

*Geothermal Energy and Policy Incentives: Sustainable Development in the Agri-Food Sector.
A Study of Twelve Case Countries.*

A thesis approved by the Faculty of Environment and Natural Sciences at the Brandenburg University of Technology Cottbus-Senftenberg in partial fulfilment of the requirement for the award of the academic degree Doctor of Philosophy (Ph.D.) in Environmental Sciences.

By
Master of Arts
Margarita Kriger
from Krasnodar, Russia

Supervisor: Prof. Eike Albrecht

Supervisor: Prof. Rolf Bracke

Day of the oral examination: 26 February 2024

<https://doi.org/10.26127/BTUOpen-6682>

Declaration

I hereby declare that this thesis has not been previously published or written by another person; neither has it been submitted nor accepted for any other academic award. It is the result of my original work carried out at Brandenburg University of Technology Cottbus-Senftenberg, Germany, within the framework of the Ph.D. Programme “Environmental and Resource Management”. All materials from other sources have been duly and adequately acknowledged.

Margarita Kriger

Cottbus, 14 June 2023

Abstract

Due to environmental impacts from anthropomorphic climate change, countries from around the world are committed to an energy transition from fossil fuels to renewable and sustainable energy sources. The heating and cooling sector represents the largest share of total energy consumption globally, not only for domestic use but also for commercial and industrial purposes of which only 11% is covered by renewable energy. One renewable source, geothermal energy, has the potential to cover much of this demand, particularly heating demand, for the agriculture and food sector. Geothermal use in the agri-food industry continues to be positive overall, yet slow adoption and inconsistent growth have not met its potential as claimed by experts. This trend may be explained by a lack of coherent policy and initiatives from regulating government bodies. This research explores the relationship and the degree of correlation between government support, expressed in terms of policy incentives, and the growth of geothermal energy use in the agri-food sector. Two hypotheses are constructed to test this relationship. The first assumes that government support through policy leads to positive growth in geothermal agri-food, and the second assumes that no relationship exists. The research is a multiple case study of twelve countries from 2010 to 2020. Methods used in this study include Likert summative scale, a statistical and content analysis of secondary sources such as policy documents, laws, and other government acts. The results show a strong correlation between policy incentives and adoption of geothermal energy in agri-food sector. However, only 23% of growth in capacity in case countries can be explained by the levels of government support. Additionally, not all policies hold equal weight in that they are implemented on different levels of governance (global, national, and local). The study observes that between these three levels, national policies have the most correlative effect on geothermal energy adoption, while global and local policies do not seem to have significant influence. These effects vary but the overall market trends are influenced heavily by leading performers. Countries that show the most growth are – Hungary, Iceland, the Netherlands, and Türkiye. They all share strong government support on a national level, targeted policies for geothermal agri-food, and geothermal energy is economically competitive when compared to other forms of energy.

Main keywords: geothermal energy, sustainable development, agri-food sector, government policies, government support.

Zusammenfassung

Aufgrund der Umweltauswirkungen des anthropomorphen Klimawandels haben sich Länder auf der ganzen Welt zu einer Energiewende von fossilen Brennstoffen zu erneuerbaren und nachhaltigen Energiequellen verpflichtet. Der Wärme- und Kältesektor macht weltweit den größten Anteil am Gesamtenergieverbrauch aus, und zwar nicht nur für den häuslichen Gebrauch, sondern auch für gewerbliche und industrielle Zwecke, von denen nur 11 % durch erneuerbare Energien gedeckt werden. Eine erneuerbare Energiequelle, die Geothermie, hat das Potenzial, einen großen Teil dieses Bedarfs zu decken, insbesondere den Wärmebedarf in der Landwirtschaft und im Lebensmittelsektor. Die Nutzung der Geothermie in der Agrar- und Ernährungswirtschaft ist insgesamt weiterhin positiv, aber die langsame Einführung und das uneinheitliche Wachstum haben das Potenzial nicht ausgeschöpft, wie von Experten behauptet. Dieser Trend lässt sich durch einen Mangel an kohärenten politischen Maßnahmen und Initiativen seitens der regulierenden Regierungsstellen erklären. Diese Studie untersucht die Beziehung und den Grad der Korrelation zwischen staatlicher Unterstützung, ausgedrückt in Form von politischen Anreizen, und dem Wachstum der geothermischen Energienutzung im Agrar- und Ernährungssektor. Es werden zwei Hypothesen aufgestellt, um diese Beziehung zu testen. Die erste Hypothese geht davon aus, dass die staatliche Unterstützung durch die Politik zu einem positiven Wachstum der geothermischen Nahrungsmittelindustrie führt, die zweite Hypothese geht davon aus, dass kein Zusammenhang besteht. Bei der Untersuchung handelt es sich um eine Multiple-Case-Studie über zwölf Länder im Zeitraum von 2010 bis 2020. Die in dieser Studie verwendeten Methoden umfassen eine summative Likert-Skala, eine statistische und eine inhaltliche Analyse von Sekundärquellen wie politischen Dokumenten, Gesetzen und anderen Regierungsakten. Die Ergebnisse zeigen eine starke Korrelation zwischen politischen Anreizen und der Einführung von geothermischer Energie im Agrar- und Ernährungssektor. Allerdings können nur 23 % des Kapazitätswachstums in den Fallländern durch die Höhe der staatlichen Unterstützung erklärt werden. Außerdem haben nicht alle politischen Maßnahmen das gleiche Gewicht, da sie auf verschiedenen Regierungsebenen (global, national und lokal) umgesetzt werden. Die Studie stellt fest, dass zwischen diesen drei Ebenen die nationale Politik die stärkste Auswirkung auf die Einführung der Geothermie hat, während die globale und lokale Politik keinen signifikanten Einfluss zu haben scheint. Diese Auswirkungen sind unterschiedlich, aber die

allgemeinen Markttrends werden stark von den führenden Akteuren beeinflusst. Die Länder mit dem größten Wachstum sind Ungarn, Island, die Niederlande und die Türkei. Sie alle haben eine starke staatliche Unterstützung auf nationaler Ebene, eine gezielte Politik für die geothermische Landwirtschaft, und die geothermische Energie ist im Vergleich zu anderen Energieformen wirtschaftlich wettbewerbsfähig.

Wichtigste Stichworte: Geothermie, nachhaltige Entwicklung, Agrar- und Ernährungswirtschaft, staatliche Maßnahmen, staatliche Unterstützung.

Table of Content

1.	Introduction	1
1.1.	Background	1
1.2.	Agriculture and Food	2
1.3.	Problem Statement	4
2.	Sustainable Development in the Agri-Food Sector	8
2.1.	Geothermal Energy Use	8
2.2.	Sustainable Agriculture and Food	10
2.3.	Basic Technical Principles of a Geothermal Greenhouse	12
2.4.	Environmental Risk Assessment of a Geothermal Greenhouse	15
2.5.	Government Support for Geothermal Agri-Food	19
3.	Methodology	22
3.1.	Design and Framework	22
3.2.	Measurement of Variables	24
3.2.1.	Policy Incentives	24
3.2.2.	Greenhouse Agriculture	33
3.3.	Sampling	34
3.4.	Content Analysis	36
4.	Case Countries	41
4.1.	Austria	44
4.2.	Greece	46
4.3.	Hungary	49
4.4.	Italy	52
4.5.	The Netherlands	55
4.6.	Spain	59
4.7.	Iceland	61
4.8.	Japan	64
4.9.	Kenya	68
4.10.	Serbia	71

4.11. Türkiye.....	74
4.12. The United States of America.....	77
5. Results	80
5.1. Comparative analysis.....	82
5.2. Regression analysis.....	96
6. Discussion and Conclusions.....	98
7. Implications and Recommendations.....	104
8. Ethical Considerations.....	105
Reference list.....	107
Appendix A	133
Appendix B	135
Appendix C	136
Appendix D	143
Appendix E.....	154
Appendix F.....	156
Appendix G	177

List of Figures

Figure 1. World installed capacities for geothermal agri-food use (in %) by region in 2020.....	10
Figure 2. Countries using geothermal energy in agri-food sector.	11
Figure 3. Position of heating installations in a geothermal greenhouse	14
Figure 4. Theoretical and empirical planes of research.....	21
Figure 5. Relationship between policy suite and greenhouse capacity	85
Figure 6. Relationship between global policy incentives and greenhouse capacity.....	86
Figure 7. Relationship between national policy incentives and greenhouse capacity ..	87
Figure 8. Relationship between local policy incentives and greenhouse capacity	88
Figure 9. Leave-on-out cross-validation for policy suite combining three levels (global, national, local).....	90

List of Tables

Table 1. Research steps and methods.....	23
Table 2. Identified policy documents for each case country.....	39
Table 3. An overview of final content analysis values relating to the hypotheses per policy and country.....	43
Table 4. Geothermal energy use in Austria, 2010-2020.....	44
Table 5. Geothermal energy use in Greece, 2010-2020.....	47
Table 6. Geothermal energy use in Hungary, 2010-2020.....	50
Table 7. Geothermal energy use in Italy, 2010-2020.....	53
Table 8. Geothermal energy use in the Netherlands, 2010-2020.....	56
Table 9. Geothermal energy use in Spain, 2010-2020.....	59
Table 10. Geothermal energy use in Iceland, 2010-2020.....	62
Table 11. Geothermal energy use in Japan, 2010-2020.....	66
Table 12. Geothermal energy use in Kenya, 2010-2020.....	69
Table 13. Geothermal energy use in Serbia, 2010-2020.....	72
Table 14. Geothermal energy use in Türkiye, 2010-2020.....	75
Table 15. Geothermal energy use in the USA, 2010-2020.....	78
Table 16. Final policy and greenhouse agriculture values.....	84
Table 17. Thematic analysis: frequency of themes in national policies.....	91
Table 18. Overview of additional influential factors.....	95
Table 19. Summary output of simple linear regression.....	97

1. Introduction

1.1. Background

There are many primary sources of renewable energy: biomass, geothermal, hydro, marine, solar and wind and since the new millennium their share in gross final energy consumption grew considerably: from 6.2% in 2004 to 20.4% in 2022 (Umweltbundesamt, 2022; United Nations, no date-a). One factor driving this energy transition are commitments by countries to reduce carbon dioxide emissions from their energy sectors. In 2015, 196 countries adopted the Paris Agreement, as a part of the United Nations Framework Convention on Climate Change (FCCC/CP/2015/10/Add.1, 2015). This accord aims to “limit the temperature increase to 1.5°C above pre-industrial levels” and is one of the first international climate focused accords (FCCC/CP/2015/10/Add.1, 2015, p. 2). According to Article 4 para. 2 each Party to the Agreement “shall prepare, communicate and maintain successive nationally determined contributions that it intends to achieve” (FCCC/CP/2015/10/Add.1, 2015, p. 23). Nationally Determined Contributions, or NDCs, are mandatory self-determined action plans that countries need to present to comply with the Paris Agreement (FCCC/CP/2015/10/Add.1, 2015, p. 4).

Other commitments by the Member States of the European Union aim to jointly reduce greenhouses gas emissions by at least 55% by 2030 and achieve carbon neutrality by 2050 (14222/1/20 REV 1, 2020, p. 9). Other countries also design climate action plans where they pledge expanded use of renewable energy and significant cut in emissions. Most of the frameworks are focused on power production and although an important part of total energy consumption, it does not represent its largest segment. According to recent energy reports, the biggest global share of the final energy consumption is attributed to the heating and cooling sector: it represents 51% of the total global consumption compared to 17% for power and 32% for transport (REN21, 2022, p. 42). About 89% of worldwide heating and cooling demand is covered by fossil fuels, which contributes up to 40% to the total global carbon dioxide emissions (International Energy Agency, 2019, p. 129). Approximately half of these emissions come from agriculture and district heating and cooling (International Renewable Energy Agency, International Energy Agency and REN21, 2018, p. 25).

For the European Union, the situation is similar. Heating and cooling accounts for half of the total energy consumption with a substantial part of it, 76%, covered by agricultural uses, commerce, and services. At the same time only 23% of EU

heating and cooling is generated from renewable sources. The European Commission states that there is a strong need for clean energy solutions to satisfy demand for energy security and growing consumption in the heating and cooling sector (European Commission, 2022a).

In the European Union geothermal energy is recognized as innovative and the Member States are encouraged to assess its potential use for the heating and cooling sector. As stated in the Article 2 (3) of the Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources, geothermal energy means “energy stored in the form of heat beneath the surface of solid earth” (OJ EU L 328, 2018, p. 102). This source has a significant potential to cover much of the world’s heat demand because it represents a domestic, efficient, reliable, and low-carbon energy resource. International experts estimate the annual technical potential for all known renewables to be around 7500 EJ (exajoules), with 5000 EJ coming from geothermal energy alone (Moriarty and Honnery, 2009, p. 121). Other estimates suggest that only one thousandth of its total technical potential is exploited (Limberger *et al.*, 2018, p. 961). At the same time geothermal (combined with solar heat) represents just 0.1% of the global heating and cooling sector, thus being the smallest part of the renewable energy mix (REN21, 2020, p. 33). In addition, as reported by the International Energy Agency global geothermal consumption of heat has seen only a miniscule increase in numbers in the past years (International Energy Agency, 2020, p. 135). In total, geothermal energy delivered about 283580 GWh/yr to the heating and cooling sector preventing the release of 252.6 million tonnes of carbon dioxide into the atmosphere in 2019 (Lund and Toth, 2020).

1.2. Agriculture and Food

The heating and cooling sector covers a wide range of uses and applications. According to the International Renewable Energy Agency (IRENA) it includes cooking, food industry, process heating, refrigeration, space heating, etc. (International Renewable Energy Agency, 2020a). Among these uses, agriculture and food industry represent a major part of the global energy consumption accounting for 35% of its final demand (Food and Agriculture Organization, 2011, p. 3). Currently only 14.5% of agriculture sector is decarbonized of which 0.1% is attributed to geothermal and solar heat (REN21, 2022, p. 60).

The United Nations Sustainable Goals (SDGs) promote clean and affordable energy supply in various sectors including agriculture. The world commitment to

combat hunger by ensuring secure and sustainable agri-food sector is expressed in the SDG 2 “Zero Hunger”, which also tackles the issues of food security, improvement of human health and nutrition. SDG 3 “Good health and well-being”, SDG 7 “Affordable and clean energy”, SDG 12 “Responsible consumption and production” and SDG 13 “Climate action” all highlight the connection between energy-food nexus and other goals such as efficient use of resources, effective energy solutions and mitigation of anthropomorphic climate change (United Nations, no date-b).

According to IRENA, the agri-food sector is less advanced and requires more attention and assertive actions than it is currently receiving. It suffers from stagnation in terms of sustainability relying on novel chemistry, pesticides, and fertilizers, which are often sourced from fossil fuels. Recent study shows that global agricultural investments are declining and growing production costs undermine the quality and availability of food. As a result, farmers and food producers need stronger support from local governments to stave off food insecurity (International Renewable Energy Agency, 2019a). As reported by the United Nations, the levels of hunger and undernutrition are rising and so does the demand for food and water, which is predicted to grow considerably. Solving these issues requires rethinking current situation in the agri-food sector to find alternative solutions for energy resources (International Renewable Energy Agency, 2022; United Nations, 2022a).

The first official statistical account of geothermal energy use dates to World Geothermal Congress 2000.¹ Since then the geothermal contribution to the agriculture has been increasing slowly – about 3.8% per year (Lund and Toth, 2020, p. 4). However, considering projected potential of this resource and the current global need to ensure sustainable production of agricultural products such growth rates are far from sufficient.

The use of geothermal energy in the agri-food industry has many advantages. First, it is not location specific. Unlike power generation that is currently only possible in the locations of known and developed high enthalpy resources, direct use of geothermal heat for agricultural purposes could be realized at far more places on the planet. Second, its use is not dependent on weather patterns or affected by day-night cycles like the use of solar energy. Third, while many countries do not have access to multiple renewable energy sources (e.g., not enough solar or wind

¹ The data from the World Geothermal Congress 1995 also exists, however it is never used as a reference for data purposes due to its fragmented nature.

energy to justify their development), geothermal resource could become one available local solution. It also facilitates energy security in the food sector and decreases the reliance on imported agricultural products and fuel. Many countries have already introduced geothermal in their national energy portfolios as a strategy to support sustainable agriculture, for example China, Hungary, Kenya, the Netherlands, New Zealand, Türkiye, etc. (Lund and Toth, 2020, p. 2).

Additionally, the use of geothermal energy in agri-food sector provides protection from volatility of food prices and contributes to local industrial development, which could additionally create new employment opportunities (International Renewable Energy Agency, 2019b, p. 10). Greenhouses can increase availability of perishable produce even in the off-season when the prices are higher for imports. Surplus in food production could potentially enable exports of stock contributing to economic development (International Renewable Energy Agency, IEA and REN21, 2018, p. 19). Another valuable benefit involves creating potential for crop cultivation and food production in areas that are not naturally suitable for agriculture: Iceland, for an extreme example, is able to grow bananas in geothermal greenhouses near the population centre of Reykjavik (Ragnarsson, Steingrimsson and Thorhallsson, 2020, p. 5). Finally, sustainable food grown in controlled environments is protected from extreme weather conditions which lowers risk of crop failure.

1.3. Problem Statement

Where the use of geothermal energy for agri-food purposes has been extensively developed it has promoted national food security and economic development, however, its contribution to this sector remains comparatively low. While total installed capacity of geothermal almost doubled in the past 20 years (from 1925 MWt in 2000 to 3666 MWt in 2020) the growth rate for every reported five-year period has fluctuated. Capacity in the agri-food sector grew 10% from 2000 to 2005, 9% from 2005 to 2010, 15% from 2010 to 2015 and 36% from 2015 to 2020 (Lund and Toth, 2020, p. 7). It is understood that part of the increase from 2010 onwards is not only attributed to the actual increase in capacity, but also to better reporting techniques. It is, however, unclear how much of this increase is due to either factor. In addition, when examined in detail, less than a third of all countries show actual increase in capacity since 2000. In 2020 only 7% of all reporting countries contributed to 62% of total installed capacity, which suggests that only a few

countries are responsible for this growth (Lund and Freeston, 2000; Lund, Freeston and Boyd, 2005; Lund, Freeston and Boyd, 2010; Lund and Boyd, 2015; Lund and Toth, 2020).

The development of geothermal agri-food market is unbalanced. Such distribution cannot be explained solely by availability of geothermal resource. In fact, some countries that have extensive known reserves that have seen growth in geothermal use for power production, show a decline in capacity for agriculture (Japan, Kenya, the USA), or capacity stagnation (El Salvador, France, New Zealand) or no use for agriculture (Costa Rica, Germany, Indonesia). Some attribute such trends to historical factors. For example, in the early 2000s, countries with the biggest share of geothermal agriculture (greenhouse heating) such as Bulgaria, Hungary, North Macedonia, and Romania have been going through political transitions. This influenced their investment strategies and as a result led to a decline of geothermal energy use (Popovski, 2009, pp. 2-5). Such examples, however, are rare. Another possibility is the uncertainty involved in a geothermal development such as exploration risks or agricultural climates that do not benefit from greenhouses. Economic reasons could include high upfront capital investments, uncertain periods of return, financial risks, and shortage of the qualified workforce. Finally, other arguments include weak attempts at information dissemination, ineffective marketing, and lack of visibility and promotion strategies (International Renewable Energy Agency, 2019b, pp. 4-5).

Despite these challenges the most frequent explanation for the unbalanced geothermal development is the lack of encouraging government support (Bloomquist, 2010, p. 545). According to many experts, government initiatives such as transparent licensing procedures, tailored policy instruments and national support schemes are necessary to promote geothermal energy development (Zaidi, 2015, p. 7; International Renewable Energy Agency, 2019b, pp. 23-25). Lack of appropriate legal framework and unclear rules about regulation of geothermal resource are also highlighted as the key barriers. These explanations, however, are not elaborated or specified further in any way, creating a gap in knowledge. Furthermore, such studies fail to distinguish between different types of geothermal application (European Renewable Energy Council, 2007a, p. 6; Ram *et al.*, 2019, p. 12). The variety of usage is very broad and geothermal power production differs significantly from uses in agri-food not only in type of technology and its level of maturity but also in supply chains to support these technologies and customer's market. As a result, the government initiatives could vary considerably.

The reasons behind slow and inconsistent growth of geothermal use in agri-food sector are unclear yet the leading claim that government initiatives influence the growth of geothermal energy is not supported by any substantial evidence or analysis. At the same time, understanding this is crucial to achieve global and national renewable commitments. If the presence of government support changes the speed of geothermal energy adoption, the establishment of proper policy initiatives is pivotal. Aligning policy instruments to specifics of geothermal resource could provide for its bigger contribution for the energy transition and ensure the long-term sustainability of the energy-food system.

Considering the various uses of geothermal energy and the importance of the agri-food sector as one of the main climate change contributors, the main research question is formulated as follows: *does government support play a role in the development of geothermal energy in the agri-food sector?* This question introduces two related factors hence, the aim of this research is to investigate the relationship and the degree of correlation between government support expressed in policy incentives and geothermal energy use in the agri-food sector represented by greenhouse agriculture.

The relationship between the two variables could take many forms. Following the literature review, the relationship that emerges and is assumed by most experts is one of direct correlation: policy incentives positively impact the sector growth. However, these claims are vaguely supported, and these two aspects could also be unrelated. To capture and evaluate either assumption two hypotheses are constructed:

- *Hypothesis 1 (main)*: there is a positive relationship between policy incentives and the adoption of geothermal energy in greenhouse agriculture.
- *Hypothesis 2 (alternative)*: there is no relationship between policy incentives and the adoption of geothermal energy in greenhouse agriculture.

To address the identified gap in literature this research looks at existing policy incentives and the way they relate to the geothermal agri-food sector. Specific research objectives include:

- Identify and explain the role of geothermal energy, geothermal heating and cooling and agri-food sector.
- Identify and explain the context of government support and to estimate validity and reliability of policy incentives by using a Likert Scale.

- Perform data analysis and establish trends of geothermal energy adoption in the agri-food sector.
- Identify case countries by using purposive sampling.
- Perform content and thematic analysis of secondary data sources such as policy documents, government reports and other relevant publications in selected case countries.
- Create country portfolios highlighting the findings of the analysis.
- Establish the degree of correlation between government support and the use of geothermal energy in the agri-food sector in selected case studies via comparative analysis.
- Substantiate if and how government support can explain various trends in the use of geothermal energy in the agri-food sector by performing single regression analysis.
- Record and report the main findings and determine the supported hypothesis.

This research consists of eight chapters. This current chapter describes study topic, its purpose and relevance. It also defines problem statement, the aim, and the objectives of this study. The second chapter includes an extensive review of literature and the state of the art in research. After explaining main study contexts two hypotheses and their variables are introduced. Chapter three outlines methodology and describes the research design by explaining the process of measurements, evaluations, and validation of variables, as well as describing the framework of how data are collected and analyzed. Chapter four offers detailed overview of twelve selected case countries, describing their policy incentives, geothermal industry trends and relevant agricultural statistics. Chapter five outlines the key results and main findings of the study highlighting the outcomes of comparative and regression analyses. Chapter six concludes with a research summary and discusses the results. Limitations exposed in the study are also outlined. Recommendations for further research are the subject of chapter seven, which also addresses research implications and interprets how they could be applied to the broader geothermal industry. Some ethical considerations encountered in the study are included in chapter eight.

2. Sustainable Development in the Agri-Food Sector

2.1. Geothermal Energy Use

Geothermal energy is the heat stored in the earth's interior. It originates from primary formation of the Earth and is augmented by the decay of radioactive elements such as isotopes of uranium (U^{238} , U^{235}), thorium (Th^{232}) and potassium (K^{40}). Concentrations of these elements vary between the three divisions of the earth's interior, which are from the centre upwards: the core, the mantle, and the crust. Conductive heat flow from the earth leads to a generally uniform transfer of energy to the surface, however, there are many areas on the planet with elevated heat flow due to variations in the structure of the Earth. These sources may include magmas from tectonic processes and plate boundaries or advection of fluids from depth. Oceanic crust typically has higher basal heat flow because it is thinner than continental crust. Although, in some tectonically and volcanically active continental regions, heat flow can be exceptionally high due to convection of mantle and fluid heat sources. Generally, heat flow out of continental and oceanic crust are 70.9 and 105.4 mW/m² (milliwatt per square meter) respectively (Glassley, 2015, pp. 15-25). This heat flow leads to an averaged geothermal temperature gradient of around 25-30°C/km of depth. For near surface geothermal resources, water is the main carrier of heat and high heat flow corresponds to higher concentrations of geothermal energy. High enthalpy resources are present all over the world but are concentrated in volcanically active regions such as e.g., Japan, New Zealand, Philippines, and the USA (Press and Siever, 2002, pp. 14-18; Dickson and Fanelli, 2003, p. 2).

Geothermal energy is extracted from the ground mainly by drilling wells to access zones with elevated temperatures. For this, two conditions must be met: the existence of a heat carrier, often water or a brine, and permeability that allows for production of this geothermal fluid (Intergovernmental Panel on Climate Change, 2011, p. 71). The energy is transferred to the surface from geothermal fluids as it passes through a region of hot rocks absorbing heat from them. The heat is restored naturally to the system by conduction from the surrounding earth and fluids are recharged from reinjection of the produced fluids back into the reservoir creating a cyclical and regenerative process, hence, it is recognized as a renewable and sustainable energy source (Glassley, 2015, pp. 118-124). Once geothermal fluid is produced at the surface it can be used for electricity generation or utilized directly for heating and cooling. Additional uses for geothermal installations include energy and carbon storage (CO₂ sequestration) through injection into permeable reservoirs,

lithium extraction from geothermal brines, and combined power and heat use from cascading heat systems (European Geothermal Energy Council, 2022). Geothermal energy is most used for these purposes in the regions where it represents a local source of energy with end customer located near the resource extraction site (Canadian Geothermal Energy Association, 2014, p. 34).

The resource temperature and depth define its possible use. By convention high temperature resources ($> 150^{\circ}\text{C}$) are used mostly for power generation while middle to low temperature resources ($< 150^{\circ}\text{C}$) are directly used. Technologies using Organic Rankin cycles (ORC) or Kalina cycles may also use some of the higher end low temperature resources for power production, and amount to an increasing share of geothermal utilization (Hijriawan *et al.*, 2019, p. 2). Depth ranges, i.e., what is considered a shallow or deep geothermal resource vary from country to country. In Germany, for example, geothermal energy near surface is 100-400 m; medium-deep is 400-1000 m; and deep is > 1000 m (Sass, 2019, pp. 60-68). Distributions vary but geothermal resources suitable for heating and cooling purposes are more widespread than those used for electricity production (Tsagarakis *et al.*, 2020, p. 2566). As of 2020, 29 countries use geothermal to produce electricity and 88 directly for heating and cooling services. Currently the top three power producers are the USA, Indonesia, and Philippines and the top three direct users are China, Türkiye, and Iceland (Huttrer, 2020, p. 2; Lund and Toth, 2020, pp. 38-39).

Reporting on geothermal utilization is separated into two tiers: geothermal power production and geothermal heating and cooling. The former only refers to geothermal energy used to produce electricity, while the latter generally means direct utilization. Geothermal heating and cooling sector includes a variety of uses and many attempts have been made to classify them. One of the first classification systems was introduced by B. Lindal in 1973. The Lindal diagram includes more than 20 uses and stratifies them according to their functional temperature ranges. Some of these categories are animal husbandry, concrete block curing, fish farming, freshwater distillation, fruit and vegetable drying, mushroom growing, lumber drying, sugar refining, and others (Dickson and Fanelli, 2003, p. 14). Classification used by K. Popovski offers a condensed viewpoint and includes only four types of industrial and agricultural applications. These are agro-industrial processes, aquaculture, greenhouse heating, and soil heating (Popovski, 2009, p. 3). The International Geothermal Association (IGA) provides another classification and divides possible uses into nine major categories. Currently, the IGA classification system is used to report official statistics on worldwide geothermal energy

utilization. In 2022 this system was updated and now includes only five groups instead of nine: 1) agriculture and food processing; 2) industrial process heat; 3) health, recreation, and tourism; 4) heating and cooling for buildings; and 5) others (Manzella and Krieger, 2022, p. 4). Since 2000, the top three applications in terms of installed capacity remained unchanged. These are health, recreation and tourism, heating and cooling for buildings, and agriculture and food processing.

2.2. Sustainable Agriculture and Food

In agri-food, geothermal energy can be applied throughout the production and supply chain. For example, in primary food production, it can deliver water for irrigation and in post-harvest phase it could contribute to cold storage and drying. The most widespread applications include aquaculture for either fish farming or aquatic plants, greenhouse heating, and food and beverage processing (International Renewable Energy Agency, 2022, p. 22). Overall, 48 countries have at least once reported the use of geothermal energy in agriculture and food production. In 2020, 32 countries reported the use in greenhouses, 22 in aquaculture and 16 for food drying processes. Figure 1 shows the total world installed capacities for geothermal agri-food use in percentage by region while Figure 2 gives an overview of types of usage per country.

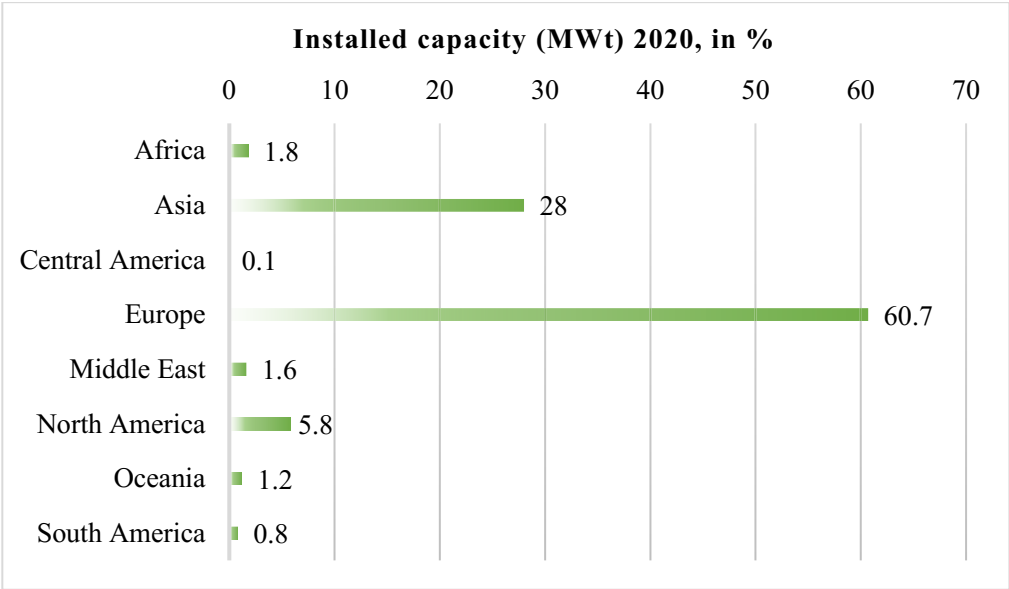


Figure 1. World installed capacities for geothermal agri-food use (in %) by region in 2020. Own elaboration.

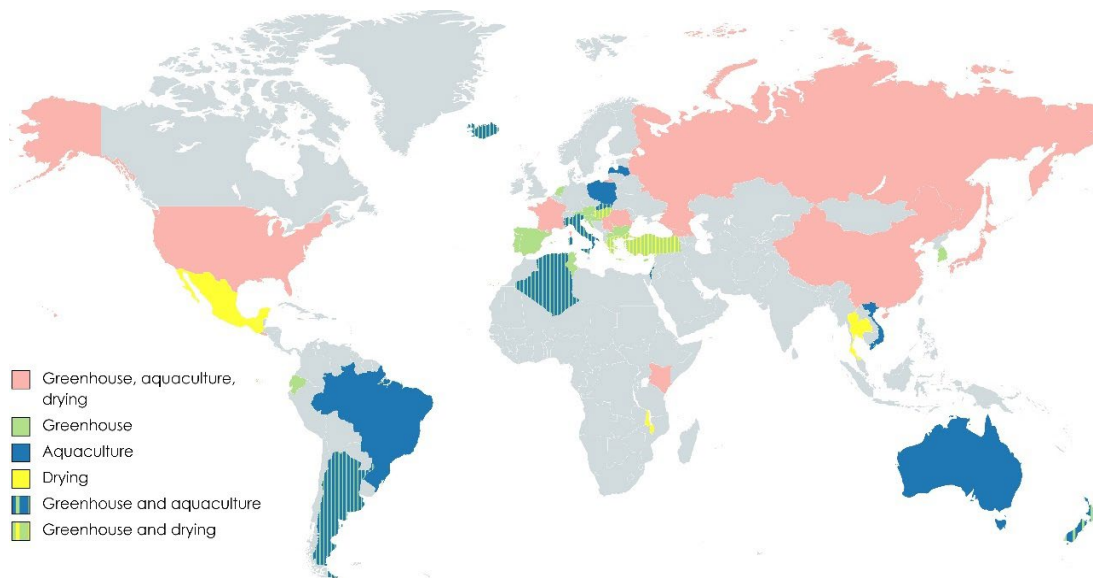


Figure 2. Countries using geothermal energy in agri-food sector.

As of 2020, 41 countries use geothermal energy in agriculture and food production.

Own elaboration created with mapchart.net.

The major share of agri-food usage is covered by greenhouses (66%) followed by aquaculture (28%) and food drying (6%). The past twenty years (2000-2020) has seen a general increase in their total installed capacities, but their ratio has remained consistent. Among all three shares only greenhouse sector showed a steady growth from 2000 onwards. Aquaculture only recently (from 2015) saw some moderate increase in capacity and agricultural drying has fluctuated significantly over the years (Lund and Toth, 2020, p. 6).

The first studies to account for geothermal energy use in agriculture and food production date back to 1970s and the first reports were delivered at the World Geothermal Congress in 1995 (Fisher, Back and Fogleman, 1978; Allegrini, Cappetti and Sbatelli, 1995). Initially, the use of geothermal energy in greenhouses saw quick development after the establishment of European Cooperative Networks on Rural Energy (FAO CNRE) – in 1981 – an entity operated by Food and Agricultural Organization Regional Office for Europe. CNRE included a collaboration from research institutions, which aim was to increase the share of renewable energies used in agriculture (Aires-Barros, 1988, p. 273). Geothermal energy was a natural fit to reduce energy requirements in rural sectors and to improve agricultural development overall. Eastern and South European countries such as Greece and North Macedonia started to use geothermal energy in greenhouse agriculture (European Geothermal Energy Council, 2006a, p. 12). As

seen in Figure 1, the European market still leads this development, which far exceeds the contribution from other regions. Hungary, Iceland, Italy, and the Netherlands are among the largest European geothermal producers, while China, Tunisia, Türkiye, and the USA lead the agricultural development outside of Europe (Lund and Toth, 2020, p. 6).

Current research indicates a lot of untapped potential for greenhouse agriculture across the world. According to some studies, 16% of earth's total continental surface is suitable for direct use of geothermal resource with 6% of that capable of greenhouse heating (Limberger *et al.*, 2018, p. 968). Thus, currently greenhouse agriculture has both the biggest share of total capacity and potential for growth.

