydrothermal power plants are mainly active in Italy and binary-ORC [21]. Despite Enel being the only company with operating plants, many other operators have requested exploration and exploitation permits after the sector liberalisation in 2010. However, few have obtained the green light to use the resource. Many associations like industry associations and clusters, environmental associations, and citizens' networks for promoting geothermal energy or opposing it deal with this sector. In addition, Italy has a long-lasting research tradition in geology and geophysics, as well as engineering topics, with many research groups involved in geothermal research centres and universities in Italy. This demonstrates that despite the sector not growing in recent years, the country's supply chain is well developed, and the national geothermal market can still be considered one of the main ones globally.

Although the sector has been stagnant during the past ten years, estimations of geothermal associations report that the electrical capacity will consistently increase by 2035, producing around 3 new TWh/year [8]. On the contrary, the installed capacity of geothermal district heating has been growing in recent years (+8% in 2017–2020, [8]), and a further increase of more than 50 MW is expected in the next few years. Last year's energy crisis led industries, citizens, and public authorities to a greater interest in geothermal heat and cooling, and Italy still has vast untapped potential. Sector associations recently stated that if 2% of the national potential were exploited, geothermal energy could contribute to 10% of electricity production by 2050 and cover 25% of heat demand, reducing natural gas consumption by 40% (News in Italian—Geotermia, nella bozza del nuovo Pniec +33% per la produzione elettrica al 2030: https://archivio.greenreport.it/news/economia-ecologica/

geotermia-nella-bozza-del-nuovo-pniec-33-per-la-produzione-elettrica-al-2030/, accessed on 30 April 2024).

Besides excessive bureaucracy burdens, long-lasting authorisation processes, and lack of incentives, other non-technical issues prevent geothermal energy from playing its role and discourage investors from being uncertain about whether and when they will see the operational plant. The lack of awareness of geothermal energy, including its impacts and benefits, results in concerns and the NIMBY syndrome. This led to echoes of contestations to damage the entire sector: opposition in Monte Amiata (Italy) reached the national government [22], which removed feed-in tariff incentives to new plants. However, concerning impacts of geothermal plants in Italy, which are all using the flash technology, it should be noted that while LCA studies report that rather high environmental impacts have been identified for some sites, in terms of greenhouse gas emissions and acidification potential, depending on the characteristics of the geothermal reservoir and therefore of the fluids (e.g., Bravi and Basosi [23]), the operator has undertaken measures to minimise environmental impacts as much as possible [24]. Regarding CO_2, Sbrana et al. [25] reported that emissions from geothermal plants appear to reduce natural emissions. Furthermore, such emissions are further reduced during the life cycle of geothermal plants, thanks to the reinjection of fluids deprived of non-condensable gases.

2.2. Icelandic Case

Iceland is a country located on an island on top of the Mid-Atlantic ridge, unlike Belgium and Italy, which are situated on the mainland [26]. Iceland's unique geological position on a volcanic rift zone provides a naturally abundant and reliable geothermal resource (Figure 3) and places Iceland as the leader in generating energy from geothermal power plants. Geothermal energy was first utilised by settlers in Iceland, who harnessed hot springs for bathing and washing. Modern geothermal energy utilisation did not start before the early twentieth century. At that time, electricity was mainly produced by coal, followed by hydropower turbines, the first one being operational in 1904, and geothermal energy was first used to heat greenhouses. In the 1930s, space heating took a larger scale as hot water was transported in pipes from Laugardalur to the capital area. However, its utilisation took a more significant expense in the 1970s during the oil price hikes [27]. Following this event, the government took the initiative to eliminate oil from district heating, replacing it with geothermal energy, with the result that the share of geothermal energy increased from 43% in 1970 to the current level of about 90% [27]. Buildings outside geothermal regions have electrical heating. About 30 separate geothermal district heating systems are operated in towns and villages in the country, and some 200 small systems in rural areas. These smaller systems supply hot water to individual farms or a group of farms as well as summerhouses, greenhouses, and other users. Geothermal space heating has enabled Iceland to import less fossil fuel, resulting in a cheaper heating cost compared to most other countries. In 2019, the construction of a 20 km hot water transmission pipeline from the geothermal field at Hoffell to the town of Höfn in Southeast Iceland started after many years of exploration in the area. The geothermal water will replace electricity as an energy source for the already existing district heating system and will serve a population of about 1800 people [28]. The current utilisation of geothermal energy for heating and other direct uses, such as swimming pool heating and snow melting, as well as industrial uses in agriculture and aquaculture, is only a tiny fraction of what this resource can provide [29]. The production of electricity from geothermal energy has increased in recent years. For instance, approximately 27% of the electrical energy comes from geothermal energy resources [30] and 75% from hydro, making Iceland's power 100% renewable [31]. The growth of its renewable energy utilisation in Iceland is an excellent example of how countries can shift to clean and renewable energy sources. The total installed capacity of geothermal generating plants is now 755 Mwe and the total production in 2018 was 6010 GWhe [32].

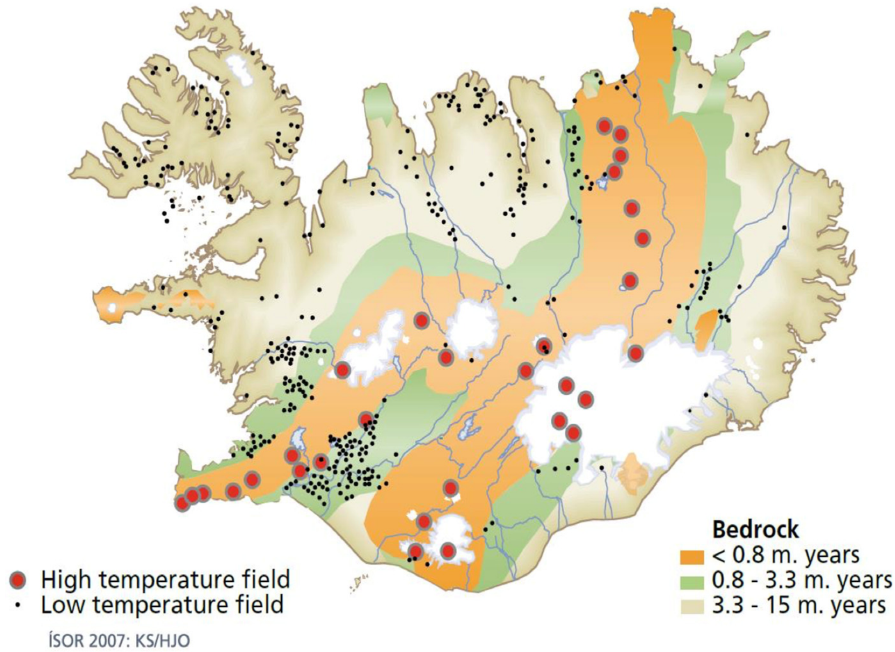

Figure 3. Geological and geothermal map of Iceland [27].

Iceland has six main geothermal power plants listed in the table below (Table 2). They are located on high-temperature zones along the plate tectonic belt, as magma can be found close to the surface. In the high-temperature (>200 °C) fields, the geothermal steam fraction is utilised for electricity generation at eight sites. The brine fraction is used for hot water production for district heating in so-called co-generation plants at three sites. Thus, energy efficiency has improved considerably. The low-temperature zones (<150 °C) are the oldest part of the crust, further away from the rift, and mainly supply hot water for district heating [27].

Table 2. Main geothermal power plants and their capacity [33].

