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Sustainable Development through Geothermal Energy: Findings from Germany, Italy, Turkey, Iceland and France

Zrównoważony rozwój w kontekście energii geotermalnej: przykład Niemiec, Włoch, Turcji, Islandii i Francji

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Abstract
Geothermal energy plays an important role in Europe's transition towards sustainable energy systems, significantly contributing to environmental, economic and social sustainability. This paper conducts a comparative analysis of geothermal energy development in Germany, Italy, Turkey, Iceland and France. It highlights their unique approaches, policy frameworks and technological advancements. The study reveals that geothermal energy strengthens energy security, reduces greenhouse gas emissions and promotes economic growth. Despite different levels of development, each country shows progress in integrating geothermal energy into their renewable energy portfolios. The findings show the importance of strong governance, policy support and technological innovation in order to achieve sustainable development by developing and using geothermal energy.

Key words: geothermal energy, sustainable development, renewable energy policy, comparative analysis

Streszczenie
Energia geotermalna odgrywa ważną rolę w przejściu Europy na zrównoważone systemy energetyczne, znacząco przyczyniając się do zrównoważoności środowiskowej, ekonomicznej i społecznej. W niniejszym artykule przeprowadzono analizę porównawczą rozwoju energii geotermalnej w Niemczech, Włoszech, Turcji, Islandii i Francji. Podkreślono w nim ich unikalne podejścia, ramy polityczne i postęp technologiczny. Badanie wykazało, że energia geotermalna wzmacnia bezpieczeństwo energetyczne, zmniejsza emisję gazów cieplarnianych i promuje wzrost gospodarczy. Pomimo różnych poziomów rozwoju, każdy kraj wykazuje postęp w integrowaniu energii geotermalnej ze swoimi portfelami energii odnawialnej. Wyniki pokazują znaczenie silnego zarządzania, wsparcia politycznego i innowacji technologicznych w celu osiągnięcia zrównoważonego rozwoju poprzez rozwój i wykorzystanie energii geotermalnej.

Słowa kluczowe: energia geotermalna, zrównoważony rozwój, polityka wobec energii odnawialnej, analiza porównawcza

1. Introduction: Understanding geothermal energy

Geothermal energy comes from the Earth's internal heat, and it is an important component in the global transition leading to sustainable and renewable energy systems. As concerns over climate change and fossil fuel depletion take place all the time, the adoption of renewable energy sources becomes higher and higher. In this case, geothermal energy stands out for its capacity to provide consistent and reliable electricity as well as heating energy, making it a versatile and resilient part of the energy mix.

Given the continental geography of Europe and its unfulfilled potential for harnessing subterranean heat to generate electricity, an increased presence of geothermal power might almost be overdue there. A strong commitment to greenhouse gas reduction and energy security in the region supports substantial market growth for geothermal. Whilst solar, wind and battery storage are essential to reduce the carbon emissions from our power production systems, geothermal energy is one of only a few sources that may be able to deliver stable renewable generation (Karlsdottir et al., 2020; Schütz et al., 2013; Procesi et al., 2013; Giambastiani et al., 2014; Stefansson, 2002).
This paper, therefore aims at to investigate geothermal energy developments in five European countries: Germany, Italy, Turkey, Iceland and France. Together these countries provide examples of various phases and approaches to applying geothermal energy, all informed by their geological landscapes, policy contexts and advances in technology. Specifically, the comparative analysis is intended to offer insights into designing geothermal energy policies that can contribute effectively to sustainable development.
This paper has the two main objectives, to analyze whether geothermal energy contributes in fulfilling two important Sustainable development goals (SDGs): affordable clean energy (SDG 7) and climate action (SDG 13). It aims to establish the environmental, economic and social benefits of geothermal projects as well as uncovering best practices and policies that are effective in different environments.
This paper solves the under-exploitation of geothermal energy, while its potential in Europe is large. While some countries like Iceland are able to incorporate thermal energy into national plans, others face barriers due to location and available resources. The policy support is not enough yet, there are technical constraints as well as infrastructural challenges and lack of public awareness and acceptance.
By analyzing the experiences of Germany, Italy, Turkey, Iceland and France, this paper has the aim to identify these barriers and propose what actions and strategies are needed to eliminate the barriers. Each country's approach offers unique insights into the benefits and challenges that come associated with geothermal energy. For instance, Germany's extensive use of geothermal heating, Italy's leadership in geothermal electricity generation, Turkey's rapid capacity expansion, Iceland's comprehensive geothermal utilization and France's innovative regulatory frameworks provide a very much diverse case studies of success and also identify the areas for future improvement.
Social and economic benefits of geothermal energy are as important as the environmental aspect. Local economic development with job creation and infrastructure investment can be driven, these acts will also ensure lower energy costs for consumers and greater national self-sufficiency in terms of supply by decreasing reliance on imported fossils. It can enhance the quality of life socially by giving a stable and sustainable source of energy, especially in areas where there is less accessibility to alternative forms for capturing renewable energies (Alsaleh and Wang 2023; Alsaleh et al., 2023; Al-Qadami et al., 2022; Soltani et al., 2021; Bashir et al., 2023). The paper also highlights how policy measures and regulatory frameworks can greatly aid the development of geothermal energy. An effective governance structure will help to build the right conditions that would foster investment, innovation, and public acceptance of geothermal technologies. The paper maps out how other regions may look to the successes of world-leading countries and emulate their policy interventions best practices, ultimately finding a way towards lasting sustainable energy solutions (Dumas, 2019; Meirbekova and et al., 2024).