The use of geothermal energy in greenhouses has many benefits. Heating and cooling a conventional greenhouse is energy intensive with around 50% of all operating costs dedicated to temperature control. An economic analysis by Kinney *et al.* (2019) shows that greenhouses using geothermal energy could reduce production costs by 50% and in some cases even reach 80% savings (p. 14). Using geothermal energy also reduces energy consumption, decreases the dependence on imported fuels and mitigates greenhouse gas emissions. Temperature control is a key component for optimizing crop growth. By using geothermal energy in greenhouses, temperature could be adjusted to fit daily variations and optimize conditions for different seasons, allowing a single facility to adjust to a consumer demand. Temperature control also reduces the probability of plant diseases, increasing production rates and shortening growing periods to allow flexibility and reaction to market fluctuations (Nguyen *et al.*, 2015, p. 22; Kinney *et al.*, 2019, p. 16). Conditioning of air and humidity, controlling water use and lighting is also possible with geothermal energy. Crops can be grown out of season and in climates that are originally unsuitable for agricultural production. Finally, the use of geothermal energy leads to a general improvement in quality of life by offering sustainable and healthy produce (Canadian Geothermal Energy Association, 2014, p. 60; Lund and Boyd, 2015, p. 14).

2.3. Basic Technical Principles of a Geothermal Greenhouse

To create a perfect climate for crop cultivation in a greenhouse such parameters as air movement, concentration of carbon dioxide and plant mass, interior temperature, light, and water are important (Popovski, 2003, pp. 93-94). Most of these parameters could be enhanced by using geothermal energy installation,

however its main use is to control soil and air temperature so to protect the crop growth. Additional uses include absorption cooling and irrigation (Pardo Garcia *et al.*, 2012, p. 12; Redko *et al.*, 2020, p. 195).

Generally, the design of a geothermal greenhouse does not differ significantly from a conventional one. The structures are simple enclosed spaces supported by frames made of aluminium, steel, or wood. Glass, fiberglass, or plastic film can be used to cover these structures to allow incoming light while conserving much of the radiated heat within the space (Panagiotou, 1996, p. 219). Geothermal system in a greenhouse typically mean to augment this heating with the use of some style of a geothermal doublet. These systems are usually closed loop and consist of two types of wells: production and injection wells. The production wells are used to extract the fluid from the subsurface, drawn through piping or heat exchanger and later pumped back into the aquifer via reinjection well. This preserves aquifer volumes and pressure and allows for sustainable energy production by heat mining from the subsurface aquifer. In some cases, reinjection wells may also serve as a method of wastewater disposal. Other disposal methods include re-use of the geothermal fluid or discharge into some drainage or disposal site, yet most frequently produced fluid is reinjected back into the reservoir to increase the life of a geothermal system (Jones, 2023; Panagiotou, 1996, p. 236). Clear understanding of the subsurface aquifer is necessary for a well-managed geothermal greenhouse system as the rate of withdrawal and injection are important for sustainable heat production. If a careful balance with the system is maintained extraction could last for periods up to or in some cases more than 100 years (Limberger *et al.*, 2018, p. 962).

The two types of heating solutions include either direct or indirect connections, which both use thermal water for heating. The less common but simpler option is a direct system, where the fluid from a borehole is collected in a tank installed above the ground level. It allows flow by gravity via transmission pipes and delivers hot water to the greenhouse. This installation is common for low-temperature fluid with low mineral content (Campiotti, 2002, p. 141; Popovski, 2003, p. 95). The indirect connection represents a more sophisticated system, which includes a heat exchanger as its major component. It is used either when geothermal fluid is not hot enough for the intended use or contains scaling and corrosive elements. In these systems the transmission pipelines are indirectly connected to the heating element, and depending on the purpose could be buried in the soil, laid on the ground surface or on benches or use aerial fans or pipes (see Figure 3) (Panagiotou, 1996, p. 221; Popovski, 2003, pp. 95-100). Although configurations vary widely, indirect heating

system design typically includes the following components: fan coil units, finned pipes, heat exchangers, and plastic tubing (Campiotti, 2002, p. 182).

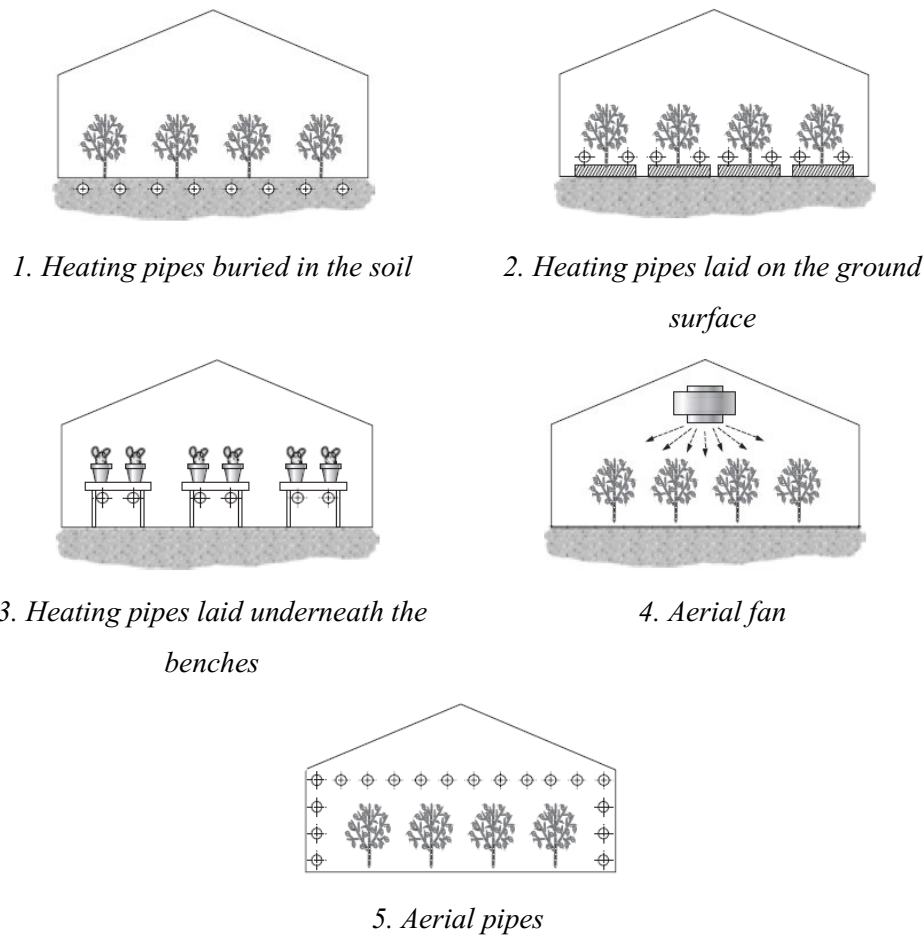


Figure 3. Position of heating installations in a geothermal greenhouse. Source: adopted from Popovski, 2003.

Typical geothermal greenhouse development consists of four basic stages. First, a discovered geothermal resource is assessed including the analysis of geothermal fluid, its composition, flow rate, and temperature potential. Next phase involves feasibility studies, investment, and market analyses. If these meet the requirements for the implementation the necessary permits are acquired to secure access to land and the resource. The decisions about cultivated crop and type of greenhouse system are assessed at this stage. Available resource temperature and production volumes will have the largest impact on the system choice. Third stage includes performing cost-benefit analysis and carrying out the final technical and economic design of a project. The final stage includes the construction of a greenhouse (adopted from Popovski, 2003, p. 109).

Commercial viability of a geothermal greenhouse depends on many factors, but the most important is the capacity for heating that ensures optimum plant growth. Since this capacity could vary daily, many designs recommend supplementing geothermal energy which covers base load demands with other types of renewable sources like solar energy, which could cover production peak loads. Technical designs that combine geothermal energy with our renewable sources could significantly lower the investment costs (Popovski, 2003, p. 95). The final price of geothermal heat could be influenced by construction design, operation costs, labour costs, and taxes among others. Usually, the use of geothermal energy is economically justified in big greenhouse complexes and not in small stand-alone projects due to initial costs and faster return on investment. Major commercial complexes consist of approximately 6 ha of greenhouses with 0.2-0.4 ha for each individual greenhouse (Canadian Geothermal Energy Association, 2014, p. 61).

On average, medium-to-low geothermal fluids with temperature range between 25-90°C are used in a greenhouse (Rafferty, 2004, p. 1). The average depth of such system is about 1000 m. Shallower depths are also possible but are not very common in Europe (van der Hout, 2021a). The products cultivated include cucumbers, eggplants, green beans, herbs, lettuce and leafy greens, mushrooms, strawberries, sweet peppers, and tomatoes. Non-food consumable products like decorative and ornamental plants, flowers and tree seedlings are also grown.

2.4. Environmental Risk Assessment of a Geothermal Greenhouse

Geothermal energy production and development involve certain risks (Kagel, Bates and Gawell, 2005; Krieger, 2018). While it is important to create a framework that enables industry growth, it is also important to ensure that its use is ecologically safe and secure. The Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources recital 46 states that:

Geothermal energy is an important local renewable energy source which usually has considerably lower emissions than fossil fuels, and certain types of geothermal plants produce near-zero emission. However, depending on the geological characteristics of an area, the production of geothermal energy may release greenhouse gases and other substances from underground fluids, and other subsoil geological formations, which are harmful for health and the environment. The Commission should therefore facilitate only the deployment of geothermal

energy with a low environmental impact and resulting in greenhouse gas emissions savings compared to non-renewable sources (OJ EU L 328, 2018, p. 88).

The environmental impact of geothermal resource production is in direct proportion to its size and scale. Factors such as fluid temperature, reservoir characteristics, resource depth, technical system designs, and type of use influence the probability of risks. Usually, deep high-temperature resources are associated with higher risks compared to shallow low-temperature resources (Hunt, 2001, p 21). Greenhouse agriculture has relatively low environmental impact, generally requiring shallow depths and low temperatures, and is thus associated with less risk. However, since every project is unique, it is impossible to fully specify the risks connected to only greenhouse agriculture. Literature also does not distinguish well between the risks for specific uses. Therefore, this chapter addresses some risks connected to development and operation of geothermal heating and cooling projects covering environmental risks on the well-being of fauna, flora, and people. Such risks as scaling and chemical mishandling, freshwater aquifer contamination, disturbance of sensitive areas, blowout and other equipment malfunctions constitute technical risks and are out of the scope of this chapter.

The environmental risks associated with geothermal heating and cooling include:

- *Air pollution.* During the initial stages of geothermal development certain pollutants might be released into the atmosphere. Large concentration of gases released from geothermal fluids, such as CO₂, H₂S, CH₄, may affect the environment. Carbon dioxide and other gases can be emitted as they naturally exist in the subsurface and are released through fluid production. Highest levels of CO₂ emissions are associated with high-enthalpy systems of volcanic regions. Such emissions however usually decrease with time as a result of fluid de-gassing (Intergovernmental Panel on Climate Change, 2011, p. 74). Hydrogen sulfide, if released in large amounts might be dangerous to individuals but again it is more common for high temperature systems (Barbier and Fanelli, 1977, p. 81). The concentration and amounts of gas vary from field to field. Usually, these gases are emitted in very low concentrations and discharge from low temperature resources does not pose significant damage to human health or environment (Hunt, 2001, p. 18).

- *Water pollution.* This risk can potentially occur during all stages of geothermal development and constitutes the contamination of surface or groundwater aquifers (Gehring and Loksha, 2012, p. 123). The environmental impact of geothermal fluid is tied to its chemical composition. Chemicals contained in geothermal water, such as arsenic, boron, mercury, etc. might present a danger to wildlife and vegetation if such contamination occurs. Low to medium temperature resources usually contain less harmful compounds than those that may be present with high temperatures. To prevent possible leakage proper construction, installation of protection equipment and adequate monitoring are required (Lienau and Lunis, 1991, p. 440; Hunt, 2001, p. 14).
- *Wastewater disposal.* The disposal of wastewater directly into natural waterbodies may negatively influence the local ecosystems. Currently, it is a common practice to reinject the wastewater back into the subsurface reservoir. Reinjection has shown minor effects on environment, living organisms, and waterways but it has been associated with seismicity and could potentially permeate to surface aquifers (Lienau and Lunis, 1991, p. 441; Hunt, 2001, p. 14).
- *Soil subsidence and seismicity.* If large amounts of geothermal fluid are extracted from beneath the surface, this may lead to soil compaction and land subsidence. Reinjecting water back into the reservoir is considered advantageous since it allows for consistent reservoir productivity and recharge but may be related to increased seismicity. Because the quantity of extracted and reinjected geothermal fluid is quite small in agri-food projects, such risks are usually negligible (McNamara and Kaufman, 1979, p. 8; Hunt, 2001 p, 20; Canadian Geothermal Energy Association, 2014, p. 103).
- *Noise pollution.* The main source of noise in heating and cooling projects comes from the installation of equipment and subsequent drilling. Noise levels during construction and operation phases are usually very insignificant to pose serious harm to the well-being of animals and people. The environmental effect of noise is considered moderate for all temperature resources (Hunt, 2001, p. 14; Canadian Geothermal Energy Association, 2014, p. 103).

- *Vegetation, wildlife, and disruption of thermal features.* Most geothermal agri-food projects are located in urban surroundings, so the disruption of natural vegetation and wildlife is estimated to be minimal (Lienau and Lunis, 1991, p. 443). Scientific evidence has shown that natural thermal features can be affected during geothermal development. Their extinction or reduction is a possible consequence of a reservoir pressure decrease. However, any degradation of naturally occurring thermal features is a concern only for high temperature liquid system (Anderson and Lund, 1979, p. 91; Hunt, 2001, p. 14).

The risks with the highest general probability of occurrence are water and chemical pollution, and complications from wastewater disposal (Lienau and Lunis, 1991, p. 437). The risk that is most relevant to greenhouse agriculture is thermal pollution of surrounding areas which might occur due to poor technical design of a heat disposal system (Popovski, 2003, p. 107). However, these and other risks are generally monitored and managed and in case of occurrence have a limited impact on the environment.

In addition, the environment, wildlife, and people's safety are protected through government regulations. Certain environmental and safety guidelines exist to ensure the secure and safe use of geothermal resources. For example, the European Union has several legal acts such as Directive 2000/60/EC establishing a framework for community action in the field of water policy, which requires every Member State to prevent the deterioration of surface waters and maintain good quality of groundwater (OJ EU L 327, 2000). Directive 2006/118/EC on the protection of groundwater against pollution and deterioration outlines monitoring and prevention mechanisms to prevent water pollution (OJ EU L 372, 2006). In addition, geothermal projects should comply with the environmental assessments based on the Directive 2001/42/EC on the assessment of the effects of certain plans and programmes on the environment and Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment, which both assess project significance and its impacts on the environment (OJ EU L 197, 2001; OJ EU L 26, 2011). Finally, Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora and Directive 2004/35/CE on environmental liability with regard to the prevention and remedying of environmental damage ensure extensive environmental protection (OJ EU L 206, 1992; OJ EU L 143, 2004).

To summarize, the environmental impact of geothermal greenhouse agriculture is limited and considered environmentally benign. Most risks can be successfully managed and do not result in long term harmful impacts. Measures prescribed in legal acts aim to minimize the consequences of geothermal development protecting biodiversity, ecosystems, and people.

2.5. Government Support for Geothermal Agri-Food

Greenhouse heating represents primary production phase in the agri-food value chain (International Renewable Energy Agency, 2022, p. 22). One of the key claims by experts is that any transformation to a value chain such as introducing geothermal energy requires support from the government. The Special Report of the Intergovernmental Panel on Climate Change (IPCC) suggests that supportive policy environment is needed to overcome institutional barriers related to geothermal energy deployment (Intergovernmental Panel on Climate Change, 2021, p. 148). The report of the European Commission on technology development stresses the importance of clear administrative procedures (Shortall and Uihlein, 2019, p. 60). A study completed by Orkustofnun, Icelandic National Agency, identifies adequate legislation as one of the necessary conditions for sector growth (Breembroek, Dijkshoorn and Ramsak, 2013, p. 25). According to other studies transparent regulations, local and national policies are required to promote geothermal development (see, e.g., European Geothermal Energy Council *et al.*, 2015, p. 26; Fell, 2018, pp. 1-2; International Renewable Energy Agency, 2020b, pp. 204-205).

In addition, experts assume that slow and unsteady growth of geothermal energy is due to inconsistencies in existing legislation such as unclear definitions, ambiguous ownership rights and its status in the law. According to these experts, effective legislation should acknowledge distinct characteristics of a resource, but in many countries geothermal energy is not or underrepresented in the legal system (Wonstolen, 1980, p. 661; Gehringer and Loksha, 2012, p. 83; Shortall and Uihlein, 2019, p. 24). Moreover, some studies suggest that geothermal energy cannot develop successfully and will not be ready to compete with other renewables without supportive measures from policymakers (Popovski, 2009, p. 8; National Renewable Energy Laboratory, 2011, p. 3; Nguyen *et al.*, 2015, pp. 43-44).

Government support can take many forms and literature dedicated to geothermal energy does not distinguish between them offering limited, general recommendations. Based on the research key government initiatives can roughly

take two forms: financial or policy incentives. The former could include insurance plans, risk mitigation schemes, tax incentives and various form of subsidies, while the latter could be expressed in administrative procedures, laws, and regulations. Although both types of incentives are important, extensive financial support requires sound legal basis. Policy and legal frameworks are built first while financial support comes second. The policies influence the industry long before any project can start – they set basic framework for geothermal development. For example, often before any initial exploration, a licence or permit is required to access to land and resource below it. Unlike policies, economic initiatives influence geothermal projects at a later stage of development, for example, at drilling and production phases. Hence transformation of a value chain should start with policy incentives.

Second, literature that addresses geothermal policies does not distinguish between various geothermal applications. As stated previously, there are many geothermal uses each with its own customer and market that involve different government support schemes. Currently, most policy or financial support mechanisms are directed at power production. The number of countries with government incentives for electricity generation is six times higher than for heating and cooling (European Geothermal Energy Council, 2006b, p. 2; International Energy Agency, 2011, p. 32; Rupprecht *et al.*, 2017, p. 42). This could be explained by a higher return on investment of power projects, which is very attractive to investors. Heating and cooling sector is also less straightforward with more diverse end uses and no single set of regulations (Shortall and Uihlein, 2019, p. 23).

The claim that government support is one of the key instruments for geothermal industry growth is not supported by any evidence or analysis. There are no clear reference points that address the relationship between government initiatives and geothermal energy development. To address the identified gap the following proposition is formulated:

Government support plays a role in the development of geothermal energy in the agri-food sector.

Figure 4 shows both theoretical and empirical planes of this research. First theoretical construct – “government support” – is conceptualized as a policy incentive represented as an independent variable. Second theoretical construct – “development of geothermal energy in the agri-food sector” – is operationalized as

adoption of geothermal energy in greenhouse agriculture and represents the dependent variable.

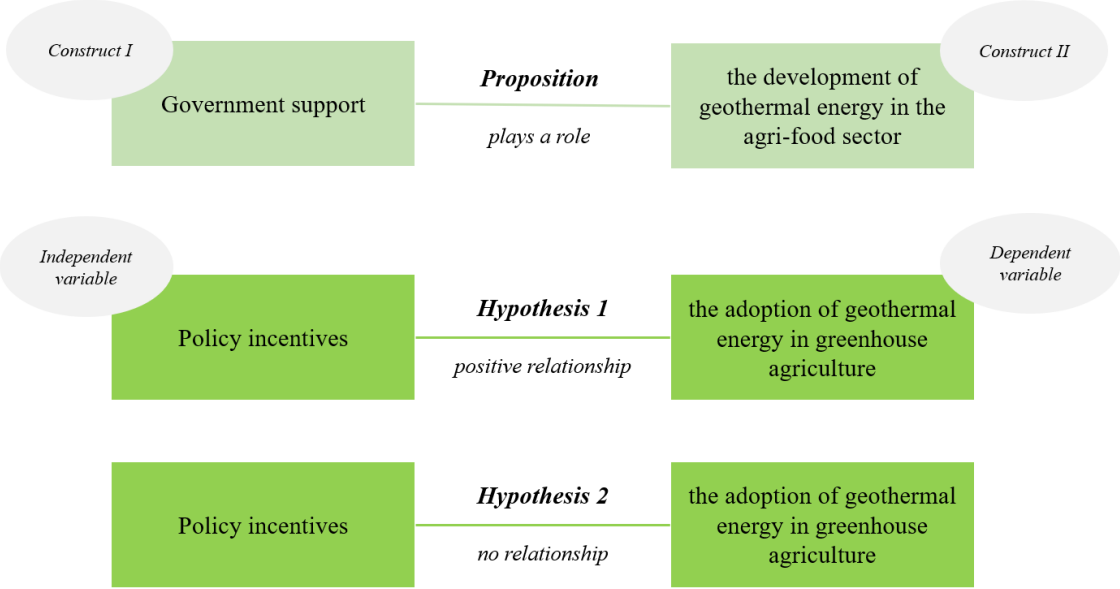


Figure 4. Theoretical and empirical planes of research. Proposition with two constructs, first main hypothesis (H1) and second alternative hypothesis (H2). Own elaboration.

Different relationships could exist between the two variables. As mentioned above, most experts claim that existence of policies supporting geothermal energy leads to its broader use and that without these policies geothermal sector will fail to develop. However, in theory these two variables could also be unrelated. To investigate the relationship and the degree of correlation between policy incentives and the adoption of geothermal energy in greenhouse agriculture two hypotheses are introduced:

- *Hypothesis 1 (main)*: there is a positive relationship between policy incentives and the adoption of geothermal energy in greenhouse agriculture.
- *Hypothesis 2 (alternative)*: there is no relationship between policy incentives and the adoption of geothermal energy in greenhouse agriculture.

The relationship could also be influenced by other factors. The following moderating variables are acknowledged to positively influence the relationship: geothermal resource availability and its proven technical potential, access to

geothermal resource data, national state-of-the-art research and existing industry institutions, high levels of public awareness and promotion strategies, available public and private funding among others (Pasquali *et al.*, 2007, p. 6).

3. Methodology

3.1. Design and Framework

To test the hypotheses a multiple case study is chosen as a research design, which includes twelve countries as case studies. This design helps derive contextual data in case sites and discover other factors that are potentially related to the hypotheses i.e., moderating variables (Bhattacharjee, 2012). Considering the purpose of the research and that is conducted in a relatively new area of inquiry and is exploratory, this framework tries to explain the observed gap in literature and identify the nature and influence of government support. The methods outlined below leverage the unique strengths of each other to help generate insights relevant to the research.

Multiple research methods are employed throughout the study. First, an exploration phase with state-of-the-art analysis of available literature is completed with respect to the research question: does government support play a role in the development of geothermal energy in the agri-food sector? Next, this question is decomposed since it presupposes the relationship between several constructs: government support and adoption of geothermal energy in the agriculture and food sector. Two hypotheses are built to explain the nature of a relationship between the two variables and to test the degree of their correlation. The instruments to measure two variables are then developed.

To measure policy incentive as independent variable the Likert summative scaling method is used. This method is often applied when a survey or a questionnaire needs to be developed. Since there exist various policy incentives and it is not possible to choose one or another without some level of subjectivity, a panel of experts is formed to ensure validity and reliability of variables. A scale of potential policy incentives is formed, and experts are invited to rate them in order of their importance to the geothermal greenhouse agriculture sector. At the end, six policy incentives are chosen as the most relevant. To measure the adoption of geothermal energy as dependent variable a secondary data analysis is performed. This includes an extensive data collection and descriptive analysis of available

industry statistics. The data analysis also helps establish sample size. A country represents a unit of analysis. Case countries are selected by using non-random purposive sampling, which is chosen because of the nature of research framework. This method of sampling sets out practical boundaries – only countries where geothermal energy is used in greenhouse agriculture are chosen.

Next, content and theme analysis are used to assess policy incentives in case countries, which includes the analysis of written documents, such as global policy documents, national government reports, and local legislative acts. The data are collected and compiled in the form of a country portfolio that includes the description of each variable and the relationship between them. A comparative analysis looks at the differences and similarities between twelve case countries. Leave-one-out cross validation estimates the performance of the dataset without one country at a time and its influence on the overall relationship between the two variables. A regression analysis is performed demonstrating how well policy incentives can explain various trends in the use of geothermal energy in greenhouse agriculture in case studies. The complete overview of research steps and their corresponding methods is presented in Table 1.

Table 1. Research steps and methods.

Research step	Method
<ul style="list-style-type: none"> • State-of-the-art analysis • Establishing a problem 	<ul style="list-style-type: none"> • Literature review
<ul style="list-style-type: none"> • Selecting research method, organizing strategy, building hypotheses 	
<ul style="list-style-type: none"> • Measuring variables • Estimating their validity and reliability 	<ul style="list-style-type: none"> • Likert Scale • Secondary data analysis
<ul style="list-style-type: none"> • Selecting a sample 	<ul style="list-style-type: none"> • Purposive sampling
<ul style="list-style-type: none"> • Compiling country portfolios • Assessing case countries 	<ul style="list-style-type: none"> • Content and theme analysis
<ul style="list-style-type: none"> • Analysis of a relationship between the two variables 	<ul style="list-style-type: none"> • Comparative analysis • Leave-one-out cross-validation • Simple regression analysis

3.2. Measurement of Variables

3.2.1. Policy Incentives

In this research government support is expressed as policy incentives, which may come in various forms and occur at different levels of governance. Policy incentives are defined as *relevant government instruments and measures directly or indirectly encouraging the use of geothermal energy*. These might include binding targets and obligations, directives, energy commitments, laws, and regulatory policies. A lot of countries also provide support for public research and development of geothermal energy. Australia, France, Germany, Italy, the Netherlands, Switzerland, and the USA have established programs to foster new geothermal developments (Shortall and Uihlein, 2019, p. 31). Research and development programs are not considered here because they are not coherent with the definition used above. These programs often involve government funding in the form of grants and are demonstrative in character (European Renewable Energy Council, 2007b, p. 115). Any similar support schemes including investment programs that are directed primarily at geothermal energy research are considered beyond the scope of the above definition.

For the purposes of this study incentives are divided between three different policy levels: global, national, and local levels. The global level includes international commitments and agreements, which are active internationally such as the Paris Agreement and Nationally Determined Contributions (NDCs). These include overarching directions and goals that most countries agree with and are committed to pursue. According to Müller *et al.* (2009) general global goals should be translated to specific targets on a national level. National policies represent more ambitious and detailed plans relevant for the specific country: national energy plans and emissions trading systems are some examples. Binding national targets are important because they guide decisions of policymakers and direct public and private sectors (European Geothermal Energy Council, 2007, p. 16). At the same time both global and national policies are unlikely to be met unless they are driven by dedicated local regulations (International Renewable Energy Agency, 2019c, p. 30). Local level policies include specific laws and legislative acts supporting and regulating energy development. For geothermal energy sector, the following components of local policies are of the most importance: definition of geothermal resource, its legal status, ownership rights, and the rules for access to and the use of the resource (based on Reed and Bloomquist, 1995, pp. 629-631; Bloomquist, 2003,

pp. 53-55). In general, the level of each policy represents the scope of its functionality. The more specific the level is the more binding the policies are. All three levels are also interconnected. The relation between national and local policies within one governance framework is a crucial factor for adopting effective strategies (Müller *et al.*, 2009, p. 34; Steinbach *et al.*, 2017, p. 12).

To measure policy incentives extensive desk research is carried out. All relevant incentives are identified. To validate their contribution and importance a Likert summative scaling method is used. First, a list of 18 identified policy incentives is assembled, where each item is assigned to a global (G), national (N), or local (L) level. In the list below, the number following the letter indicates its position in a Likert questionnaire: it includes four global, eleven national and three local policies. Some items such as carbon tax (N5), tax rebate (N6), tax relief (N7), tax credit (N8), feed-in-tariff (N9) and feed-in-premium (N10) could be regarded as either legal or financial incentives. They are included in the list because they combine both aspects and research literature is not clear in their distinction.

The initial policy incentives for Likert questionnaire include:

1. *G1, Paris Agreement*. A legally binding international agreement on climate change. According to its Article 2 para. 1a its main goal is to:

hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels (FCCC/CP/2015/10/Add.1, 2015, p. 4).

Article 2 para 1b seeks to further:

increase the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production (FCCC/CP/2015/10/Add.1, 2015, p. 22).

2. *G2, Nationally Determined Contributions (NDCs)*. A mandatory self-determined action plan to comply with the Paris Agreement. Article 4 para. 2 of Paris Agreement requires that “each party shall prepare, communicate, and maintain successive (FCCC/CP/2015/10/Add.1, 2015, p. 23). Each signatory can determine its contributions in the context of its country’s national priorities and capabilities. Countries use this document to

communicate their plans for greenhouse gas reductions (International Renewable Energy Agency, 2020b, p. 91; United Nations, no date-c).

3. *G3, Long-Term Low Emission Development Strategies*. An optional long-term vision plan for NDCs. Article 4 para. 19 of the Paris Agreement states that “all parties should strive to formulate and communicate long-term low greenhouse gas emission development strategies” (FCCC/CP/2015/10/Add.1, 2015, p. 24). These strategies aim to place NDCs into the context of development priorities, provide a vision and direction for a future development (United Nations, no date-d).
4. *G4, National Sustainable Development Strategy*. A voluntary strategy for achieving Sustainable Development Goals. This concept was introduced in 1992 at the United Nations Conference on Environment and Development in the document called Agenda 21. As its Chapter 8 para. 8.7 states:

governments, in cooperation, where appropriate, with international organizations, should adopt a national strategy for sustainable development based on, inter alia, the implementation of decisions taken at the Conference, particularly in respect of Agenda 21. This strategy should build upon and harmonize the various sectoral economic, social and environmental policies and plans that are operating in the country. The experience gained through existing planning exercises such as national reports for the Conference, national conservation strategies and environment action plans should be fully used and incorporated into a country-driven sustainable development strategy. Its goals should be to ensure socially responsible economic development while protecting the resource base and the environment for the benefit of future generations (United Nations, 1992, p. 66; United Nations, 2022b).

As a follow up mechanism these strategies are now being presented at High Level Political Forum (HLPF) and submitted in the form of Voluntary National Reviews (VNRs) (United Nations, no date-e).

5. *N1, Emissions Reduction Targets*. A policy instrument to cut greenhouse gas emissions in specific sectors (agriculture, housing, transport, etc.). It is based on NDCs and is connected to a carbon budget concept – maximum

allowed amount of emitted CO₂ that will result in limiting global warming (Intergovernmental Panel on Climate Change, 2021, p. 28).

6. *N2, Renewable Energy Action Plan, or similar.* A document outlining targets for renewable energy development. It may come in various forms and could be called differently in different countries. For example, Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources Article 3 para. 2 requires each Member State to prepare national energy and climate plans, which address energy efficiency, greenhouse gas emission, renewables, etc. (OJ EU L 328, 2018, p. 105).
7. *N3, Renewable Portfolio Standards.* An obligation for energy supply companies to produce a certain amount of energy from renewable sources. Here, the country defines what technologies and utilities are subject to these standards and includes them in the legislation (Heeter, Speer and Glick, 2019, pp. 1-3). This incentive is common for the electricity market and in the case of geothermal energy claims to support the development of high temperature resources (International Energy Agency, 2011, p. 31).
8. *N4, Emissions Trading System.* An incentive to trade emissions to control pollution and one of the instruments to reach N1, Emissions Reduction Targets. It represents a form of carbon pricing and is also known as cap-and-trade model. Participants in this system are energy and industry companies, which acquire an emissions right certificate. It establishes a certain limit of allowed emissions. If it is exceeded, the company needs to buy the right for additional emissions from other participants. Conversely, if a company performs below the limit, it has the right to sell its certificate (Schubert, 2019a, pp. 26-28; German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, 2021, pp. 19-20).
9. *N5, Carbon Tax.* A tax levy on carbon emissions and one of the instruments to reach N1, Emissions Reduction Targets. Similar to N4, Emissions Trading System it also represents a form of carbon pricing. A government sets a fee that businesses, companies, consumers, and households must pay for each amount of greenhouse gas, or other pollutant they emit (Tax Policy Center, 2020, p. 455; Center for Climate and Energy Solutions, no date).
10. *N6, Tax Rebate.* A tax refund for renewable energy production.
11. *N7, Tax Relief.* A tax reduction for renewable energy producers. An initiative aimed to promote installations of renewable systems. It affects the

operational phase of a project where main revenues are generated (Wendel and Hiegl, 2010, p. 4; Pasquali, 2013, p. 19).

12. *N8, Tax Credit*. A tax deduction for installing renewable energy systems. According to the Report of the Intergovernmental Panel on Climate Change, tax credits work best in countries with numerous private companies (Intergovernmental Panel on Climate Change, 2011, p. 152).
13. *N9, Feed-in-Tariff (FIT)*. A long-term compensation for renewable energy producers. It secures an income over a long-term period as a guarantee of minimum price per unit of energy. It also ensures that energy is bought from the producer at a fixed rate. FIT affects the operational phase of a project where main revenues are generated (Poux, 2009, pp. 33-34). While it is usually applied in electricity market, it can also be valuable for combined power and heat production. The study of Jimenez Navarro, Cejudo Lopez and Connolly shows that FIT supporting combined power and heating and cooling system leads to its improved economic performance (p. 447).
14. *N10, Feed-in-Premium*. A premium paid to renewable energy producers in addition to the wholesale price. Usually, introduced as an alternative to feed-in-tariff when a premium above the market price is paid. It is seen as a guarantee against additional operational costs (Schubert, 2019b, p. 30).
15. *N11, Geothermal Energy Action Plan*. A stand-alone dedicated national plan for developing geothermal energy. It could describe priority actions, set goals, and identify regions where geothermal resource development is foreseen. Such plan could be aimed at a specific sector (electricity or heating and cooling) or provide support for the industry in general. Although rare, such plans exist e.g., in France, Iceland, the Netherlands, and New Zealand (Ministry of Industries and Innovation, 2014; Stichting Platform Geothermie *et al.*, 2018; Ministère de la Transition Énergétique, 2023; New Zealand Geothermal Association, 2023). These plans could be a product of a government initiative (France) or represent a collaboration of private and public sectors (the Netherlands).
16. *L1, Definition of geothermal resource*. A legal definition of geothermal resource. The way the resource is defined is crucial to the implementation of legislation and hence the development of geothermal industry. The presence of geothermal resource definition ensures legal certainty and clarity (Pasquali *et al.*, 2007, p. 13). The scope of a definition could include some physical properties of a resource, main heat carrier (water, gas), its

temperature and depth limits (Rupprecht *et al.*, 2017, p. 10). A definition could also precondition the use of certain applications. For example, if a definition excludes shallow depths the use of geothermal ground source heat pumps might not be regarded as geothermal use (European Geothermal Energy Council, 2006b, p. 3). The definition of geothermal resource does not only vary from country to country but might also differ between administrative units of one country, as is the case in Italy and the USA.

17. *L2, Ownership rights and regulation of geothermal resource.* Legally defined ownership rights of geothermal resource and its status. Multiple studies outline these two components as important parts of a coherent legal framework (Lienau and Lunis, 1991, p. 396; European Geothermal Energy Council *et al.*, 2013, p. 75; Pasquali and O'Neill, 2015, p. 6). Based on a definition of geothermal resource appropriate laws are applied. Although it is easier to specify geothermal energy within an existing legal framework, new acts are often required when national laws are not originally meant to regulate this energy source (van der Hout, 2021b). Geothermal regulation defines the resource status, for instance, as a gas, mineral, water, or as their combination depending on its temperature and depth outlined in the definition (European Geothermal Energy Council, 2006b, p. 2). The relevant regulation could thus be spread across multiple laws: mineral, mining, and water management. The legal owner of the resource should also be secured in the law (Dumas *et al.*, 2013, p. 23). In countries with young or underdeveloped geothermal energy markets there are usually no specifications about the resource ownership. In more established geothermal markets, the resource could belong to the general public, landowner, municipalities, or state.

18. *L3, Access to and the use of geothermal resource.* Legally defined process for access to and the use of geothermal resource. It includes resource rights regulation and energy development, land use and corresponding permitting processes. Exploration and exploitation of geothermal resource is subject to licencing in all countries (Balan and Nador, 2018, pp. 1-3). Efficient licensing procedures for land and resource access are a prerequisite for efficient geothermal energy legislation (Gehring and Loksha, 2012, p. 79).