Power Plant	Capacity (MW)	Start of Operation	Owner
Hellisheiði	303	2011	ON Power
Nesjavellir	120	1990	ON Power
Reykjanes	100	2006	HS Orka
Theistareykir	90	2017	Landsvirkjun
Svartsengi	75	1977	HS Orka
Krafla	60	1978	Landsvirkjun

All forms of energy production require engineering and construction activities that result in disturbances to the environment. Sustainable practises ensure long-term viability, as overexploitation can lead to depletion or environmental disruptions. Additionally, geographically isolated geothermal pockets necessitate meticulous planning and infrastructure development for effective nationwide utilisation. Though geothermal energy is a renewable energy source, its development will lead to some emissions of gases. The relative amounts of greenhouse gas emissions from electricity of a geothermal origin are only a fraction of the amounts coming from fossil fuel, and are of the same magnitude as most other renewable energy sources, such as hydro and solar energy [34,35]. The CO_2 emissions per kWh from geothermal energy range from 0.01 to 0.05 kg per kWh [36]. The largest geothermal plant in Iceland, Hellisheiði, is known for its low CO_2 emissions, in the range of 0.15–0.24 kg per kWh [37].

The plant further tries to reduce its emissions by implementing novel carbon capture and storage technologies. This technology dissolves the gases in water prior to reinjecting into the storage formations compared to other CO_2 storage solutions where the gases are directly injected. Results obtained from the pilot trials at the Hellisheiði power plant site show that the approach developed of dissolving the gases during injection results in immediate subsurface solubility trapping of the gases. The method promotes carbon precipitation within the host rock (basalt), thus facilitating the safe long-term sequestration of CO_2 [38].

A comprehensive protocol, Geothermal Sustainability Assessment Protocol (GSAP) [39], designed to ensure the sustainable development of geothermal energy projects has been developed in Iceland [40]. The aim of the protocol is to promote best practises in geothermal energy development globally, and it has been tested and implemented in New Zealand and Kenya, showcasing its adaptability and effectiveness in various contexts. The GSAP emphasises the importance of seeking appropriate expertise for each project to address the variability in environmental conditions. It prioritises avoiding and mitigating adverse environmental impacts and, when unavoidable, implementing compensation measures proportional to the project's risks and impacts.

By adhering to this comprehensive protocol, Iceland ensures that its geothermal sector develops responsibly, balancing the needs of the environment, society, and the economy. The GSAP incorporates various sustainability factors that can be broadly categorised into environmental, social, and economic dimensions. In this context, indicators are related to geothermal production and its influence on the resource itself. The GSAP uses a combination of qualitative and quantitative assessments, incorporating stakeholder input and adaptive management practises. The exploitation of geothermal resources requires a permit from the National Energy Authority (NEA) [32], according to Natural Resources Act no. 57/1998. The NEA delivers licences for utilising geothermal resources, manages extensive geothermal exploitation databases, and collaborates with various public and international entities. Their duties include maintaining records of geothermal activities, supervising power generation from these sources, and ensuring compliance with environmental and resource management regulations. The law on research and the utilisation of resources on the ground, no. 57/1998, gives the right to the NEA to deliver access to geothermal resources whether they are located on private or public property. Installing a geothermal power plant with more than 1 MW capacity requires a licence from the NEA, according to Electricity Act no. 65/2003.

Additionally, Iceland fosters a culture of innovation in the geothermal sector, with planned expansions like the 30 MWe Reykjanes plant utilising high-pressure brine separators [28]. Future drilling activities will likely focus on makeup and reinjection wells for existing power plants and district heating systems [28]. However, the geothermal industry in Iceland encounters obstacles in technology development and global representation. Energy companies heavily depend on international vendors, restricting collaboration with local suppliers. Service firms face post-crisis competition and limit joint ventures, impeding their ability to provide comprehensive solutions. Additionally, repetitive international presentations and the undervaluation of smaller, specialised firms hinder showcasing the sector's full potential. Addressing these issues requires promoting collaboration between energy companies and local suppliers, encouraging partnerships among service firms, diversifying international presentations, and elevating the visibility of smaller firms with specific expertise. Despite all these challenges, Iceland's pioneering efforts in geothermal energy serve as a successful model for other nations seeking a sustainable and secure energy future.

2.3. Belgian Case

Belgium has limited underground natural resources such as oil and gas, so the country heavily relies on energy imports. The federal government aims to reduce this dependency and to make the energy supply more sustainable. With a heat demand representing 50%

of Belgium's energy needs, geothermal energy offers a pivotal opportunity to achieve sustainability goals by contributing significantly to heating networks. As fossil fuels will gradually be phased out in building heating, geothermal energy's role is expected to strengthen further.

Nevertheless, geothermal energy production remains marginal in Belgium compared to other renewable energies (mainly wind and photovoltaic). In particular, the potential of deep geothermal energy exists and is demonstrated in some regions but remains underused at the country scale. Exploration campaigns are still needed to assess the geothermal potential in underexplored regions, for example, in urban areas that could benefit greatly from geothermal applications. Geothermal energy is indeed an ideal candidate for feeding district heating networks as well as for the aquaculture, horticulture, and agro-food industries. Currently, the primary focus is to generate heat rather than electricity, owing to the limitations of the local geological context, which offers a low- to mid-enthalpy geothermal potential. Figure 4 shows the various applications that can benefit from geothermal energy in Belgium and the current limits.

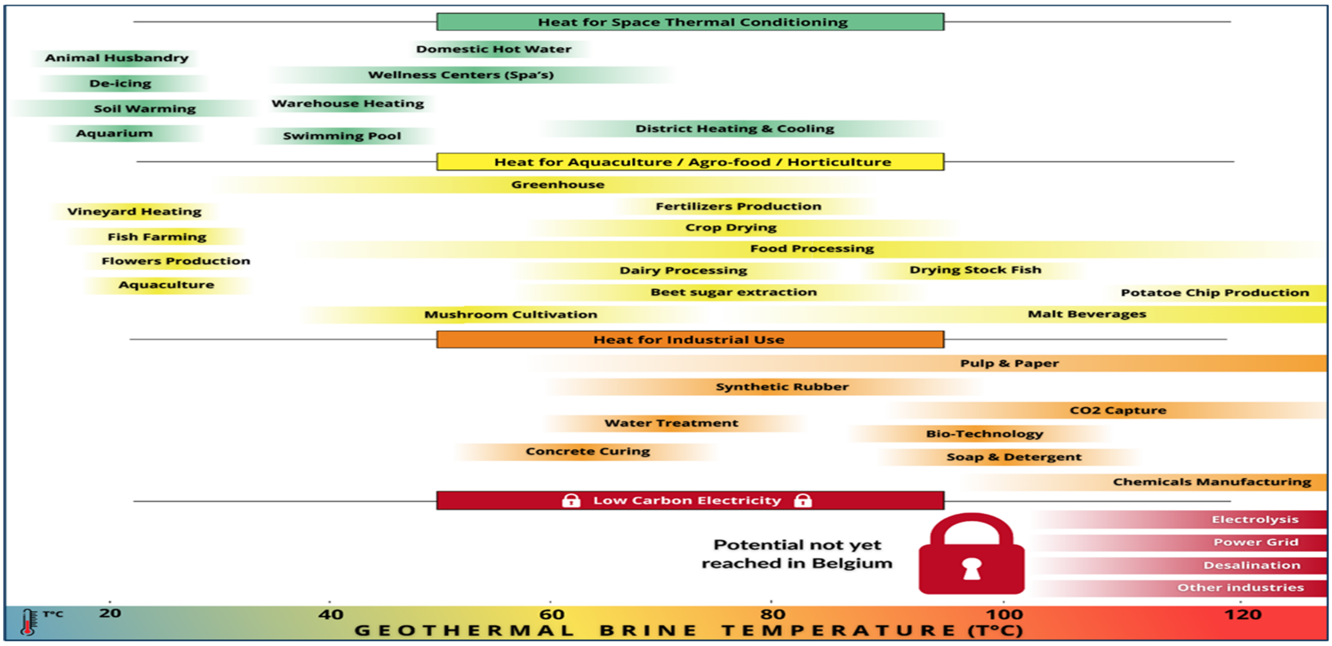

Figure 4. Various business applications that can benefit from geothermal energy in Belgium and the limits reached so far (heat below 130 °C).