2. Literature review

Geothermal energy represents a small but nonetheless a significant portion of the renewable energy mix in Europe. According to the European Parliament, geothermal energy accounted for 0.2% of electricity generation in the EU in 2022, showing its potential as a reliable and sustainable energy source (European Parliament, 2023). The European Geothermal Energy Council (EGEC) describes geothermal energy as an *endless source of renewable energy* (World Economic Forum, 2021).
In Central Europe, the use of sustainable decentralized shallow geothermal systems is anticipated to grow substantially, with expectations that 50% of new buildings in Austria will utilize such systems (Sitzenfrei et al., 2011). Similarly, Toth (2024) discusses the potential for Eastern Europe to leverage new EU funding and possible upcoming renewable energy legislation to support geothermal energy integration into the currently existing energy systems.
The governance of the geothermal energy industry is very important for its future sustainable development. The GEOENVI project emphasizes the importance of addressing environmental concerns and promoting best practices within the geothermal sector (GEOENVI, 2024). Additionally, governance factors have a high level of influence to the sustainability of geothermal energy in EU economies, with emerging economies that are showing greater improvements through better governance (Alsaleh & Abdul-Rahim, 2023). Avci, Kaygusuz, and Kaygusuz (2020) highlight that despite geothermal energy's potential, there is a lack of formal or general frameworks for assessing its sustainability. Their study calls for the creation of strong sustainability assessment frameworks to ensure that both current and coming geothermal projects contribute positively to sustainable development goals (Avci, Kaygusuz, & Kaygusuz, 2020).
The European Parliament's adoption of a strategic approach for geothermal energy development has the aim to harmonize standards and to promote sustainable growth across the geothermal energy sector (European Parliament,

2024). Economic sustainability and market conditions are of very high importance for the growth of geothermal energy. The geothermal energy market in Europe is expanding every year, with 130 geothermal electricity plants operational and numerous projects under development (European Geothermal Energy Council, 2020). However, appropriate market conditions will be needed in order for this growth to continue effectively.
Geothermal energy's role in reducing greenhouse gas emissions and providing constant baseload energy generation makes it a high-profile player in the transition to sustainable energy systems (European Parliament, 2023). The review by Shortall et al. (2015) shows the significant sustainability impacts of geothermal energy projects that are also including their contributions to reducing environmental pollution and combating climate change. Ozer and Kizilay (2021) analyze the alignment of geothermal energy projects with the United Nations Sustainable Development Goals (SDGs), showing their contributions to clean energy (Goal 7), zero hunger (Goal 2), economic growth and well-being (Goal 8) and clean water (Goal 6).
Technological advancements are very important for the sustainable development of geothermal energy. The use of information and communication technology (ICT) positively impacts the sustainability of the geothermal energy industry and therefore the economic sustainability outputs increase together with technological advancements (Wang and Alsaleh, 2023).
Future scenarios predict that geothermal technology could contribute 4-7% to overall geothermal power generation in Europe and significant increases in geothermal heat usage by 2050 (Dalla Longa et al., 2020). The continuous development of geothermal strategies and frameworks, as seen in the GEOENVI project, are and in the future will definitely be of high importance for addressing environmental concerns and ensuring the sustainable growth of geothermal energy (GEOENVI, 2024).