These 18 items are listed into the structured web questionnaire with a five-point Likert scale, with interval-level response format. Each item includes a name and its definition formulated as a worded statement to which respondents could indicate the

extent of agreement or disagreement ranging from “strongly agree” to “strongly disagree”. A neutral anchor is also introduced to avoid a forced choice approach. A field is also given to include other policies not listed. Two additional fields at the end of the questionnaire ask for personal information: sector and country of employment. The questionnaire ends with an open field for respondents to leave their comments and feedback. A blank copy of a questionnaire is included in Appendix A.

Special attention was paid to eliminating ambiguity and removing bias in question statements and sequences. Before administering the questionnaire to respondents, it was pre-tested by the Executive Director of the International Geothermal Association to check the syntax and to make certain that language and structure are well understood.

A panel of expert judges was formed to assess the scale validity. A desk study was performed to find industry professionals with expertise in the research topic. In total, 127 representatives were identified and invited to participate in the questionnaire. The expert panel showed diversity of expertise and geography: experts came from 23 countries including EU and non-EU states. Industry professionals from academia, government agencies, and private sectors were contacted. They were approached via the standardized tool – electronic mail – with an invitation to participate in the study including the web link to the questionnaire. The invitation email is included in Appendix B.

The questionnaire was administered over the internet via Google Forms on behalf of the International Geothermal Association. It was open for two weeks between 30 April – 14 May 2021 and consisted of three rounds:

- *Round 1*: the survey was sent out via email to 127 experts on 30 April 2021. Out of 127 emails 26 bounced and two experts declined the invitation for reasons of not having enough qualification. They, however, recommended two additional industry professionals who were not on the initial list but were added to it for the next round.
- *Round 2*: a second reminder was sent to 127 experts on 3 May 2022. Expert email addresses were checked for spelling and all bounced emails were once again included in a mailing.
- *Round 3*: a third reminder was sent to the valid addresses of 107 experts on 12 May 2021, two days before the deadline. Twice confirmed inactive email addresses were excluded from the mailing.

The survey was closed on 14 May 2021. A total of 32 responses were obtained, which accounted for a 30% response rate (excluding inactive emails). No invitation to contact the experts for follow-up questions was administered. During the survey execution complete confidentiality was preserved. No subject was aware of the responses of the other subject.

Next, survey responses were coded and entered into an MS Excel spreadsheet, where their analysis was performed. First, the data were checked for central tendency bias: three entries with extreme response categories irrespective of content were identified and removed from the subsequent analysis. The remaining 29 responses were examined for each item separately.

Final items were chosen based on a few characteristics. First, to check the overall importance of policies the total sum for each item was calculated. This was completed by summing all values of each item as selected by a respondent excluding neutral anchor, i.e., scores 1, 2, 4, and 5 excluding the score 3 as a neutral response. The maximum overall score for each item is 144 because the score 145 would imply extreme response categories and hence would disqualify the entry as biased. Only the items with the highest item-to total correlation ($\geq 70\%$) were chosen. Eight items showed high-item-to-total correlation score.

To further explore the relevance of policy incentives, central tendency measured as each item's weighted average was acquired. This time nine items on the list had a high weighted average value with four or higher. Finally, to measure the level of agreement between the experts on policy significance, dispersion measured as standard deviation was calculated. The items with values under one standard deviation i.e., with the smallest spread of values around central tendency were chosen. Ten scale items were identified.

The above-mentioned statistics – total score, weighted average, and standard deviation – were identified as the most relevant for the data at hand. Considering the low number of respondents, acquired Likert scale data do not justify more sophisticated statistical tests, like T-test or Pearson correlation. To avoid overinterpreting the results, these description statistics are sufficient (Perez, 2023). All three statistical values complement each other providing the full picture of both policy's overall importance and levels of agreement about it between the experts.

The final decision on the most relevant policies was based on the composite score of each item, which included a combination of the highest total sum and weighted average with the smallest value spread. The final selection included six items with the highest composite score:

- G2, Nationally Determined Contributions.
- G4, National Sustainable Development Strategy.
- N1, Emissions Reduction Targets.
- N2, Renewable Energy Action Plan.
- N11, Geothermal Energy Action Plan.
- L2, Ownership rights and regulation of geothermal resource.

Across all statistical tests, N11, Geothermal Energy Action Plan received the highest scores, which means that among all surveyed policy incentives experts regard it as the most important.

Half of the six incentives capture the period of 2010 onwards, e.g., G2, Nationally Determined Contributions, G4, National Sustainable Development Strategy and N1, Emissions Reduction Targets appeared only after the enactment of Paris Agreement in 2015.

Other impactful policy incentives suggested by the respondents could be grouped into four categories (from the most to least frequent). These are *a*) geothermal de-risking and mitigation schemes and strategies, e.g., for geological uncertainties; *b*) national resource mapping, which includes databases and general liberalization of well data; *c*) inclusion of geothermal energy to environmental, mining, and labor safety laws; *d*) market and price regulation for geothermal energy. Categories *a*) and *d*) include financial and economic incentives, which are out of the scope of this research. Category *b*) involves geothermal resource data availability, which is acknowledged as a moderating variable and category *c*) entails incorporation of geothermal energy to existing regulations, which represents the scope of item L2, Ownership rights and regulation of geothermal resource.

Most experts were representatives of government agencies or independent consultants and researchers (25% for each) followed by respondents from academic institutions and industry non-profits (18% for each). Other work sectors included companies for-profit (4%) and category other (10%). For the latter experts identified themselves as representatives of public bodies (consortium of municipalities and regional governments), research and energy agencies.

The responses canvassed across a variety of countries – 16 in total. All experts come from Europe (incl. Türkiye). Most respondents come from Italy, followed by France, Greece, Hungary, Iceland, the Netherlands, and Slovenia. The complete Likert scale codebook with questionnaire answers and their analysis is attached in Appendix C.

3.2.2. Greenhouse Agriculture

In this research, the development of geothermal energy in the agri-food sector is expressed in its adoption in greenhouse agriculture. This use ranks the third biggest globally within heating and cooling sector excluding heat pumps (Lund and Toth, 2020, p. 6). It is also the biggest contributor to the geothermal agri-food sector representing 67% of its total capacity and use in 2020. It has one of the largest predicted technical potentials when compared to other agri-food uses, such as aquaculture and agricultural drying. In addition, greenhouse agriculture has the most available and comprehensive dataset as it is the most recorded agri-food use of the resource. In the context of this study, adoption of geothermal greenhouse agriculture is defined as *the total installed capacity of geothermal greenhouses measured in megawatts thermal (MWt)*.

To measure the adoption of geothermal energy in greenhouse agriculture a data analysis is performed. Many organizations collect and report on geothermal energy statistics, among them are European Geothermal Energy Council, International Energy Agency, International Geothermal Association, International Renewable Energy Agency, etc. As a recent study claims, datasets vary considerably among these entities as consequence of differing data collection methods, data classification and reporting systems. As a result, the reported values such as capacity and actual energy use differ from organization to organization (Krieger, Kurek and Brommer, 2022, p. 10). This is especially evident with heating and cooling statistics. While collection of power data is more straightforward, heating and cooling reporting is more ambiguous and lacks common data standards and reporting methods which complicates this issue. However, among all global data collecting entities, International Geothermal Association (IGA) has the largest and the most complete heating and cooling dataset, which is why most organizations use the IGA data as a point of reference (Krieger, Kurek and Brommer, 2022, pp. 6-10). For this reason, it is selected as the most comprehensive data source. The IGA development statistics are published in the World Geothermal Congress Worldwide Reviews and Country Updates. The IGA Country Updates are submitted directly by industry experts, while the IGA Worldwide Reviews comprise data from the Country Updates with additional insights from its authors. Because the data between these sources do not always match, they were examined and cross-referenced. In cases of discrepancy between the energy values the Country Updates were given priority as they represent original submissions.

The IGA development dataset covers many statistical and technical values. The former covers installed capacity and energy produced; the latter includes enthalpy, flow rate, temperature, and other categories. The most relevant figure reflecting the rate of adoption of geothermal energy in greenhouse agriculture is expressed in total installed capacity. Unlike final energy use, which could fluctuate from year to year depending on day-and-night cycles, weather conditions, and market demand, total capacity more accurately shows actual additions to the sector.

Other values considered for the analysis but not used as a final measurement are:

- *Number of greenhouses.* Such numbers are very rarely reported in development statistics therefore they cannot be used as a comprehensive assessment measure of geothermal energy adoption.
- *Number of wells drilled for greenhouse agriculture.* Such data are not always available online. In some countries the well data including its intended use could be made public only after a certain time, so it is not always on hand. Additionally, depending on the resource discovered after the exploration phase, its use could be adjusted.
- *Number of issued permits.* Such data, when available, are almost always published in the native language of a country issuing a permit, which constitutes an accessibility barrier.

The available IGA data covers the period from 2000 to 2020 and is represented as a total installed capacity snapshot for every five-year period, i.e., for 2000, 2005, 2010, 2015, 2020. Thus, in total, five datasets are available. The data analysis was performed to identify the total number of countries reporting greenhouse agriculture together with their individual energy capacities for every five-year period. A total of 288 individual datasets contained in the IGA Worldwide Reviews and Country Updates were analyzed and cross-compared. The complete list of used sources per country is included in Appendix D.

3.3. Sampling

To select case countries a non-random purposive sampling is used. This method is the most practical way to draw a sample: both hypotheses imply the use of geothermal greenhouse agriculture, hence only the countries that report its use are relevant for this study (Bouma and Atkinson, 1995, p. 143). An individual country represents a single unit of analysis. According to the data analysis, in the period of

2000-2020 a total of 88 countries used geothermal energy for heating and cooling. Out of them 48 reported agri-food use but only 39 countries have used geothermal energy in greenhouse agriculture. These 39 countries constitute the initial sampling pool and can be found in Appendix E.

Each country has five datasets – five available capacity snapshots for every five-year period. However, since policy incentives are present from 2010 onwards only three datasets of 2010, 2015, and 2020 are used to derive a sample. This way both variables cover the same timeline, which allows for consistent observations.

To find countries that could provide the best insights into the research topic, deeper analysis is required. First, the data integrity is checked – asking is reporting present in all three datasets? Since it is not possible to make any sound conclusions with incomplete data, the countries where values are not available for any one point in the dataset are removed from the analysis. These are Algeria, Belgium, Bosnia and Herzegovina, Croatia, Cyprus, Ecuador, Egypt, Mexico, Mongolia, Poland, and the United Kingdom.

Next, the hypotheses imply an existence of a relationship between the two variables. To test this relationship a certain data trend must be present in a country. To establish the correlation between policy incentives and greenhouse agriculture, the capacity values should show a certain change in capacity, e.g., a decline or a growth. Countries with no changes across two or more datasets including those with no differences between the values in two latest datasets – 2015 and 2020 – are not considered relevant for this study. These countries do not allow for sound conclusions in relation to the hypotheses and are excluded from further research. The changes of 1 MWt or less are considered rounding errors and are disregarded. Countries with no apparent trend are Argentina, Bulgaria, El Salvador, France, Israel, New Zealand, North Macedonia, Portugal, Romania, Russia, South Korea, Tunisia. The country of Slovakia also does not show a clear trend, where values fluctuate from year to year.

In addition, when examined in detail, the original data source – the IGA Country Updates – consists of two data subsets. Both are represented as tables: one table shows utilization per type of use in a country and another table shows final summary of uses. In three countries the data between these two subsets do not match in terms of trends, these are China, Georgia, and Slovenia. For example, in China's Updates, one dataset implies the growth of the industry and another no growth: one set of values shows rapid increase of more than 100%, while another shows no changes in

capacity within the same time period (see Zheng, Han and Zhang, 2010, pp. 7-9; Zheng *et al.*, 2015, pp. 6-7; Tian *et al.*, 2020, pp. 7-8).

The final sampling pool consists of twelve countries. Each country has a certain development tendency in terms of capacity values. Two data trends are identified:

- *growth*, with a continuous increase in capacity. These countries are Austria, Greece, Hungary, Iceland, the Netherlands, Spain, and Türkiye.
- *decline*, with a continuous decrease in capacity. These countries are Italy, Japan, Kenya, Serbia, and the USA.

As no further criteria for elimination were established these countries constitute the final sampling pool. The number of selected cases corresponds to the commonly accepted range of sample size (Zaborek, 2009, pp. 7-8). The sample of twelve countries (31% of the initial population of 39 countries) reflects the richness of available information, is expected to support the study's aim and to provide meaningful insights in relation to the hypotheses. The complete overview of the sampling procedure can be found in Appendix E.

3.4. Content Analysis

Six validated policy incentives (G2, Nationally Determined Contributions; G4, National Sustainable Development Strategy; N1, Emissions Reduction Targets; N2, Renewable Energy Action Plan; N11, Geothermal Energy Action Plan; L2, Ownership rights and regulation of geothermal resource) appear as an outcome of scaling process presented above. They are used to measure government support in case countries. To make systematic comparisons between them, a content analysis is applied. This method allows to gain insights into the research topic by using themes related to the hypotheses (Hsieh and Shannon, 2005, p. 1286). The main theme is geothermal energy and in this study content analysis attempts to answer the question of how present geothermal energy is in the policy documents and how relevant it is to a country.

First, for every policy incentive a document or a series of documents are identified and gathered. Since the research covers the period between 2010 and 2020, policies that were active and in place by 2010 are included in the analysis while those that were enacted in 2020 and beyond are excluded. Main sources used for policy research include Grantham Research Institute on Climate Change and the Environment (London School of Economics and Political Science, 2022), FAOLEX Database (Food and Agriculture Organization, 2022), IEA Policies Database

(International Energy Agency, 2022), RES LEGAL Europe (European Commission, 2012), and Raw Materials Information System (European Commission, 2022b).

The following documents for each policy incentive are identified:

- *G2, Nationally Determined Contributions (NDCs)*. According to Article 4 para. 2 of the Paris Agreement, NDCs are submitted every five years (United Nations, no-date-c). The first versions were submitted in 2016 and the second round followed in 2021-2022. Türkiye is the only country that submitted its first NDCs very recently in 2021. All European Union countries submit NDCs via a joint document. According to the Treaty of Lisbon Article 2C (2) introduced in 2007, energy topics became an area of shared competence between European Union Member States (OJ EU C 306 , 2007).
- *G4, National Sustainable Development Strategy, or Voluntary National Reviews (VNRs)*. There is no stated frequency for submitting the VNRs since they are not mandatory. The UN Secretary-General recommends the submission of at least two documents during the 15-year period (United Nations, no date-e). The first VNRs were submitted in 2016-2017 and many countries already submitted their second VNRs. Austria submitted its first VNR in 2020 and the USA has not submitted any to this date.
- *N1, Emissions Reduction Targets*. There are no official documents outlining Emissions Reduction Targets. This incentive is included in the NDCs as one of its parts, so it is analyzed together with G2 incentive.
- *N2, Renewable Energy Action Plan, or similar*. There exist a variety of documents that outline targets for renewable energy development. Until 2021 the EU Member States were required to submit their plans by using a special template based on the Directive 2009/28/EC² and 2009/548/EC Commission Decision (OJ EU L 140, 2009; OJ EU L 182, 2009). Some non-EU countries (Iceland, Serbia, and Türkiye) adopted the same templates, and their contributions are in line with EU directives. All European Union countries had two submissions: in 2010 and 2020; the frequency of non-EU submissions varies. Countries like

² This Directive is now repealed and substituted by Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources, which according to para. 8 requires EU Member States to prepare their Integrated National Energy and Climate Plans as their contribution to the common Union target of “at least 32% of renewable energy” (OJ EU L 328, 2018, p. 105).

Japan and Kenya have two documents available that fall within the research timeline.

- *N11, Geothermal Energy Action Plan.* Iceland and Netherlands are the only countries that have a stand-alone dedicated national plan for developing geothermal energy.
- *L2, Ownership rights and regulation of geothermal resource.* Status of geothermal resources and its ownership are usually a part of the existing local legislative acts, such as Mining or Water Acts. Most of them were enacted before 2010 and are still in use today.

Table 2 below shows the identified policy documents for each case country. Most countries have at least one document per policy, exceptions are Türkiye that has no G2, Nationally Determined Contributions and Austria and the United States with no G4, Voluntary National Reviews. The majority of countries also lack N11, Geothermal Energy Action Plan. The corresponding cells are marked with *n/a* as an indication of the lack of any document related to the incentive. Some countries have more than one document, e.g., Türkiye has two submitted G4, Voluntary National Reviews and Japan and Kenya two N2, Renewable Energy Action Plans each. L2 policy incentive is sometimes represented by multiple documents since ownership and status of geothermal resources are often spread across multiple regulations. These usually include Natural Resources, Mining, or Water legislative acts. The only exception is the United States where federal status and ownership of geothermal resources are defined by judicial decisions. All European Union countries share one common document for G2, Nationally Determined Contributions and N1 has no separate document as it is a part of G2.

Other names for N2, Renewable Energy Action Plans include:

- NCCAP – National Climate Change Action Plan in Kenya.
- NREAP – National Renewable Energy Action Plan in the European Union Member States and other countries that selected the same template for submission.
- SEP – Strategic Energy Plan in Japan.

Table 2. Identified policy documents for each case country. “N/a” indicates the lack of any document related to the incentive.

	G2	G4	N1	N2	N11	L2
Austria	NDCs 2016	n/a	No separate document. Included in the G2 incentive.	NREAP 2010	n/a	Water Rights Act 1959
Greece		VNR 2018		NREAP 2010	n/a	Mining Code 1973
Hungary		VNR 2018		NREAP 2010	n/a	Act on mining 1993 Act on Water Management 1995
Italy		VNR 2017		NREAP 2010	n/a	Legislative Decree No. 22 2010
Netherlands		VNR 2017		NREAP 2010	Master Plan Geothermal Energy 2018	Mining Act 2002 Water Act 2009
Spain		VNR 2018		NREAP 2010	n/a	Law on Mines 1973
Iceland	NDCs 2016	VNR 2019		NREAP 2014	The Master Pan Act 2011	Natural Resource Act 1998
Japan	NDCs 2016	VNR 2017		SEP 2014 SEP 2018	n/a	Industrial Water Law 1956 Civil Code Act 1896
Kenya	NDCs 2015	VNR 2017		NCCAP 2013 NCAAP 2018	n/a	Geothermal Resource Act 1982
Serbia	NDCs 2017	VNR 2019		NREAP 2013	n/a	Law on Mining and Geological Explorations 2015
Türkiye	n/a	VNR 2016 VNR 2019		NREAP 2014	n/a	Law on Geothermal Resources and Mineral Waters 2007
USA	NDCs 2016	n/a		The President’s Climate Action Plan 2013	n/a	Ottobonie vs. the United States of America 1977 Pariani vs. State of California 1980

After compiling the documents for content analysis, the coding categories are identified. These will differ for different policy levels. Main theme of this research predetermines coding categories for global and national policies, which comprise of individual words such as “geothermal”, “thermal”, “geothermal energy”, “geothermics” and other related words. The coding process for global and national policies includes analyzing policy documents by identifying and counting all occurrences of individual words and phrases. The frequency of categories is recorded per document. The words are counted based on their full context, relevance and meaning. The main questions to answer are “How well geothermal energy is represented in a policy incentive?” and “How relevant are the references to the geothermal greenhouse sector?”. All references that acknowledge geothermal energy and describe its importance to the country are recorded and counted, but some of them are identified as “unaccounted references”, which means they are not thematically relevant for this research and so are excluded from the final count. These include mentions of specific markets (electricity, heating and cooling, etc.), simple factual statements of how much geothermal energy is produced in a country and negative mentions, or barriers to geothermal development. In the final analysis only the references relevant for hypotheses testing are considered. These represent mentions that advocate and encourage the use of geothermal energy and that are relevant to greenhouse agriculture. Also, if the same categories appear twice or more in a single document, they are counted only once. For instance, if geothermal energy is mentioned as a key sustainable resource for a country several times it counts as one occurrence because these two instances cover the same context. Such an approach ensures that scope and pertinence of research themes directly related to the hypotheses are captured (Hsieh and Shannon, 2005, p. 1281).

Coding process for local policies involves identifying if ownership and status of geothermal resources are stated in the law. Coding categories here are “ownership”, “regulation”, “status”, which unlike global and national policies are not represented by the number of occurrences, but as factual presence in the law and are also recorded per document. These two aspects – ownership and status – could be covered in separate laws, but the main questions to answer are: “Is the owner of geothermal resource legally defined in a clear way?” and “Is the law clear on geothermal resource status, i.e., does it explicitly say how it is regulated and under what jurisdiction it is?”. In general, geothermal resources could belong to the state or be public property, it could be attached or not attached to the land ownership; geothermal resource could be regulated as water, gas, mineral, or sui generis. Since

there are only two aspects in which presence is counted, two is the maximum value for the local level.

Each policy document is coded manually, and all relevant data are recorded in MS Word. The content analysis codebook and record sheet with complete overview of measuring units, categories and values are included in Appendix F.

4. Case Countries

This chapter integrates data collected for analysis into individual country portfolios. Each portfolio includes an overview of geothermal industry and a content analysis of global, national, and local policies in the case country. It begins with a generalized review of geothermal energy applications. Figures on installed capacities are represented by their reported values from the IGA Country Updates. Electricity generation values are reported in megawatt electric (MWe), and heating and cooling uses in megawatt thermal (MWt). To allow for comparisons, electricity generation (MWe) relates to thermal energy (MWt) by the aggregate efficiencies of the power generating facilities. These typically convert thermal to electrical energy at an efficiency of 10-20% i.e., 1 MWe of power generated at 10% efficiency may consume 10 MWt (Moon and Zarrouk, 2012, p. 1).

The review is followed by the analysis of greenhouse agriculture covering its history and recent data trends. In some cases, examples of greenhouse projects are given including their location, size and products grown. An overview of existing policy incentives follows describing their pertinence to the geothermal industry summarizing specific context-relevant examples. These include a country's ambitions for geothermal utilization, existing and planned programs with measures supporting geothermal energy development. The number in parenthesis e.g., (2) following each policy indicates the total number of geothermal references relevant to greenhouse agriculture in a document. The higher the number, the better geothermal energy is represented in a policy. The (*n/a*) indicates the lack of a certain policy document from the analysis, often because it is not present and the value zero (0) indicates no relevant references in a document. An asterisk superscript (*) signifies an explicit mention of geothermal energy use for greenhouse agriculture.

An overview of these values as they pertain to the geothermal agri-food sector per country is presented in Table 3, where G2 stands for Nationally Determined Contributions with NI, Emissions Reduction Targets as a part of it. G4 stands for

Voluntary National Report, *N2* for Renewable Energy Action Plan, *N11* for Geothermal Energy Action Plan, and *L2* for Ownership rights and regulation of geothermal resource. The table also contains columns *Ownership* and *Status*, which elaborate on *L2* policy. These indicate how ownership and status of geothermal resource are defined in the law of each case country. For example, in Greece, Italy, Kenya, Serbia, Türkiye, and the USA, the state owns all geothermal energy resources. In Spain they are declared public property and in Iceland resource ownership is based on the ownership of land. The status of geothermal resources also varies from country to country: geothermal energy is considered a mineral resource in Greece, Italy, and the USA and implicitly as groundwater or thermal waters in Austria and Hungary respectively. *Implicit* refers to the implied status and ownership of the resources through a broader legal framework versus an explicit mention of geothermal energy in the law. In cases like this, the value for *L2* is zero. All values in Table 3 should only be compared amongst each other, as these are only relative values within the group of case countries.

Lastly, each country portfolio ends with a short analytical summary combining the information about the national agri-food sector, geothermal greenhouse agriculture, and supportive policy measures aimed at its development. The complete record of all content analysis categories per document and country can be found in Appendix F. Since EU countries share some policy incentives, they are described first and are followed by non-EU Member States in alphabetical order.

Table 3. An overview of final content analysis values relating to the hypotheses per policy and country. Policies are represented by codes, “G2 – L2”. “N/a” indicates the lack of a certain policy document, the value zero “0” indicates no relevant references in a document and an asterisk superscript “” signifies an explicit mention of geothermal energy use for greenhouse agriculture. “Ownership” and “Status” further elaborate on L2 and indicate how ownership and status of geothermal resource are defined in the law of each case country. “Implicit” ownership or status refers to the implied status and ownership of the resources through a broader legal framework.*

Country	G2, N1	G4	N2	N11	L2	Ownership	Status
Austria	0	n/a	7	n/a	0	based on landownership (implicit)	groundwater (implicit)
Greece	0	1	8	n/a	2	state	mineral resource
Hungary	0	1	8	n/a	1*	based on landownership	thermal waters (implicit)
Italy	0	0	9	n/a	2	state	mineral resource
Netherlands	0	0	5	16*	0	state (implicit)	terrestrial heat (implicit)
Spain	0	0	11	n/a	2	public	mineral deposits
Iceland	0	5	12*	0	1*	based on landownership	natural resource (implicit)
Japan	0	0	3	n/a	0	based on landownership (implicit)	industrial water (implicit)
Kenya	2	0	12	n/a	1	state	natural resource (implicit)
Serbia	0	0	8	n/a	1	state	geological resource (implicit)
Türkiye	n/a	0	14*	n/a	1	state	sui generis (implicit)
USA	0	n/a	1	n/a	2	state	mineral resource

4.1. Austria

Geothermal energy and greenhouse agriculture

Austria primarily uses geothermal energy for district heating and cooling. As of 2020, greenhouse agriculture represents the second largest sector followed by recreational use in terms of installed capacity (see Table 4). Other uses – industrial process heat and electricity generation – are minor contributors and have not shown any significant capacity changes since 2010. Although growing slowly, the Austrian geothermal industry is quite small and has overall not been very active during the study period of 2010-2020 (Goldbrunner, 2020, p. 1).

The first Austrian geothermal greenhouse was built in 1978 in Waltersdorf but only recently has the country expanded this use. A considerable jump from 2 MWt in 2015 to 22 MWt in 2020 is attributed to the operation of a new greenhouse complex Frutura in Bad Blumau. It covers 26 ha and grows various kinds of tomatoes as well as cucumbers, eggplants, peppers, and radishes, which are sold exclusively in the local market (Goldbrunner, 2020, p. 7; Frutura, no date). Other geothermal greenhouses, located in Bad Waltersdorf and Geinberg, are both part of a cascading system, where geothermal energy is used for multiple purposes including district heating and recreation (Goldbrunner, 2005, pp. 2-3).

Table 4. Geothermal energy use in Austria, 2010-2020.

The hyphen (-) indicates an unreported gap in data for a certain year and application.

Sources: Goldbrunner, 2010; Goldbrunner, 2015; Goldbrunner, 2020.

Geothermal energy application	Installed capacity, MWe/MWt³		
	2010	2015	2020
District heating and cooling	50	50	62
Electricity generation	1	1	1
Greenhouse agriculture	2	2	22
Industrial process heat ⁴	2	1	-
Recreational use	9	10	12

³ Installed capacity measured in MWe (megawatt electric) applies only to electricity generation while MWt (megawatt thermal) to all other direct uses.

⁴ Industrial process heat is defined as “thermal energy used directly in the preparation or treatment of materials used to produce manufactured goods” (Patil and Srivastava, 1984, p. 1). According to the classification of Manzella and Krieger (2022) geothermal industrial process heat includes concrete curing, manufacturing of chemicals and pharmaceuticals, textiles, wood and wood products, recovery of metals and minerals, etc. (p. 5).

Policy incentives

G2 and N1 (0). Nationally Determined Contributions and Emissions Reduction Targets are outlined in the common EU document of 2016-2020 (Latvian Presidency of the Council of the European Union, 2015). EU NDCs set a target to reduce emissions by at least 40% by 2030 compared to 1990 levels. This target covers economy-wide absolute reductions with no distinctions per sector and is to be fulfilled by all EU Member States jointly. This policy does not mention geothermal energy.

G4 (n/a). The first Austrian National Voluntary Report was submitted in 2020, hence is out of the scope of this research.

N2 (7). Geothermal energy is mentioned in the National Renewable Energy Action Plan for Austria mainly in connection with financial support schemes for both electricity and heating and cooling sectors (Karner *et al.*, 2010). Funding support for companies and individuals installing geothermal applications is provided via the Environmental Assistance Program (Umweltförderung im Inland) (p. 63). This program has existed since 1993 and in part incentivizes the use of geothermal heating and cooling. Additional financial support for geothermal heating plants covers drilling and reinjection (pp. 63-69). Small-scale geothermal power plants are supported by feed-in-tariffs and fixed price schemes (p. 149). The repurposing of existing oil wells for geothermal purposes is also promoted (p. 98). In general, the state could cover investment costs for new geothermal projects of up to 30% (pp. 67-69).

N11 (n/a). No Geothermal Energy Action Plan or its equivalent has been identified.

L2 (0). In Austria, geothermal energy is not explicitly covered in law. Generally, all Austrian provinces have their own rules for handling geothermal energy systems. On a federal level, a definition of ground water is provided, which is described as “underground water contained in a plot of land” in the Wasserrechtsgesetz 1959 (BGBl. Nr. 215/1959, 1959). According to para. 3 and para. 4, groundwater is attached to the land regardless of it being a spring or a subsurface aquifer: on public land it belongs to the state and on private land to the owner. The Water Rights Act was amended both in 2003 and 2018 when a new definition of groundwater bodies as a “delineated volume of groundwater within one or more aquifers” was introduced (Federal Ministry of Agriculture, Forestry, Regions and Water Management, no date).

Analytical summary

The agri-food sector is small in Austria's economy amounting to only 1.1% of GDP with 2.5% of the population employed there (Advantage Austria, Austrian Federal Economic Chamber, 2023). Nonetheless, agriculture is important for the country as it supplies products for both internal consumption and export. This sector also has a tendency for sustainability and environmentally friendly practices that have been promoted strongly in the country since 1970s (Advantage Austria, Austrian Federal Economic Chamber, 2023). Austrian agri-food market is also supported by the EU-wide Common Agricultural Policy (CAP) that offers subsidies and direct payments to companies, farmers, and other industry stakeholders (Federal Ministry of Agriculture, Forestry, Regions and Water Management, 2022, p. 21). Recent uptake in geothermal greenhouse agriculture is attributed to the construction of new complexes. Their successful implementation might lead to more similar projects. In fact, in March 2022 BIOhof Geinberg constructed another geothermal greenhouse complex with 11 ha growing cucumbers, peppers, and tomatoes (Bundesverband Geothermie, 2022).

On a policy level, geothermal energy has not been playing a significant role, although national incentives offer financial support, such as federal state co-financing, feed-in-tariffs, and project funding for various geothermal projects. Global policy incentives do not explicitly cover this energy source, and local legislation only implicitly mentions it with no legal acts clearly directed at geothermal energy development. This lack of local regulation has been heavily criticized in Austria. According to some experts the current legal framework does not support a significant increase of geothermal energy market (Goldbrunner and Goetzl, 2016, p. 6).

4.2. Greece

Geothermal energy and greenhouse agriculture

The main uses of geothermal energy in Greece in terms of installed capacity are for recreation and greenhouse agriculture (see Table 5). These are also the only uses that showed growth since 2010. Other applications include individual heating and cooling, which has reportedly unchanged over the study term and fish farming, which was not reported in 2020. New uses that appeared recently include spirulina cultivation (Papachristou *et al.*, 2020, p. 13) but in general, utilization of geothermal

energy in Greece is small and unremarkable in terms of number of installations and size of application.

Geothermal greenhouse agriculture started in Greece in the early 1980's and its growth of 4 MWt from 2015 to 2020 is attributed to the significant investments in a few low-temperature fields in the northern part of the country (Papachristou *et al.*, 2019, pp. 4-5). These include Eratino-Chrysoupolis and Neo Erasmio, which gradually expanded its greenhouse surface area from 4.2 ha to 18.5 ha. As per Papachristou *et al.* (2020) these fields attracted government and public investments because local communities consider geothermal energy “as a source of environmental, financial, and social benefits” (p. 10). Another likely reason for such interest is the financial savings as in northern Greece, 1 MWt can cover as much as 90% of the annual heating needs for an average 7-10 ha greenhouse (Andritsos *et al.*, 2010, p. 4). Currently operating greenhouses are typically stand-alone projects located primarily in northern Greece in Langadas, Nea Apollonia, Nea Kessani, Nigrita and Polichnitos (Andritsos *et al.*, 2010, p. 4). Main crops cultivated there include cucumbers, flowers, green beans, herbs, lettuce, strawberries, sweet peppers, and tomatoes. These are grown for the local market.

Table 5. Geothermal energy use in Greece, 2010-2020.

The hyphen (-) indicates an unreported gap in data for a certain year and application.

Sources: Andritsos et al., 2010; Andritsos et al., 2015; Papachristou et al., 2020.

Geothermal energy application	Installed capacity, MWt		
	2010	2015	2020
Fish farming	9	8	-
Greenhouse agriculture	34	34	38
Individual heating and cooling	2	2	2
Other uses	0	0	2
Recreational use	39	43	43

Policy incentives

G2 and N1 (0). EU wide, see Austria.

G4 (1). As per Greek Voluntary National Review, geothermal energy is identified as a renewable source with high potential. The country aims to increase its usage specifically in the heating and cooling sector (General Secretariat of the Government of Greece, 2018, p. 70).

N2 (8). Geothermal energy is referenced in the National Renewable Energy Action Plan for Greece in a very general sense. Some policy and financial support schemes exist that are aimed at both electricity generation and heating and cooling (Ministry of Environment, Energy and Climate Change of Greece, 2010, p. 90). The country provides fiscal incentives and regulatory framework for shallow geothermal applications (p. 64) and defines permitting and licence procedures for geothermal power plants (p. 30). Power plants are also supported with feed-in-tariffs and remuneration schemes, although currently no electricity is produced with geothermal resources (pp. 70-72). Greece promotes district and individual heating and cooling as well as co-generation of electricity and heat from geothermal resources (p. 46).

N11 (n/a). No Geothermal Energy Action Plan or its equivalent has been identified. However, according to Varvitsioti and Tsifoutidis (2021), Greece envisions an introduction of a Geothermal Potential Development Plan. This document will identify strategic goals for regions and sectors of interest and state plans for its future development (p. 9).

L2 (2). In Greece, geothermal energy ownership and regulation are within the scope of Legislative Decree 210/1973, also called the Mining Code (Government Gazette, Series I, No 277, 1973). According to Article 2 geothermal potential is regulated as a mineral resource (mined mineral or ore). Article 3 states that land ownership does not extend to geothermal potential irrespective of its location. As explained further in Article 143 only the state has the right to explore and exploit geothermal potential, but it can also lease “geothermal fields for the exploitation of geothermal fluids”. Both exploration and use of geothermal resources are defined as mining activities. The definition of geothermal potential can be found in another law – Law 1475/84 on exploitation of the geothermal potential – that defines it as a “surface or underground waters with temperatures > 25°C, natural vapor, or heat from geological formations” (Government of Greece, 1984, Article 1). Geothermal energy is identified as the energy contained within this potential.

Analytical summary

The Greek agri-food sector emphasizes organic, natural, and sustainable produce and represents one of the main exporting sectors in the country. From 2010 to 2020 agriculture, as percentage of GDP, grew by 1.2% expanding from 3% in 2010 to 4.2% in 2020 (World Bank, 2023). As other EU States, Greece benefits from Common Agricultural Policy that heavily subsidizes country’s agribusinesses (Enterprise Greece, Ministry of Foreign Affairs, 2022). Slight growth of geothermal

greenhouse agriculture is prompted by its economic allure and support from the government and local communities. The successful operation of newly constructed geothermal greenhouses in northern Greece promises future growth and many new projects are already under consideration. The company AGRITEX Energy S.A., which operates 10 ha of greenhouses has been looking into geothermal energy as a substitution for natural gas heating. Some local municipalities like Paggaio are also looking to invest in geothermal greenhouse agriculture (Papachristou *et al.*, 2020, p. 9).