The limited number of operational projects reflects that Belgium's geothermal sector is in its early stages [5]. In Wallonia, the use of deep geothermal energy is currently limited to the Mons-Borinage area in the central part of Hainaut, where three single production wells with reinjection in surface water systems are in production. In Flanders, the two existing projects are two doublets located in the province of Antwerp [41]. Four geothermal plants are in full operation and supply heating networks (in Saint-Ghislain, Douvrain, Ghlin, and Beerse). In addition, the Balmatt plant (Mol) is still under testing and operating at limited flow rates. There is still ongoing learning on the technical and regulatory hurdles. There is a need for political support and financial incentives to encourage the development of current geothermal plants and new projects. Other projects are under investigation in Flanders, and seismic exploration will be performed in Wallonia to assess the deep potential further.

In Belgium, deep geothermal energy falls mainly in regional competencies, and deep geothermal projects are regulated by separated actors and bodies of law (i.e., Flanders and Wallonia). The Flemish Decree (2009) governs geothermal projects deeper than 500 m. Exploration and production licences grant exclusive rights to exploration and production from a well-defined 3D volume in the subsurface. Exploration permits are valid for five years, allowing well drilling and testing. A production plan is required for obtaining a production licence, and an environmental permit is also necessary. In the Walloon region, the Subsoil Decree (March 2023) regulates underground resource exploration and extraction. Deep geothermal energy is defined as a renewable source, and the decree outlines conditions for exploration and extraction with exclusive permits. While an insurance system for geological risk has existed since 2018 in Flanders, a similar guarantee scheme is not yet present in Wallonia but is recommended for deep geothermal sector deployment in the region.

Despite some technical and non-technical challenges, there is a growing momentum for recognising geothermal energy potential. The current geopolitical context and the goals set by international climate agreements create a push for projects to harness this sustainable energy source from the subsurface. Moreover, the ongoing geothermal projects in Belgium play a crucial role in shaping the country's emerging market. These projects are pivotal, capable of either driving forward or hindering the progress of the Belgian geothermal industry.

Belgium has no volcanic activity, nor is the country gifted with an above-average geothermal gradient. Throughout the country, the geothermal gradient is about 32 °C per kilometre depth. The significant representation of the London Brabant Massif in the country limits suitable areas for classical deep geothermal doublets. Such projects can be developed in sedimentary basins such as the Campine Basin in Flanders or the Hainaut Basin in Wallonia. Maps of the top Dinantian are presented in Figure 5 and it highlights the presence and depth of the reservoir in the Walloon and Flemish regions. The basins are relatively limited in space but also suffer from under-exploration. The ongoing deep geothermal projects exploit the Dinantian reservoir, almost entirely composed of carbonates. However, these reservoir characteristics can vary greatly and unpredictably due to karstification or faults. The local geological and hydraulic characteristics of the reservoir have a substantial impact on the project's viability.

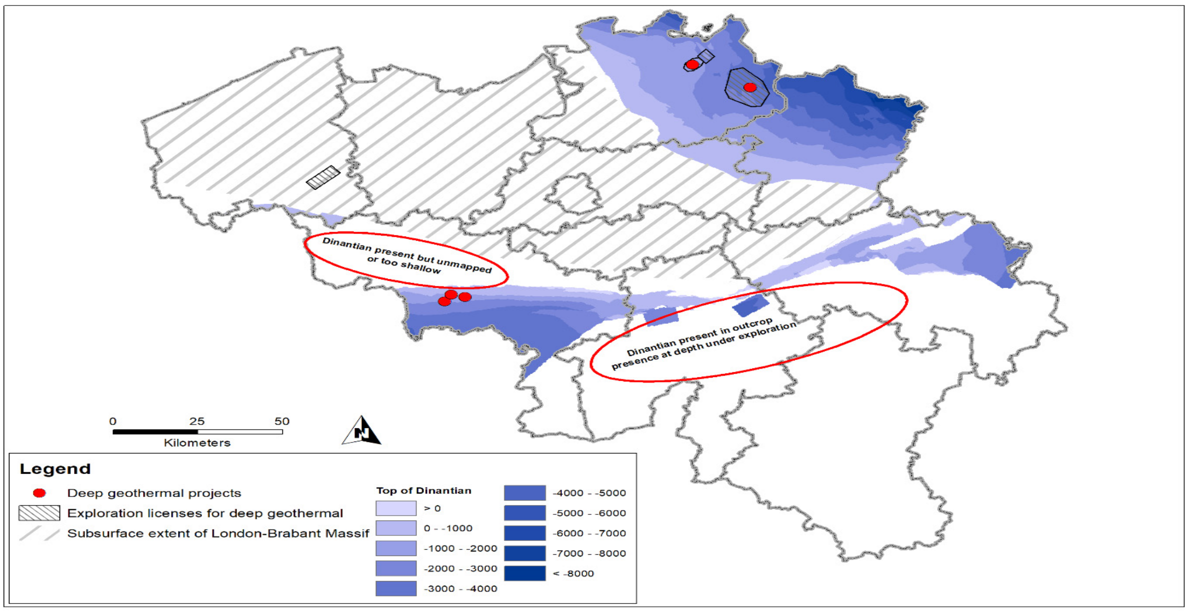

Figure 5. A map showing the depth of the top of the Dinantian (base Namurian) based on the latest DGE-RollOut project model as compiled by [42]; for Flanders, this has been updated by the G3Dv3 model of [43].

Innovative technologies are necessary to unlock the full potential of deep geothermal energy. For instance, closed-loop systems offer an alternative solution in areas where the geological context is not favourable to deploying classical doublet systems, provided that they are economically viable. They are used to harness the heat in the subsurface, relying mainly on heat conduction processes, and could play a role in Flanders, where no permeable reservoirs are present.

Another obstacle to developing the sector common to both Flanders and Wallonia is the lack of subsurface data and the limited seismic exploration in areas that could most benefit from geothermal heating, namely the urban areas. This scarcity of subsurface data currently observed in Belgium, partly stemming from unsuccessful petroleum exploration campaigns, compounds the challenges confronting the geothermal industry within the country. In Wallonia, the first wells utilised for geothermal purposes in the Mons region were drilled between the late 1970s and the early 1980s, like those in Île-de-France (France). Despite this alignment in timing, Wallonia's geothermal industry significantly lags behind the advancements achieved in France. As in Flanders, stimulating geothermal energy growth in Wallonia requires decisive political actions. Public funding is essential for conducting subsurface imaging, including seismic campaigns, significantly diminishing uncertainties and attracting private investment. Exploratory initiatives must expand beyond the confines of the Sambre-et-Meuse corridor to encompass various regions of Wallonia.