3. Methodology

This study develops a comparative analysis of geothermal energy progress in Germany, Italy, Turkey, Iceland and France. These countries were selected due to their advanced geothermal infrastructures, diverse geological conditions, varying levels of geothermal energy adoption and availability of detailed data. This range offers insights into both well-established (Iceland, Italy) and emerging (Turkey, France) geothermal energy markets, as well as unique policy and technological approaches. Data were sourced from the European Geothermal Energy Council (EGEC) market reports (2019-2023) and supplemented with Eurostat and national energy statistics (references included under sourced data).
The steps to make a comparative analysis were as follows:

1. Country selection. Countries with significant geothermal activities and detailed data in the EGEC reports were selected.
2. The identification of key metrics. Metrics included installed geothermal capacity, annual energy production, number of geothermal plants, policy support measures and technological advancements.
3. Data analysis. Data were analyzed to identify trends, patterns and disparities. Graphical representations were created to visualize comparisons.
4. Contextual analysis. The data were framed within the context of sustainable development goals (SDGs), focusing on environmental, economic and social impacts.

The following sustainable development aspects were considered:

1. Environmental impact. The reduction in greenhouse gas emissions through the use of geothermal energy was quantified and compared among the countries (Ozcelik, 2022).
2. Economic benefits. The economic impact of geothermal energy was evaluated by examining job creation, investment in local economies and energy cost savings (Hackstein and Madlener, 2021).
3. Social impacts. The social benefits, such as energy security, accessibility and community acceptance of geothermal projects, were analyzed (Liao, 2023).
4. Policy and regulatory frameworks. The effectiveness of policy measures and regulatory frameworks in promoting geothermal energy was compared (Doğan et al., 2022).

The findings were synthesized to receive meaningful conclusions about the main topic of geothermal energy in sustainable development. By focusing on a comparative analysis of geothermal energy development across different European countries, this study shows just how significant the contributions of geothermal energy to sustainable development are. This type of methodology makes sure that there is a thorough examination of the environmental, economic and social impacts and therefore it provides a comprehensive understanding of how geothermal energy can support a sustainable future.

4. Results & discussion

Germany, Italy, Turkey, Iceland and France were chosen due to their advanced geothermal infrastructures, diverse regulatory frameworks and contributions to sustainable development. Germany is leading in geothermal heating applications and the scale of research they are doing. Italy has a long-lasting history perspective with its geothermal sector. Turkey is rapidly progressing rapid with its expansion and therefore there is a strategic investment in geothermal projects that have an effective policy-driven growth. Iceland has plenty of abundant high-temperature resources, it is a benchmark for any possible integrated geothermal energy use. France has high ambition and progressive policies in geothermal heating systems, they also demonstrate innovative regulatory support.

Table 1. Geothermal energy capacity, production, and policy support measures in selected countries, created by Authors