As for policy incentives, the country shows strong support on all three levels. It aims to utilize and develop its available geothermal resources, which show promise. National incentives offer support for both heating and cooling and power sectors. Existing financial (feed-in-tariff, remuneration scheme, tax incentive) and policy (legislative framework, licencing and permitting regulations) support measures are available for geothermal developers. The use of geothermal energy for space heating (district and individual) is encouraged but as of recent reporting remains quite uncommon. Local legislation is very comprehensive and covers both ownership and regulation of geothermal resources. Existing laws are continuously updated, and new policies are under development.

4.3. Hungary

Geothermal energy and greenhouse agriculture

Hungary has a diverse geothermal industry but in 2020, the largest portion in terms of installed capacity was used for greenhouses agriculture, followed by recreation, district and individual heating and cooling (see Table 6). Other applications include agricultural drying and industrial process heat. The data for other minor uses such as animal and fish farming are not reported for 2020 so only estimates can be made for their capacity trend. In 2018, the first geothermal power plant was commissioned in Tura near Budapest with 3 MWe installed capacity (Huttrer, 2020, p. 7). Overall, apart from recreational use, all applications saw an increase in installed capacity in the study period.

Hungary has the largest geothermal greenhouse market in the European Union and one of the longest traditions of using thermal waters for agriculture. Research in Hungary began in 1960's and the first geothermal greenhouse went into operation in 1980's (Ehret-Berczi and Nemeth, 2014, p. 276). The country's greenhouse agriculture grew on average 5% yearly in the past decade, which is due to new

projects and public investments. Continuous greenhouse development is also prompted by government support and financial benefits: using geothermal energy in a greenhouse is the most economic option on the market (Ehret-Berczi and Németh, 2014, p. 277). As of 2020, there were more than 330 ha of greenhouses including simple constructions (plastic tents) with geothermal heat supply. The main facilities are located in south-eastern Hungary in the proximity of Csongrád, Kistelek, Makó, Szarvas, Szeged, Szegvár and Szentes. Most greenhouses are a part of a cascading system combining this use with agricultural drying, district heating, and recreation (Toth, 2020, p. 4). Products grown include vegetables (cucumbers, sweet and spicy peppers, tomatoes), tree seedlings and flowers (gerbera).

Table 6. Geothermal energy use in Hungary, 2010-2020.

The hyphen (-) indicates an unreported gap in data for a certain year and application.

Sources: Toth, 2010; Toth, 2015; Toth, 2020.

Geothermal energy application	Installed capacity, MWe/MWt		
	2010	2015	2020
Agricultural drying	10	25	25
Animal farming	2	4	-
District heating and cooling	95	154	223
Electricity generation	0	0	3
Fish farming	4	6	-
Greenhouse agriculture	196	271	358
Individual heating and cooling	24	33	77
Industrial process heat	12	19	19
Recreational use	272	352	249

Policy incentives

G2 and N1 (0). EU wide, see Austria.

G4 (1). Geothermal energy is mentioned in the Hungarian Voluntary National Review as a resource with very good potential (Ministry of Foreign Affairs and Trade of Hungary, 2018, p. 30).

N2 (8). National Renewable Energy Action Plan of Hungary states that geothermal energy is a “natural treasure”, and its use represents “one of the pillars of green economy” (Ministry of National Development of Hungary, 2010, p. 15). The document covers mainly financial incentives, such as the National Energy Saving Program, which offers support in the form of non-refundable aid,

preferential loans, and tariffs for both geothermal electricity and direct heat (pp. 133-135). Since development costs represent one of the limiting factors for this sector's growth investments and third-party financing are planned (pp. 39-41). The country aims to increase the capacity and efficiency of the existing geothermal heat supply systems (p. 159) as well as to install and/or renew the existing electric grids powered by geothermal energy (p. 134).

N11 (n/a). No Geothermal Energy Action Plan or its equivalent has been identified.

L2 (I).* In Hungary, geothermal energy is within the scope of Act XLVIII of 1993 on Mining (Government of Hungary, 1993). Para. 3 states that geothermal energy is the property of the state and para. 49 defines geothermal energy as “the internal thermal energy of the earth's crust”. Geothermal exploration and exploitation activities are considered mining activities performed below a depth of 2500 m. Another piece of legislation – Act LVII of 1995 on Water Management – covers thermal waters above 2500 m (Government of Hungary, 1995). This Act attributes the ownership of thermal waters to the landowner (para. 6) and defines thermal waters as “any water or groundwater (from an aquifer) origin with temperature (measured at the surface) of 30°C or more”. The Act also covers the use of thermal water resources for agricultural purposes (para. 10). According to both laws the use of geothermal energy depends on both depth and the presence of water extraction. If no water is extracted and/or the targeted depth is below 2500 m the resource use will be regulated by the Act on Mining. In other cases, the Act on Water Management will apply (Nador, 2014, p. 47). Since a typical geothermal well for greenhouse installations in Hungary is 1000-2400 m deep, most geothermal resources are considered thermal water and thus fall under the Act on Water Management (Szita, 2005, p. 1).

Analytical summary

Agriculture in Hungary does not represent a large domestic industry amounting to only 3.4% of GDP in 2020 (World Bank, 2023). This sector is heavily subsidized by the government: the Ministry of Agriculture pledged to increase co-financing and number of available subsidies allocating a total of 12.95 billion € from 2021 to 2027 (Ministry of Agriculture, Nature and Food Quality, 2022). The country also benefits from the EU-wide Common Agricultural Policy, which encourages Hungarian agribusiness “to take up innovation, from precision farming to agro-ecological production methods” (European Commission, 2022c). Geothermal energy has long been applied in greenhouses across the country and its use keeps on growing.

Continuous development of new projects is motivated by economic feasibility and government support. In 2019 Hungarian government announced the construction of a new farming city in municipalities Bezenye and Hegyeshalom with 1000 residential buildings and 330 ha of geothermal greenhouses (Block, 2019; Schneider, 2019). Another project that will heat government buildings and a 10-ha greenhouse is planned in municipalities Kiskunhalas and Zsana (Nador, Kijbus and Toth, 2019, p. 4). A report by Toth (2020) indicates that a new greenhouse park with 13 ha total is planned next to Tótkomlós (p. 3). Considering these envisioned projects, Hungarian geothermal greenhouse market is expected to grow further.

Hungary shows strong support for geothermal energy across all three levels of policy. Global policies acknowledge geothermal energy as a resource with high potential and national policies indicate the importance of its further development. Financial support (investments, loans, tariffs, etc.) available for both heating and cooling and power markets. Local legislation offers a comprehensive yet complex framework. Two different acts – the Act on Water Management and Act on Mining – govern geothermal energy development, where its use for agri-food purposes is explicitly regulated. Although resource ownership is defined, its status is only implicitly covered. According to some experts, such a diverse legal framework might lead to confusion and inconsistencies since regulating authorities need to share competences on the same subject (Poux, 2009, p. 10; Breembroek, Dijkshoorn and Ramsak, 2013, p. 25). At the same time, Hungarian local legislation is uniquely strong, because it regulates the use of geothermal energy for agricultural production.

4.4. Italy

Geothermal energy and greenhouse agriculture

Italy has a very long and foundational tradition of geothermal energy utilization. As shown in the Table 7 the key uses are (from largest to smallest) electricity generation, recreational use, district heating and cooling, fish farming and individual heating and cooling. Greenhouse agriculture represents Italy's sixth largest use in terms of capacity followed by industrial process heat. Apart from greenhouse agriculture all uses had an increase in installed capacity from 2010.

The use of geothermal energy for agricultural purposes dates back to the 19th century when a thermal spring at Acqui Terme was used to heat a greenhouse. By the middle of the 20th century some greenhouses were using excess heat from the Lardarello power station (Dickson and Fanelli, 1996). Greenhouse agriculture use

slightly decreased from 69 MWt in 2010 to 67 MWt in 2020 but it is not clear why. A possible explanation could be that a decision by Italian government to retract “renewable” status from geothermal energy negatively impacted the industry since it reduced support for the sector (Il Tirreno, 2018). The exclusion of geothermal energy from FER1 Ministerial Decree that grants incentives to renewables could be another reason (Dentons, 2019). Despite these changes, a new greenhouse complex cultivating spirulina opened in Chiusdino, Tuscany in 2017 (European Geothermal Energy Council, 2017). Almost all Italian greenhouses are a part of a cascading system using the downstream fluid from geothermal power plants. Most complexes grow flowers and plants and are located in the regions of Friuli-Venezia Giulia, Lazio, Tuscany, and Veneto (Carella and Sommaruga, 2000, p. 119; Buonasorte, Rizzi and Passaleva, 2010, p. 3).

Table 7. Geothermal energy use in Italy, 2010-2020.

Sources: Cappetti, Romagnoli and Sabatelli, 2010; Conti et al., 2015; Razzano and Cei, 2015; Bargiacchi et al., 2020; Serra, Cei and Lupi, 2020.

Geothermal energy application	Installed capacity, MWe/MWt		
	2010	2015	2020
District heating and cooling	68	79	150
Electricity generation	842	915	915
Fish farming	121	122	130
Greenhouse agriculture	69	69	67
Individual heating and cooling	67	78	75
Industrial process heat	14	18	15
Recreational use	418	421	456

Policy incentives

G2 and N1 (0). EU wide, see Austria.

G4 (0). Italy’s Voluntary National Report does not mention geothermal energy (Italian Ministry for the Environment, Land and Sea, 2017).

N2 (9). Italian National Renewable Energy Plan extensively covers geothermal energy in connection with financial and policy support aimed at both electricity and heating and cooling sectors (Italian Ministry for Economic Development, 2010). Some financial incentives include aid schemes for operation of high temperature geothermal resources and funding support for geothermal power plants under the Community Support Framework (pp. 53-56). This Framework was in effect until

2013 and provided investments for the development of innovative geothermal power plants in the south of Italy. The users of geothermal district heating and cooling networks can profit from tax relief measures and energy efficiency credit schemes are offered for the installation of geothermal heat pumps (pp. 26-31). A variety of existing policies are highlighted including federal and local level acts. The former includes, for example, Legislative Decree 22/2010 on research and mining of geothermal resources and the latter Apulia Regional Law 19/200 on administrative procedures relating to geothermal resources (pp. 198-202). Also present are laws that regulate technical requirements for geothermal installations in buildings (p. 41)

N11 (n/a). No Geothermal Energy Action Plan or its equivalent has been identified.

L2 (2). In Italy, the main legislation governing geothermal energy resource ownership and its regulation is the Legislative Decree No. 22 of February 11, 2010 describing reorganization of regulations on research and cultivation of geothermal resources (Government of Italy Presidency of the Council of Ministers, 2010). Article 1.6 states that under Civil Code 1942, Article 826 geothermal resources are patrimony of the state and cannot be owned privately (Government of Italy, 1942). They are regulated as mineral resources and are classified between high ($> 150^{\circ}\text{C}$), medium ($90\text{-}150^{\circ}\text{C}$) and low ($< 90^{\circ}\text{C}$) enthalpy resources (Article 1). The law also defines small local uses which comprises geothermal plants of less than two MWt with a depth of up to 400 m (Article 10). As per Article 1.7 each administrative unit (region, or province) could have its own rules concerning geothermal exploration and development.

Analytical summary

Although agriculture represents only about 2% of GDP, this sector is very important for Italian economy: it contributes to domestic economic growth and country's exports (World Bank, 2023). Italy is the largest EU producer of apples, artichokes, eggplants, grapes, pears, tomatoes, and other agricultural products (Fondazione Edison and Confagricoltura, 2020, p. 9). As do other European countries, Italy benefits from the EU-wide Common Agricultural Policy that provides considerable subsidies to farming regions.

Despite Italy's pioneering contribution to the development of geothermal energy, its contribution to the greenhouse agriculture has been declining from 2010 onwards, possibly due to retraction of government support. According to Manzella *et al.* (2019) a lack of support schemes for direct use of geothermal heat contributes to its underdevelopment and stunted growth (p. 11). However, the Italian

government announced that there are plans to reintroduce some incentives, e.g., by including geothermal resources in FER2 Ministerial Decree, a successor to previous regulation on renewable energy development, which will incentivize the construction of new geothermal plants (Greenreport, 2020). If accomplished, this could potentially revive growth of greenhouse agriculture projects.

As for policy incentives, context-wise they are very rich, covering various support schemes for electricity and heating and cooling. Although geothermal energy is not represented in policies on a global level, the national and local support is very strong. Extensive national financial and legal assistance is available in Italy, e.g., regulatory framework with decrees and laws directing and promoting the use of geothermal resource in such regions as Apulia and Tuscany, government funding via Community Support Framework, and tax relief measures for users connected to geothermal heating and cooling networks among others. Local legislation is very comprehensive and covers both ownership and regulation of geothermal resources. It is however spread across various administrative units, which according to some experts overcomplicates and slows down geothermal energy adoption (Buonasorte, Rizzi, and Passaleva, 2010, p. 5).

4.5. The Netherlands

Geothermal energy and greenhouse agriculture

In the Netherlands geothermal energy is used almost exclusively for greenhouse heating. The country is also the second largest market in Europe for greenhouse agriculture after Hungary. Other minor use includes district heating and cooling, which according to available data has had a slight decline in installed capacity from 2010-2020 (see Table 8).

The Netherlands' first attempt to explore geothermal resources started in the 1980's and gained extensive support from the private horticulture industry. However, it was not until 2007 when the first project – a tomato greenhouse in Bleiswijk – was successfully implemented (van Heekeren and Bakema, 2015, p. 4). For the past decade the Netherlands was growing its geothermal greenhouse capacity jumping from 10 MWt in 2010 to 230 MWt in 2020 (see Table 8). Continuously increasing interests and partnerships between private and public sectors have added to this growth. For example, private-public partnership “Knowledge Agenda” and its successor KIRA (Knowledge and Innovation Roadmap Geothermal Energy) aim to enhance the national horticulture sector by

promoting research, data, and knowledge transfer. These are co-funded by both private agricultural companies and the Dutch Ministry of Economic Affairs (Bakema, Provoost and Schoof, 2020, p. 4; Kas als Energiebron, 2022). As of 2020, there are 21 operating projects and 20 more are under development. The biggest greenhouse complexes include ECW Energy located at Agriport in Middenmeer, Harting Holland in De Lier, Hoogweg Paprikakwekerijen in Luttelgeest, and Nature’s Heat in Kwintsheul. The main products grown are cucumbers, eggplants, flowers (orchids), tomatoes, and strawberries, which are consumed domestically as well as exported to Belgium, Germany, and the UK (Whiting, 2019).

Table 8. Geothermal energy use in the Netherlands, 2010-2020.

The hyphen (-) indicates an unreported gap in data for a certain year and application. Sources: van Heekeren and Koenders, 2010; Lund and Boyd, 2015; Bakema, Provoost and Schoof, 2020; Lund and Toth, 2020.

Geothermal energy application	Installed capacity, MWt		
	2010	2015	2020
District heating and cooling	6	-	3
Greenhouse agriculture	10	100	230

Policy incentives

G2 and N1 (0). EU wide, see Austria.

G4 (0). Dutch Voluntary National Report does not mention geothermal energy (Ministry of Foreign Affairs of the Netherlands, 2017).

N2 (5). Geothermal energy is very substantially covered in Dutch National Action Plan for Energy from Renewable Sources (Government of the Netherlands, 2010). Its development is a part of regional renewable energy strategies (p. 113). In addition to agriculture, the use of geothermal energy for large scale district heating networks is envisioned (p. 55). A goal of a ten-fold increase of energy produced from deep geothermal resources was projected by 2020, and successfully achieved (p. 106).

N11 (16*). The Netherlands is one of a few countries with a dedicated National Geothermal Energy Action Plan (Stichting Platform Geothermie *et al.*, 2018). It is called “Master Plan Geothermal Energy in the Netherlands” and was prepared jointly by industry (Dutch Association of Geothermal Operators, Stichting Platform Geothermie) and government (Ministry of Economic Affairs and Climate and the Ministry of the Interior and Kingdom Relations). The document outlines goals and

ambitions for the geothermal energy sector and covers targets for policy, financial support, education, research, and the heating and cooling sector, in addition to greenhouse agriculture. It recognizes geothermal energy as the most economical sustainable solution, which is envisioned to become the main baseload energy source (pp. 9-12). To achieve this, the country should promote information sharing about geothermal resources, establish data collection and management systems, and generate models for public participation (pp. 39-54). Research and innovation are encouraged, e.g., to improve the energy safety management systems and to further develop Ultra-Deep Geothermal, also known as deep enhanced geothermal systems (pp. 10-12). As for policy support, an adaptation and optimization of existing framework to better fit the geothermal market is planned. Financial assistance includes expansion of SDE+ (a subsidy scheme for renewables), introduction of predictable price policies and overall cost reduction through asset management and innovation (pp. 15-17). Greenhouse agriculture will remain a priority sector with the goal of meeting at least half of its heating demand with geothermal energy (pp. 9-12). Expanding its use beyond horticulture, the development for industrial uses (breweries, dairy factories) and district heating networks are planned for urban environments (pp. 11-12). Finally, a ten-fold increase in employment in the geothermal industry from 240 to approximately 2400 full time equivalent (FTE) in 2030 is forecasted (p. 12).⁵

L2 (0). In the Netherlands, there are two laws regulating geothermal energy: *Mijnbouwwet* (Mining Act) and *Waterwet* (Water Act). The Mining Act passed in 2002 implies the regulation of deep geothermal resources below the depth of 500 m (Government of the Netherlands, 2003, Article 2). The Act does not explicitly mention geothermal energy, but Article 1 defines terrestrial heat as “heat present in the subsoil that has originated there by natural causes”. Its exploration and production are considered mining work (Article 1). As per Article 3 minerals and other substances are state property, but the same is not explicitly stated for terrestrial heat. The Water Act regulates shallow geothermal resources above a depth of 500 m (Government of the Netherlands, 2009). Passed in 2009, it consolidated eight laws (Government of the Netherlands, no date-a). Chapter 1 para. 1 defines groundwater as “water below the surface of the earth, including the substances

⁵ According to Eurostat Statistics Explained (2020), a full-time equivalent, or FTE, is “a unit to measure employed persons or students in a way that makes them comparable although they may work or study a different number of hours per week. A full-time person is counted as one FTE”.

therein”. Its ownership and status are undefined. Since all greenhouses in the Netherlands use deep geothermal energy the Mining Act applies.

Analytical summary

The Netherlands is the second largest exporter of food and agricultural products in terms of value after the United States: on average about 65 billion € of agricultural goods are exported annually (Whiting, 2019; Government of the Netherlands, no date-b). Although agriculture constitutes only 1.6% to nation GDP, it is vital for the country as it’s one of its key employers (World Bank, 2023). As the other EU Member States, the Netherlands implements Strategic Plans under Common Agricultural Policy that distributes funding and supports small and medium-sized farms, particularly young farmers (European Commission, 2022d). According to the Government of the Netherlands (no date-b) sustainable agriculture is a priority for the country and the available subsidies and knowledge transfer should stimulate businesses to use more renewable energy. Indeed, remarkable growth of geothermal greenhouse market is attributed to public and private incentives, strong interest in geothermal energy, and financial support from the government. The use of geothermal energy in greenhouses is also economically attractive due to its cheap price. Considering the current growth rate of three to five greenhouse projects a year as well as existing and planned support for the industry, further expansion of this sector is anticipated.

In terms of policy incentives, geothermal energy is not represented on a global level, but national support is uniquely strong due to the existence of a Geothermal Energy Action Plan, which covers all aspects of geothermal industry development but especially heating and cooling. Greenhouse agriculture is regarded as the most important sector to be advanced via ongoing research activities, and available support schemes. The local legislation is limited: ownership and regulation are explicitly defined neither in the Mining Act nor the Water Act. The legislation, however, has been evolving and changing quickly. In the early 2000s there was no dedicated legal framework for geothermal. The Mining Act initially developed in 2002 for oil and gas activities passed four amendments and adapted to accommodate geothermal energy. The Dutch government also plans to introduce new Environmental and Planning Act, which will consolidate 26 existing regulations including the current Water Act into a single piece of legislation (Government of the Netherlands, no date-c).

4.6. Spain

Geothermal energy and greenhouse agriculture

In Spain, geothermal research and development started in the 1980's but to date only greenhouse agriculture, individual space heating and cooling, and recreation apply this resource. Among them greenhouse agriculture is the largest use and has seen a positive growth in the study period (see Table 9). Its capacity grew by 7 MWt from 2015 to 2020 but it is unclear what stimulated this as there are no reports of new greenhouse projects in the country during this period. Still, in 2015, there were plans to build the first combined heat and power plant in Andalusia (close to the cities of Almeria and Nijar), which would heat neighboring greenhouse facilities. Yet it was not until 2022 that this project was partially realized. The first Spanish heating plant came into operation in Nijar delivering service to greenhouses cultivating tomatoes (Fenoy, 2015; Sevilla, 2022). In general, the post-pandemic period saw an increase in greenhouse facilities and some principalities started to express interest in geothermal energy. Asturias principality became interested in adapting its old mining galleries for greenhouse agriculture, yet it is not clear as of this writing if the project has progressed (Energias Renovables, 2020). Other operating greenhouse complexes include stand-alone projects located in south-eastern Spain, next to Cartagena, Montbrió and Zujar (Arrizabalaga *et al.*, 2015, p. 8).

Table 9. Geothermal energy use in Spain, 2010-2020.

The hyphen (-) indicates an unreported gap in data for a certain year and application. Sources: Sanchez-Guzman and Garcia de la Noceda, 2010; Arrizabalaga et al., 2015; Lund and Toth, 2020.

Geothermal energy application	Installed capacity, MWt		
	2010	2015	2020
Greenhouse agriculture	15	15	22
Individual heating and cooling	6	4	5
Recreational use	-	3	4

Policy incentives

G2 and N1 (0). EU wide, see Austria.

G4 (0). Spanish Voluntary National Report does not mention geothermal energy (Government of Spain, 2018).

N2 (11). Geothermal energy is extensively mentioned in Spain's National Renewable Energy Action Plan in connection with electricity and heating and cooling markets (Ministry of Industry, Trade and Tourism, 2010). Most references are general in character e.g., geothermal energy is considered new and unknown in Spain. The policy also mentions that geothermal heat pump market has just started to emerge in the country (p. 38). The promotion of district heating and cooling is planned via pilot financing programs, but capacity additions are not expected to be significant (p. 143). The country's ambition for power generation is obvious: to produce feasibility studies for geothermal electricity in deep sedimentary basins, to pilot EGS projects, and to commission new high-temperature power plants (pp. 142-143). Based on the resource availability the development of geothermal power projects is envisioned mainly on the Canary Islands. Although no power is yet generated with geothermal energy in Spain, there are certain remuneration schemes for energy producers via regulated tariffs (p. 113). The country also plans to introduce financial aid and risk reduction programs, disseminate information, and promote knowledge on geothermal potential as a regulatory measure (p. 53). At the same time, the policy states that current use of geothermal energy for greenhouse agriculture and recreation is stable and no growth is expected due to the resource novelty, technical uncertainties, and lack of development experience (p. 143).

N11 (n/a). No Geothermal Energy Action Plan or its equivalent has been identified.

L2 (2). In Spain, geothermal energy and its ownership are regulated by the Law 22/1973, of July 21, 1973, on Mines (BOE-A-1973-1018, 1973). Geothermal resources are classified as mineral deposits in Category D together with coal, radioactive minerals, and bituminous rocks (Article 3). Their use for electricity and heat generation are governed by Section D of the same legislation. All mineral and geological resources are declared public property (Introduction).

Analytical summary

Agriculture and food sector in Spain is of economic, social, and strategic importance: about half of country's land is used for agricultural activities (crops, forestry, and pastures) but at the same time in 2020 agriculture accounted only to 2.9% of national GDP (World Bank, 2023). Agri-food is nonetheless the country's leading industrial sector (La Moncloa, Government of Spain and the Council of Ministers, no date). It is stimulated by EU Common Agricultural Policy that funds agribusiness in their transition towards sustainable production (European Commission, no date). Despite the projected stable trend in geothermal greenhouse

agriculture, its installed capacity has slightly increased. This is, however, hard to explain as there were no apparent projects commissioned between 2010 and 2020. New developments started in 2022, so a further slight increase in greenhouse agriculture is expected.

Regarding policy incentives, Spain has weak global support but strong national and local policies. National level covers electricity and heating and cooling sectors in very broad terms, outlining general aims and ambitions for their development. Geothermal energy technologies remain new and unknown for Spain and the government does not project any significant changes or positive capacity additions. According to Spain's National Renewable Energy Plan, its geothermal future depends on the availability of geothermal resources and the development of Enhanced Geothermal Systems (Ministry of Industry, Trade and Tourism, 2010, p. 142). Local legislation is comprehensive and covers both ownership and regulation of the resource.

4.7. Iceland

Geothermal energy and greenhouse agriculture

Iceland possesses large reserves of geothermal energy and has an extensive history of its use. Currently, the largest sectors are district heating and cooling, electricity generation, snow melting, and recreational use. These are followed by fish farming and industrial process heat. Greenhouse agriculture is the smallest use in terms of installed capacity. As seen from the Table 10 all uses have seen an increase in capacity since 2010.

Despite being the smallest application, geothermal greenhouse agriculture is one of the oldest having started in 1924. From 2010 to 2020 its capacity increased by 12 MWt, but the total surface area of greenhouses decreased (Ministry of Industries and Innovation, 2014, p. 7). This is due to the better efficiency of existing greenhouses. Because of CO₂ enrichment and efficient use of lighting the growing season can be extended throughout the year. As per Ragnarsson, Steingrímsson and Thorhallsson (2020) this resulted in declining demand for new facilities (p. 5). Most greenhouses are located in the southern part of the country, and they are all part of a cascading system. Their total surface area covers about 200 000 m² of which half is used for growing crops (bananas, cucumbers, sweet peppers, tomatoes) and half for flower and plant cultivation (Björnsson, 2010, p. 29). All produce is grown exclusively for the domestic market.

Table 10. Geothermal energy use in Iceland, 2010-2020.

Sources: Ragnarsson, 2010; Ragnarsson, 2015; Ragnarsson, Steingrímsson and Thorhallsson, 2020.

Geothermal energy application	Installed capacity, MWe/MWt		
	2010	2015	2020
District heating and cooling	1500	1550	1650
Electricity generation	573	663	755
Fish farming	75	85	110
Greenhouse agriculture	45	45	57
Industrial process heat	75	70	80
Recreational use	80	90	210
Snow melting	125	195	260

Policy incentives

G2 and N1 (0). Nationally Determined Contributions of Iceland do not mention geothermal energy (Government of Iceland, no date). The NDC is in line with the European Union contribution as it “aims to be part of a collective delivery by European countries” (p. 1). It establishes the same Emissions Reduction Target of economy-wide absolute reductions of 40% with no distinctions per sector by 2030 when compared to 1990 levels.

G4 (5). Among all other Voluntary National Reports, Iceland’s is the strongest in terms of geothermal energy coverage. It mainly references geothermal energy with regard to planned and existing research and educational activities (Government of Iceland Prime Minister’s Office, 2010). Export of geothermal knowledge, experience and training of young professionals is of key importance for the country (pp. 61-66). Current research activities are dedicated to carbon dioxide sequestration in geothermal fluids and environmental studies such as impacts to air quality coming from geothermal power plants (p. 66). There are also government grants that support geothermal energy exploration and construction of new district heating and cooling systems (p. 53).

N2 (12)*. National Renewable Energy Action Plan of Iceland is submitted in accordance with the EU Directive 2009/28/EC on the promotion of the use of energy from renewable sources and the 2009/548/EC Commission Decision of 30 June 2009 on a template for the national renewable energy action plans (OJ EU L 140, 2009; OJ EU L 182, 2009). The document mentions geothermal energy to great extent: various markets (electricity, heating and cooling) are included but it mainly

highlights planned research activities, such as technical and scientific innovations (Ministry of Industries and Innovation, 2014). Also included are the potential for joint international projects and knowledge import in the field of geothermal energy (p. 56). This emerges from the fact that 90% of the buildings in the country are supplied with geothermal heat and/or electricity. Iceland offers grants and loans via National Energy Fund to explore so-called “cold areas”, where geothermal resources have not yet been discovered. In the case of a negative outcome, the funding could be partially or completely waived (pp. 25-28). Additional financial support is available for geothermal research and drilling (p. 43). Although the use of geothermal resources is very economical, its rational use is prioritized: the Nature Conservation Act No 44/1999 prescribes a balanced approach to avoid its aggressive exploitation (p. 37). To stimulate further transition from fossil fuels to geothermal energy in district heating and cooling systems, state subsidies are offered to geothermal developers (p. 36). Iceland’s National Renewable Energy Action Plan also targets certain industries, such as agriculture and recycling, where the use of geothermal energy is promoted (p. 4).

N11 (0). A dedicated Master Plan Act No 48/2011 exists in Iceland (Government of Iceland, 2011). It represents a planning tool to combine efficient use of geothermal energy with nature protection (Björnsson, 2010, p. 7; Ministry of Industries and Innovation, 2014, p. 19). It aims to identify geothermal projects with high economic potential, low environmental impact, and positive societal influence (Petursson and Ketilsson, 2015, p. 86). Within its scope are high temperature resource areas of > 200°C and < 1000 m depth suitable for power production (Article 2). The Master Plan itself was developed by the Icelandic government in 1999. Since then, it has been gradually updated and has now reached its fifth phase (Orkustofnun, no date). It outlines geothermal development areas for power plants where sustainability, environmental preservation, tourism, land use, and regional development might be of concern.

L2 (I)*. In Iceland, the key legislation regulating geothermal energy resource is the Act on Survey and Utilization of Ground Resources 1998 No 57 of 19 June, also known as Natural Resource Act (Government of Iceland, 1998). Article 2 defines geothermal energy twofold as “reserves of energy in the bedrock” and as “a constant flow of heat from the earth which does not constitute groundwater”. The ownership of a resource is based on the ownership of land, so according to Article 3 if located on private land the resource belongs to the landowner and if located on public land it belongs to the state. Such regulation is due to constitutional property rights:

geothermal resources cannot be separated from land unless required by public interests. Landowners may use the resource on their lands without any permission of up to 3.5 MWt for “household and agricultural purposes, including greenhouse cultivation” (Article 10). The law does not define the status of geothermal energy.

Analytical summary

Due to climate and weather conditions, agriculture accounts only to 4.6% of country’s GDP (World Bank, 2023). However, in terms of area covered (19%) this is an important sector for Iceland (ClimateChangePost, 2023). Climate change and new technologies shape the development of agriculture and food sector in the country. The big success of horticulture is attributed to thermal waters and warm soils in geothermal areas (Business Iceland, 2023). Although geothermal greenhouse agriculture has seen an increase in capacity, according to some experts, this trend will not continue for long, since innovative use of CO₂ and artificial lighting in greenhouses has increased their efficiency (Björnsson, 2010, p. 29). This leads to more crops being grown in a shorter period of time with better cultivating conditions. As a result of market maturation and low return on investment, no major expansion of greenhouse agriculture is projected.

On a policy level, Iceland’s main interests lie in the export of its geothermal knowledge and experience to other countries since most of national energy demands are covered with geothermal energy. Policies on all levels are very strong and among other case countries, Iceland has the strongest global and one of the strongest national initiatives. Global policies stimulate the research and education activities, and national policies encourage the use of horticulture stations. On a national level, various financial incentives are offered: grant, loans, and subsidies are available to support geothermal exploration and drilling. Local legislation covers the use of geothermal resources for agricultural purposes, but it regulates only the ownership of the resource and not its status.

4.8. Japan

Geothermal energy and greenhouse agriculture

Japan is best known for its recreational use of geothermal energy but also as the main producer of geothermal power equipment – Japanese industries cover 70% of the global market. As Table 11 on p. 66 shows recreation constitutes the largest sector followed by electricity generation, space heating and snow melting. Greenhouse agriculture rates fifth in terms of total installed capacity. Other minor

uses include agricultural drying, fish farming, and industrial process heat. Category “other uses” include cooking meat and vegetables in Kagoshima but might also include air conditioning (Yasukawa *et al.*, 2020, p. 6). Overall, it is hard to estimate geothermal data trends in Japan because most statistics are highly unreliable and sometimes contradict each other. Geothermal applications marked with a plus superscript (+) in Table 11 on p. 66 indicate such instances. For example, the values for electricity show a declining trend. In the same source however another value of 554 MWe for 2020 is given, which would imply fluctuating but overall positive trend. Categories “space heating” and “other uses” vary definition-wise within various Country Updates and are represented here as a combination of separate uses (e.g., space heating combines values for district and individual heating). If only reliable data are considered, Japanese geothermal sector could be characterized by a general decline except for recreational use.

The first geothermal agricultural application in a country was a part of a cascading system using residual heat from a Hachimantai geothermal power plant constructed around 1950s (International Renewable Energy Agency, 2018). Greenhouse agriculture decreased by 12 MWt in 2020 compared to 2015, but it is unclear what spurred this decline. Some experts state that demand for a direct use of geothermal resources for anything other than hot springs (also called onsens) is relatively low in Japan (Sugino and Akeno, 2010, p. 7). Most operating greenhouses are located in the prefectures of Akita, Aomori, Hokkaido, Iwate, Kagoshima, Miyagi, Oita and Tokyo, where they are complemented by fish breeding, industrial process heat and recreation uses. Various fruits, mushrooms, vegetables, and flowers are grown there. Some examples include cultivation of cucumbers, tomatoes and mangos in Hokkaido and green soybeans in Iwate (Cariaga, 2022).

Policy incentives

G2 and N1 (0). Nationally Determined Contributions mention geothermal energy once with regard to power production: by 2030 1% of Japan’s power is planned to be produced from geothermal resources. The country sets the Emissions Reduction Target of 26% by 2030 compared to 2013 levels. Most reductions are expected to come from the industrial sector (ceramics, chemicals, clay, iron, steel, and stone) followed by commercial and transportation sectors (Government of Japan, 2016).

G4 (0). Japanese Voluntary National Report does not mention geothermal energy (SDGs Promotion Headquarters, 2017).

Table 11. Geothermal energy use in Japan, 2010-2020.

The hyphen (-) indicates an unreported gap in data for a certain year and application. A plus superscript (+) indicates that reported values are unreliable for the application due to inconsistencies in data sources. Sources: Sugino and Akeno, 2010; Lund and Boyd, 2015; Yasukawa and Sasada, 2015; Yasukawa et al., 2020.

Geothermal energy application	Installed capacity, MWe/MWt		
	2010	2015	2020
Agricultural drying	-	-	6
Electricity generation ⁺	535	518	500
Fish farming	8	8	8
Greenhouse agriculture	37	37	25
Industrial process heat	1	1	1
Other uses ⁺	-	46	15
Recreational use	1810	1810	1999
Snow melting	153	107	150
Space heating ⁺⁶	77	77	203

N2 (3). Japan has a few Strategic Energy Plans and two of them fall within the research timeline. The Fourth Strategic Energy Plan published in 2014 covers mainly production of electricity from geothermal resources (Government of Japan, 2014). Geothermal energy is considered a “base-load powerhouse” that can supply electricity in a stable manner and at low cost (p. 22). At the same time, certain difficulties with geothermal power development are mentioned: high initial investment costs, long development times, challenges with regulation, regional coordination, and environmental assessment of the resource (p. 45). To overcome these issues research activities for its appropriate use and evaluation are planned (p. 85). Other foreseen activities include streamlining of safety regulations and mitigation of investment risks (p. 44). The country also anticipates an increase in geothermal combined power and heat and heating and cooling supply facilities (p. 45). The successor document – the Fifth Strategic Energy Plan published in 2018 – exclusively highlights geothermal power: the country aims to promote geothermal energy as an independent and competitive power source (Government of Japan, 2018, pp. 120-123).