The development of deep geothermal energy is faced with additional technical challenges. In this respect, the risk of induced seismicity is recognised in Flanders as one of the main challenges when developing geothermal projects in deep heterogeneous fractured reservoirs. To address this issue, VITO has set up a research programme on its geothermal site in Mol to analyse the seismological behaviour of the Dinantian reservoir. The research aims to understand better the risks involved and mitigate them efficiently. Finally, the experience in Mol has demonstrated that communication with stakeholders, authorities, and the general public is crucial to ensure the development of deep geothermal energy.

In Wallonia, the situation is slightly different; so far, the three geothermal heating networks operating rely on the use of unique deep wells targeting the Dinantian reservoir at shallower depths. Induced seismicity has not been reported for these projects, nor is it considered a major issue. They are all managed and still developed by IDEA, the regional economic intermunicipality. The main challenge faced by the geothermal sector is linked to surface limitations. The earliest geothermal energy project in this region, located in the Mons sedimentary basin at Saint-Ghislain, has sustained a brine temperature of 73 °C and a production flow of 100 m^3/h since the 1980s. Over the years, this project has demonstrated consistent geothermal potential with stable production. However, during the summer months, when the heating demand significantly decreases, the thermal output of Saint-Ghislain remains underutilised, resulting in a loss of potential earnings for the project. Despite geothermal energy's inherent baseload characteristics, its economic viability throughout the year is impeded by the absence of surface infrastructure that efficiently utilises heat, making it challenging to operate the plant all year round.

Finally, in addition to the technical challenges, currently, the main non-technical challenges that hamper the development of the geothermal energy sector identified in the country are funding, regulatory compliance, and the lack of stable market demand to ensure a solid purchase agreement. From a financial perspective, deep geothermal projects (single or doublet systems) are also facing challenges, and for many companies, CAPEX is refraining from taking on these initiatives. Overall, for either Flanders or Wallonia, there is a potential positive shift if technical and economic viability is established over the existing projects or the ones to come involving single-well technologies.

Countries with abundant renewable energy sources gain a significant advantage in the race for global energy transition. However, with their intermittent generation, REs such as wind and solar require more delicate electricity system operation design and operation [44]. At this point, geothermal energy, with a capacity factor of up to 96% [45], serves as a baseload like other conventional energy plants, such as coal and gas. It allows countries to pursue net-zero targets while alleviating fossil fuel dependency. Besides power generation, geothermal energy offers many other direct utilisation applications such as district heating, greenhouse heating, use in thermal facilities, agricultural drying, geothermal cooling, and application of heat pumps. This way, it offers various benefits to the locals, such as increasing employment opportunities, decreasing heating costs, and raising household welfare. Nonetheless, some financial, political/regulatory, technical, and social barriers still hinder geothermal energy development and reaching its real potential.

Geothermal energy still has relatively high upfront costs, from project development to power plant installation and required civil engineering. Indeed, it has lagged behind cheaper fossil fuels and renewable energy technologies with their continuously declining costs in terms of market competitiveness. When considering the Levelized Cost of Electricity (LCOE) between 2010 and 2020, it is remarkable that the LCOE for geothermal energy increased by 45%, while it decreased by 85% for solar PV and 56% for onshore wind [46]. This cost can further increase, considering the possibility of drilling wells that may end up with little or no steam after great investments in the geothermal field. Indeed, it entails some risk mitigation schemes for compensation for unsuccessful drilling. These schemes in the form of geothermal guarantees, risk insurance, and capital grants have been applied in some countries, such as Denmark, France, Germany, Iceland, the Netherlands, Switzerland, and Turkiye [47]. Nonetheless, the lack of government-led incentives or risk-mitigating schemes continues to be a critical barrier for investors in many countries facing high risks and uncertainties in the exploration and development phases. As a prominent example, Turkiye experienced a drastic increase in the geothermal installed capacity between 2010 and 2020 following initiating an incentive scheme for power generation, highlighting the crucial role of financial incentives in attracting investors to the market [48].

Despite technological advances and increasing know-how in the energy sector, geothermal technologies are still not competitive enough with other energy sources. Geothermal energy inherently requires much more complex machinery, and the operation and maintenance of technology, mostly imported from other countries with current human resources, are quite difficult [49]. Nonetheless, offering incentives promoting domestic equipment use/production and increasing R&D efforts with national and international collaborations drive new technological advances in the geothermal sector. On the other hand, the lack of industrial standards and reservoir management issues, exacerbated by overexploitation, pose significant technical barriers to utilising geothermal resources in a more efficient and environmentally friendly manner.

The absence of centralised management of geothermal energy, lengthy and arduous permitting processes, and insufficient information for investors primarily result in project delays or abandonment [50]. Furthermore, the lack of a clear and comprehensive legal framework to regulate conflicts between geothermal developers and entities that hold rights, such as indigenous claims or local communities, is among the significant regulatory barriers [51], which also fuels social resistance to geothermal energy.

Low social acceptance is also a crucial obstacle to realising geothermal projects. There are many country examples indicating this specific issue, such as [52] for Colombia, [22] for Italy, [53] for China, [54] for Chile, [55] for Korea, and [56] for Turkiye. Improper applications of the plant operators, who only pursue their profits without environmental concerns, and the mission of informing the locals about their projects bring about social resistance to geothermal energy [48]. Limited knowledge or misconceptions, association of geothermal energy with induced seismicity, or speculative health risks are other important reasons attributed to low social acceptance. Thus, bringing all relevant stakeholder groups together and introducing geothermal energy and its potential benefits to the locals seem critical.

3. Methodology: Semi-Structured Interviews

Unlike a quantitative analysis using numerical data and conducting statistical analyses, a qualitative analysis concentrates on gaining a better insight into the research question. At this point, applying interviews is one of the most opted for qualitative approaches to collect data and gather opinions from individuals with experience in specific industry sectors. It constitutes a direct method of acquiring information from individuals having adequate information and experience on the topic of interest. Based on this method, the researchers can know how compatible their prior information on a specific issue is with the behaviour and perceptions of significant actors in the research area [4]. As stressed by [57], semi-structured interviews offer much more freedom to the researchers to acquire complete, interesting, and relevant information from the participants according to the flow of the interview. For this study, to reveal the opportunities and challenges of geothermal energy development in four different markets, from infant to mature ones, simultaneous semi-structured interviews were conducted in the scope of the GeoSmart project between 2021 and 2023. Furthermore, before reaching the final interviewers, all countries applied the stakeholder mapping procedure and determined the critical actors in their geothermal energy sectors. Based on these lists, the interviewers from different groups tried to contact and continued to find more participants along with their suggestions following a snowball sampling approach.

The interview, consisting of 15 questions, was primarily designed to uncover the interviewee's viewpoints on the geothermal energy sector, emphasising the importance of geothermal resources and exploring the tools necessary to harness their potential. Additionally, the interview context involved exploring potential incentives and schemes to enhance the flexibility of geothermal power plants. Educational and work experiences were regarded as important in obtaining accurate information from the interviews. Thus, the researchers attached particular importance to the interviewees' diverse experiences in the geothermal industry. To aid in preparation, the participants received the document containing the interview questions in advance via email. After the interviews were conducted face to face or online, the meetings were recorded with the explicit consent of the interviewees, and further transcriptions were created to analyse the answers in detail. The methodological steps are summarised in Figure 6.

Figure 6. Methodological steps for semi-structured interviews.