Country	Installed Geothermal Capacity (MWe, MWth)	Gross Electric Production (GWh)	Gross Heat Production (GWh/Y in 2021)	Number of Geothermal Plants (electric, thermal)	Policy Support Measures	Technological Advancements
Germany	50.1 MWe (electric), 6349 MWth (thermal)	207.7 GWh (electric)	1,324.99 GWh (thermal)	12 plants (electric), 40 plants (thermal)	FIT, priority dispatch, subsidies, Renewable Energy Sources Act (EEG)	Binary cycle (ORC), Enhanced geothermal systems
Italy	915.79 MW (electric), 518 MWth (thermal)	5,731.59 GWh (electric)	478.435 GWh (thermal)	36 plants (electric), 31 plants (thermal)	FER 2 subsidy scheme, Regional support frameworks	High-enthalpy resources, Combined heat and power
Turkey	1,691.31 MW (electric), 999 MWth (thermal)	9,092.61 GWh (electric)	2,026.39 GWh (thermal)	72 plants (electric), 19 plants (thermal)	Renewable Energy Law, Capacity payments	High-temperature resources, Deep drilling techniques
Iceland	754.4 MW (electric), 2,262 MWth (thermal)	5,633.9 GWh (electric)	6,827.09 GWh (thermal)	10 plants (electric), 44 plants (thermal)	National energy strategy, Geothermal energy plan	Flash steam plants, Direct use applications
France	17.2 MW (electric), 3122 MWth (thermal)	127 GWh (electric)	2,062.346 GWh (thermal)	3 plants (electric), 79 plants (thermal)	Multi-annual Energy Plan (PPE), Subsidies for heat networks	Geothermal heat pumps, District heating systems

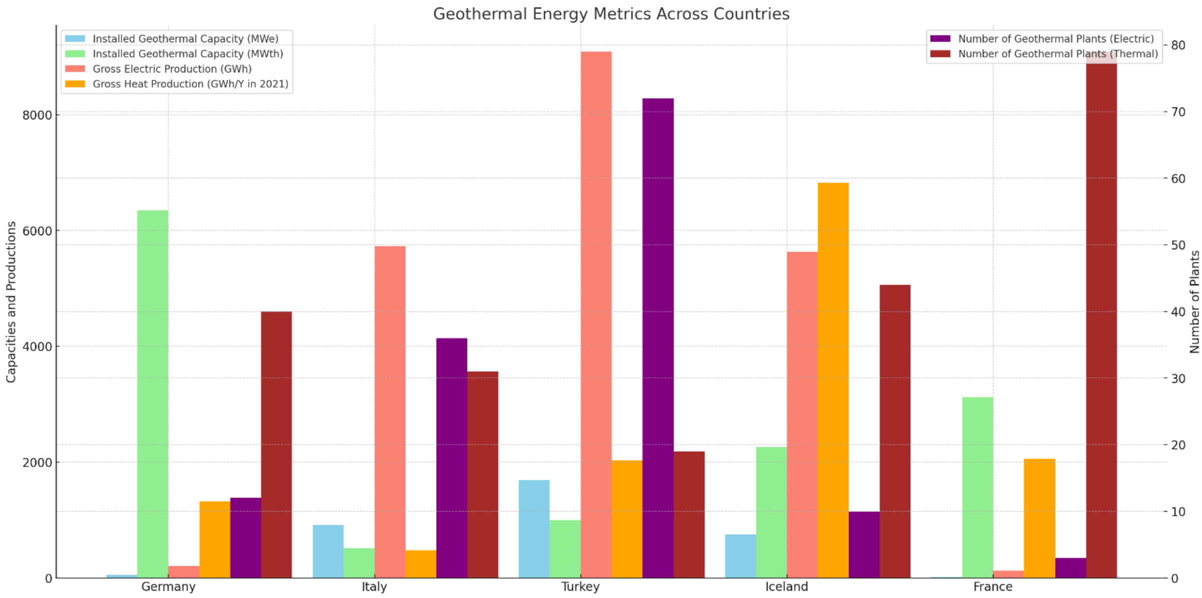

Figure 1. Geothermal energy metrics between selected countries, created by Authors

Turkey leads in installed geothermal electric capacity with 1,691.31 MWe, followed by Italy at 915.79 MWe and Iceland at 754.4 MWe. France has the lowest installed capacity at 17.2 MWe, indicating a relatively underdeveloped geothermal electric sector. In terms of thermal capacity, Germany is the frontrunner with 6,349 MWth, followed by France with 3,122 MWth and Iceland with 2,262 MWth. Italy and Turkey have significantly lower thermal capacities, suggesting different strategic focuses.

When examining gross electric production, Turkey again stands out with 9,092.61 GWh, highlighting its extensive utilization of geothermal resources for power generation. Italy and Iceland also have substantial electric production at 5,731.59 GWh and 5,633.9 GWh, respectively. France lags significantly in this area with only 127 GWh of geothermal electricity produced. This disparity indicates varying levels of efficiency and scale in geothermal electricity generation among the countries.