⁶ Values for 2010 and 2015 include space heating values and 2020 value combines data for individual and district heating as reported in identified sources.

N11 (n/a). No Geothermal Energy Action Plan or its equivalent has been identified.

L2 (0). No local legislation was identified that explicitly regulates geothermal energy status and ownership: analyzed polices include the Act No. 289 of December 20, 1950, on Mining, the Water Cycle Basic Act No. 16 of 2014, and the Water Resources Development Promotion Law No. 217 of 1961 (Government of Japan, 1950; Government of Japan, 1961; Government of Japan, 2014). The Industrial Water Law No. 146 of 1956 comes closest to the purposes of geothermal energy development (Government of Japan, 1956). According to Article 1 its goals are:

to assure the rational supply of industrial water and to promote the conservation of underground water resources in specified areas, with a view to contributing to sound industrial development and prevention of land subsidence in such areas (Government of Japan, 1956, p. 164).

Almost the entire Act is dedicated to the regulation of drilling wells to extract underground water, but it mentions neither the ownership nor status of geothermal energy. The basic principle of land ownership is outlined in the Civil Code Act No. 89 of 1896: Article 207 states that land ownership extends above and below the surface so it could be assumed that resources ownership is based on land ownership (Government of Japan, 1896).

Analytical summary

Although agriculture represents about 1% of Japan's GDP the country is among the top ten largest agricultural producers (World Bank, 2023). Recently however the production has declined and the land under cultivation reduced probably because of the rapidly aging workforce (Goedde *et al.*, 2016, pp. 1-3). Japanese geothermal greenhouse agriculture market is quite small, and its total installed capacity also declined in the study period. This is likely due to the lack of demand for such applications. As indicated in Japan's policies its main national interest lies in the development of geothermal power sector, so a further decline or stagnation is projected for greenhouse agriculture.

Despite Japan possessing the world's third largest reserves of geothermal energy, policy incentives are weak and do not support geothermal energy development (Government of Japan, 2014, p. 24). Out of all case countries, Japanese policies are among the weakest. Global incentives do not cover this resource and national incentives are directed primarily at the electricity market. These national

incentives are vague and general in character with no specific financial or legal support schemes provided to energy developers. Local legislation does not offer a clear framework for both regulation and ownership of geothermal resources. The recent efforts of Japanese government to revise its legislation to stimulate geothermal energy development are also aimed solely at power generation (Nikkei, 2021).

4.9. Kenya

Geothermal energy and greenhouse agriculture

In Kenya, the biggest use of geothermal energy is electricity production. Direct uses of geothermal heat constitute a very small share and are limited to recreation, greenhouse agriculture and agricultural drying. Other uses include milk processing and laundry units, which are both part of a cascade system located in Menengai geothermal field (Omenda *et al.*, 2020, p. 10). The lack of data for many uses makes it hard to estimate geothermal development trends in the country. The available statistics presented in the Table 12 clearly show that electricity generation is the only growing sector since 2010. It also seems that some applications such as agricultural drying are receding.

The first geothermal greenhouse began its operation around 2006 as a part of a cascading system located at Olkaria field. It grows roses for export covering about 50 ha and is enhanced by CO₂ recovered from geothermal fluids (Omenda and Simiyu, 2015, p. 4; Omenda *et al.*, 2020, p. 10). Another cascading project is located next to Menengai and combines aquaculture, greenhouse heating, grain drying and milk pasteurization. This greenhouse complex grows bell peppers and tomatoes. From 2015 to 2020 the total installed capacity of greenhouse agriculture in Kenya declined by 11 MWt. This is attributed mainly to the reduction in technical capacity of Olkaria field and the absence of clear policies promoting geothermal use, which in turn stunts financing (Omenda *et al.*, 2020, pp. 10-11).

Table 12. Geothermal energy use in Kenya, 2010-2020.

The hyphen (-) indicates an unreported gap in data for a certain year and application.

Sources: Simiyu, 2010; Omenda and Simiyu, 2015; Omenda et al., 2020.

Geothermal energy application	Installed capacity, MWe/MWt		
	2010	2015	2020
Agricultural drying	-	1	0
Electricity generation	167	573	865
Greenhouse agriculture	16	16	5
Other uses	-	-	4
Recreational use	-	5	9

Policy incentives

G2 and N1 (2). Nationally Determined Contributions mention the expansion of geothermal energy as one of the climate mitigation options for Kenya (Ministry of Environment and Natural Resources, 2015). The strategy for geothermal development is revised when needed to reflect its current deployment trends (pp. 1-4). Kenya sets an Emissions Reduction Target of 30% by 2023 compared to a business-as-usual scenario of 143 MtCO₂eq (million tonnes of carbon dioxide equivalent) (p. 2).

G4 (0). Kenya Voluntary National Report does not mention geothermal energy (Presidency Ministry of Devolution and Planning, 2017).

N2 (12). Kenya has multiple National Climate Change Action Plans (NCCAP), which serve as implementation tools for their National Climate Change Response Strategy 2010 and Kenya's Vision 2030 (Government of Kenya, 2010). The first NCCAP covers the scope of 2013-2017 and mentions geothermal energy as the most promising baseload energy source that can improve energy security (Government of Kenya, 2013, p. 147). Kenyan Ministry of Energy prioritizes its safe and reliable use. The country promotes the import of geothermal knowledge, international cooperation, education, and training activities (p. 210). These include but are not limited to data collection, resource mapping, and analysis of gaps and barriers in geothermal development (p. 119).

Additional strategies include the use of new and innovate technologies (directional, deep drilling, well-head technologies) and communication strategies via newspaper, radio, and television (p. 111). To further expand on resource knowledge, Kenya plans to form a bilateral initiative with Japan to learn from the country about geothermal power development chain (p. 162). Despite general

support for the industry, the plan concentrates mostly on geothermal power generation, claiming this use should be the priority since it has the largest potential for CO₂ abatement and is cost-competitive on a life-cycle basis (p. 66). To encourage its deployment, Kenya aims to involve private sector investments via financial support (grants, loans, and risk mitigations schemes) and policy (improvement of regulatory framework) (p. 80). Feed-in-tariffs are also available for geothermal energy developers (p. 11). Development barriers are also mentioned: exploration risks, high investment costs, and unsustainable use of resources resulting in operation deficiencies (pp. 138-139). The successor document – National Climate Change Action Plan 2018-2022 – has many fewer geothermal energy mentions. It includes general plans to reduce greenhouse gas emissions by investing in geothermal energy and to train geothermal professionals (Ministry of Environment and Forestry, 2018, pp. 86-90).

N11 (n/a). No Geothermal Energy Action Plan or its equivalent has been identified.

L2 (1). In Kenya, geothermal energy is governed by Geothermal Resources Act 1982. Article 2 defines geothermal resources as:

any product derived from and produced within the earth by natural heat; and includes steam, water and water vapour and a mixture of any of them that has been heated by natural heat whether as a direct product or resulting from other material introduced artificially into an underground formation and heated by natural heat (Government of Kenya, 1982, p. 5).

Unextracted geothermal resources are a property of the state (Article 3). The law is not clear about the transfer of ownership rights between the state and the geothermal license holder (Tharani, Raore and Karimbux-Khan, 2017, p. 95). The law also does not define resource status, but Article 260 of the Constitution of Kenya states that renewable and non-renewable surface and groundwater resources are considered “natural resources” (Government of Kenya, 2010).

Analytical summary

Agriculture in Kenya plays a vital role in country’s economy: it amounts to 22.6% of national GDP and accounts for 65% of all exports (World Bank, 2023; Food and Agriculture Organization, 2023). This sector employs about 80% of the rural residents and due to population growth of about 2% annually, the demand for food is projected to keep rising (International Fund for Agricultural Development,

no date). To combat climate change, which exacerbates droughts that in turn threaten security of agricultural and food production, the country employs renewable energy. Despite these challenges, geothermal greenhouse agriculture sector is, however, very small and has declined in the past years. The country is focused mainly on electricity generation, which is more attractive economically. This might be the reason why small projects do not get a lot of attention.

Kenya's goals to expand geothermal power development are especially evident from the incentives on a national level. They extensively cover plans to stimulate this market and multiple financial support schemes such as grants, feed-in-tariffs, loans, and risk mitigation schemes are offered to power developers. Geothermal power is considered the fundamental contributor to the country's growth and a main driver of its local economy (Government of Kenya, 2013, p. 147). Kenya offers strong support on other levels as well: global policies include geothermal energy in its climate mitigation strategy and local legislation defines the ownership of the unextracted geothermal resource but does not cover its regulation.

4.10. Serbia

Geothermal energy and greenhouse agriculture

In Serbia, geothermal energy is not currently used very extensively: the largest applications include space heating and cooling as well as recreation. Other minor uses include agricultural drying, animal and fish farming and greenhouse agriculture. The latter represents the third largest use in the country. Industrial process heat was reported in the country only in 2010 but has not been officially reported thereafter (see Table 13). Overall, Serbian geothermal sector has been gradually declining with the only exception of space heating and cooling that steadily improved in installed capacity.

Geothermal research began in Serbia in 1974 and in 1990 the first wells were drilled (Oudech and Djokic, 2020, p. 1). The total installed capacity of greenhouse agriculture reached 19 MWt in 2000. Shortly after it started to decline and dropped to 5 MWt in 2020. This decline could be attributed to a difficult economic and political situation in the late the 1990's as a result of the reorganization of the Soviet sector and civil conflicts, when many geothermal projects were closed. Around 2015, prompted by the interest from Chinese, French and Icelandic companies the appeal for geothermal energy was renewed. Examples include French-Serbian cooperation on development of deep geothermal energy for industrial uses and an

investigation by Icelandic company HS Orka to construct a geothermal power plant in Serbia (Richter, 2017; Mouchot *et al.*, 2019, p. 1). Progress with these projects, however, faded over the years due to financial and licensing obstacles. A few operating geothermal greenhouses in the country are located next to the cities of Bogatić, Debrce, Dublje, Kucura, Petrovac and Srbobran. Some of them are stand-alone facilities with less than 1.5 MWt installed capacity; others are combined with additional uses such as space heating and recreation (Oudech and Djokic, 2020, p. 8). Flowers and vegetables are grown there.

Table 13. Geothermal energy use in Serbia, 2010-2020.

The hyphen (-) indicates an unreported gap in data for a certain year and application.

Sources: Martinovic and Milivojevic, 2010; Oudech and Djokic, 2015; Oudech and Djokic, 2020.

Geothermal energy application	Installed capacity, MWt		
	2010	2015	2020
Agricultural drying	1	1	1
Animal and fish farming	6	6	6
Greenhouse agriculture	19	13	5
Industrial process heat	5	-	-
Recreational use	40	52	34
Space heating and cooling	21	33	54

Policy incentives

G2 and N1 (0). Serbia's Nationally Determined Contributions do not mention geothermal energy (Republic of Serbia, 2017). The country established the Emissions Reduction Target of 9.8% by 2030 compared to 1990 emissions (p. 2)

G4 (0). Serbia's Voluntary National Report does not mention geothermal energy (Republic of Serbia, 2019).

N2 (8). For its National Renewable Energy Action Plan Serbia adopted a template according to the EU Directive 2009/28/EC on the promotion of the use of energy from renewable sources for the national renewable energy action plans (OJ EU L 140, 2009; Republic of Serbia Ministry of Energy, Development and Environmental Protection, 2013). It mentions geothermal energy resources mainly with regards to the heating and cooling sector and is considered as a replacement for fossil fuels in district heating and cooling networks (p. 87). Although no electricity is yet produced with geothermal energy, the document sets a goal of producing 1

MWe by 2020, which was not realized (p. 130). Legal tools that govern exploration and use of geothermal resources include the Law on Mining and Geological Explorations (pp. 32-35) and a Rulebook on the Content of Mining Design, which complements the main framework and covers the design of geothermal systems (p. 151). Trying to attract financial investments Serbia published a development guide for businesses that covers the construction of plants and generation of heat and electricity (p. 50).

N11 (n/a). No Geothermal Energy Action Plan or its equivalent has been identified.

L2 (1). In Serbia, the law governing geothermal resource is the Law on Mining and Geological Explorations 2015 (RS Official Gazett no. 101/2015, 2015). Article 3 defines geothermal resources as a “set of renewable geological resources encompassing ground water and heat from rock masses from which thermal energy extraction is possible”. Geothermal resources are considered those with temperatures of 30°C and higher. Under the same Article, development of geothermal resources is considered a mining operation. Article 4 vests geothermal resources in the state, but its status is not defined.

Analytical summary

Agriculture and food sector is important for Serbia as it accounts for 23% of all country’s exports (Shamsiev and Bucik, 2016). Yet, agricultural share of GDP slightly declined from 6.6. in 2010 to 6.3% to 2020 (World Bank, 2023). Although Serbia has favourable conditions for agricultural production and a large technical geothermal potential its actual use in agri-food remains low. As reported by Republic of Serbia Ministry of Energy, Development and Environmental Protection (2013) geothermal potential remains largely underdeveloped: currently this energy source accounts to only 3% of all renewables in Serbia (p. 7). Greenhouse agriculture covers only a small part of the geothermal sector, and its use has declined over the years. The initial decline was attributed to political instability of the region, but now a lack of foreign investments and licencing obstacles impede its further development.

On a global policy level, Serbia has a weak policy framework, which does not mention geothermal energy development. However, national incentives are strong: they acknowledge geothermal energy as a substitute option for fossil fuels and cover primarily heating and cooling sector. Serbia also expects to attract external investments to stimulate both geothermal heat and electricity production, but internally the country does not offer any comprehensive financial support. Local

legislation covers only resource ownership but is not clear on how geothermal energy is regulated.

4.11. Türkiye

Geothermal energy and greenhouse agriculture

Türkiye uses geothermal energy for several purposes. As indicated in Table 14, the three largest uses include electricity generation, recreational use, and district heating and cooling. Greenhouse agriculture represents the country's fourth largest use followed by individual heating and cooling. Agricultural drying is also reported in the country but is very minor. Overall, geothermal use in Türkiye is growing for all applications since 2010.

The first Turkish geothermal greenhouse project supported by the United Nations Development Program was completed in 1973 in Denizli-Kizildere (Mertoglu *et al.*, 2010, p. 2). Over the years greenhouse agriculture grew considerably: rising from 483 MWt to 820 MWt from 2010 to 2020. This is the largest reported jump in geothermal greenhouse agriculture for any nation. This growth coincided with the adoption of new Geothermal Resources and Natural Mineral Water Act in 2007. It resulted in the issuance of more than 3000 licences for geothermal development (Tsagarakis *et al.*, 2020, p. 2565). In addition, favorable economic conditions make investments highly desirable: the payback time does not exceed 15-20 years (Zenginli, 2022). Major greenhouse complexes are located close to the towns of Afyon, Balçova, Edremit, Dikili, Gediz, Izmir, Simav, Tuzla, Urfa, Urganli, etc. (Serpen, 2006, p. 684). Greenhouse heating is always combined with other uses, such as balneology and district heating. Most greenhouses employ innovative soilless cultivation techniques and grow tomatoes for export. As of 2020, the total area of geothermally heated greenhouses constituted a total of 4.3 million m² (Mertoglu, Simsek and Basarir, 2020, p. 5).

Table 14. Geothermal energy use in Türkiye, 2010-2020.

The hyphen (-) indicates an unreported gap in data for a certain year and application.

Sources: Mertoglu et al., 2010; Mertoglu, Simsek and Basarir, 2015; Mertoglu, Simsek and Basarir, 2020.

Geothermal energy application	Installed capacity, MWe/MWt		
	2010	2015	2020
Agricultural drying	-	2	2
District heating and cooling	792	805	1033
Electricity generation	82	400	1549
Greenhouse agriculture	483	612	820
Individual heating and cooling	219	420	420
Recreational use	552	1005	1205

Policy incentives

G2 and N1 (n/a). The first Nationally Determined Contributions was submitted in 2021, so it is out of the scope of this research.

G4 (0). During the 2010-2020 period Türkiye published two Voluntary National Reviews. The first one published in 2016 does not mention geothermal energy (Government of Türkiye, 2016). The second introduced in 2019 references geothermal power production only, which is considered one of the key components of the Turkish policy framework (Government of Türkiye, 2019, p. 79). The country offers a purchase guarantee tariffs for developers generating electricity from geothermal resources (p. 77).

N2 (14)*. Turkish National Renewable Energy Action Plan is carried out according to the methodology presented in the EU Directive 2009/28/EC on the promotion of the use of energy from renewable sources and the 2009/548/EC Commission Decision of 30 June 2009 on a template for the national renewable energy action plans (OJ EU L 140, 2009; OJ EU L 182, 2009; Republic of Türkiye Ministry of Energy and Natural Resources, 2014). It frequently mentions geothermal energy use for both electricity and heating and cooling sectors with the emphasis on the former. Many legal and financial incentives exist in the country: regulatory framework managing development of geothermal resources (p. 13), administrative procedures supporting power companies (p. 33), risk-sharing mechanisms and mitigation schemes offered to private sector investors that finance field exploration with their own company's equity (pp. 27), and feed-in-tariffs for geothermal power (p. 54). The support for heating and cooling includes feed-in-

premiums for early-stage private geothermal greenhouse agriculture projects (pp. 30-31). Additionally, information support on geothermal resources is offered to investors (p. 36). The country acknowledges the fact that if its big geothermal potential is not used, it will be a missed opportunity which is why investors are encouraged and incentivized (p. 53). There are also plans to expand geothermal energy use for district heating and cooling networks (p. 48). According to this policy, geothermal energy is one of the key contributors to the national renewable energy mix (p. 8).

N11 (n/a). No Geothermal Energy Action Plan or its equivalent has been identified in the country.

L2 (1). In Türkiye geothermal energy is regulated via Law No. 5686 on Geothermal Resources and Mineral Waters 2007 (T. C. Resmî Gazete 26551, 2007). As per Article 3 geothermal resources are defined as:

locations that have temperatures constantly higher than the annual atmospheric average temperature of the region with the effect of the temperature of the earth's crust depending on the geological structure, that may contain melted materials and gas in an amount higher than the surrounding water resources, where water, vapor and gas naturally erupt or are naturally extracted along with places where water, vapor and gas are obtained via heating by the earth's crust or heated dry rocks through man-made structures underground (T. C. Resmî Gazete 26551, 2007, p. 1).

State is the single owner of all geothermal resources and natural mineral waters on both public and private lands (Article 4). The law does not define the status of geothermal energy.

Analytical summary

Türkiye is in the top ten of the world's largest agricultural producers. Agri-food sector is also the country's largest employer, representing about 16% of workforce (Organisation for Economic Co-operation and Development, no date). More than half of the land in Türkiye is suitable for agricultural production and about 6.7% of national GDP is attributed to this sector (World Bank, 2023). Big geothermal potential in the country contributes to the development of greenhouse agriculture, which saw a rapid increase in capacity from 2010 onwards. This is explained by policy and financial incentives, which attract investors. According to experts, greenhouse market became saturated in 2020, which could potentially lead to a decline in investments in the next few years (Mertoglu, Simsek and Basarir, 2015,

p. 5). So far, however, this does not seem to be the case, as many companies are expanding on old facilities and investing in new greenhouse projects. Examples include projects in Afyon and Diyadin both commissioned in 2022 (Richter, 2022). Prompted by the energy crisis and the Covid-19 pandemic further investment has been recorded in this sector.

In terms of policy landscape, global level initiatives are weak but national incentives are exceptionally strong offering multiple financial incentives to both heating and cooling and power sectors such as investment support, mitigation of capital risk, and others. Feed-in-premiums are also available for early-stage development projects (incl. the use of thermal water in greenhouses) for the private sector. Geothermal energy is also supported by a strong local legislation that covers resource ownership but not its status.

4.12. The United States of America

Geothermal energy and greenhouse agriculture

The largest use of geothermal energy in the USA is electricity generation, of which the USA is also the largest single producer in the world. The country uses heat directly for the following applications (from largest to smallest): fish farming, district and individual heating and cooling, recreational use, and greenhouse agriculture where the latter ranks sixth in terms of total installed capacity. Other minor uses include agricultural drying, animal farming, industrial process heat, and municipal snow melting. According to the available data presented in Table 15 below, most applications – agricultural drying, fish farming, greenhouse agriculture, individual heating and cooling, industrial process heat, recreation use, and snow melting – have declined since 2010. The few exceptions are district heating and cooling and electricity generation.

The first American commercial greenhouse came into operation in 1926 in Boise, Idaho. Edwards greenhouse is still in operation today and grows various flowers, fruits, and vegetables like asparagus, basil, cucumber, eggplant, melon, mint, peppers, potatoes, pumpkins, squash, strawberries, tomatoes, etc. (Edwards greenhouse and flowershop, 2023; Governor's Office of Energy Resources, no date). As of 2020, greenhouse facilities were present in nine states: Alaska, Arizona, Colorado, Idaho, Montana, New Mexico, Oregon, Utah, and Wyoming. Idaho contains the largest number of greenhouse sites, currently 13 in total, and Utah has the largest installed capacity, 34 MWt (Lund *et al.*, 2020, p. 8). Greenhouses in the

USA are both stand-alone facilities and have been combined with other uses, like agricultural drying and beverage brewing. The combined projects include greenhouse complexes in Klamath Falls, Oregon that are cascading into district heating and snow melting systems (Lund *et al.*, 2005, p. 5). The produce grown there includes vegetables, flowers, nursery stock, potted plants, and tree seedlings. Interesting and perhaps the most unusual greenhouse uses as reported by Lund *et al.* (2005) includes insecticulture with the cultivation of spider mites grown on lima bean plants in Klamath Falls, Oregon, which demonstrates the diversity of geothermal applications (p. 6). Yet in the past years, greenhouse agriculture saw a decline in total installed capacity from 97 MWt in 2010 to 80 MWt in 2020. This decline is likely attributed to a shutdown of facilities in Susanville, California and Ennis, Montana but in fact, the gradual closure of greenhouse facilities started in the early 2000s, when their products could no longer compete with cheaper imports from neighboring markets (Snyder, Beckers and Young, 2017, p. 6).

Table 15. Geothermal energy use in the USA, 2010-2020.

The hyphen (-) indicates an unreported gap in data for a certain year and application.

Sources: Lund et al., 2010; Boyd, Sifford and Lund, 2015; Lund et al., 2020; Robertson-Tait et al., 2020.

Geothermal energy application	Installed capacity, MWe/MWt		
	2010	2015	2020
Agricultural drying	22	22	6
Air conditioning ⁷	2	2	-
Animal farming	-	-	2
District heating and cooling	75	82	90
Electricity generation	3165	3477	3806
Fish farming	142	142	122
Greenhouse agriculture	97	97	80
Individual heating and cooling	140	140	89
Industrial process heat	17	15	1
Recreational use	113	113	90
Snow melting	3	3	2

⁷ The lack of data for 2020 could be possibly attributed to the merge of this use with e.g., district heating and cooling.

Policy incentives

G2 and N1 (0). Nationally Determined Contributions of the United States do not mention geothermal energy. The country commits to the economy-wide Emissions Reduction Target of 26-28% by 2025 compared to 2005 emission levels (Government of the United States of America, 2016)

G4 (n/a). The United States of America has not produced any Voluntary National Reports yet.

N2 (1). The President's Climate Action Plan comes closest to the National Renewable Energy Action Plans that are available in other countries. It mentions geothermal energy primarily with regards to electricity: the country has doubled its capacity for power production having installed at least eleven new plants since 2009 (Executive Office of the President, 2013, pp. 4-6). The US Navy has long operated a large geothermal power plant in Naval Air Weapons Station China Lake in California and further potential to develop geothermal energy for military installations is envisioned (p. 7). The USA is also eager to promote and negotiate for specific tax regulations and free trade in geothermal energy technologies (p. 19).

N11 (n/a). No Geothermal Energy Action Plan or its equivalent has been identified. However, in 2022 a plan called "2022–2026 Multi-Year Program Plan" was introduced by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (Porse *et al.*, 2022). Its strategic goals include development of 60 gigawatts of electricity from Enhanced Geothermal Systems and installing geothermal heat pumps in 28 million households across the country.

L2 (2). The key legislation governing geothermal resources is the federal Geothermal Steam Act of 1970 (Government of the United States of America, 1970). It defines geothermal resources as "all products of geothermal processes" found or introduced into geothermal formations. These could be in the form of steam, heat, hot water or brine, gas, and other fluids (Section 2). The act, however, defines neither ownership nor the status of the resource. These are both identified by court orders prompted by insistent involvement of the private sector. Following the cases of *Ottobonie vs. the United States of America* 1977 (in Bloomquist, 1991, p. 410) and *Pariani vs. State of California* (Justia US Law, 1980) geothermal energy is regulated as a mineral resource for the purposes of leasing and ownership on a federal level. The state owns geothermal resources where it holds mineral rights, for example on federal lands, but if the land is classified as indigenous or private other rules might apply. Such regulation of geothermal resource is applied only at a

federal level but in general, each state can characterize, define, and regulate geothermal resources, including ownership and status in their own way.

Analytical summary

In 2020 US agriculture amounted to 0.9% of national GDP and employed 10.5% of the population in 2021 (U.S. Department of Agriculture, 2023; World Bank, 2023). The agri-food industry is prominent in the USA and considered nationally important despite contributing only a small part to its gross domestic product. The government supports agri-food sector with large subsidies in the form of direct monetary payments with most directed at development, conservation, research, and risk mitigation (U.S. Department of Agriculture, no date). The contribution of geothermal energy for greenhouse agriculture has been declining gradually since the 2000s and one of the main reasons for that is economic feasibility and market competitiveness as growing vegetables and fruits cannot compete financially to the produce imported from abroad.

In terms of policy incentives, support for geothermal energy is very weak on both global and national levels. The resource is not mentioned at all in global policies and sparsely represented on national level. Local legislation, however, is extensive and covers both ownership and regulation. The legal framework consists of federal and state levels, which do not necessarily match. On a federal level ownership and status are defined; on a state level ownership is usually present, but status is not necessarily explained. Moreover, regulations of geothermal energy may also vary from state to state.

5. Results

This chapter consists of two parts. The first part includes a *comparative analysis* of policy incentives, where the results of the content analysis are presented. Case studies are compared in terms of their context from three evaluated policy levels: global, national, and local. To establish if a relationship exists between the two variables – policy support and the adoption of geothermal energy in greenhouse agriculture – the values for both are plotted on the graphs. Based on the available data, Hypothesis 1, that there is a positive relationship between policy incentives and the adoption of geothermal energy in greenhouse agriculture, is accepted, while Hypothesis 2, that no such relationship exists, is rejected.

Of the evaluated documents, national policies appear to be the most influential of the policy suite. An additional thematic analysis is carried out on national incentives to see if their thematic content impacts the adoption of geothermal energy in greenhouse agriculture. This analysis classifies content themes into two groups: target use (electricity generation, heating and cooling, and other uses) and the nature of their support (financial, policy, or other). This research finds that the existence of targeted policies that specifically mention the intended use of geothermal energy correlates well with the expansion of the market they are aimed at.

The outcomes also reveal that market outliers – a few countries that lead greenhouse agriculture development – tend to drive most of the growth in the industry. To understand the influence of any one such country outlier on the total industry performance, a leave-one-out cross-validation is performed, which shows that no one country skews the data and is solely responsible for the trends.

During this research some other factors were discovered that might further influence the adoption of geothermal energy in greenhouse agriculture. Such factors include the role of agri-food industry and its importance to the national economy, the beginning of domestic geothermal research, and the medium-term (10 years) development trend of geothermal heating and cooling sector in a country. These factors may explain the variations in energy adoption, for instance, in a country such as Italy that offers a relatively strong policy support coupled with a decline in capacity. The analysis, however, shows that these additional factors are not relevant for explaining the trend. While multiple reasons could contribute to a capacity decline there are only a few common factors that all market leaders share: strong government support on a national level, targeted policies for geothermal agri-food, and a competitive price when compared to other forms of energy.

The second part consists of *regression analysis* that aims to further examine the relationship and to support Hypothesis 1. It shows how well policy incentives can explain the differences in capacity changes in twelve case countries. Although the regression analysis is not useful for predicting the amount of energy adoption with respect to policies, as the standard error is quite high, the outcome still shows that 23% of all capacity changes can be explained by variance in policy values. This indicates that despite policy incentives playing an important role in the adoption of geothermal energy in greenhouse agriculture they are not the single most important factor but one of many.

5.1. Comparative analysis

Twelve selected case countries are analyzed for both their current policies and greenhouse agriculture trends. Based on the content analysis the following observations are made regarding policy levels:

- On a global level, initiatives in most countries do not cover geothermal energy. Most significant exceptions include Iceland with its Voluntary National Review and Kenya with its Nationally Determined Contributions. Greece and Hungary also have stronger than average Voluntary National Reviews. Globally, Japan and Türkiye only mention the geothermal electricity market.
- On a national level, geothermal energy is referenced most often, and all countries cover it at least once in their policies. Iceland, the Netherlands, and Türkiye have the strongest representation on a national level, and these are also the only countries that explicitly connect geothermal energy development with greenhouse agriculture. Greece, Hungary, Italy, Kenya, Serbia, and Spain also extensively support geothermal energy development in their National Renewable Energy Action Plans. Countries that are marginally below the average score (i.e., lower than eight) are Austria, Japan, and the USA: they do not extensively mention this energy source. National Renewable Energy Action Plans of Japan, Kenya, Spain, and Türkiye mostly cover electricity production since their governments highlight this market as a development priority. The most important policy rated by experts – National Geothermal Action Plan – is present only in Iceland and the Netherlands. The Dutch plan is very broad and covers various markets including greenhouse agriculture while the Icelandic plan is dedicated solely to high temperature energy resources and electricity production.
- On a local level, legislation is quite diverse. Geothermal energy could be included in water, mining, or natural resource regulations. A few countries have legal acts specifically aimed at geothermal resources. These include Italy, Kenya, Türkiye, and the USA. Both ownership and status of geothermal energy are explicitly mentioned in the laws of Greece, Italy, Spain, and the United States. Other countries – Hungary, Iceland, Kenya, Serbia, and Türkiye – cover only one aspect of geothermal energy, its ownership, but do not define its status. Unlike

other countries, local legislative acts of Hungary and Iceland specifically regulate geothermal resource use for agricultural purposes. The remaining – Austria, Japan, and the Netherlands – do not explicitly cover geothermal energy but have laws that imply its ownership and status through a broader legal framework. For example, in Austria ownership and status of geothermal resources are implied through groundwater regulation, where in Japan industrial water law applies. In the Netherlands, depending on the depth of a resource, either the Mining or Water Acts apply.

To test the hypotheses the relationship is established between the two variables – the change in geothermal greenhouse agriculture capacity (dependent variable) and the qualifying mentions of incentivizing policy (independent variable) – by plotting their corresponding values on a graph. The values used are shown in Table 16. For policy incentives, the score is combined per level. *Global policy* score combines the values of policies G2 and G4; the *national policy* score combines N2 and N11 policy values; *local policy* score consists of a single policy. *Total policies* show the combined score for all three levels. An asterisk superscript (*) indicates the explicit connection between geothermal energy and greenhouse agriculture in at least one of the policies. The adoption of geothermal energy in greenhouse agriculture is represented by the *change in installed capacity* as the difference in total capacity in MWt between 2010 and 2020.

To support the Hypothesis 1 which suggests a positive relationship between the variables, robust policies that support geothermal development should correspond to growth in the industry, in other words strong policies should result in more adoption of geothermal energy. The inverse would also hold in that countries in decline should show a relative lack of supporting policies. To support Hypothesis 2 and infer that there is no relationship between these two variables, trends in a country's geothermal industry should not correlate or rather should not respond to any level of policy support.

Table 16. Final policy and greenhouse agriculture values.

An asterisk superscript (*) indicates the explicit connection between geothermal energy and greenhouse agriculture in at least one policy.

Country	Global policy	National policy	Local policy	Total policies	Change in installed capacity from 2010-2020 (MWt)
Austria	0	7	0	7	20
Greece	1	8	2	11	4
Hungary	1	8	1*	10*	162
Italy	0	9	2	11	-2
Netherlands	0	21*	0	21*	220
Spain	0	11	2	13	7
Iceland	5	12*	1*	18*	12
Japan	0	3	0	3	-12
Kenya	2	12	1	15	-11
Serbia	0	8	1	9	-14
Türkiye	0	14*	1	15*	337
USA	0	1	2	3	-17

Figure 5 below depicts change in capacity in MWt that reflects greenhouse adoption on a vertical axis and a score for policy incentives on a horizontal axis for each case country. It combines the scores for global, national, and local support and represents the connection between all policy incentives (policy suite) and the adoption of geothermal energy in greenhouse agriculture. Countries are color-coded: green depicts a positive change in capacity and red a decline. Asterisk superscript (*) indicates the explicit connection between geothermal energy and greenhouse agriculture in at least one policy.

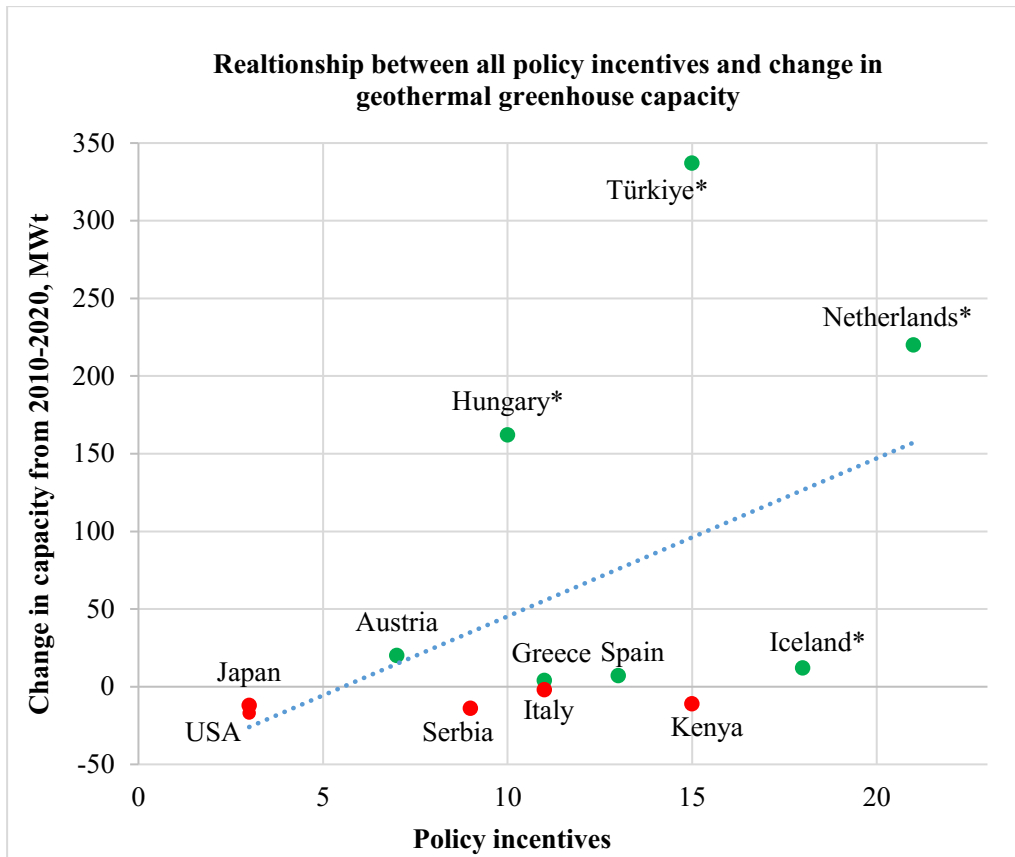


Figure 5. Relationship between policy suite and greenhouse capacity.