The interviews mostly concerned stakeholders potentially interested in the GeoSmart project outcomes, as identified by the consortium's plan for the exploitation and dissemination of results, dividing these players into six groups. Compared to the original classification, project developers and engineering contractors have been added to the first group since they may have interests similar to operators' interests within the GeoSmart aims. A seventh group of transmission and distribution grid operators has been added. Although these subjects are not linked to geothermal energy, they may be interested in the development and implementation of the flexible technologies proposed by GeoSmart, which may increase the dispatching capacity of the networks they manage. A short description of each stakeholder group is reported in Table 3. Since the development of the geothermal sector has followed a different pattern among the countries, the interview groups and the number of interviewees to be reached have also differed.

Table 3. Stakeholders' groups interviewed in Italy, Iceland, and Belgium.

Group	Group Categorization	No of Italian Stakeholders	No of Icelandic Stakeholders	No of Belgian Stakeholders
Group 1	Ultimate end users and beneficiaries: geothermal power operators, project developers, and engineering contractors	8	9	3
Group 2	Optional end users: solar thermal power sector	0	1	0
Group 3	Manufacturers	3	1	0
Group 4	Primary influential bodies/industry association	5	1	2
Group 5	Investors	0	2	0
Group 6	Others: academia and public	3	3	2
Group 7	Grid operators	0	1	0
Total		19	18	7

Nineteen stakeholders have been interviewed despite the large number of actors mapped in Italy. This is due to many reasons, notably the characteristics of these actors. Many players, such as technical services, builders, and manufacturers of equipment for plant components, often specialise in specific fields not exclusively linked to the geothermal sector but also to other industries. In contrast, some companies are very small and work exclusively for Enel Green Power. Additionally, some identified stakeholders belong to parts of the supply chain that are not directly interested in GeoSmart technologies, such as resource exploration and subsurface operations. However, in some cases, it was not possible to find contacts of stakeholders, or they were not available for interviews.

As reported in the table below, no stakeholders from groups 2, 5, and 7 were interviewed. This is because the solar sector is underdeveloped in Italy, and there are difficulties in reaching investors and grid operators. The number of stakeholders in each group differs but involving the perceptions of all groups, special emphasis has been given to a certain group. The number of interviewees has been picked by using a stakeholder mapping and keeping the interest power matrix in mind.

The Icelandic geothermal stakeholders were mapped and interviewed about their perspectives on geothermal challenges and smart geothermal energy generation opportunities. In total, 18 out of 31 identified stakeholders responded to the interview questions. Recognised stakeholders for project dissemination include energy companies, research institutions, and government agencies.

The interviews were conducted with candidates from diverse backgrounds, with diverse experiences and positions in the geothermal industry in Iceland and abroad. Efforts were made to obtain at least one company from each group to receive a broader view from various angles. Despite the strong geothermal utilisation in Iceland, there are not many companies in other groups compared to group 1. This can also reflect the low population in Iceland.

Though Iceland is sparsely populated, it has large operators that are both private and state-owned, such as Landsvirkjun (National Power Company), Orkuveita Reykjavik and its daughter companies ON Power and Veitur (municipality-owned), HS Orka and HS Veitur (privately owned), and Rarik (Iceland State electricity and district heating operator, state-owned). Energy companies are the most actively involved in R&D and often have their own innovation and research departments. Many service engineering companies also actively promote geothermal energy both domestically and internationally. They provide training and consulting in geothermal exploration, feasibility studies, and various engineering services. The most known engineering consulting companies include Verkís, Mannvit, and Efla, which have been merging with smaller engineering companies after the financial collapse of 2008. There is a limited number of drilling companies, Iceland Drilling and Ræktunarsamband Flóa og Skeiða. The geothermal energy companies buy most of their equipment from international suppliers, as deficient equipment manufacturers are available in Iceland. However, there could be bigger opportunities in developing technical components for the geothermal sector, where a lot of experience and learning curves have been obtained. Often, these manufacturers also produce equipment for other important industries in Iceland, such as fisheries and heavy industry.

Primary influential bodies consist of energy clusters and the energy authority that provide policies and support for geothermal activities. Energy clusters play an important role in connecting all the geothermal stakeholders where know-how is shared. This sector also has few investors despite Iceland's success story in geothermal energy. Due to the lack of financial support in the geothermal sector, there are few research activities in academia and research organisations. The transmission system operator, Landsnet, is state-owned and owns and operates the whole transmission system in Iceland. They are responsible and have the right to develop the new transmission facilities.

For the Belgium case, seven interviews were conducted. The experts selected belong to 7 stakeholders out of the 68 identified and represent diverse facets of the geothermal energy sector in Belgium. The selected panel consists of experts from diverse backgrounds, including geology, geochemistry, hydrogeology, engineering, business development, and project management. These professionals bring valuable insights from their roles in research institutes, national authorities, and private sector operations. The interviewees are involved in various aspects of the geothermal sector development, including deep geothermal potential mapping in Belgium, understanding subsurface fluid dynamics, project development, and policy advising at a national level. As stakeholders in Belgium, they play a strategic role in the decision-making that will advance geothermal energy adoption and address legislative gaps for sustainable deployment in the country. Attention was paid to interviewing stakeholders in both Wallonia and Flanders; three groups listed in Figure 6 were reached out to. To ensure efficiency, we have engaged the influential stakeholders in the country, selected based on their significant contributions to the advancement in the geothermal energy sector in Belgium over the past decades. Their proven track record underscores their pivotal role in driving progress within this industry.

4. Interview Results

The selected geothermal stakeholders were interviewed following the methodology outlined in Section 3. The same questions were asked in the three interviews held in Italy, Iceland, and Belgium. (These interviews have been performed as a part of the GeoSmart project in four countries including Türkiye. Turkish results have been published as a separate paper [48]. Original questionnaires include technical questions regarding the GeoSmart project. Non-technical questions could be shared upon request).

4.1. Italy: Interview Results

As part of the GeoSmart project activities, the main geothermal stakeholders in Italy were identified and interviewed. The 19 stakeholders interviewed have different roles and interests in the geothermal sector, from operators to the research sector and local authorities hosting power plants in their territories. Most stakeholders were operators and companies involved in the project design and development. However, many associations, including environmental groups and industry representatives, provided interesting feedback. No investors were interviewed because of the difficulties the geothermal sector is experiencing in Italy. In contrast, the lack of interviews with solar thermal power actors is due to the country's deficient development of this sector.

Most of the interviewees confirmed that the length and complexity of the authorisation processes are the main challenges to developing geothermal energy in Italy and pointed out the need for a national energy strategy that includes geothermal power and heat. The reason is probably the lack of solid lobbying activity compared to other renewable energy sources, as reported by interviewees, combined with low acceptance. The poor consideration of geothermal energy could also cause the lack of incentives for direct use. Most stakeholders also agreed on the need for incentives supporting innovative plants and schemes for geothermal risk mitigation to revitalise geothermal development.

Capacity building and awareness raising are two critical factors for most stakeholders' geothermal energy development. Indeed, despite Italy being a mature geothermal country with a well-developed supply chain and actors whose skills are recognised globally, a higher number of qualified technicians is required, as well as greater skill development in utilities (that usually manage district heating systems). At the same time, many geothermal projects are hampered by local resistance and poor social acceptance. Interviewees highlighted the need to increase awareness of citizens and politicians on geothermal technologies and their effects. Public opinion should be aware of the peculiarity of geothermal energy in providing renewable heat and power and that it has a high potential to generate new job opportunities. However, citizens should also be informed about potential environmental and landscape impacts. A lack of awareness may lead to the NIMBY phenomenon and lack of acceptance, despite all wanting to decarbonise energy production. In addition, geothermal projects should involve and liaise with territories and local communities before requesting permits.