Iceland is noteworthy for its gross heat production, boasting 6,827.09 GWh, which showcases its effective use of geothermal resources for heating. Germany follows with 1,324.99 GWh, and France with 2,062.346 GWh. Italy and Turkey produce less geothermal heat, at 478.435 GWh and 2,026.39 GWh, respectively. This trend indicates that some countries prioritize geothermal heat applications more heavily than others.

Turkey has the highest number of geothermal plants for electricity generation, with 72 plants, indicating robust infrastructure development. Italy and Germany follow with 36 and 12 plants, respectively, while France has the fewest electric plants at 3. For thermal plants, France leads with 79 plants, underscoring its focus on geothermal heating solutions. Germany and Iceland also have significant numbers of thermal plants, reflecting their extensive use of geothermal energy for heating applications.

Regarding the policy support measures and technological advancements, they vary across the countries. All have implemented various measures to promote geothermal energy, including subsidies, feed-in tariffs as well as national energy plans. Technological advancements include binary cycle plants (ORC) in Germany, high-enthalpy resources and combined heat and power in Italy, high-temperature resources and deep drilling techniques in Turkey, flash steam plants and direct use applications in Iceland, also geothermal heat pumps and district heating systems in France. These differences reflect each country's strategic priorities and technological innovations in geothermal energy utilization accordingly.

Germany, Italy, Turkey, Iceland and France each demonstrate unique strengths in their geothermal energy development, significantly contributing to two important Sustainable development goals: SDG 7 (affordable and clean energy) and SDG 13 (climate action). Germany's focus on thermal capacity (6,349 MWth) and its 40 geothermal thermal plants highlight its commitment to clean heating solutions, supported by policies like the Renewable Energy Sources Act (EEG) and advancements in binary cycle and enhanced geothermal systems. Italy leads in geothermal electricity generation with a capacity of 915.79 MWe and a production of 5,731.59 GWh, driven by the FER 2 subsidy scheme and regional support frameworks. These efforts ensure access to reliable and modern energy, reducing carbon emissions. Turkey's leadership in electric capacity (1,691.31 MWe) and the highest gross electric production (9,092.61 GWh) underline its significant contribution to clean electricity, supported by the Renewable Energy Law and capacity payments. Iceland excels in heat production, with 6,827.09 GWh and a national energy strategy that promotes sustainable heating solutions. France emphasizes geothermal heating with 3,122 MWth of installed capacity and 79 thermal plants, supported by the Multi-annual Energy Plan (PPE) and subsidies for heat networks, although it has potential for growth in geothermal electricity.

The calculation of emissions reductions involved comparing the greenhouse gas emissions from geothermal energy to those from fossil fuel sources. Using the provided data on installed geothermal capacity and annual energy production for each country, we applied emissions factors of 0.1 kg CO_2e/kWh for geothermal energy and 1.0 kg CO_2e/kWh and 0.5 kg CO_2e/kWh for coal and natural gas, respectively. We first estimated the potential emissions from fossil fuels by multiplying the annual energy production by the fossil fuel emissions factor. Then, we calculated the actual emissions from geothermal energy by applying the geothermal emissions factor. The difference between these two values gave the emissions reduction. This process was conducted separately for electric and thermal energy, and the results were summed and converted from kilograms to metric tons for clarity.

Table 2. CO_2e reductions from geothermal energy in selected countries, created by Authors

Country	Electric CO_2e Reduction (t)	Thermal CO_2e Reduction (t)	Total CO_2e Reduction (t)
Germany	186,930	529,996	716,926
Italy	5,158,431	191,374	5,349,805
Turkey	8,183,349	810,556	8,993,905
Iceland	5,070,510	2,730,836	7,801,346
France	114,300	824,938	939,238

The results showed significant emissions reductions for each country, reflecting the environmental benefits of geothermal energy. Turkey led with a total reduction of 8,993,905 metric tons of CO_2e, followed by Iceland with 7,801,346 metric tons. Italy also achieved substantial reductions, totaling 5,349,805 metric tons. Germany and France, while having lower total reductions, still demonstrated notable decreases in emissions with 716,926 and 939,238 metric tons, respectively.