Green colored countries show a positive change in capacity and red a decline. Asterisk superscript (*) indicates the explicit connection between geothermal energy and greenhouse agriculture in a policy. A linear trendline is depicted in blue. Own elaboration.

As a trendline suggests, comprehensive three-level policy support strongly correlates with changes in installed capacity: the more geothermal energy is represented in policies, generally, the larger the growth in capacity in greenhouse agriculture. A similar micro-trend of positive correlation can be witnessed in Greece, Spain, and Iceland. The proximity of Italy and Kenya to this group could be explained by their strong interest in geothermal energy on a national level and mature power market. Four countries – Hungary, Iceland, Netherlands, and Türkiye – clearly stand out in the graph as they are located at its far edges. They all cover geothermal energy use specifically for greenhouse agriculture in their policies and display considerable growth.

The relationship observed between a policy suite combining incentives on a global, national, and local levels and greenhouse capacity are consistent with Hypothesis 1: there is a strong positive correlation between policy incentives and

the adoption of geothermal energy in greenhouse agriculture. Based on these data, Hypothesis 1 is accepted, and Hypothesis 2 is rejected.

However, since policy support functions on various levels, it is important to understand which level – global, national, or local – most influences this relationship. Three additional graphs below show the correlation between the change in capacity and policy level separately for global policies (Figure 6), national policies (Figure 7), and local policies (Figure 8).

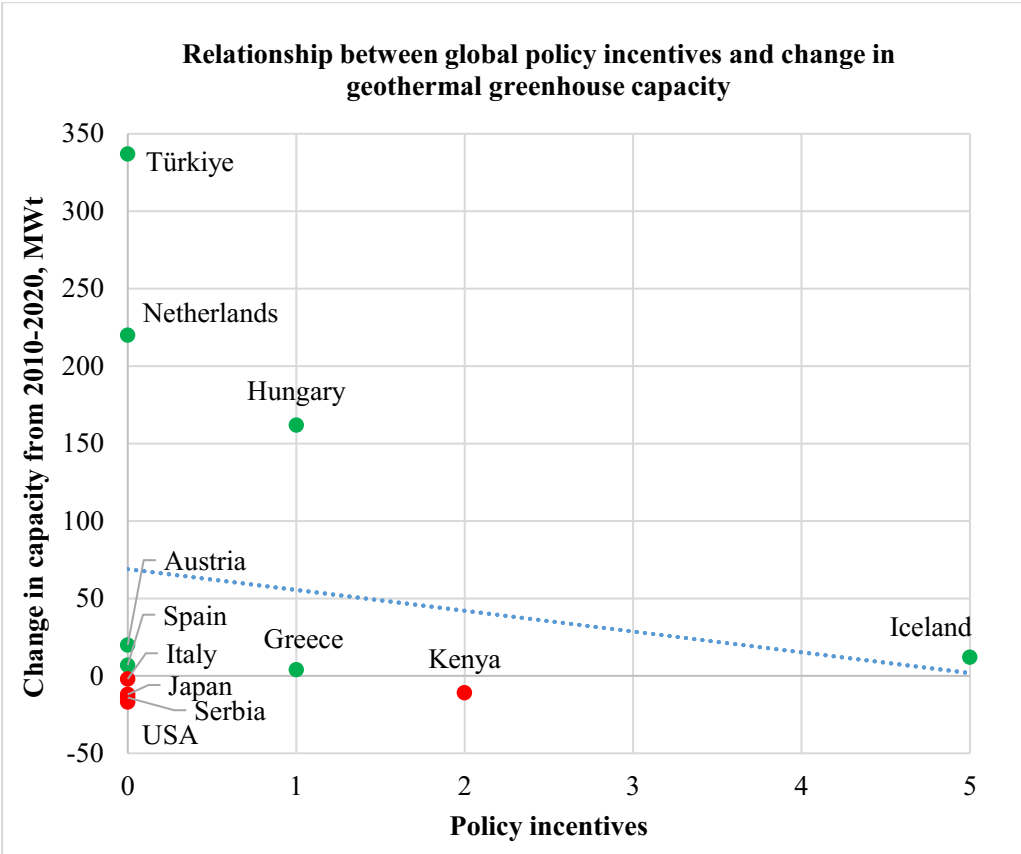


Figure 6. Relationship between global policy incentives and greenhouse capacity. Green colored countries show a positive change in capacity and red a decline. A linear trendline is depicted in blue. Own elaboration.

Figure 6 suggests that global policy incentives do not correlate with the adoption of geothermal energy in greenhouse agriculture. Countries with both positive (Austria, the Netherlands, Spain, Türkiye) and negative (Italy, Japan, Serbia, the USA) change in installed capacity are equally not supportive of geothermal energy on a global level. Greece and Hungary sparsely include geothermal energy in its policies, but both show growth in greenhouse agriculture. Kenya experiences a decline in its capacity but includes more geothermal energy mentions than all other

countries excluding Iceland. Iceland is a single outlier that shows both growth and strong policy support on a global level.

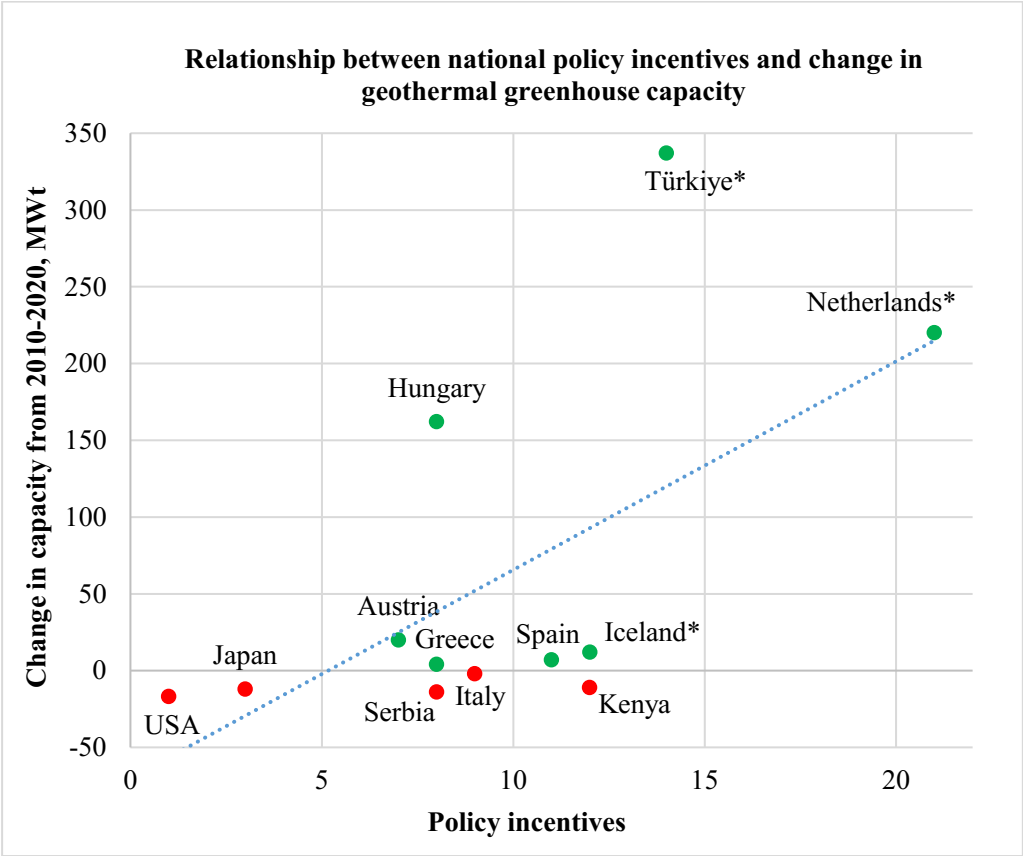


Figure 7. Relationship between national policy incentives and greenhouse capacity.

Green colored countries show a positive change in capacity and red a decline. An asterisk superscript (*) indicates the explicit connection between geothermal energy and greenhouse agriculture in a policy. A linear trendline is depicted in blue. Own elaboration.

Figure 7 depicts a relationship between two variables on a national level. As the trendline in blue suggests, there is a strong correlation between national policy incentives and the adoption of geothermal energy. Japan and the USA sparsely cover geothermal energy and show a decline in capacity. Several countries are clustered together although they have different capacity trends. One group includes Austria, Greece, Italy, Serbia and another Iceland, Kenya, and Spain. Both Kenya and Italy are well-known geothermal power producers, and their high national policy scores could be explained by their strong interest in geothermal development. The case of Serbia is harder to explain, although the country reports various uses of geothermal energy for heating and cooling. It could well be that historical legacy plays a role here: Serbia was once eager to develop geothermal resources, but the development

slowed down after 1990s due to political instability in the region. Now geothermal energy is again being mentioned in the national policies. A positive micro-trend is visible with Spain and Iceland, where a better representation of geothermal energy in national policies corresponds to growth. Countries located at the far edges of a diagram – Hungary, the Netherlands, and Türkiye – clearly stand out since they have the largest positive capacity changes and the strongest policy support. Countries marked with the asterisk superscript (Iceland, the Netherlands, and Türkiye) explicitly connect geothermal energy with the greenhouse agriculture in their policies.

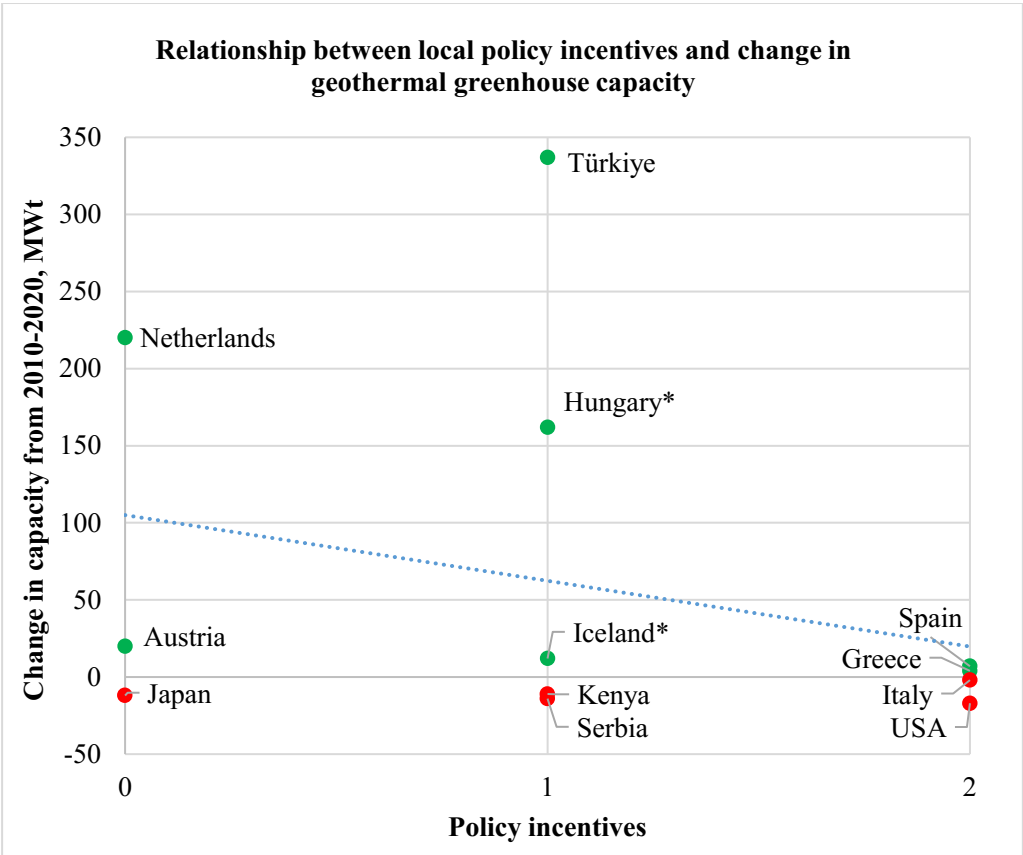


Figure 8. Relationship between local policy incentives and greenhouse capacity. Green colored countries show a positive change in capacity and red a decline. An asterisk superscript (*) indicates the explicit connection between geothermal energy and greenhouse agriculture in a policy. A linear trendline is depicted in blue. Own elaboration.

Figure 8 shows a relationship between local policies and the adoption of geothermal greenhouse agriculture. Similar to global policies, no obvious correlation can be established between these two variables on a local level. Countries that display low or implicit local support for geothermal energy and score

zero show both growth (Austria, the Netherlands) and decline (Japan) in capacity. The opposite is also true: countries that have a value of two on the graph and that regulate both ownership and status of geothermal energy report either positive change (Greece, Spain) or decline in capacity (Italy, the USA). The same can be observed in countries that regulate only one aspect of geothermal resources, its ownership, and have a score of one: Hungary, Iceland, Kenya, Serbia, Türkiye. Among these, Iceland and Hungary are the only two countries that specifically regulate geothermal energy use in greenhouse agriculture in their local legislative acts.

As observed in Figures 6-8, there are different relationships between each policy level and the adoption of geothermal energy in greenhouse agriculture. While global and local policies do not seem to correlate with the adoption of geothermal energy, national policies do. This could be explained by the fact that global level policies offer broad and unspecific support for geothermal industry and local policies are too sparse and diverse to allow for any convincing conclusions. Since the hypotheses make no distinction between different policy levels, which emerged during this research, evidence for accepting or rejecting either of them is based on the complete policy suite as represented in Figure 5.

Comparative analysis revealed some additional patterns. As seen in Figure 5 on p. 84, market leading performers – countries that lead greenhouse agriculture development – set the trends for the whole industry. For greenhouse agriculture these are Hungary, Iceland, the Netherlands, and Türkiye. To make sure that no one country is driving the positive trend leave-one-out cross-validation (LOOCV) was performed in Python. Such statistical cross-validation is appropriate here due to the small size of a sample (McElreath, 2020, pp. 221-223). It helps to estimate the predictive accuracy of a model – in this research the model of a relationship between the two variables presented in Figure 5 – by leaving one datapoint (country) out from the sample and computing a new trendline with the partial dataset of eleven countries. The process of removing one country at a time is repeated until twelve new trendlines are drawn. The outcome of LOOCV is presented in Figure 9 below. Each colour trendline corresponds to a new dataset without the indicated country, i.e., the blue trendline depicts the relationship between the variables without the data from Austria, orange without Greece, green without Hungary, etc. This figure clearly shows that not a single country, including market leading performers is responsible for the relationship between the adoption of geothermal energy in greenhouse agriculture and policy incentives. In other words, the influence of data

from e.g., Türkiye (or any other country) does not change the positive relationship, but only slightly changes its slope. The code used in Python for computing the LOOCV is included in Appendix G.

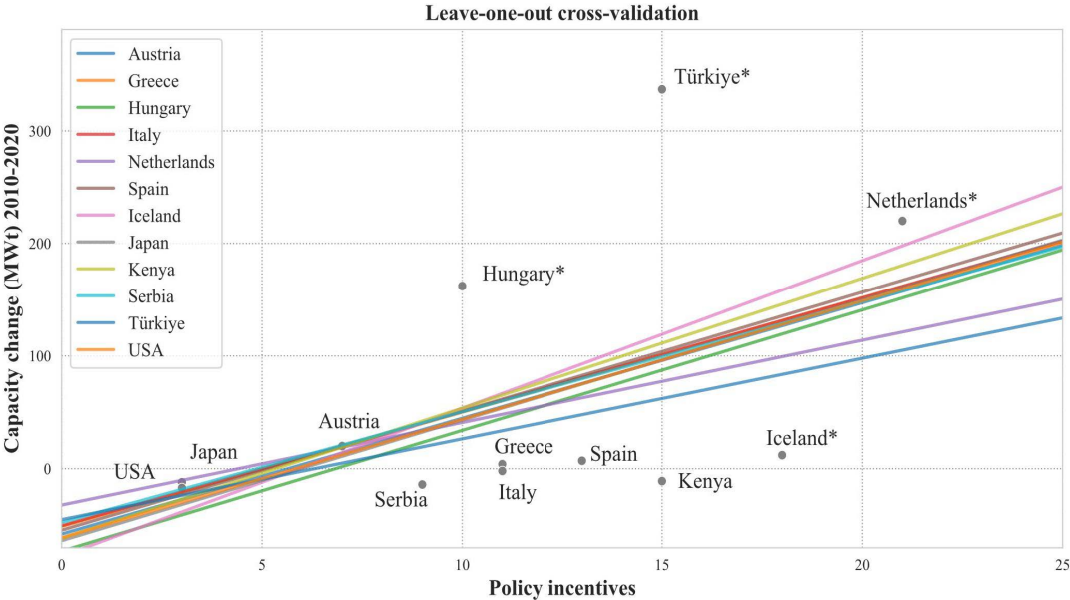


Figure 9. Leave-on-out cross-validation for policy suite combining three levels (global, national, local). Own elaboration created with Python.

According to Figure 7 on p. 86, national policies correlate the most with the adoption of geothermal energy. To further understand their content and see if it may impact the adoption of geothermal energy, national policies are analyzed in terms of themes they cover. Each mention of geothermal energy covers one or more themes. The main recurring themes are policy and finance support directed at electricity, heating and cooling, or geothermal industry at large. Table 17 below shows the frequency of themes present in national policies in each case country. These are first separated by sector (*electricity, heating and cooling*) and then by content topic (*general, policy, finance*). If, for example, a policy mention covers financial support for district heating and cooling it would be attributed to *heating and cooling – finance* and if it speaks to a law that regulates geothermal resources for power production to *electricity – policy*. Category *general* for both sectors include mentions that could not be attributed to either policy or finance themes, but that clearly cover either sector. Sometimes the theme is not straightforward, e.g., some policies or financial incentives cover both heating and cooling and electricity sectors, and, in this case, it is counted for both. The *other* in the last column indicates

miscellaneous mentions that are not directed specifically at either sector. These include statements on general industry support, limiting factors for its development, and research and education activities aimed at geothermal energy promotion. If a certain theme is covered in a national policy, it is indicated in Table 17 with a number that corresponds to its frequency, e.g., Greek national policies mention heating and cooling sector the most as indicated by number “4”, while Kenyan policies concentrate mainly on the electricity sector with “14” mentions in total. Numbers are also colour coded. Green indicates the above average amount of mentions, blue – below average and white – zero mentions. Thematic analysis codebook and record sheet for each individual theme can be found in Appendix F.

Table 17. Thematic analysis: frequency of themes in national policies.

	Heating and cooling			Electricity			Other
	General	Policy	Finance	General	Policy	Finance	
Austria	2	1	4	1	0	5	0
Greece	4	2	1	2	3	2	2
Hungary	3*	1	2	2	0	2	3
Italy	4	6	3	2	5	3	0
Netherlands	9*	5	3	3	4	3	8
Spain	8	4	2	7	3	2	3
Iceland	4	2	3	3	3	2	4
Japan	3	0	0	9	1	1	2
Kenya	2	2	0	14	3	2	10
Serbia	3	3	2	1	3	2	3
Türkiye	4	3	3*	4	4	3	6
USA	1	0	0	3	0	0	1

Table 17 shows that countries are quite inclusive in their national policies and include most themes. Some countries cover both sectors equally (Austria, Greece, Iceland, Türkiye), others give preference to heating and cooling (Hungary, Italy, the Netherlands, Spain, Serbia) while the rest to electricity (Japan, Kenya, the USA). What is notable is that Japan, Kenya, and the United States do not seem to provide

any comprehensive support for the heating and cooling sector and simultaneously their capacity in greenhouse agriculture has been declining. At the same time, all three countries show support for geothermal electricity, which they largely utilize: all countries include plans to expand the geothermal power capacity in their national policies. The same association, however, is not observed in Italy and Serbia, which both show a general decline in geothermal greenhouse agriculture but support heating and cooling sector. Italy has a small decline in capacity, which could be attributed to other reasons, e.g., to reorganization of its legislation relating to search for and mining of geothermal resources or to some other technical operating issues. For Serbia the reason for decline, as already mentioned, are likely due to difficult economic and political situation in the region.

Despite such discrepancies, the thematic content of policies appears to influence the adoption of geothermal energy. This is also evident in Figure 5 on p. 84 showing policy suites, where country outliers – Hungary, Iceland, the Netherlands, and Türkiye – all explicitly cover geothermal energy development in agri-food sector and show its prominent growth. Hungary and Iceland regulate geothermal resource use for agricultural purposes on a local level via favourable legislative frameworks and Iceland, the Netherlands and Türkiye outline the plans to support its expansion on a national level. To be precise Iceland support this use legally, the Netherlands identifies geothermal horticulture as a priority sector due to its economic appeal and Türkiye offers financial support via feed-in-premiums for greenhouse projects. Based on these data it is safe to assume that policy content is generally related to the development trends: the existence of targeted policies correlates with the expansion of the market they are aimed at.

The discrepancies point to other factors that could influence geothermal energy adoption in greenhouse agriculture. Some of these factors discovered during the research include the importance of agri-food industry to the national economy, the beginning of domestic geothermal research, and the medium-term (10 years) development trend of geothermal heating and cooling sector in a country. To evaluate their importance, these factors were collected and compiled as an overview in Table 18 below. The first column shows the importance of agri-food sector to the country, which is assessed relative to the case countries as high, middle, and low and is based on the percentage of their national GDP in 2020 (World Bank, 2023). The percentage of gross domestic product gives us information about the significance of agri-food sector to the national economy and its size. The assessed percentages are divided into three tiers and are indicated in parenthesis. The

countries with four lowest values – Austria, Japan, the Netherlands, and the United States – belong to the category *low tier*, the *middle tier* comprises of Greece, Hungary, Italy, Spain, and Iceland, while Kenya, Serbia and Türkiye belong to the group with *high* importance. Relevance of these levels should only be assessed relative to each other and not as absolute as this is a case country specific ranking.

Second column indicates the year when geothermal energy research for agri-food sector began in a country. The earliest research activities began in Italy in the 19th Century, followed by Iceland and the USA in 1920's. The remaining countries all started later with Kenya being the most recent to use geothermal energy for agri-food purposes.

The development trend of geothermal heating and cooling sector is shown in the third column while the trend for geothermal greenhouse agriculture occupies the fourth. Both columns show either *growth (+)* or *decline (-)* in capacity between 2010 and 2020 with the capacity change in MWt in parenthesis. All countries except the United States showed growth in geothermal heating and cooling, however the values vary considerably. For example, Greece, Kenya, and Serbia have only slight growth, while Iceland, Hungary, and Türkiye show considerable additions. In some countries these additions are mostly due to the consistent growth in all heating and cooling applications (Hungary, Iceland, Italy, Türkiye), while in others primarily to the growth of greenhouse agriculture (Austria, Greece, the Netherlands, Spain), or some other application, e.g., in Japan to recreation and space heating and cooling, in Kenya to recreation and other uses (such as milk processing and laundry units), and in Serbia to space heating and cooling.

The fifth and final column shows the most likely reason for the geothermal development trend in greenhouse agriculture. Based on the content analysis, some reasons for a positive trend include strong government support and financial appeal as is the case in Greece, Hungary, Iceland, the Netherlands, Türkiye. In other countries such as Austria, Italy, and Spain the lack of data is not conducive to making any solid conclusions. A negative trend is usually harder to explain since the reasons for a capacity decline could be multiple: some of them include low demand (Japan), financially uncompetitive geothermal agri-food sector (the United States), or possible technical issues (Kenya).

As we can deduce from the Table 18 below, the importance of the domestic agri-food sector as well as the start of geothermal agri-food research are unlikely to be coupled to the adoption of greenhouse agriculture. Although generally trends for geothermal heating and cooling coincide with the trends in greenhouse agriculture,

there are again some discrepancies as in Italy, Japan, and Kenya both trends do not coincide. It is thus assumed, that none of these three factors – the importance of agri-food industry to the national economy, the beginning of domestic geothermal research, and the medium-term (10 years) development trend of geothermal heating and cooling sector in a country – additionally influence geothermal energy adoption in greenhouse agriculture.

In conclusion, the reasons for a lack of geothermal energy development are multiple and varied, rather than trying to understand why some countries fail to develop geothermal energy, it is more helpful and important to look at leading market performers and those countries that have succeeded in adopting geothermal energy for greenhouse agriculture on a large scale. These countries are Hungary, Iceland, the Netherlands, and Türkiye. What these four countries have in common are good coverage of geothermal energy in government initiatives on a national level, targeted policies aimed at geothermal greenhouse agriculture development, and favourable economic environment for geothermal resource development, which allows it to be financially appealing and competitive. For all these countries, geothermal energy is one of the cheapest and best economic solutions on the market.

Table 18. Overview of additional influential factors.

	Importance of agri-food sector (% of GDP)	Beginning of geothermal agri-food research	Geothermal heating and cooling energy trend (MWt)	Geothermal greenhouse agriculture (MWt)	Reason for the geothermal agri-food trend
Austria	low (1.1%)	1978	growth (+33)	growth (+20)	unknown; lack of data
Greece	middle (4.2%)	1980s	growth (+1)	growth (+4)	community and government support; financial appeal
Hungary	middle (3.4%)	1960s	growth (+336)	growth (+162)	government support; financial appeal
Italy	middle (2%)	19 th Century	growth (+136)	decline (-2)	unknown; lack of data
Netherlands	low (1.6%)	1980s	growth (+217)	growth (+220)	business and government support; financial appeal
Spain	middle (2.9%)	1980s	growth (+10)	growth (+7)	unknown; lack of data
Iceland	high (4.6%)	1924	growth (+467)	growth (+12)	financial appeal
Japan	low (1%)	1950s	growth (+321)	decline (-12)	unknown; likely low demand
Kenya	high (22.6%)	2006	growth (+2)	decline (-11)	unknown; likely technical problems
Serbia	high (6.3%)	1974	growth (+8)	decline (-14)	unknown; likely unstable political situation
Türkiye	high (6.7%)	1973	growth (+1434)	growth (+337)	financial appeal
USA	low (0.9%)	1926	decline (-129)	decline (-17)	non-competitive financially

5.2. Regression analysis

To further support Hypothesis 1 and to demonstrate how well policy incentives can explain various trends in the use of geothermal energy for greenhouse agriculture in the twelve case countries a simple regression analysis is performed. The analysis further examines if and how statistically important the context of policy incentives is. For this analysis the values from Table 16 on p. 83 are used, where final policy and greenhouse agriculture values are shown. Policy value as independent variable shows the combined score for all three policy levels in a country and capacity change as dependent variable shows the capacity difference between 2010-2020 for geothermal greenhouse agriculture. The analysis is performed in Excel via “Data Analysis” option in the Analysis ToolPak applet. Table 19 below presents the summary output of the regression statistics as well as the separate components of the actual regression model. The analysis of key components is performed based on the publication of Mathews (2018) and personal communication with Stefanescu-Cuntze (2023). Some components of the linear regression analysis include:

- *Multiple R* value that represents a correlation coefficient, which measures the strength of a linear relationship. The value 0.48 indicates a positive relation between the policy incentives and greenhouse agriculture.
- *R square* indicates what percentage of variability in capacity changes can be explained by policy support. The linear regression model is able to explain only 23% of capacity variation, which is not significant.
- *Standard error of the regression model* indicates how precise the model is if it were to be used to predict the rates of geothermal energy adoption. The standard error of 106 is considered high, which means that policy incentives should not be relied upon when predicting the growth of geothermal industry.
- *Observations* stand for twelve case countries, or number of observations in the model.
- *Intercept coefficient* represents the expected capacity value if the policy incentives are absent. In other words, the model suggests that with no policies encouraging the use of geothermal energy in agri-food sector, its decline of 56.48 MWt is expected.

- On the other hand, *policy value coefficient* indicates that for every targeted mention of geothermal energy in policies the agri-food sector capacity could increase by 10.17 MWt. However, since the 95% *confidence level* for this variable includes the value zero (-2.85, 23.19) the slope of 10.17 is not significant at 5% significance level. A separate calculation shows that it is significant at 85% confidence level, which means that the real value of capacity increase for every policy mention could be as low as 1.06 MWt or as high as 19.28 MWt.
- It is important to note that both value coefficients should be approached with caution and cannot be relied upon when predicting geothermal industry development since the *standard error of each coefficient* is relatively high. Their excessive variability implies that these coefficients as estimated in the model have an extremely high chance of being inaccurate and should not be used for predictive analytics.

Table 19. Summary output of simple linear regression.

<i>Regression Statistics</i>	
Multiple R	0.48
R Square	0.23
Standard Error	106.58
Observations	12.00

	<i>Coefficients</i>	<i>Standard Error</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 85%</i>	<i>Upper 85%</i>
Intercept	-56.48	73.03	-219.19	106.24	-170.34	57.39
Policy value	10.17	5.84	-2.85	23.19	1.06	19.28

To summarize: although numerical values as presented in the linear regression model are not reliable for extrapolation and should not be utilized for making predictions about the development of the geothermal industry, they nevertheless support the Hypothesis 1 by statistically showing that a positive relationship indeed exists between policy incentives and the adoption of geothermal energy in greenhouse agriculture. Despite being unfit for predictive analysis, the model shows that only 23% of all capacity changes in case countries can be explained by variance in policy values. This also suggests that policy support is not the single most important factor influencing geothermal energy adoption but one of many.

6. Discussion and Conclusions

The shift from fossil fuels to more sustainable and environmentally friendly energy sources is motivated by rapid climate change. Countries across the globe are committed to introducing renewable energy sources to their national energy mixes. Most of the commitments are directed towards the power sector, while the largest share of final energy consumption is covered by the heating and cooling market which still relies heavily on fossil fuels. A part of this market, the agri-food industry, could benefit significantly from a reliable and green energy resource. The literature review shows that the use of geothermal energy is one of the cheapest and most sustainable ways to promote national food security and economic development. Yet, its contribution to the agri-food sector is surprisingly low. Frequently, a lack of government support and a proper policy framework is used as justification for impeded development. However, the assumption that government initiatives influence the growth of geothermal energy is not well supported by any substantial evidence or analysis.

The aim of this research was to investigate the relationship and the degree of correlation between government support expressed in policy incentives and geothermal energy use in the agri-food sector represented by greenhouse agriculture. To fill this existing gap in understanding and to test the assumption that these two aspects are related, two hypotheses were proposed. The primary hypothesis (Hypothesis 1) asserts there is a positive relationship between policy incentives and greenhouse agriculture while an alternative hypothesis (Hypothesis 2) states that these two aspects are unrelated and that policies have no effect on growth.

To test these hypotheses, the role of geothermal energy, geothermal heating and cooling, and agri-food sector was assessed and explained. Geothermal energy can be used for electricity production or directly as a heat source. Direct applications are diverse, but agri-food and particularly greenhouse agriculture represent its largest share (excluding space heating and cooling). Next, the context of government support was identified, which could include policy and financial incentives. Policy incentives lay the foundation for the financial incentives since they influence the industry long before any project can start. Policy incentives are defined as any relevant government instruments and measures directly or indirectly encouraging the use of geothermal energy. These policy incentives can take various forms and appear on different levels: global, national, and local. Geothermal industry experts

estimated the validity and reliability of these policy incentives and identified six most relevant incentives: two global, three national and one local policies. To see how government support relates to the adoption of geothermal energy in the agri-food sector, the development trends were identified and analyzed in twelve case countries, which were chosen via purposive sampling. Next, policy incentives and greenhouse agriculture development were assessed in each selected case country. To accomplish this, content and thematic analyses of secondary data sources were performed, and their outcomes were presented in a form of a country portfolio. Comparative and regression analyses allowed us to establish the degree of correlation between government support and the use of geothermal energy in greenhouse agriculture in selected case studies. The results of this study support the Hypothesis 1, which is accepted and is likely to be correct given the data and Hypothesis 2 is rejected.

In general, the following conclusions can be derived from this study:

- Based on the example of greenhouse agriculture, the research shows there is a strong positive relationship between policy incentives and the adoption of geothermal energy. However, only 23% of all capacity changes in case countries can be explained by varied levels of policy support. This implies that, although important, policy support is not the single most important factor influencing the relationship since other additional factors are likely to impact it too.
- It is extremely important to differentiate between various policy types and their regulatory levels because they do not hold equal weights. The research literature fails to make such a distinction. This study showed that policy incentives could occur on global, national, and local levels. Among them, national support correlates best with the growth of geothermal industry. Of any level considered in this research, national policies also mention geothermal resources the most. Global and local policies do not correlate with the adoption of geothermal energy and data on both levels are unclear. Global level apparently offers broad and unspecific support for geothermal industry and local policies are too sparse and diverse to allow for any convincing conclusions.
- While national policy incentives positively impact the adoption of geothermal energy their presence and context cannot and should not be used to predict the development trends in greenhouse agriculture or for forecasting industry trends in general.

- Policy content and thematic analyses show that context matters. In general, the more geothermal energy is represented in a national policy, the more probable its growth. This is observed for both power and greenhouse agriculture markets. However, it is not enough just to include geothermal energy in a policy, the goals for energy development should be specific and aimed at a certain market. As this research shows, targeted policies appear to work best and that clear and explicit connection of geothermal energy to a particular market correlates with a strong increase in installed capacity. Countries with policies that specifically address the agri-food sector tend to expand this market faster than those without. Such countries as Hungary, Iceland, the Netherlands, and Türkiye have substantially expanded geothermal use in greenhouse agriculture due to the presence of targeted policy support.
- Most greenhouse market growth, in terms of capacity, is represented by a few outliers, or countries that lead its development. These, again, include Hungary, Iceland, the Netherlands, and Türkiye. The leave-one-out cross-validation shows that no one outlier influences the market performance and that the positive trend remains without any one market leader.
- Finally, rather than trying to understand why some countries are performing well while others are not especially when their geothermal industry development trends are similar, it is more sensible to learn from the outliers. The factors contributing to the lack of growth or to the decline of geothermal industry are more disparate and diverse than the factors contributing to its growth. Examples of Italy and Serbia support this suggestion. While we might outline likely reasons for their negative trends (in Italy – retractive government support or technical issues, Serbia – unstable political situations in the region), this will not help us understand the success factors and steps that need to be implemented to reverse these trends. On the other hand, if we look at the examples of market leaders (again these are Hungary, Iceland, the Netherlands, and Türkiye) that show substantial increase in greenhouse agriculture capacity, we find a few common elements between them. These are:
 - Strong coverage of geothermal energy in national policies, i.e., mentions of its relevance to the national energy development, specific goals, and targets for its expansion. All four countries

outline the importance of heating and cooling sector but also aim to promote the use of geothermal energy in national research and education. This encourages energy developers to explore and exploit geothermal resource as one of the sustainable solutions.

- Targeted policies aimed at geothermal energy development in greenhouse agriculture. All countries either on a national or local level regulate the use of geothermal resources for the agri-food sector. This incentivizes energy developers to pursue the opportunities in this sector.
- Favourable economic environment for geothermal resource development. In all four countries geothermal energy is considered financially appealing. It can compete in the energy market due to its low price and is considered the cheapest renewable energy source in Hungary, Iceland, Italy, and the Netherlands. This encourages investors to consider geothermal energy a beneficial economic opportunity, which in turn unlocks funding for geothermal resource developers.

Although not analyzed in depth here, financial support is the next important element that appears to promote the growth of geothermal industry. Local demand, financial attractiveness, insurance schemes and other elements are likely to encourage its further expansion. In fact, in all four performance outliers such financial support frameworks exist, and their governments are interested in investing in geothermal energy. In Hungary, for example, the guaranteed feed-in-tariff existed since 2003 and a new de-risking scheme for deep geothermal energy was introduced in 2021 (Georisk, 2021). Similar de-risking plans aimed at supporting geothermal projects by covering the exploration risks of the first drilled wells also exist in Iceland, the Netherlands and Türkiye. In addition, Iceland offers considerable tax incentives for geothermal energy companies, the Netherlands feed-in-premium for heat plant operators and Türkiye feed-in-tariffs and bonus payments for geothermal developers among others.