Direct heat and higher acceptance are the two main critical factors for the use and higher acceptance that are the two key factors for geothermal development. In addition, stakeholders considered the high potential and possibility of making geothermal flexible important opportunities. Changes in electricity consumption and the increase in renewables in the energy mix led to the rise in turbo gas plants and system charges in the energy bill. Indeed, the current market conditions favour the baseload energy production for geothermal energy, and flexibility should be rewarded, e.g., with special tariffs and instructions from the grid manager to better understand the plant requirements and sizes.

Despite one interviewee's generalisation reporting that geothermal energy is a site-specific resource and generalisation could be considered a futile effort, most actors believed that establishing technical standards, such as standardised protocols like the Geothermal Sustainability Assessment Protocol [58], may give more certainty to investors. According to what was reported during interviews, technical standards should concern heat production, extraction of raw materials, and performance testing of geothermal plants since developers usually satisfy the customer by proposing performances higher than the real ones. Stakeholders deemed it necessary to bring together the entire geothermal supply chain (notably technology providers and developers) to promote new standards, as conducted for the O&G industry. In addition, relationships with the O&G industry should be established to adapt their standards to the geothermal sector.

4.2. Belgium: Interview Results

In Belgium, the results are based on the seven interviews of experts conducted and reflect the perception of the three stakeholder groups they belong to. It is important to note that the Belgian geothermal industry primarily focuses on heat delivery. Indeed, all Belgian deep geothermal projects currently operating tap into the Dinantian carbonate reservoir with temperatures ranging from 73 °C to 130 °C according to where it is developed in the country. Although electricity production remains perceived as potentially interesting for the energy sector, its development is hampered by the lack of optimal technical solutions to produce electricity under the Belgian local geological constraints that limit the feasibility of standard geothermal technologies. Consequently, the interviews pointed out that heat production remains the main focus for geothermal energy production in the short term in the country and that geothermal electricity production is a longer-term goal.

The interviews also highlighted that to maximise geothermal energy potential in Belgium, there is a need for technological solutions (innovations for the deployment of alternative systems) in environments where the geology does not offer deep-lying reservoirs/aquifers (with good porosity network), at high temperatures. There is also the need for financial and political support, tailored regulations, a legal framework, and investment in research.

The industry is sometimes challenged by inconsistent political support, urging stronger legislative frameworks. Policy initiatives in Flanders (decree on deep subsurface and the implementation of an insurance system) illustrate policy support in this region. They highlight the political motivation of seeing geothermal share growing in the energy mix. In the Walloon region, until the beginning of 2024, there was a lack of tailored environmental permits specific to geothermal projects, which was a great cause of uncertainty among the geothermal potential project developers. The adoption in March 2024 of the decree for underground resources management by the Walloon Government shows the political willingness to develop deep geothermal energy in the region. It is perceived positively by the stakeholders as it clarifies the regulation for deep geothermal projects and supports the development of deep geothermal energy. The text replaces the obsolete Mining Code and aims to better manage mining resources.

Some experts have proposed implementing financial incentive schemes to ensure a decent profit margin or return on investment, especially when gas production is cheaper. They also suggest considering dedicated financial incentives for geothermal projects, such as recoverable loans and insurance, to support the sector's development.

Another viewpoint underscores the critical importance of securing commitments to utilise the geothermal heat produced. Without a dedicated party committing to fully utilise the generated geothermal heat, the project might face challenges securing financing through project funding. Government involvement in ensuring heat off-take commitments is a significant factor for successful business cases.

In Belgium, geothermal energy is so far perceived as a baseload source of energy that can provide heat to heating networks mostly during the heating season and to a lower extent during the summer for specific applications. Currently, the cascading use of the resource is seen as a flexible component of geothermal plants. However, stakeholders recognise that adding some flexibility to the plant would be beneficial to make the facilities more resilient and efficient. If it is demonstrated that adding thermal storage at affordable costs to geothermal heating plants combined with smart installation control would increase the plant's productivity, this solution would also be interesting for the Belgian market. To enhance flexibility, some interviewees suggested integrating geothermal plants with complementary technologies like cooling absorption machines, heat pumps, smart district heating networks, and thermal energy storage. With regards to the heating distribution only, there will always be a willingness to dedicate a percentage of capacity to flexible use if a well-designed and successful business plan is in place.

The interviews also revealed that there is a critical need for public outreach to foster social acceptance and engagement to facilitate the growth of geothermal projects. They outlined that communication with stakeholders, authorities, and the public is crucial to ensure the development of deep geothermal energy and that transparency is a key element. Successful ongoing geothermal initiatives and the benefits of geothermal energy should be highlighted and promoted, serving as inspiration for new projects. Moreover, the public is often confronted with contradictory information, and the scientific community should provide objective answers to its questions and concerns. As an example, the recent seismic events felt in 2022 by the population in Mol during the development of the Balmatt deep geothermal plant have triggered concerns in local communities. To address these, preventive measures were taken by VITO nv, including the extension of the existing monitoring system and the operational Traffic Light Systems (TLSs), which help to manage and mitigate induced seismicity. Allocating a suitable budget for seismic studies to image the deep subsurface mitigates risks and enhances the public's trust and engagement. Some interviewees underlined the importance of seismic monitoring systems in detecting and localising events when they occur. Also, engaging with local communities regularly is key. A collaborative platform involving policymakers, citizens, and the industry could facilitate better communication and establish national standards for improving the acceptance of geothermal energy.

It is also crucial to emphasise the concurrent advancement in surface installations, like heat pumps and energy systems, to establish a robust local energy market. Belgium currently faces a circular challenge: the effective use of subsurface heat is constrained by inadequate heat network infrastructure. In contrast, such infrastructure development is stymied by limited access to geothermal energy. To overcome this, leveraging geothermal heat must align with establishing compact district heating systems at the surface. The synergy between these technologies will meet the demand effectively, facilitating widespread geothermal deployment and positioning it as a key element of the energy mix to roll out from fossil energies and move towards a net-zero industry. Developing surface installations to valorise the harnessed heat is a critical factor. Surface and subsurface operations must be organised efficiently, as securing the projects' economic viability via Heat Purchase Agreements (HPAs) is key.

Furthermore, in most parts of Belgium, the lack of subsurface data refrains companies from investing in geothermal projects requiring a high CAPEX without a guaranteed return on investment. Although effective policies and regulations are currently being implemented to provide financial incentives for companies to take the initiative, the interviews reveal that there is still a need to promote subsurface data transparency. The latter is essential to reduce further the exploration risks for additional investors and stakeholders interested in pursuing such projects.

The stakeholders interviewed highlighted the challenge of harmonising standards due to geological differences while advocating for a balance between safety and sustainability. Additionally, they emphasised the necessity for comprehensive studies to establish best practises and technologies for the geothermal industry.

4.3. Iceland: Interview Results

By following GSAP protocol guidelines, Iceland exemplifies sustainable geothermal development, successfully harmonising environmental, economic growth, and social well-being, and provides perfect case studies, examining them in practise. However, unlike Italy and Belgium, geothermal energy is one of the main sources of energy in Iceland and in that way, the challenges faced by Iceland are mainly technical. Critical technical indicators such as resource efficiency, reliability, and maintenance are connected to one root cause problem, which is silica scaling. The silica scaling hinders utilising the geothermal reservoir sustainably. It limits the temperature at which energy can be extracted, thereby reducing heat transfer efficiency and decreasing the heat supply from geothermal power plants, thereby reducing both geothermal utilisation efficiency and the primary energy efficiency.