The economic benefits of geothermal energy were calculated by evaluating job creation, investment in local economies and energy cost savings. Job creation was estimated using industry averages: 1.5 jobs per MW of installed capacity during construction and 0.3 jobs per MW during operation and maintenance (O&M). Investment was calculated based on an average cost of €4.5 million per MW installed. Energy cost savings were estimated by comparing the cost of geothermal energy (€0.05/kWh) with that of fossil fuels, and then multiplying the difference by the annual energy production. These calculations were applied to each country's installed geothermal capacity and annual energy production data to determine the overall economic impact.

Table 3. Geothermal energy: employment, investment and energy savings in selected countries, created by Authors

Country	Construction Jobs	O&M Jobs	Total Jobs	Investment (EUR)	Annual Energy Cost Savings (EUR)
Germany	9570	1920	11,490	€28.8 billion	€76.64 million
Italy	2140	431	2571	€6.45 billion	€310.5 million
Turkey	4035	803	4838	€12.05 billion	€555.95 million
Iceland	4548	906	5454	€13.6 billion	€623.5 million
France	4690	942	5632	€14.8 billion	€109.47 million

The results demonstrate substantial economic benefits from geothermal energy across the analyzed countries. Germany, with its large installed thermal capacity, shows significant job creation (11,490 total jobs) and a high investment of €28.8 billion, though its annual energy cost savings are relatively modest at €76.64 million. Italy, focusing more on electric capacity, creates 2571 jobs with a total investment of €6.45 billion and achieves notable annual savings of €310.5 million. Turkey leads in job creation (4838 total jobs) and annual energy cost savings (€555.95 million), reflecting its significant geothermal electric capacity and production. Iceland, despite a smaller population, shows impressive economic benefits with 5454 jobs, €13.6 billion in investments, and €623.5 million in annual savings, highlighting its extensive use of geothermal energy. France, with a strong focus on geothermal heating, creates the most jobs (5632) and attracts €14.8 billion in investments, but its annual savings are lower at €109.47 million, indicating room for growth in electric capacity.

The capacity factor for each country's geothermal electric capacity is calculated by dividing the actual energy production by the maximum possible output if the plant operated at full capacity continuously. For instance, Iceland's capacity factor is approximately 85.3%, indicating high efficiency and reliability of its geothermal plants. The contribution to energy mix is derived by comparing geothermal energy production to the total energy supply, showing how much geothermal energy contributes to each country's overall energy needs. The resilience rating and recovery time are qualitative measures based on available data and industry standards.

Table 4. Geothermal energy capacity, energy mix contribution, and resilience in selected countries, created by Authors

Country	Capacity Factor (Electric)	Contribution to Energy Mix (%)	Resilience Rating (1-5)	Recovery Time (hours)
France	84.2%	0.2%	4	12
Turkey	61.4%	1.7%	4	12
Iceland	85.3%	70%	5	10
Germany	47.2%	0.1%	3	15
Italy	71.3%	1.6%	4	12

The results highlight significant variations in geothermal energy utilization and efficiency among the countries. Iceland shows the highest capacity factor and very high contribution to its energy mix, reflecting its extensive reliance on geothermal energy. France and Germany have relatively low contributions to their energy mixes, indicating that geothermal energy plays a minor role in their overall energy strategies. However, Germany has a high installed thermal capacity, and it shows its focus on geothermal heating solutions. Turkey and Italy show balanced contributions with efficient utilization, but they still have room to increase their reliance on geothermal energy. The resilience ratings and recovery times indicate that Iceland and Italy have more robust systems in place, ensuring quicker recovery from disruptions, which is very important for maintaining energy security. Germany's slightly lower resilience rating reflects its moderate development in geothermal infrastructure compared to other energy sources.