Other additional factors that might positively influence the relationship and promote the growth of geothermal energy include geothermal resource availability and its proven technical potential, access to geothermal resource data, national state-of-the-art research and the availability of industry institutions including the pool of trained professionals. High levels of public awareness and community support, as well as marketing and promotion strategies aimed at information dissemination

about geothermal resource and its potential benefits might also influence the rates of its adoption.

During this study the author came across potential limitations due to restrictions in chosen methodology; some limitations, such as limited access to good quality data, were evident before the start of the study. These limitations could have potentially influenced the research outcome; however, each was addressed with consideration. The researcher acknowledges the following limitations present in the study:

- *High reliance on secondary data, its availability, completeness, and quality.* As discussed in Krieger and Kurek (2023) the IGA data used in this study is not always collected in a systematic and verifiable manner. Although it still offers one of the most comprehensive datasets, the IGA data collection and reporting methods are inconsistent, which raises questions about its reliability. Due to the lack of other comprehensive datasets, the values reported by the IGA are by far considered the most authoritative in the geothermal industry. To address the reliance on imperfect data the IGA sub datasets were cross-analyzed and compared to each other. All evidence of bad data quality (discrepancies in values between sub datasets) were examined and removed from the research, so that only countries with highly reliable data were considered.
- *Sampling procedure.* Purposive sampling does not allow for the findings to be broadly generalized to other sectors because they are highly contextual. The researcher limits the results and conclusions to the research context only (i.e., to the greenhouse agriculture sector) however it may well be that these conclusions will also be valid in other situations. For the outcomes to be applied in broader contexts, additional research is required to see if the same relationship exists in other markets and countries, e.g., in electricity and district heating and cooling markets.
- *Sample size.* The sample of twelve case countries is small but representative of the intended population as it accounts for 43% of all countries valid for the data sampling in terms of data integrity and consistency.
- *Likert scale structure and its context.* Regarding Likert scale structure, some policies were included that should not have been listed as separate items: N1, Emissions Reduction Targets, is based on G2, Nationally

Determined Contributions, and does not have a separate document connected to it; N4, Emissions Trading System, and N5, Carbon Tax, are instruments to reach N1, Emissions Reduction Targets. Their inclusion might have skewed the expert responses. As for Likert scale context, the questions in the survey were formed in as clear, deliberate, and unambiguous way as possible. An external independent expert validated the question wordings before administering the survey to the experts. The questions were formulated to serve a specific research purpose.

- *Policy validation and measurement.* Only experts with extensive and adequate knowledge on the topic were asked to contribute to the survey. Based on the common expertise of judges only the most highly rated policies were chosen. However, most experts were representatives of Europe or European Union countries, which might have skewed the final policy scale.
- *Non-response bias.* To encourage adequate survey response rates a few email reminders were sent restating the purpose and the upcoming deadlines. Email invitation and reminders were specific and context relevant. The survey was respondent-friendly – as in, it was short, questions were simple, and easy to engage with. The survey was endorsed and distributed on behalf of the International Geothermal Association, which echoed the importance of the study to the experts.
- *Respondent bias.* To avoid biased and ambiguous answers, they were checked for accuracy and extreme response categories irrespective of content were identified and removed from the subsequent analysis.
- *Random error.* The researcher is aware of other unknown and uncontrollable external factors that might have randomly influenced the assessments of experts.
- *Moderating variables.* The researcher is aware of other possible alternative explanations for the relationship and acknowledges their existence throughout the study. Other moderating variables might include resource availability and its potential, access to geological data, national state-of-the-art research, the pool of trained professionals, existence of industry institutions, public awareness, marketing and promotion strategies, and available public and private funding among others.

7. Implications and Recommendations

This research is a multiple case study of twelve countries from 2010 to 2020. It explored the relationship and degree of correlation between policy incentives and adoption of geothermal energy in greenhouse agriculture and showed that these two aspects positively correlate. When comparing the policy suite (global, national, and local support), national policies are the most important. The countries with targeted policies directed at specific market promote a faster energy take off. To encourage geothermal energy development in a country, its government should integrate strong policies coupled with financial incentives and offer specific support to sectors it aims to elevate. The implications of these findings are two-fold.

For the geothermal industry, it suggests more calibrated approach towards lobbying for policy incentives. Despite the claims of some industry experts that a lack of local legislative framework impedes geothermal energy development, this research showed that this is not necessarily the case. Most case countries have comprehensive legal frameworks regulating ownership and/or status of geothermal resources but the adoption rates of geothermal energy are declining. Irrespective of their context and type, local policies do not correlate with the industry growth. Local level policies might be too dependent on a country-specific legal system or framework that are not directly comparable to each other.

It is also important to distinguish between different policy forms and levels of their functionality and understand that not all policies hold equal weight. Industry experts should stop criticizing generic “policy support” and blame governments for the “lack of policy initiatives”. More social research is required in geothermal industry to understand the influence of various factors on its development. Only upon extensive research should geothermal industry experts make recommendations to the policymakers and lobbying organizations. These recommendations should be precise and relevant to the context at hand.

For policymakers and advisers, this research provides evidence that global policies might be too generic and overarching to make any positive difference on geothermal energy adoption. National incentives are the most influential when it comes to the energy take off as they are more detailed and binding. As a policymaker, it is important to learn from the “best practice” examples – the countries that succeeded to develop geothermal energy at a fast and significant way. The lesson learned from such countries is that targeted policies directed at specific

sector tend to have the most influence and that financial incentives should complement a comprehensive policy framework.

One of the most important findings of this research is that geothermal industry lacks high quality, transparent and reliable statistics of its use. It is often the case that geothermal data (installed capacity and energy used) are reported in various and sometimes contradicting ways by industry association, government energy agencies and geothermal energy operators. This is due to the lack of clear reporting methods and guidelines, but also to lobbying and business interests of geothermal companies. The discrepancies in data contribute to a distorted image of the geothermal industry in international energy reports, as values are often under- or over-reported. It is thus recommended to create an independent digital database, which would rely on industry guidelines and report the values in a consistent, transparent, and reliable manner free of charge.

To further expand on results of this study, the following recommendations are made. To understand if the same outcomes as presented in this research hold valid in other contexts, an analysis with different market segments such as electricity, or district heating and cooling is suggested. To better understand other moderating variables influencing the adoption of geothermal energy in greenhouse agriculture, an analysis of financial incentives, as the likely most important element promoting the growth of geothermal industry, is advised. To explore how policies used in this research evolve and continue to relate to the geothermal market, a longitudinal study past 2020 is recommended. Finally, since three main factors define the successful and prompt adoption of geothermal energy in agri-food sector – strong government support on a national level, targeted policies for geothermal agri-food, and a competitive price when compared to other forms of energy – a deeper study is recommended to define the degree of their importance.

8. Ethical Considerations

This chapter acknowledges ethical considerations taken into account during this research particularly during participation from industry experts in the Likert scale panel. For the panel, voluntary participation of all parties involved was assured: all experts were aware that their participation was voluntary, and they had a right not to participate. Experts were not harmed in any way because of their non-participation. Complete privacy and confidentiality were preserved: to protect the

subject's interest and their participation was anonymous. No identification numbers or tags were used to track their identity. Response and private data were not given to any third parties. The Likert scale responses presented in a codebook in Appendix C cannot be identified with a certain respondent. An ethical obligation to provide some information about the study before its execution was fulfilled via the invitation email that stated the goals and purposes of the survey and the people involved in conducting it. In the analysis and reporting of findings, all unexpected and negative outcomes are fully disclosed.

Reference list

14222/1/20 REV 1 (2020) *Outcome of proceedings. Submission to the UNFCCC on behalf of the European Union and its Member States on the update of the nationally determined contribution of the European Union and its Member States.* Available at: <https://data.consilium.europa.eu/doc/document/ST-14222-2020-REV-1/en/pdf> (Accessed: 26 March 2023).

Advantage Austria, Austrian Federal Economic Chamber (2023) *Agriculture. Overview.* Available at: <https://www.advantageaustria.org/> (Accessed: 21 April 2023).

Aires-Barros, L. (1988) 'FAO-European cooperative networks on rural energy', *Geothermics*, 17(1), pp. 269-275. Doi: [https://doi.org/10.1016/0375-6505\(88\)90019-3](https://doi.org/10.1016/0375-6505(88)90019-3)

Allegrini, G., Cappetti, G. and Sbatelli, F. (1995) 'Geothermal development in Italy: country update report', *World Geothermal Congress 1995*. Florence, Italy, 18-31 May, pp. 201-208. Available at: <https://www.geothermal-library.org/> (Accessed: 25 February 2021).

Anderson, D. N. and Lund W. J. (eds) (1979) *Direct utilization of geothermal energy: a layman's guide*. Special report no. 8. Klamath Falls: Geothermal Resource Council and Geo-Heat Utilization Centre, Oregon Institute of Technology.

Andritsos, N., Arvanitis, A., Papachristou, M., Fytikas, M. and Dalambakis, P. (2010) 'Geothermal activities in Greece during 2005-2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-10. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 25 September 2022).

Andritsos, N., Dalambakis, P., Arvanitis, A., Papachristou, M. and Fytikas, M. (2015) 'Geothermal developments in Greece – country update 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-11. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 25 September 2022).

Arrizabalaga, I., De Gregorio, M., de la Noceda Celestino, G., Hidalgo, R. and Urchueguía, J. F. (2015) 'Country update for the Spanish geothermal sector', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-9. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 December 2022).

Bakema, G. Provoost, M. and Schoof, F. (2020) 'Netherlands country update', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-15. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 October 2022).

Balan, L.-L. and Nador, A. (2018) *Regulatory framework in DARLINGe partner countries*. Interreg Danube Transitional Program DARLINGe D.5.5.1. Available at: <https://www.interreg-danube.eu/> (Accessed: 31 March 2023).

Barbier, E. and Fanelli, M. (1977) 'Non-electrical uses of geothermal energy', *Progress in Energy and Combustion Science*, (3)2, pp. 73-103. Doi: [https://doi.org/10.1016/0360-1285\(77\)90009-0](https://doi.org/10.1016/0360-1285(77)90009-0)

Bargiacchi, E., Conti, P., Manzella, A., Vaccaro, M., Cerutti, P. and Cesari, G. (2020) 'Thermal uses of geothermal energy, country update for Italy', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-15. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 27 September 2022).

BGBI. Nr. 215/1959 (1959) *Wasserrechtsgesetz 1959* [Water Rights Act 1959]. Available at: <https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=10010290> (Accessed: 11 September 2022).

Bhattacharjee, A. (2012) *Social science research: principles, methods, and practices*. 2nd edn. Tampa: University of South Florida.

Björnsson, S. (ed.) (2010) *Geothermal development and research in Iceland*. Reykjavik: Orkustofnun.

Block, I. (2019) 'Hungary plans €1 billion greenhouse city powered by renewable energy', *Dezeen*, 31 May. Available at: <https://www.dezeen.com/2019/05/31/hungary-greenhouse-city-renewable-energy/> (Accessed: 25 September 2022).

Bloomquist, R. G. (1991) 'Regulatory and commercial aspects', in Lienau, P. J. and Lunis, B. C. (eds.) *Geothermal direct use engineering and design guidebook*. Klamath Falls: Geo-Heat Center, pp. 305-435.

Bloomquist, R. G. (2003) 'United States geothermal policy – provision of access and encouraging project development', *International Geothermal Conference 2003 "Multiple integrated uses of geothermal resources"*. Reykjavik, Iceland, 14-17 September, pp. 53-65. Available at: <https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2003-01-05.pdf> (Accessed: 13 September 2021).

Bloomquist, R. G. (2010) 'Policy implementation to enable accelerated geothermal development', *ARGEО-C3, Third East African Rift Geothermal Conference*. Djibouti, 22-25 November 2010, pp. 545-548. Available at: <https://theargeo.org/fullpapers/papers3.html> (Accessed: 5 January 2021).

BOE-A-1973-1018 (1973) Law 22/1973, of July 21, 1973, on Mines. Available at: <https://www.boe.es/buscar/pdf/1973/BOE-A-1973-1018-consolidado.pdf> (Accessed: 8 December 2022).

Bouma, G. D. and Atkinson, G. B. J. (1995) *A handbook of social science research. A comprehensive and practical guide for students*. 2nd edn. New York: Oxford University Press.

Boyd, T. L., Sifford, A. and Lund, J. W. (2015) 'The United States of America country update 2015', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-12. Available at:

<https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 January 2023).

Breembroek, G., Dijkshoorn, L. and Ramsak, P. (2013) *Geothermal energy status and policy review. Part A analysis*. Available at: <http://www.geothermaleranet.is/> (Accessed: 9 May 2021).

Bundesverband Geothermie (2022) *Geothermie liefert die Wärme für Biogemüse* [Geothermal energy provides heat for organic vegetables]. Available at: <https://www.geothermie.de/aktuelles/nachrichten/news-anzeigen/news/geothermie-liefert-die-waerme-fuer-biogemuese.html> (Accessed: 17 September 2022).

Buonasorte, G., Rizzi, F. and Passaleva, G. (2010) 'Direct uses of geothermal energy in Italy 2005-2009: update report and perspectives', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-5. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 27 September 2022).

Business Iceland (2023) *The greenhouse revolution in Iceland*. Available at: <https://www.visiticeland.com/article/the-greenhouse-revolution-in-iceland> (Accessed: 29 April 2023).

Campiotti, C. A. (2002) 'Geothermal energy as sustainable energy resource in agriculture', *International Summer School on Direct Application of Geothermal Energy*. January 2002, pp. 180-185. Available at: https://pangea.stanford.edu/ERE/db/IGAstandard/record_detail.php?id=5356 (Accessed: 12 February 2021).

Canadian Geothermal Energy Association (2014) *Direct utilization of geothermal energy: suitable application and opportunities for Canada*. Available at: https://www.cangea.ca/store/p7/Direct_Utilization_of_Geothermal_Energy_2014.html (Accessed: 20 May 2020).

Cappetti, G., Passaleva, G. and Sabatelli, F. (2000) 'Italy country update report 1995-1999', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-8. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 27 September 2022).

Cappetti, G., Romagnoli, P. and Sabatelli, F. (2010) 'Geothermal power generation in Italy 2005-2009 update report', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-10. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 27 September 2022).

Carella, R. and Sommaruga, C. (2000) 'Geothermal space and agribusiness heating in Italy', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 117-122. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 27 September 2022).

Cariaga, C. (2022) *Edamame beans being grown using geothermal heat in Hachimantai, Japan*, 6 October. Available at: <https://www.thinkgeoenergy.com/edamame-beans-being-grown-using-geothermal-heat-in-hachimantai-japan/> (Accessed: 17 January 2022).

Center for Climate and Energy Solutions (no date) *Carbon tax basics*. Available at: <https://www.c2es.org/content/carbon-tax-basics/> (Accessed: 10 September 2021).

ClimateChangePost (2023) *Agriculture and horticulture Iceland*. Available at: <https://www.climatechangepost.com/iceland/agriculture-and-horticulture/> (Accessed: 23 April 2023).

Conti, P., Grassi, W., Passaleva, G. and Cataldi, R. (2015) 'Geothermal direct uses in Italy: country update for WGC2015', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-10. Available at: <https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2003-01-05.pdf> (Accessed 27 September 2022).

Dentons (2019) *Italy: the 2019-2020 incentives regime for renewable energy plants*. Available at: <https://www.dentons.com/en/insights/alerts/2020/december/17/fer1-decree-2019-2020-incentives-regime-for-renewable-energy-plants> (Accessed: 27 September 2022).

Dickson, M. H. and Fanelli, M. (1996) 'Non-electric uses of geothermal energy in Italy', 18th *New Zealand Geothermal Workshop*. Auckland, New Zealand, January 1996, pp. 5-10. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 27 September 2022).

Dickson, M. H. and Fanelli, M. (2003) 'Geothermal background' in Dickson, M. H and Fanelli, M. (eds.) *Geothermal energy. Utilization and technology*. Paris: UNESCO, pp. 1-27.

Dumas, P., Serdjuk, M., Kutschick, R., Fraser, S., Reith, S. and Koelbel, T. (2013) *Report presenting proposals for improving the regulatory framework for geothermal electricity*. Geolec deliverable 4.1. Available at: <http://www.geoelec.eu/> (Accessed: 17 September 2021).

Edwards greenhouse and flowershop (2023) *Our story*. Available at: <https://www.edwardsgreenhouse.com/our-story> (Accessed: 22 January 2023).

Ehret-Berzi, I. and Nemeth, S. (2014) 'Geothermal energy utilization in the greenhouse vegetable sector in Hungary', in Dorais, M. and Bishop, S. D. (eds) *Proceedings Ist IS on organic greenhouse agriculture*. Belgium: Acta Horticulturae, pp. 275-280.

Energias Renovables (2020) 'Minas de Asturias ayer... invernaderos subterráneos, almacenes de medicamentos y centrales de producción de geotermia mañana' [Asturias mines yesterday... subway greenhouses, medicine warehouses and geothermal production plants tomorrow.], *Energias Renovables*, 24 August. Available at: <https://www.energias-renovables.com/panorama/minas-de-asturias-a---invernaderos-subterraneos-20200824> (Accessed: 8 December 2022).

Enterprise Greece, Ministry of Foreign Affairs (2022) *Greek quality food and agriculture products*. Available at: <https://www.enterprisegreece.gov.gr/en/invest-in-greece/sectors-for-growth/food-agriculture> (Accessed: 21 April 2023).

European Geothermal Energy Council (2006a) *Key issues for renewable heat in Europe (K4RES-H). Key issue 5: innovative applications. Geothermal utilization for industrial processes*. Brussels: EGEC.

European Geothermal Energy Council (2006b) *Key issues for renewable heat in Europe (K4RES-H). Key issue 3: regulations for geothermal energy*. Brussels: EGEC.

European Geothermal Energy Council (2007) *Key issues for renewable heat in Europe (K4RES-H). Geothermal heating and cooling action plan for Europe*. Brussels: EGEC.

European Geothermal Energy Council (2017) *First greenhouse for algae cultivation heated by geothermal plant launches today*. Available at: <https://www.egec.org/first-greenhouse-algae-cultivation-heated-geothermal-plant-launches-today/> (Accessed: 27 September 2022).

European Geothermal Energy Council (2022) *Find out Europe's five most innovative geothermal projects of 2021*. Available at: <https://www.egec.org/find-out-europes-five-most-innovative-geothermal-projects-of-2021/> (Accessed: 24 August 2022).

European Geothermal Energy Council, Bureau De Recherches Géologiques et Minières, Centre For Renewable Energy Sources and Saving, Consiglio Nazionale Delle Ricerche, Istituto Di Geoscienze e Georisorse, Asociacion De Productores De Energias Renovables (APPA – ES), Gaßner, 111rowth, Siederer & Coll., EnBW Energie Baden-Württemberg, Helmholtz Zentrum Postdam – Deutsches Geoforschungszentrum, Nederlandse Organisatie Voor Toegepast Natuurwetenschappelijk Onderzoek (2013) *Towards more electricity generation in Europe*. Geolec report. Available at: <http://www.geolec.eu/> (Accessed: 17 September 2021).

European Geothermal Energy Council, Universidad Politécnica de Valencia, Romanian Geoexchange Society, Bureau Recherches Géologiques Minières, UbeG GbR of Wetzlar, Germany, Centre for Renewable Energy Sources and Saving, SP Technical Research Institute of Sweden, Nationale Geologiske Undersøgelser for Danmark og Grønland, SLR Consulting, IF Technology, Scuola Superiore di Studi Universitari e di Perfezionamento Sant'Anna, Service Public de Wallonie (2015) *Developing geothermal heat pumps in smart cities and communities*. Regeocities report. Available at: <https://www.egec.org/media-publications/developing-geothermal-heat-pumps-smart-cities-communities/> (Accessed: 9 May 2021).

European Renewable Energy Council (2007a) *Key issues for renewable heat in Europe (K4RES-H). Renewable heating action plan for Europe*. Brussels: European Renewable Energy Council.

European Renewable Energy Council (2007b) *Key issues for renewable heat in Europe (K4RES-H). Action plan for renewable heating and cooling*. Brussels: European Renewable Energy Council.

European Commission (2012) *RES LEGAL Europe*. Available at: <http://www.res-legal.eu/> (Accessed: 26 January 2022).

European Commission (2022a) *Heating and cooling*. Available at: https://ec.europa.eu/energy/topics/energy-efficiency/heating-and-cooling_en?redir=1 (Accessed: 3 July 2022).

European Commission (2022b) *EU science hub. Raw materials information system (RMIS)*. Available at: <https://rmis.jrc.ec.europa.eu/> (Accessed: 26 January 2022).

European Commission (2022c) *The Commission approves the CAP strategic plan for Hungary*. Available at: https://agriculture.ec.europa.eu/news/commission-approves-cap-strategic-plan-hungary-2022-11-07_en (Accessed: 23 April 2023).

European Commission (2022d) *The Commission approves the CAP strategic plan of the Netherlands*. Available at: https://agriculture.ec.europa.eu/news/commission-approves-cap-strategic-plan-netherlands-2022-12-13_en (Accessed: 23 April 2023).

European Commission (no date) *CAP strategic plans*. Available at: https://agriculture.ec.europa.eu/cap-my-country/cap-strategic-plans_en (Accessed: 23 April 2023).

Eurostat Statistics Explained (2020) *Glossary: full-time equivalent (FTE)*. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Thematic_glossaries (Accessed: 2 June 2023).

Executive Office of the President (2013) *The President's climate action plan*. Available at: <https://obamawhitehouse.archives.gov/sites/default/files/image/president27sclimateactionplan.pdf> (Accessed: 20 January 2023).

FCCC/CP/2015/10/Add.1 (2015) *Paris agreement*. Available at: <https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf> (Accessed: 5 June 2020).

Federal Ministry of Agriculture, Forestry, Regions and Water Management (2022) *Facts and figures 2022*. Available at: <https://info.bml.gv.at/service/publikationen/allgemeine-themen/facts-and-figures-2022.html> (Accessed: 1 April 2023).

Federal Ministry of Agriculture, Forestry, Regions and Water Management (no date) *Water Rights Act 1959 (WRG 1959)*. Available at: <https://info.bml.gv.at/en/topics/water/water-in-austria/water-law/water-law-1959-wrg1959.html> (Accessed: 11 September 2022).

Fell, H.-J. (2018) *Policy framework to achieve 100% renewable energy*. Berlin: Energy Watch Group.

Fenoy, C. (2015) 'El agro recobrará competitividad en fechas clave con la geotermia' [Geothermal energy to help agriculture regain competitiveness at key dates], *Diario de Almería*, 8 June. Available at: https://www.diariodealmeria.es/almeria/recobrara-competitividad-fechas-clave-geotermia_0_923907850.html (Accessed: 8 December 2022).

Fisher, L. A., Back, A. R. and Fogleman, S. F. (1978) 'Total energy recovery system for agribusiness: Lake County study', *Geothermal Resources Council 1978 Annual Meeting*. Hilo, USA, 25-27 July, pp. 193-194. Available at: <https://www.geothermal-library.org/> (Accessed: 25 February 2021).

Fondazione Edison and Confagricoltura (2020) *Italy's strengths in agriculture: a leading producer of vegetable products in Europe and the world. 2020-2021 edition*. Available at:

<https://www.fondazioneedison.it/it/news/italys-strengths-in-agriculture/LibrettoAgricoltura.pdf>

(Accessed: 21 April 2023).

Food and Agriculture Organization (2011) *Energy-smart food for people and climate*. Available at: <https://www.fao.org/family-farming/detail/en/c/285125/> (Accessed: 5 June 2020).

Food and Agriculture Organization (2022) *FAOLEX database*. Available at: <https://www.fao.org/faolex/country-profiles/en/> (Accessed: 5 June 2020).

Food and Agriculture Organization (2023) *Kenya at a glance*. Available at: <https://www.fao.org/kenya/fao-in-kenya/kenya-at-a-glance/en/> (Accessed: 25 April 2023).

Frutur (no date) *Climate-friendly Blumau vegetables*. Available at: <https://frutura.com/en/about-us/freshness-edge/thermal-gemuesewelt/> (Accessed: 1 April 2022).

Gehring M. and Loksha V. (2012) *Geothermal handbook: planning and financing power generation*. ESMAP technical report 002/12. Washington, DC: World Bank.

General Secretariat of the Government of Greece (2018) *Voluntary national review on the implementation of the 2030 agenda for sustainable development*. Available at: <https://hlpf.un.org/vnrs> (Accessed: 22 September 2022).

Georisk (2021) *Hungary becomes the 7th country in Europe to introduce a de-risking scheme for deep geothermal projects*. Available at: <https://www.georisk-project.eu/hungarian-risk-mitigation-scheme-available/> (Accessed: 28 May 2023).

German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (2021) *Climate action in figures. Facts, trends and incentives for German climate policy*. Berlin: Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection.

Glassley, W. E. (2015) *Geothermal energy. Renewable energy and the environment*. 2nd edn. Boca Raton: CRC Press.

Goedde, L. (2016) *Empowering Japanese agriculture for global impact*. Available at: <https://www.mckinsey.com/~media/mckinsey/featured%20insights/asia%20pacific/strengthening%20japanese%20agriculture%20to%20maximize%20global%20reach/empowering-japanese-agriculture-full-report.ashx> (Accessed: 24 April 2023).

Goldbrunner, J. (2005) 'State, possible future developments in and barriers to the exploration and exploitation of geothermal energy in Austria – country update', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-11. Available at: <https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2003-01-05.pdf> (Accessed: 1 April 2022).

Goldbrunner, J. (2010) 'Austria – country update', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-16. Available at: <https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2003-01-05.pdf> (Accessed: 1 January 2023).

Goldbrunner, J. (2015) ‘Austria – country update’, *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-13. Available at: <https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2003-01-05.pdf> (Accessed: 1 January 2023).

Goldbrunner, J. (2020) ‘Austria – country update’, *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-17. Available at: <https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2003-01-05.pdf> (Accessed: 1 January 2023).

Goldbrunner, J. and Goetzl, G. (2016) ‘Geothermal energy use, country update for Austria’, *European Geothermal Congress 2016*. Strasbourg, France, 19-24 September, p. 1-11. Available at: <http://europeangeothermalcongress.eu/wp-content/uploads/2018/10/proceedings.pdf> (Accessed: 1 April 2022).

Government Gazette, Series I, No 277 (1973) *Legislative Decree 210/1973 [The Mining Code]*. Available at: https://rmis.jrc.ec.europa.eu/uploads/legislation/MiningDecree_Greece_ENGLISH.pdf (Accessed: 25 September 2022).

Government of Greece (1984) *Law 1475/84 on exploitation of the geothermal potential*. Available at: <https://www.lexadin.nl/wlg/legis/nofr/eur/lxwegri.htm> (Accessed: 25 September 2022).

Government of Hungary (1993) *Act XLVIII of 1993 on Mining*. Available at: <https://www.fao.org/faolex/country-profiles/en/> (Accessed: 25 September 2022).

Government of Hungary (1995) *Act LVII of 1995 on Water Management*. Available at: <https://www.fao.org/faolex/country-profiles/en/> (Accessed: 25 September 2022).

Government of Iceland (1998) *Act on Survey and Utilization of Ground Resources 1998 No 57 of 19 June* [Natural Resource Act]. Available at: https://www.stjornarradid.is/media/atvinnuvegaraduneyti-media/media/acrobat/log_57_1998_ens_020107.pdf (Accessed: 17 December 2022).

Government of Iceland (2011) *Master Plan Act No 48/2011*. Available at: <https://www.ramma.is/english/general-information/laws-and-regulations/the-master-plan-act/> (Accessed: 16 December 2022).

Government of Iceland (no date) *Iceland’s intended nationally determined contributions*. Available at: <https://unfccc.int/NDCREG> (Accessed: 16 December 2022).

Government of Iceland Prime Minister’s Office (2010) *Iceland’s implementation of the 2030 agenda for sustainable development. Voluntary national review*. Available at: <https://hlpf.un.org/vnrs> (Accessed: 16 December 2022).

Government of Italy (1942) *Civil Code 1942*. Available at: <https://leap.unep.org/countries/it/national-legislation/civil-code> (Accessed: 30 September 2022).

Government of Italy Presidency of the Council of Ministers (2010) *Legislative Decree No. 22 of February 11, 2010, on reorganization of regulations on research and cultivation of geothermal resources*. Available at: <https://www.normattiva.it/uri-res/N2Ls?urn:nir:stato:decreto.legislativo:2010-02-11;22~art1-com3bis> (Accessed: 30 September 2022).

Government of Japan (1896) *Civil Code Act No. 89 of 1896*. Available at: <https://www.fao.org/faolex/results/details/en/c/LEX-FAOC210722> (Accessed: 17 December 2022).

Government of Japan (1950) *Act No. 289 of December 20, 1950 [Mining Act]*. Available at: <https://faolex.fao.org/docs/pdf/jap40744.pdf> (Accessed: 17 December 2022).

Government of Japan (1956) *Industrial Water Law No. 146 of 1956*. Available at: <https://www.fao.org/faolex/results/details/en/c/LEX-FAOC020668> (Accessed: 17 December 2022).

Government of Japan (1961) *Water Resources Development Promotion Law No. 217 of 1961*. Available at: <https://www.fao.org/faolex/results/details/en/c/LEX-FAOC002485> (Accessed: 17 December 2022).

Government of Japan (2014) *Fourth strategic energy plan*. Available at: https://www.enecho.meti.go.jp/en/category/others/basic_plan/ (Accessed: 17 December 2022).

Government of Japan (2014) *Water Cycle Basic Act No. 16 of 2014*. Available at: <https://www.fao.org/faolex/results/details/en/c/LEX-FAOC178769> (Accessed: 17 December 2022).

Government of Japan (2016) *Submissions of Japan's intended nationally determined contribution (INDC)*. Available at: <https://unfccc.int/NDCREG> (Accessed: 27 January 2023).

Government of Japan (2018) *Fifth strategic energy plan*. Available at: https://www.enecho.meti.go.jp/en/category/others/basic_plan/ (Accessed: 17 December 2022).

Government of Kenya (1982) *Geothermal Resources Act 1982*. Available at: <https://www.ecolex.org/details/legislation/geothermal-resources-act-cap-314a-lex-faoc101440/> (Accessed: 9 December 2022).

Government of Kenya (2010) *Constitution of Kenya*. Available at: <http://kenyalaw.org/kl/index.php?id=398> (Accessed: 8 December 2022).

Government of Kenya (2010) *National climate change response strategy*. Available at: https://cdkn.org/sites/default/files/files/National-Climate-Change-Response-Strategy_April-2010.pdf (Accessed: 8 December 2022).

Government of Kenya (2013) *National climate change action plan 2013-2017*. Available at: <https://cdkn.org/sites/default/files/files/Kenya-National-Climate-Change-Action-Plan.pdf> (Accessed: 8 December 2022).

Government of the Netherlands (2003) *Mijnbouwwet [Mining Act]*. Available at: <https://www.nlog.nl/en/legislation> (Accessed: 8 October 2022).

Government of the Netherlands (2009) *Waterwet [Water Act]*. Available at: <https://www.nlog.nl/en/legislation> (Accessed at: 8 October 2022)

Government of the Netherlands (2010) *National action plan for energy from renewable sources Directive 2009/28/EC*. Available at: https://energy.ec.europa.eu/documents_en (Accessed: 8 October 2022).

Government of the Netherlands (no date-a) *Water management*. Available at: <https://www.helpdeskwater.nl/secundaire-navigatie/english/legislation/> (Accessed: 9 October 2022).

Government of the Netherlands (no date-b) *Agriculture and horticulture*. Available at: <https://www.government.nl/topics/agriculture/agriculture-and-horticulture> (Accessed at: 22 April 2023).

Government of the Netherlands (no date-c) *Revision of environmental and planning laws*. Available at: <https://www.government.nl/topics/spatial-planning-and-infrastructure/revision-of-environment-planning-laws> (Accessed: 9 October 2022).

Government of Spain (2018) *Spain's report for the 2018 voluntary national review*. Available at: <https://hlpf.un.org/vnrs> (Accessed: 9 December 2022).

Government of Türkiye (2016) *The report prepared on occasion of the 20th anniversary of the Beijing Declaration and Platform for Action (Turkey)*. Available at: <https://hlpf.un.org/vnrs> (Accessed: 25 December 2022).

Government of Türkiye (2019) *Turkey's sustainable development goals. 2nd VNR 2019 "Strong ground towards common goals"*. Available at: <https://hlpf.un.org/vnrs> (Accessed: 25 December 2022).

Government of the United States of America (1970) *Geothermal Steam Act of 1970*. Available at: https://www.fs.usda.gov/sites/default/files/media_wysiwyg/geothermal-steam-act-of-1970.pdf (Accessed: 20 January 2023).

Government of the United States of America (2016) *Nationally determined contributions*. Available at: <https://unfccc.int/NDCREG> (Accessed: 27 January 2023).

Governor's Office of Energy Resources (no date) *Idaho geothermal history. A detailed history*. Available at: https://oemr.idaho.gov/wp-content/uploads/idaho_geothermal_history.pdf (Accessed: 22 January 2023).

Greenreport (2020) 'Incentivi alla geotermia, Rossi: il Fer 2 uscirà «entro l'estate»' [Geothermal incentives, Rossi: Fer 2 will come out "by summer"], *Greenreport*, 4 June. Available at: <https://greenreport.it/news/economia-ecologica/incentivi-alla-geotermia-rossi-il-fer-2-uscira-entro-lestate/> (Accessed: 30 September 2022).

Heeter, J., Speer, B. and Glick, M. B. (2019) *International best practices for implementing and designing renewable portfolio standard (RPS) policies*. Available at: <https://www.nrel.gov/docs/fy19osti/72798.pdf> (Accessed: 8 September 2021).

Hijriawan, M., Pambudi, N. A., Biddinika, M. K., Wijayanto, D. S., Kuncoro, I. W., Rudiyanto, B. and Wibowo, K. W. (2019) 'Organic Ranking Cycle (ORC) in geothermal power plants', *Journal of Physics: Conference Series*, 1402(4), pp. 1-6. Doi: <https://doi.org/10.1088/1742-6596/1402/4/044064>

Hsieh, H-F. and Shannon, S. E. (2005) 'Three approaches to qualitative content analysis', *Qualitative Health Research*, 15(9), pp. 1277-1288. Doi: <https://doi.org/10.1177/1049732305276687>

Hunt, T. M. (2001) *Five lectures on environmental effects of geothermal utilization*. Reports 2000, number 1. Available at: <https://raflhadan.is/bitstream/handle/10802/23370/UNU-GTP-2000-01.pdf> (Accessed: 9 June 2021).

Huttrer, G. W. (2020) ‘Geothermal power generation in the world 2015-2020 update report’, *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-17. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 3 December 2021).

Il Tirreno (2018) ‘Timori per la geotermia dopo l’esclusione 117ale “rinnovabili” [Fears for geothermal energy after exclusion from “renewables”], *Il Tirreno*, 5 November. Available at: https://www.iltirreno.it/piombino/cronaca/2018/11/05/news/timori-per-la-geotermia-dopo-l-esclusione-dalle-rinnovabili-1.17431620?refresh_ce (Accessed: 27 September 2022).

Intergovernmental Panel on Climate Change (2011) *Special report on renewable energy sources and climate change mitigation. Summary for policymakers and technical summary. Special report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (2021) *Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. Summary for policy makers*. Available at: <https://www.ipcc.ch/report/ar6/wg1/downloads/> (Accessed: 5 March 2022).