According to interviews, addressing this issue by implementing scaling reduction systems could significantly decrease maintenance time, operational complexity, and costs throughout the various stages of power plant operations. Therefore, the stakeholders expressed interest in silica scaling solutions, which could bring significant benefits such as profits from retained silica sales and increased energy recovery due to reduced reinjection temperatures. The operation of the plants has become relatively easy after over 50 years of operation. The geothermal sector is still growing, although some plants are more difficult to run than others. Interviewers specified that there is a possibility of utilising low- pressure steam more efficiently than now. Plants with high intake pressure have an abundance of low-pressure steam in Iceland.

New possibilities in utilisation techniques will eventually make the utilisation of super-critical fluid possible. It will greatly increase geothermal energy production. The geothermal sector has large possibilities for further growth in Iceland, as the demand for green electricity and hot water is constantly growing. In doing so, it will face many challenges like environmental concerns, slow licencing authorities, inflexible legal framework, etc [59]. New opportunities in utilising geothermal energy, like deep drilling and a magma bed, will open new possibilities to enormous power potential for the geothermal sector once utilisation techniques become available. The stakeholders point out that using elements and minerals in the spent fluid, like silica, lithium, magnesium, calcium, heavy metals, etc., has been lacking in Iceland. Possibilities are available, and waste material could be turned into valuable products.

From the perspective of energy clusters representing Iceland's entire energy industry, the geothermal sector efficiently utilises Iceland's geothermal resources. However, they highlight the importance of maximising utilisation through innovation and broader market access, suggesting that geothermal energy should continue to play a significant role in Iceland's energy mix. The most efficient power plants are Nesjavellir and Svartsengi with their utilisation efficiency ranging from 50 to 60% due to their co-generation capabilities, providing district heating to neighbouring communities, Hellisheiði and Reykjanes, which only produce electricity, and have similar utilisation efficiencies of around 37% [60]. The primary energy efficiency is consistent across all power plants, ranging from 12% to 15.6% [60]. Krafla ranks third in utilisation efficiency (38%) and primary energy efficiency (13%).

The current plants have slowly but steadily been expanding their operations, such as providing hot water for space heating. If it had not been for the supply of hot water from Nesjavellir PP and later Hellisheiði PP to the metropolitan area, a shortage of hot water would have been imminent in the 1990s. Other plants like HS Orka also supply hot water to neighbouring municipalities. HS Orka is also providing local businesses with spent hot water—a good example being the Blue Lagoon. Power operators emphasise the direct use of geothermal fluid for heat or its conversion into electricity, which presents a substantial opportunity, particularly in Iceland. The feasibility of storing geothermal energy for both direct use and electricity production remains a promising avenue. However, creating storage systems large enough to substantially impact power plants remains economically and technically challenging. Therefore, looking for new technologies that provide energy storage solutions is important.

This provides an opportunity to increase the fraction of geothermal energy further by pairing it with other renewable energies, such as wind power, which has received significant interest in recent years. Few turbines have been operating with 2.4 MW, which is expected to increase. Geothermal energy can serve as a baseload, maintaining energy supply when wind is unavailable, thus playing a crucial role in the global transition from fossil fuels to renewable energy sources and achieving the climate goals outlined in the Paris Agreement. Power operators also agree that Iceland has been utilising geothermal resources efficiently but see room for improvement as 27% of electricity is still produced using geothermal energy [30] and over 89% of heat energy. Some stakeholders said that geothermal energy should have closer to a 100% share of heat energy. In contrast, others said that it would be inefficient for some countryside parts due to long distances and accompanying energy losses. Instead, heat pumps, as used in European countries with low-enthalpy geothermal areas, should be reviewed. They stress the importance of innovation and collaboration, advocating for hybridisation projects to increase flexibility. They seek advanced equipment and maintenance techniques to mitigate scaling issues and optimise energy production.

Social acceptance of geothermal energy is another vital aspect of GSAP social indicators that needs addressing. Community engagement, health and safety, and cultural heritage are highly encouraged in Iceland. The stakeholders stress the importance of social acceptance of geothermal energy, claiming that the operation of the geothermal plants will be difficult without it. It is undoubtful that using spent water for spas has supported the social acceptance of geothermal energy in Iceland and globally. Interviews with Icelandic geothermal stakeholders revealed a generally positive outlook for the industry, with widespread social acceptance. However, some resistance exists due to concerns about the disturbance of natural beauty, H_2S, and carbon emissions. Nevertheless, the injection of CO_2 is being elevated to a much larger scale than what is emitted from geothermal power plants. Carbfix, a daughter company of Orkuveita Reykjavik, has provided a natural and permanent storage solution by turning CO_2 into stone underground near the Hellisheiði geothermal power plant. There is also a need for increased diversity within the sector. Promoting gender and age diversity could enhance different marketing approaches, improving social acceptance. Diversity would help to make different marketing approaches to improve social acceptance, as today it seems it is mainly a man-dominating sector. Reykjavik's historical transition from a smoky town to one utilising a small geothermal system highlights how societal shifts can successfully embrace geothermal energy. Initiatives to promote geothermal energy's applicability across various regions can further change public perception, demonstrating its feasibility beyond volcanic areas.

Engineering consulting companies pointed out that economic challenges also play a significant role in developing geothermal energy projects. While the initial costs are high, the operational costs are relatively low. Addressing these economic challenges, especially in the context of the European energy crisis, requires a shift towards reducing energy demand and increasing renewable energy usage where the district heating systems using geothermal energy can enhance economic viability and social acceptance, particularly in developing regions where low-income populations benefit from affordable heating solutions. The inclusion of social scientists and economists in engineering projects has become crucial for addressing these broader economic and social concerns.

The stakeholders point out that another benefit of having more flexibility and storage solutions was to balance the grid from the disturbances that may occur from the large energy consumers, such as aluminium or silicon smelters. Therefore, geothermal energy could be used to stabilise the grid. However, one should remember that these geothermal units are quite sensitive to power quality, like frequency deviations, due to the nature of using high-speed turbines. These technical challenges should be investigated and optimised. Once you have optimised and utilised, integrating geothermal energy with renewable sources like hydro or wind could lead to a more robust and stable energy grid. For instance, it could be economical to have the geothermal power plant running at a constant rate and let the hydropower plants operate at a more flexible rate, particularly during periods of low water inflow into the water reservoir. Currently, grid limitations are hindering utilisation in very productive areas in Iceland.

Iceland also provides a good case for applying environmental GSAP indicators and stakeholders emphasised the importance of ensuring the long-term sustainability of geothermal resources through careful monitoring and developing regulations to prevent overexploitation. For instance, the low-temperature reservoirs in the capital region could be rested in the summertime when there is less demand for heat by providing heat from Hellisheiði high-temperature reservoirs.

The stakeholders in the drilling sector mentioned that technology knowledge, supporting policies, and drilling risk mitigation standards would help utilise the geothermal energy potential at the highest level in Iceland.

Many stakeholders also claim that incentives such as schemes to promote the use of geothermal energy in other sectors and support for small and large industries that can benefit from geothermal energy where multiple sectors mutually benefit can increase the flexibility of geothermal plants.

For example, geothermal energy can be combined with tourism (e.g., Helliðheiði Exhibition Center, where tourists receive an introduction to how geothermal power plants operate). This also includes actions to promote the use of heat to other small industries such as Friðheimar where tomatoes are grown all year round in the greenhouses. They welcome tourists and offer a menu based on tomatoes at the greenhouse.