Effective policy measures and regulatory frameworks are very important if you want to promote geothermal energy. Italy's FER 2 subsidy scheme and regional support frameworks work very much as an example, providing financial incentives and regulatory stability that encourage investment in geothermal projects (Think Geo Energy, 2024). Turkey's Renewable Energy Law and capacity payments create a favorable environment for geothermal development, attracting significant private investments (Lise and Uyar, 2022). Germany's Renewable Energy Sources Act (EEG) and priority dispatch policies ensure long-term support for geothermal energy, facilitating market integration (Yang et al., 2021). Iceland's national energy strategy and geothermal energy plan provide a coherent framework that supports both domestic and international geothermal projects (Jónsson et al., 2019). France's Multi-annual Energy Plan (PPE) and subsidies for heat networks are effective in promoting geothermal heating but they also require enhancements to support electricity projects more robustly (Think Geo Energy, 2021). Identification and adoption of best practices from these frameworks can help other countries accelerate their geothermal energy adoption.

Of the environmental benefits identified by the literature on geothermal energy, a prominent one is a reduction in greenhouse gas emissions. CO_2 emissions from geothermal plants are much less than those from conventional fossil fuel plants, and this fact has been proven by the results which indicated a considerable reduction in emissions, especially for countries with greater geothermal capacity. For instance, the highest installed electric capacity in

Turkey significantly diminishes CO_2 emissions, being consistent with the findings of literature that advocates the role of geothermal energy in fighting against climate change (World Bank, 2021; Lise and Uyar, 2022).
This is rather in contrast to the literature, which generally provides a very optimistic view of geothermal energy's environmental benefits, with deployment in countries like France and Germany raising certain limitations. Although France has a relatively high thermal capacity, the electric production is still lower, thus implying that the reduction in emissions will only be maximized when the combination of electric and thermal capacities can be fully tapped into with geothermal energy (International Energy Agency, 2010; Dumas, 2019). The fact that interest in thermal applications in Germany has been revived suggests that the potential for geothermal solutions to aid in emission reduction is far from tapped.
Another major area focused in the literature is the economic impact that will be effected by geothermal energy from job creation, local investments, and savings on energy costs. The results from Germany, Italy, Turkey, Iceland, and France tie up with these findings showing great benefits economically. The high investments that Italy has made in new projects by ENEL and strategic investments by Turkey have also led to stimulating the local economies with numerous jobs (Meirbekova et al., 2024; AGBI, 2024). These are, actually, in line with the assertions in the literature regarding the positive economic impact of geothermal energy development. The results, however, captured differences in economic benefits between countries. Economic gains are significant for Italy and Turkey, whereas it is only moderate for France, which can be explained by its lower installed electric capacity. This discrepancy indicates that the economic impact of geothermal is directly related to scale and focus. Therefore, countries with higher ambition levels for geothermal electric power tend to benefit more economically.
In these respects, literature underlines the social benefits of geothermal energy: increased energy security, accessibility, and community acceptance. Iceland offers an example of high acceptance, with geothermal energy almost covering 100% of heating needs. Success in the development of this field by Turkey and plenty of geothermal power plants are, again, direct evidence of public acceptance and improvement of accessibility to this green resource. The literature describes some problems with the awareness of the public and accepts them to be correct in the given example of France and Germany (Renoth et al., 2023). These countries, however, still face problems in reaching wider social acceptance and popularization, despite the fact that substantial geothermal potential exists. This proves another key area where the policy measures and public engagement strategies have to be further strengthened, particularly in regard to the advancement and progress of the social benefits of geothermal energy.
The literature highlights that policy measures and regulatory frameworks are vital for the promotion of effective geothermal energy. The comparative analysis finds that countries with strong policy support—for instance, the FER 2 subsidy scheme in Italy and the Renewable Energy Law in Turkey—have displayed advancement in the development of geothermal energy (CMS, 2023). The policies give incentives in money terms and the regulatory regime to guide investments and further innovation. Others, such as Germany's EEG and Iceland's national energy strategy, have been instrumental in implementing geothermal energy. It suggests that, for the further galvanization of the geothermal electricity sector, the policy measures of France, although supportive to geothermal heating, it involves the need for enhancements. This observation supports literature citation that suggests a need for more extensive and supportive regulatory framework in order to maximize the potential of geothermal energy (International Energy Agency, 2021).
S&T innovations are of great importance for sustainable geothermal development. The literature highlights the importance of technological innovations regarding binary cycle plants, enhanced geothermal systems, and high-temperature drilling techniques. The results reveal that countries in which advanced technologies are used, such as Germany with binary cycle plants and Turkey with deep-drilling techniques, are relatively more successful at expanding their geothermal capacities. For instance, the literature revealed that constant technological advancement to get rid of environmental hazards and incorporate efficiency is the prime necessity. The GEOENVI project under consideration also works with a vision towards identifying best practices and sustainability assessment frameworks. It is found that countries like Iceland, where 'flash steam plants' and 'direct use applications' are found, set examples for others regarding the integration of advanced technology and sustainable practice. Such findings would suggest that a one-size-fits-all approach cannot be ideal. What is needed, therefore, are customized strategies that take into account specific national contexts, geological conditions and policy environments. For instance, best practices need to be emulated in countries with a high geothermal potential but low current utilization, like in the case of France, from leader countries like Italy and Turkey while developing public engagement and policy support (International Renewable Energy Agency (IRENA), 2017; Tomarov and Shipkov, 2017; National Renewable Energy Laboratory (NREL), 2024).
The analysis revealed that, unlike other renewable energy sectors such as solar and wind, geothermal energy development was largely unaffected by the COVID-19 pandemic. Geothermal projects, particularly those already in operation, demonstrated high resilience due to their baseload capacity and low dependency on short-term supply chain dynamics. Geothermal energy's consistent performance during this period shows its reliability as a stable and long-term renewable energy source, even amid global disruptions. This resilience gives a unique position within the renewable energy landscape, contrasting with more variable renewables that experienced notable fluctuations during the pandemic.

5. Conclusions

1. Geothermal energy is a valuable part of Europe's sustainable energy transition. It is offering reliable and low-emission power that can reduce greenhouse gas emissions. For instance, Turkey's highest installed geothermal electric capacity of 1691.31 MWe and gross electric production of 9092.61 GWh highlight its effectiveness in reducing CO_2 emissions compared to conventional coal-fired plants, where geothermal plants emit approximately 5% of the CO_2.
2. The comparative analysis reveals significant disparities in geothermal energy development across Germany, Italy, Turkey, Iceland and France, driven by unique geological conditions, policy frameworks, and technological advancements. Germany leads in thermal capacity with 6349 MWth and extensive geothermal heating applications, while Turkey excels in electric capacity and production, indicating varying strategic focuses among countries.
3. Technological advancements and effective policy support are essential for expanding geothermal capacities and improving efficiency. Germany's use of binary cycle plants and enhanced geothermal systems, alongside Turkey's deep drilling techniques and high-temperature resources, illustrate how innovation drives geothermal energy success. Italy's support through the FER 2 subsidy scheme has also been pivotal in achieving 915.79 MWe capacity and 5731.59 GWh production.
4. Calculations highlighted substantial emissions reductions, with Turkey achieving the highest reduction of 8,993,905 metric tons of CO_2e, followed by Iceland with 7,801,346 metric tons. These reductions underscore the potential of geothermal energy to mitigate climate change effectively. Economically, geothermal energy fosters considerable job creation, investment, and energy cost savings. Germany's high investment and job creation are contrasted with its modest energy cost savings, while Turkey and Iceland showcase both strong economic and environmental gains. Italy and France also benefit notably, though each country exhibits unique strengths reflecting their geothermal energy utilization patterns.
5. Tailored strategies that consider specific national contexts, geological conditions, and policy environments are necessary for maximizing geothermal energy's impact. Iceland's comprehensive utilization of geothermal energy for electricity (754.4 MW) and heat production (6827.09 GWh) demonstrates high community acceptance and integration. In contrast, France, with its focus on geothermal heating (3122 MWth capacity and 79 thermal plants), needs to enhance policy support for geothermal electricity to fully leverage its geothermal potential.
6. The analysis found no significant direct relationship between the COVID-19 pandemic and geothermal energy development. The sector's resilience and stability during this global disruption reaffirm its strategic importance as a dependable renewable energy source for achieving long-term sustainable development goals.

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