From the interviews, common themes emerge, emphasising the efficiency and significance of Iceland's geothermal sector, along with identified areas for improvement and shared optimism for the geothermal energy's positive impact. First and foremost, geothermal energy should provide baseload power, as it is a baseload renewable energy source. In addition, it is and will be increasingly important to supply hot water to the ever-growing metropolitan areas. The discussion underscores the importance of incentives such as increased financing and hybridisation projects to enhance flexibility. Recommendations encompass continued government support, investment in hybridisation, sustained research and development efforts, and educational initiatives to foster public understanding and acceptance. In conclusion, the collective insights depict a positive outlook for Iceland's geothermal sector, underscoring the ongoing need for collaboration, innovation, and stakeholder engagement.

Considering the interview results in these three countries, we see that although many differences exist as the settings are different, there is a great emphasis on incentive policies and the role of geothermal energy in terms of energy policies and plans in these three countries. Although it comes as no surprise that energy policies are very important and improvements could be particularly important, the design of it is especially important. Although technical studies dominate geothermal energy studies, there is more need for policy studies that could direct us towards the best policy exercises that could improve geothermal energy use and extraction. Appropriate financial incentives also seem important. Although participants agree that financial incentives could be useful, they are not very sure which financial incentives could be better. Policy exercises with different financial incentives and impact analyses seem important. Technical solutions like solutions to silica scaling, alternative systems where there is no deep-lying reservoir, heat pump systems, and designing different hybridisation systems with geothermal energy also seem important. It is also particularly important to note that geothermal energy could not be used extensively and exploit its potential as a renewable energy source without the existence of society. We need to explore the social acceptance towards geothermal energy and why it is extremely low in certain areas. Even in the countries where acceptance is remarkably high, public engagement should be held successfully.

5. Conclusions and Policy Recommendations

This paper aims to discover the opportunities and challenges of geothermal energy in three country settings: Italy, Belgium, and Iceland. Semi-structured interviews were held with the main stakeholders that represent the quadruple helix (science, policy, industry, and society) in these countries. The objective was to understand the similarities and differences in terms of opportunities and challenges in countries with different geothermal potentials and policy frameworks due to their unique geological and regulatory contexts.

Italy has a long history of geothermal energy, starting from ancient times and continuing with an industrialisation process in the 20th century. Power generation in Italy uses deep geothermal resources concentrated in Tyrrhenian regions, with the Enel Green Power company operating all 34 geothermal plants. Italy produced approximately 6 TWh in 2021 but still faces bureaucratic hurdles, lengthy authorisation processes, and limited public awareness, impacting investor confidence. The stakeholders interviewed mention the complex and lengthy authorisation process as an important barrier. There is also a need for a cohesive national energy policy that emphasises geothermal energy. Despite the mature geothermal sector in Italy, the deficient lobbying efforts and incentives hamper the development of geothermal energy. Lack of public awareness and certain social resistance seem to increase the challenges mentioned above. Innovative plant schemes, direct-use incentives, and capacity building are the opportunities mentioned by the stakeholders.

In Belgium, geothermal energy production is relatively marginal compared to other renewable energy sources, such as wind and solar energy. Therefore, Belgium is heavily reliant on energy imports. Due to geological constraints, rather than electricity, the potential for deep geothermal energy is primarily used for heating. There is a focus on district heating, aquaculture, horticulture, and agro-food industries. Belgium has five operational deep geothermal plants located in Wallonia and Flanders. Lack of subsurface data and induced seismicity are perceived as the main challenges. On the other hand, recent legislative changes and financial incentives are seen as support to the development of geothermal energy. According to the stakeholders interviewed, technological innovations like closed-loop systems could enable the development of geothermal applications in regions where standard doublet technology is not feasible. In addition, effective communication with stakeholders is seen as crucial. Public engagement has been emphasised to increase social acceptance and mitigate societal concerns about energy.

In contrast, Iceland has an advanced geothermal sector that is used for both heating and electricity generation and has become one of the global leaders in geothermal energy utilisation. Iceland's high-temperature geothermal resources are used for space heating electricity and various industrial production processes. Geothermal energy contributes quite a bit to its energy mix, accounting for 30% of total electricity generation. The strong emphasis on environmental sustainability, innovation, and comprehensive planning contributed to the geothermal energy sector in Iceland. The National Energy Authority oversees the country's strategic energy approach and regulatory support. This could set a valuable model for other nations to enhance their national energy portfolios. Stakeholders in Iceland suggest that the main challenges revolve around sustainable resource exploitation and some technical issues like silica scaling. Innovation in utilisation techniques and better management of environmental aspects are seen as being advocated for by the Icelandic stakeholders. Unlike Italy and Belgium, social acceptance is high in Iceland, but stakeholders mention that diversity and public engagement are still very important for the country. Improvements in grid stability seem to be an important opportunity that could be achieved by hybrid systems with the integration of geothermal energy with other renewables.

From a policy perspective, when we consider the three countries, the following four strands of policy advice could be extracted. The first policy advice could be simplifying the regulatory frameworks and improvement in the incentive schemes. The authorisation process seems to be very complicated in Italy and needs simplification. There is also a need to develop a comprehensive national strategy that could prioritise geothermal energy using incentives for direct use and innovation schemes for geothermal plants. In Belgium, there is a need to have supportive and consistent legislative frameworks across all regions through financial incentives such as recoverable loans and insurance schemes to decrease investment risks. In Iceland, the initial regulations can be supported to prevent over-extraction, and improvements in hybridisation projects and technological innovations within the geothermal sector could be crucial.

Another policy that could be suggested is to increase public awareness and capacity building. It could be recommended that Italy invests in capacity building by amplifying the number of qualified technicians and improving the skills within utilities managing district heating systems. Meeting occasionally with the public and launching awareness campaigns to educate the public and policymakers on the potential benefits of geothermal energy and its actual possible impacts on the environment seem important. In Belgium, with an emphasis on successful geothermal projects, public outreach to improve social acceptance could be promoted. This could build up public trust and support for geothermal energy. Emphasising the environmental and economic benefits of geothermal energy through public engagement and education could be important in Iceland as well, even though social acceptance is quite high initially compared to Italy and Iceland. Addressing the concerns about natural beauty and emissions also seems important in the Icelandic setting.

Improving technological innovation and integration seems to be other relevant policy advice in these areas. The three countries could work to improve technological innovation in diverse ways. Italy can encourage the development and implementation of technical standards for geothermal energy production. Belgium could invest in technological innovation for heat production in geographically challenging environments in combination with technologies like heat pumps and smart networks. Iceland could concentrate on innovative utilisation techniques that could improve resource efficiency. Strategies to mitigate scaling issues and energy recovery could be areas of improvement from a technical perspective.

One other important policy could be within the framework of boosting flexibility and resilience of geothermal power plants for the three countries. Italy could recognise and reward flexibility through special tariffs, and instructions could be given to grid managers to promote flexible and resilient geothermal plants. Belgium could encourage the use of thermal storage and smart business plans to support the flexible use of geothermal energy. Iceland could integrate geothermal energy with other renewable sources, such as hydropower and wind, to improve flexibility.

Lastly, the collaboration with the public and stakeholder engagement seems to be relevant policy advice for the countries. In Italy, engagement with geothermal stakeholders, including technology providers and local communities, is needed to promote new standards and increase social acceptance. Belgium needs to establish communication platforms with citizens, policymakers, and industrial players to improve communication and to produce national geothermal standards. Iceland could also support its ongoing engagement with its stakeholders to address the challenges and to promote and explore new opportunities for its geothermal sector.

Italy, Belgium, and Iceland, as three countries with different potential for the geothermal sector, have common as well as different opportunities and challenges. Similar policy actions with country-specific inclusion could improve the uptake of geothermal energy applications in these three countries, helping the clean energy transition in these countries.

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