International Energy Agency (2011) *Technology roadmap. Geothermal heat and power*. Available at: <https://www.iea.org/reports/technology-roadmap-geothermal-heat-and-power> (Accessed: 31 June 2021).

International Energy Agency (2019) *Renewables 2019. Analysis and forecast to 2024*. Available at: <https://www.iea.org/reports/renewables-2019> (Accessed: 15 July 2020).

International Energy Agency (2020) *Renewables 2020. Analysis and forecast to 2025*. Available at: <https://www.iea.org/reports/renewables-2020> (Accessed: 20 April 2021).

International Energy Agency (2022) *Policies database*. Available at: <https://www.iea.org/policies/about> (Accessed: 26 January 2022).

International Fund for Agricultural Development (no date) *Kenya*. Available at: <https://www.ifad.org/en/web/operations/w/country/kenya> (Accessed: 25 April 2023).

International Renewable Energy Agency (2018) *Unlocking geothermal potential in Japan through small-scale generation*. Available at: <https://www.irena.org/news/articles/2009/Apr/Unlocking-geothermal-potential-in-Japan-through-small-scale-generation> (Accessed: 17 December 2022).

International Renewable Energy Agency (2019a) *Addressing food security and boosting development with geothermal heat*. Available at: <https://www.irena.org/newsroom/articles/2019/Apr/Addressing-Food-Security-and-Boosting-Development-with-Geothermal-Heat> (Accessed: 8 March 2020).

International Renewable Energy Agency (2019b) *Accelerating geothermal heat adoption in the agri-food sector: key lessons and recommendations*. Available at:

<https://www.irena.org/publications/2019/Jan/Accelerating-geothermal-heat-adoption-in-the-agri-food-sector> (Accessed: 7 March 2020).

International Renewable Energy Agency (2019c) *NDCs in 2020: advancing renewables in the power sector and beyond*. Available at: <https://www.irena.org/publications> (Accessed: 4 September 2021).

International Renewable Energy Agency (2020a) *Heating and cooling*. Available at: <https://www.irena.org/heatingcooling> (Accessed: 7 March 2020).

International Renewable Energy Agency (2020b) *Global renewables outlook: energy transformation 2050*. Available from: <https://www.irena.org/publications> (Accessed: 9 May 2021).

International Renewable Energy Agency (2022) *Powering agri-food value chains with geothermal heat: a guidebook for policy makers*. Available at: <https://www.irena.org/publications/2022/Jun/Powering-Agri-food-Value-Chains-with-Geothermal-Heat> (Accessed: 22 August 2022).

International Renewable Energy Agency, International Energy Agency and REN21 (2018) *Renewable energy policies in a time of transition*. Available at: <https://www.irena.org/publications/2018/apr/renewable-energy-policies-in-a-time-of-transition> (Accessed: 30 July 2020).

Italian Ministry for Economic Development (2010) *Italian national renewable energy action plan (in line with the provisions of Directive 2009/28/EC and Commission Decision of 30 June 2009)*. Available at: https://energy.ec.europa.eu/documents_en (Accessed: 27 September 2022).

Italian Ministry for the Environment, Land and Sea (2017) *Voluntary national review. Italy national sustainable development strategy*. Available at: <https://hlpf.un.org/vnrs> (Accessed: 27 September 2022).

Jimenez Navarro, J. P., Cejudo Lopez, J. M. and Connolly, D. (2017) 'The effect of feed-in-tariff supporting schemes on the viability of a district heating and cooling production system', *Energy*, 134(2017), pp. 438-448. Doi: <https://doi.org/10.1016/j.energy.2017.05.174>

Jones, A. (2023) Email exchange, 3 May.

Justia US Law (1980) 'Pariani vs. State of California'. *Court of Appeals of California, First Appellate District, Division Two, Civ. No. 47185*. Available at: <https://law.justia.com/cases/california/court-of-appeal/3d/105/923.html> (Accessed: 20 January 2023).

Kagel, A., Bates, D. and Gawell, K. (2005) *A guide to geothermal energy and the environment*. Available at: <https://www.osti.gov/servlets/purl/897425> (Accessed: 5 September 2022).

Karner, A., Koller, S.-C., Kettner, C., Kletzan-Slamanig, D., Köppl, A., Leopold, A., Lang, R., Nakicenovic, N., Reinsberger, N., Resch, G., Schleicher, S., Schnitzer, H. and Steininger, K. (2010) *National renewable energy action plan 2010 for Austria (NREAP-AT) under Directive 2009/28/EC of the European Parliament and of the Council*. Available at: https://energy.ec.europa.eu/documents_en (Accessed: 10 April 2022).

Kas als Energiebron (2022) *Greenhouse as a source of energy*. Available at: <https://www.kasalsenergiebron.nl/en/> (Accessed: 8 October 2022).

Kenya vision 20230 (no date) Available at: <https://vision2030.go.ke/> (Accessed: 8 December 2022).

Kinney, C., Dehghani-Sanij, A., Mahbaz, S. B., Dusseault, M. B., Nathwani, J. S. and Fraser, R. A. (2019) 'Geothermal energy for sustainable food production in Canada's remote northern communities', *Energies*, 12(21), pp. 1-25. Doi: <https://doi.org/10.3390/en12214058>

Krieger, M. (2018) *Geothermal energy use and risk assessment*. Master thesis. Ruhr University Bochum.

Krieger, M. and Kurek, K. A. (2023) *Geothermal industry statistics: a revised model for data collection and reporting*. The Hague: International Geothermal Association, World Geothermal Congress 2023. Unpublished.

Krieger, M., Kurek, K. A. and Brommer, M. (2022) 'Global geothermal industry data collection: a systematic review', *Geothermics*, 104(2022), pp. 1-13. Doi: <https://doi.org/10.1016/j.geothermics.2022.102457>

La Moncloa, Government of Spain and the Council of Ministers (no date) *Agriculture*. Available at: <https://www.lamoncloa.gob.es> (Accessed: 22 April 2023).

Latvian Presidency of the Council of the European Union (2015) *Submission by Latvia and the European Commission on behalf of the European Union and its member states. Intended nationally determined contribution of the eu and its member states*. Available at: <https://unfccc.int/NDCREG> (Accessed: 10 April 2022).

Lienau P. J. and Lunis, B. C. (1991) *Geothermal direct use engineering and design guidebook*. 2nd edn. Klamath Falls: Geo-Heat Centre.

Limberger, J., Boxem, T., Pluymaekers, M., Bruhn, D., Manzella, A., Calcagno, P., Beekman, F., Cloetingh, S. and van Weesa, J.-D. (2018) 'Geothermal energy in deep aquifers: a global assessment of the resource base for direct heat utilization', *Renewable and Sustainable Energy Reviews*, 82(1), pp. 961-975. Doi: <https://doi.org/10.1016/j.rser.2017.09.084>

London School of Economics and Political Science (2022) *Grantham research institute on climate change and the environment*. Available at: <https://www.lse.ac.uk/granthaminstitute/> (Accessed: 26 January 2022).

Lund, J. W. and Freeston, D. H. (2000) 'World-wide direct uses of geothermal energy 2000', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-21. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 19 March 2020).

Lund, J. W. and Boyd, T. L. (2015) 'Direct utilization of geothermal energy 2015 worldwide review', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-31. Available at:

<https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 19 March 2020).

Lund, J. W. and Toth, A. (2020) 'Direct utilization of geothermal energy 2020 worldwide review', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-39. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 19 March 2020).

Lund, J. W., Freeston, D. H. and Boyd, T. L. (2005) 'Worldwide direct uses of geothermal energy 2005', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-20. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 19 March 2020).

Lund, J. W., Freeston, D. H. and Boyd, T. L. (2010) 'Direct utilization of geothermal energy 2010 worldwide review', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-23. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 19 March 2020).

Lund, J. W., Bloomquist, R. G., Boyd, T. L. and Renner, J. (2005) 'The United States America country update', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-19. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 January 2023).

Lund, J. W., Gawell, K., Boyd, T. L. and Jennejohn, D. (2010) 'The United States of America country update 2010', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-18. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 January 2023).

Lund, J. W., Sifford, A., Hamm, S. G. and Anderson, A. (2020) 'The United States of America direct utilization update 2019', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-16. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 January 2023).

Manzella, A. and Krieger, M. (2022) *Geothermal heating & cooling data. Data collection. Update for the World Geothermal Congress*. Available at: <https://www.lovegeothermal.org/portfolio-item/geothermal-data-standards/> (Accessed: 21 March 2022).

Manzella, A., Serra, D., Cesari, G., Bargiacchi, E., Cei, M., Cerutti, P., Conti, P., Giudetti, G., Lupi, M. and Vaccaro, M. (2019) 'Geothermal energy use, country update for Italy', *European Geothermal Congress*. The Hague, the Netherlands, 11-14 June, pp. 1-19. Available at: <http://europeangeothermalcongress.eu/wp-content/uploads/2018/10/proceedings.pdf> (Accessed: 30 September 2022).

Martinovic, M. and Milivojevic, M. (2010) 'Serbia country update', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-11. Available at:

<https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 December 2022).

Mathews, S. (2018) *Interpreting regression output – without all the statistics theory*. Available at: <https://www.graduatetutor.com/statistics-tutor/interpreting-regression-output/> (Accessed: 27 May 2023).

McElreath, R. (2020) *Statistical rethinking: a Bayesian course with examples in R and STAN*. Boca Raton: CRC Press. 2nd edn.

McNamara, J. J. and Kaufman, E. L. (1979) *Hot dry rock geothermal resource ownership and the law*. Los Alamos: Los Alamos Scientific Laboratory, University of California.

Mertoglu, O. Simsek, S. and Basarir, N. (2015) ‘Geothermal country update report of Turkey (2010-2015)’, *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-9. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 28 December 2020).

Mertoglu, O., Simsek, S. and Basarir, N. (2020) ‘Geothermal energy use: projections and country update for Turkey’, *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-11. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 25 December 2022).

Mertoglu, O., Simsek, S., Dagistan, H., Bakir, N. and Dogdu, N. (2010) ‘Geothermal country update report of Turkey (2005-2010)’, *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-9. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 28 December 2022).

Ministère de la Transition Énergétique (2023) *Géothermie: un plan d’action pour accélérer*. Available at: https://www.ecologie.gouv.fr/sites/default/files/02.02.2023_DP_Geothermie.pdf (Accessed: 31 March 2023).

Ministry of Agriculture, Nature and Food Quality (2022) *Hungary: €12.95 billion in agriculture subsidies until 2027*. Available at: <https://www.agroberichtenbuitenland.nl/actueel/nieuws/2022/12/02/hungary-%E2%82%AC12.95-billion-in-agriculture-subsidies-until-2027> (Accessed at: 21 April 2023).

Ministry of Environment and Forestry (2018) *National climate change action plan (NCCAP) 2018-2022*. Available at: <https://climate-laws.org/geographies/kenya/policies/national-climate-change-action-plan-2018-2022-nccap> (Accessed: 8 December 2022).

Ministry of Environment and Natural Resources (2015) *Kenya’s intended nationally determined contributions (INDC)*. Available at: <https://unfccc.int/NDCREG> (Accessed: 8 December 2022).

Ministry of Environment, Energy and Climate Change of Greece (2010) *National renewable energy action plan in the scope of directive 2009/28/EC*. Available at: https://energy.ec.europa.eu/documents_en (Accessed: 25 September 2022).

Ministry of Foreign Affairs and Trade of Hungary (2018) *Voluntary national review of Hungary on the sustainable development goals of the 2030 agenda. Transformation towards sustainable and resilient societies*. Available at: <https://hlpf.un.org/vnrs> (Accessed: 26 September 2022).

Ministry of Foreign Affairs of the Netherlands (2017) *Report on the implementation of the sustainable development goals*. Available at: <https://hlpf.un.org/vnrs> (Accessed: 8 October 2022).

Ministry of Industries and Innovation (2014) *The Icelandic national renewable energy action plan for the promotion of the use of energy from renewable sources in accordance with Directive 2009/28/EC and the Commission Decision of 30 June 2009 on a template for the national renewable energy action plans*. Available at: <https://www.climate-laws.org/geographies/iceland/policies/renewable-energy-action-plan> (Accessed: 16 December 2022).

Ministry of Industry, Trade and Tourism (2010) *Spain's national renewable energy action plan 2011-2020*. Available at: https://energy.ec.europa.eu/documents_en (Accessed: 8 December 2022).

Ministry of National Development of Hungary (2010) *Renewable energy. Republic of Hungary national renewable energy action plan 2010-2020*. Available at: https://energy.ec.europa.eu/documents_en (Accessed: 26 September 2022).

Moon, H. and Zarrouk, S. J. (2012) 'Efficiency of geothermal power plants: a worldwide review', *New Zealand Geothermal Workshop*. Auckland, New Zealand, 19-21 November 2012, pp. 1-13. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 5 June 2023).

Moriarty, P. and Honnery, D. (2009) 'Renewable energy in a warming world', *Energy Policy*, 16(4), pp. 119-145. Available at: https://www.researchgate.net/publication/235747534_Renewable_energy_in_a_warming_world (Accessed: 3 August 2020).

Mouchot, J., Vranjes, A., Genter, A. and Lazarevic, N. (2019) 'Geothermal energy development in Serbia: a French-Serbian collaborative project', *European Geothermal Congress 2019*. The Hague, the Netherlands, 11-14 June, pp. 1-5. Available at: <http://europeangeothermalcongress.eu/wp-content/uploads/2018/10/proceedings.pdf> (Accessed: 9 December 2022).

Müller, U., Eichberger, I., Rummen, J., Russel, S., Thonon, B. and Nordman, R. (2009) *ProHeatPump. Promotion of efficient heat pumps for heating. Final results and conclusions*. Deliverable 33. Available at: <https://ec.europa.eu/energy/intelligent/projects/en/projects/geofar> (Accessed: 1 September 2021).

Nador, A. (2014) *Danube region strategy energy. Danube region geothermal report*. Available at: <https://energy.danube-region.eu/> (Accessed: 25 September 2022).

Nador, A., Kujbus, A. and Toth, A. (2019) 'Geothermal energy use, country update for Hungary', *European Geothermal Congress 2019*. The Hague, the Netherlands, 11-14 June, pp. 1-11.

Available at: <http://europeangeothermalcongress.eu/wp-content/uploads/2019/07/CUR-13-Greece.pdf> (Accessed: 25 September 2022).

National Renewable Energy Laboratory (2011) *Policymakers' guidebook for electricity generation*. Available at: <https://www.nrel.gov/docs/fy11osti/49476.pdf> (Accessed: 15 June 2021).

New Zealand Geothermal Association (2023) *Geoheat strategy for Aotearoa NZ, 2017-2030*. Available at: <https://www.nzgeothermal.org.nz/geothermal-in-nz/geoheat/> (Accessed: 31 March 2023).

Nguyen, M. V., Arason, S., Gissurarson, M. and Pálsson, P. G. (2015) *Uses of geothermal energy in food and agriculture. Opportunities for developing countries*. Available at: <https://www.fao.org/3/a-i4233e.pdf> (Accessed: 10 June 2020).

Nikkei (2021) 'Geothermal power generation shortened to 8 years until decarbonization target Ministry of the Environment', *Nikkei*, 27 April. Available at: <https://www.nikkei.com/article/DGXZQOUA2711C0X20C21A4000000/> (Accessed: 17 December 2022).

OJ EU L 26 (2011) *Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment*. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32011L0092> (Accessed: 17 March 2022).

OJ EU L 140 (2009) *Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC*. Available at: <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009L0028> (3 March 2022).

OJ EU L 143 (2004) *Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage*. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32004L0035> (Accessed: 17 March 2022).

OJ EU L 182 (2009) *2009/548/EC Commission Decision of 30 June 2009 establishing a template for national renewable energy action plans under Directive 2009/28/EC of the European Parliament and of the Council*. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009D0548> (Accessed: 3 March 2022).

OJ EU L 197 (2001) *Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment*. Available at: <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32001L0042> (Accessed: 17 March 2022).

OJ EU L 206 (1992) *Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora*. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31992L0043> (Accessed: 7 March 2022).

OJ EU C 306 (2007) *Treaty of Lisbon amending the Treaty on European Union and the Treaty establishing the European Community* (2007/C 306/01). Available at: <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:C:2007:306:FULL:EN:PDF> (Accessed: 12 February 2021).

OJ EU L 327 (2000) *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy*. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32000L0060> (Accessed: 17 March 2022).

OJ EU L 328 (2018) *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG (Accessed: 3 June 2020).

OJ EU L 372 (2006) *Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration*. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32006L0118> (Accessed: 17 March 2022).

Omenda, P. and Simiyu, S. (2015) 'Country update for Kenya 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-11. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 December 2022).

Omenda, P., Mangi, P., Ofwona, C. and Mwangi, M. (2020) 'Country update report for Kenya 2015-2019', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-16. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 December 2022).

Organisation for Economic Co-operation and Development (no date) *Evaluation of agricultural policy reforms in Turkey*. Available at: <https://www.oecd.org/turkiye/evaluationofagriculturalpolicyreformsinturkey.htm> (Accessed: 29 April 2023).

Orkustofnun (no date) *Master plan*. Available at: <https://nea.is/geothermal/master-plan/> (Accessed: 19 December 2022).

Oudech, S. and Djokic, I. (2015) 'Geothermal energy use, country update for Serbia', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-10. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 December 2022).

Oudech, S. and Djokic, I. (2020) 'Geothermal energy use, country update for Serbia', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-11. Available at:

<https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 December 2022).

Panagiotou, C. (1996) *Geothermal greenhouse design*. Reports 1996, number 11. Available at: <https://rafhladan.is/handle/10802/23305> (Accessed: 7 March 2021).

Papachristou, M., Arvanitis, A., Mendrinou, D., Dalabakis, P., Karytsas, C. and Andritsos, N. (2019) 'Geothermal energy use, country update for Greece (2016-2019)' *European Geothermal Congress 2019*. The Hague, the Netherlands, 11-14 June, pp. 1-11. Available at: <http://europeangeothermalcongress.eu/wp-content/uploads/2019/07/CUR-13-Greece.pdf> (Accessed: 25 September 2022).

Papachristou, M., Dalampakis, P., Arvanitis, A., Mendrinou, D. and Andritsos, N. (2020) 'Geothermal developments in Greece – country update 2015-2020', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-14. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 25 September 2022).

Pardo Garcia, N., Vatopoulos, K., Krook-Riekkola, A., Perez Lopez, A. and Olsen, L. (2012) *Best available technologies for the heat and cooling market in the European Union*. Available at: <https://publications.jrc.ec.europa.eu/repository/handle/JRC72656> (Accessed: 2 December 2020).

Pasquali, R. (2013) *Best practice analysis report*. Regeocities deliverable D.3.1. Available at: <http://ubeg.de/> (Accessed: 15 September 2021).

Pasquali, R. and O'Neill, N. (2015) *Recommendation guidelines for a common European regulatory framework*. Regeocities deliverable D3.4. Available at: <http://ubeg.de/> (Accessed: 15 September 2021).

Pasquali, R., Goodman, R., Bujakowski, W., Kepinska, B., Pajak, L., Holojuch, G., Pussak, M., Tomaszewska, B., Hámor, T., Earls, G. and Reay, D. (2007) *Deficient regulation questionnaire*. GeoThermal Regulation for Heat (GTR-H) feedback report. Available at: <http://geodh.eu/library/> (Accessed: 22 June 2021).

Patil, P. G. and Srivastava, A. (1984) 'State-of-the-art of solar thermal industrial process heat technologies for use in developing countries', in Curtis, F. A. (ed.) *Energy developments: new forms, renewables, conservation. Proceedings of ENERGEX '84, The Global Energy Forum*. Regina, Saskatchewan, Canada, 14–19 May, pp. 577-583. Doi: <https://doi.org/10.1016/B978-0-08-025407-4.50105-8>

Perez, M. (2023) Face-to-face conversation, 18 January.

Petursson, B. and Ketilsson, J. (eds.) (2015) *Geothermal policy options and instruments for the Andean region based on the Icelandic and international geothermal experience*. Reykjavik: Orkustofnun.

Popovski, K. (2003) 'Greenhouse heating', in Dickson, M. H. and Fanelli, M. (eds.) *Geothermal energy. Utilization and technology*. Paris: UNESCO, pp. 91-112.

Popovski, K. (2009) 'Agricultural and industrial uses of geothermal energy in Europe', *International Conference on national development of geothermal energy use and international course/EGEC business seminar on organization of successful development of a geothermal project*. Častá-Papiernička, Slovakia, 26-29 May 2009, pp. 1-11. Available at: <https://pangea.stanford.edu/ERE/pdf/IGAstandard/ISS/2009Slovakia/III.1.Popovski.pdf> (Accessed: 26 December 2020).

Porse, S., Winick, J., Tasca, C. and Blankenship, D. (2022) *Geothermal technologies office. Fiscal years 2022-2026 multi-year program plan*. Available at: <https://www.energy.gov/eere/geothermal/geothermal-technologies-office-multi-year-program-plan> (Accessed: 20 January 2023).

Poux A. (2009) 'The GEOFAR project' [PowerPoint presentation]. GTRH closing conference. Available at: <https://ec.europa.eu/energy/intelligent/projects/en/projects/geofar> (Accessed: 10 September 2021).

Presidency Ministry of Devolution and Planning (2017) *Review of the implementation of the Beijing platform for action*. Available at: <https://hlpf.un.org/vnrs> (Accessed: 8 December 2022).

Press, F. and Siever, R. (2002) *Understanding earth*. 3rd edn. United States: W. H. Freeman & Co Ltd.

Rafferty K. (2004) *Direct-use temperature requirements: a few rules of thumb*. Available at: <https://www.yumpu.com/en/document/view/19085621/direct-use-temperature-requirements-a-few-geo-heat-center> (Accessed: 22 May 2021).

Ragnarsson, A. (2010) 'Geothermal development in Iceland 2005-2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-12. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 17 December 2021).

Ragnarsson, A. (2015) 'Geothermal development in Iceland 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-15. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 17 December 2021).

Ragnarsson, A., Steingrímsson, B. and Thorhallsson, S. (2020) 'Geothermal development in Iceland 2015-2019', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-15. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 17 December 2021).

Ram, M., Bogdanov, D., Aghahosseini, A., Gulagi, A., Oyewo, A. S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., Barbosa, L. S. N. S., Fasihi, M., Khalili, S., Dalheimer, B., Gruber, G., Traber, T., De Caluwe, F., Fell, H.-J. and Breyer, C. (2019) *Global energy system based on 100% renewable energy – power, heat, transport and desalination sectors*. Available at: <https://energywatchgroup.org/wp->

[content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf](#) (Accessed: 5 January 2021).

Razzano, F. And Cei, M. (2015) ‘Geothermal power generation in Italy 2010-2014 update report’, *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-10. Available at: <https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2003-01-05.pdf> (Accessed 27 September 2022).

Redko A., Redko O. and DiPippo R. (2020) *Low temperature energy systems with applications of renewable energy*. London: Academic Press.

Reed, M. J. and Bloomquist, R. G. (1995) ‘National geothermal policy and regulation in the United States’, *World Geothermal Congress 1995*. Florence, Italy, 18-31 May, pp. 629-633. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 17 September 2021).

REN21 (2020) *Renewables 2020 global status report*. Available at: <https://www.ren21.net/reports/global-status-report/> (Accessed: 12 February 2021).

REN21 (2022) *Renewables 2022 global status report*. Available at: <https://www.ren21.net/reports/global-status-report/> (Accessed: 30 July 2020).

Republic of Serbia (2017) *Intended nationally determined contribution of the Republic of Serbia*. Available at: <https://unfccc.int/NDCREG> (Accessed: 8 December 2022).

Republic of Serbia (2019) *Voluntary national review of the Republic of Serbia on the implementation of the 2030 agenda for sustainable development*. Available at: <https://hlpf.un.org/vnrs> (Accessed: 8 December 2022).

Republic of Serbia Ministry of Energy, Development and Environmental Protection (2013) *National renewable energy action plan of the Republic of Serbia (in accordance with the template foreseen in the Directive 2009/28/EC – Decision 2009/548/EC)*. Available at: https://www.mre.gov.rs/sites/default/files/2021/03/national_renewable_energy_action_plan_of_the_public_of_serbia_28_june_2013.pdf (Accessed: 8 December 2022).

Republic of Türkiye Ministry of Energy and Natural Resources (2014) *National renewable energy action plan for Turkey*. Available at: <https://climate-laws.org/geographies/turkey/policies/national-renewable-energy-action-plan-2369a00e-076c-425b-ba29-044e1e09bb03> (Accessed: 25 December 2022).

Richter, A. (2017) ‘KS Orka plans to start Serbia’s first geothermal power plant in 2018’, *ThinkGeoenergy*, 18 October. Available at: <https://www.thinkgeoenergy.com/ks-orka-plans-to-start-serbias-first-geothermal-power-plant-in-2018/> (Accessed: 25 December 2022).

Richter, A. (2022) ‘Koyuncu Group has completed Turkey’s most modern greenhouse’, *ThinkGeoenergy*, 14 March. Available at: <https://www.thinkgeoenergy.com/koyuncu-group-has-completed-turkeys-most-modern-greenhouse/> (Accessed: 25 December 2022).

Robertson-Tait, A., Harvey, W., Hamm, S. and Boyd, L. (2020) ‘The United States of America Country Update 2020 – power generation’, *World Geothermal Congress 2020+1*. Reykjavik, Iceland,

April-October 2021, pp. 1-15. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 28 April 2023).

RS Official Gazett no. 101/2015 (2015) *Law on Mining and Geological Explorations 2015*. Available at: <http://gras.org.rs/wp-content/uploads/2017/10/law-on-mining-and-geological-explorations-of-serbia-2015.pdf> (Accessed: 9 December 2022).

Rupprecht, D., Steiner, C., Heiermann, M. and Riedel, P. (2017) *Summary of national legal requirements, current policies and regulations of shallow geothermal use*. Interreg Central Europe GeoPLASMA-CE D.T2.4.1. Available at: <http://www.interregcentral.eu/> (Accessed: 22 June 2021).

Sanchez-Guzman, J. and Garcia de la Noceda, C. (2010) ‘The evolution of geothermal energy in Spain – country update (2005-2009)’, *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-8. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 December 2022).

Sass, I. (2019) ‘Geothermal’, in: RENAC (ed.) *Renewable Energy. Lessons from the German experience of the energy transition. A guide for engineers, policymakers and administrators*. Berlin: Verband Beratender Ingenieure, pp. 60-70.

Schneider, A. (2019) ‘Could a €1 billion carbon-neutral town filled with greenhouses be coming to Hungary?’, *The Calvert Journal*, 5 June. Available at: <https://www.calvertjournal.com/articles/show/11197/billion-carbon-neutral-town-filled-greenhouses-hungary-sustainability-technology> (Accessed: 26 September 2022).

Schubert, T. (2019a) ‘International climate protection policies and emissions trading’ in: RENAC (ed.) *Renewable energy. Lessons from the German experience of the energy transition. A guide for engineers, policymakers and administrators*. Berlin: Verband Beratender Ingenieure, pp. 17-28.

Schubert, T. (2019b) ‘Incentive mechanisms’ in: RENAC (ed.) *Renewable energy. Lessons from the German experience of the energy transition. A guide for engineers, policymakers and administrators*. Berlin: Verband Beratender Ingenieure, pp. 29-34.

SDGs Promotion Headquarters (2017) *Japan’s voluntary national review. Report on the implementation of the sustainable development goals*. Available at: <https://hlpf.un.org/vnrs> (Accessed: 17 December 2022).

Serpen, U. (2006) ‘Present status of geothermal energy and its utilization in Turkey’, *Geothermal Resource Council 2006 Annual Meeting*. San Diego, USA, 10-13 September, pp. 683-688. Available at: <https://www.geothermal-library.org/> (Accessed: 25 December 2022).

Serra, D., Cei, M. and Lupi, M. (2020) ‘Geothermal energy use, country update for Italy (2015-2019)’, *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-8. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 27 September 2022).

Sevilla, I. (2022) ‘Así funcionará la primera planta geotérmica para climatizar invernaderos en Almería’ [This is how the first geothermal plant to heat greenhouses in Almeria will operate], *Nius*, 2

February. Available at: https://www.niusdiario.es/espana/andalucia/asi-funcionara-primer-planta-geotermica-climatizar-invernaderos-almeria_18_3279421400.html (Accessed: 8 December 2022).

Shamsiev, B. and Bucik, M. (2016) *Securing Serbia's farming future*, 5 May. Available at: <https://blogs.worldbank.org/europeandcentralasia/securing-serbia-s-farming-future> (Accessed: 28 April 2023).

Shortall, R. and Uihlein, A. (2019) *Geothermal energy: technology development report*. Available at: <https://publications.jrc.ec.europa.eu/repository/handle/JRC118299> (Accessed: 20 May 2021).

Simiyu, S. M. (2010) 'Status of geothermal exploration in Kenya and future plans for its development', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-11. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 December 2022).

Snyder, D. M., Beckers, K. F. and Young, K. R. (2017) 'Update on geothermal direct-use installations in the United States', *42nd workshop on geothermal reservoir engineering*. Stanford, USA, 13-15 February 2017, pp. 1-7. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 January 2023).

Stefanescu-Cuntze, C. (2023) Email correspondence, 30 March.

Steinbach, J., Popovski, E., Fleiter, T., Hummel, M., Chassein, E., Bedoya, I. and Rex, M. (2017) *ProgRESs HEAT policy recommendations to decarbonize European heating and cooling systems*. Available at: <https://www.isi.fraunhofer.de/> (Accessed: 1 September 2021).

Stichting Platform Geothermie, Dutch Association of Geothermal Operators, Stichting Warmtenetwerk, Energie Beheer Nederland (2018) *Master plan geothermal energy in the Netherlands. A broad foundation for sustainable heat supply*. Available at: https://geothermie.nl/images/bestanden/Masterplan_Aardwarmte_in_Nederland_ENG.pdf (Accessed: 8 October 2022).

Sugino, H. and Akeno, T. (2010) '2010 country update for Japan', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-7. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 17 December 2022).

Szita, G. (2005) 'Decreases opportunities for geothermal in Hungary', *World Geothermal Congress 2005*. Antalya, Turkey, 24-29 April, pp. 1-5. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 26 September 2023).

Tax Policy Center (2020) *The Tax Policy Center's briefing book. A citizen's guide to the fascinating (though often complex) elements of the federal tax system*. Available at: <https://www.taxpolicycenter.org/briefing-book> (Accessed: 9 September 2021).

T. C. Resmî Gazete 26551 (2007) *Law No. 5686 on Geothermal Resources and Mineral Waters 2007*. Available at: <https://climate-laws.org/geographies/turkey/laws/act-no-5686-on-geothermal-resources-and-mineral-waters> (Accessed: 25 December 2022).

Tharani, A., Raore, T. J. and Karimbux-Khan, F. (2017) 'Kenya' in *Geothermal transparency guide. An overview of regulatory frameworks for geothermal exploration and exploitation*. Reykjavik: BBA, pp. 95-110.

Tian, T., Dong, Y., Zhang, W., Wei, J., Jin, H. and Liu, Y. (2020) 'Rapid development of China's geothermal industry – China national report of the 2020', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-9. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 December 2021).

Toth, A. N. (2010) 'Hungary country update 2005-2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-8. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 25 September 2022).

Toth, A. N. (2015) 'Hungarian country update 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-8. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 25 September 2022).

Toth, A. N. (2020) 'Country update for Hungary', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-10. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 25 September 2022).

Tsagarakis, K. P., Efthymiou, L., Michopoulos, A., Mavragani, A., Anđelković, A. S., Antolini, F., Bacić, M., Bajare, D., Baralis, M., Bogusz, W., Burlon, S., Figueira, J., Genç, M. C., Javed, S., Jurelionis, A., Koca, K., Ryzynski, G., Urchueguia, J. F. and Zlender, B. (2020) 'A review of the legal framework in shallow geothermal energy in selected European countries: need for guidelines', *Renewable energy*, 147(2), pp. 2556-2571. doi: <https://doi.org/10.1016/j.renene.2018.10.007>

Umweltbundesamt (2022) *Indicator: renewable energies*. Available at: <https://www.umweltbundesamt.de/en/data/environmental-indicators/indicator-renewable-energy#at-a-glance> (Accessed: 30 June 2022).

United Nations (1992) 'Agenda 21', *United Nations Conference on Environment and Development*. Rio de Janeiro, Brazil, 3-14 June 1992, pp. 1-351. Available at: <https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf> (Accessed: 4 September 2021).

United Nations (2022a) *Food security and nutrition and sustainable agriculture*. Available at: <https://sustainabledevelopment.un.org/topics/foodagriculture> (Accessed: 19 March 2022).

United Nations (2022b) *National sustainable development strategies*. Available at: <https://sustainabledevelopment.un.org/topics/nationalsustainabledevelopmentstrategies> (Accessed: 4 September 2021)

United Nations (no date-a) *What is renewable energy?* Available at: <https://www.un.org/en/climatechange/what-is-renewable-energy> (Accessed: 26 March 2023).

United Nations (no date-b) *The 17 goals*. Available at: <https://sdgs.un.org/goals> (Accessed: 6 March 2020).

United Nations (no date-c) *Nationally determined contributions (NDCs)*. Available at: <https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/nationally-determined-contributions-ndcs#eq-1> (Accessed: 4 September 2021).

United Nations (no date-d) *Long-term strategies portal*. Available from: <https://unfccc.int/process/the-paris-agreement/long-term-strategies> (Accessed: 4 September 2021).

United Nations (no date-e) *Voluntary national reviews*. Available at: <https://hlpf.un.org/vnrs> (Accessed: 4 September 2021).

U.S. Department of Agriculture (2023) *Ag and food statistics: charting the essentials*. Available from: <https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/> (Accessed: 29 April 2023).

U.S. Department of Agriculture (no date) *Agricultural subsidies*. Available from: <https://www.nal.usda.gov/economics-business-and-trade/agricultural-subsidies> (Accessed: 29 April 2023).

Van der Hout M. (2021a) Zoom conversation, 13 May.

Van der Hout M. (2021b) Zoom conversation, 21 August.

Van Heekeren, E. V. and Koenders, M. (2010) ‘The Netherlands country update on geothermal energy’, *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-7. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 October 2022).

Van Heekeren, V. and Bakema, G. (2015) ‘The Netherlands country update on geothermal energy’, *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-31. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 October 2022).

Varvitsioti, E. and Tsifoutidis, G. (2021) ‘Regulatory roadmap to the past, present and future of geothermal energy in Greece’, *International Conference on Raw Materials and Circular Economy*. Athens, Greece, 5-9 September 2021. Doi: <https://doi.org/10.3390/materproc2021005010>

Wendel, M. and Hiegl, M. (2010) ‘GEOFAR – financing geothermal energy in European regions’, *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-11. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 15 September 2021).

Whiting, K. (2019) *These Dutch tomatoes can teach the world about sustainable agriculture* Available at: <https://www.weforum.org/agenda/2019/11/netherlands-dutch-farming-agriculture-sustainable/> (Accessed: 8 October 2022).

Wonstolen, K. A. (1980) 'Geothermal energy: basic legal parameters', *Geothermal Resource Council Annual Meeting and Conference*. Salt Lake City, USA, 9 September 1980, pp. 661-663. Available at: <https://www.osti.gov/biblio/6297546> (Accessed: 9 May 2021).

World Bank (2023) *Data catalogue. World development indicators: structure of value added*. Available at: <http://wdi.worldbank.org/table/4.2> (Accessed: 21 April 2023).

Yasukawa, K. and Sasada, M. (2015) 'Country update for Japan: renewed opportunities', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-6. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 17 December 2022).

Yasukawa, K., Nishikawa, N., Sasada, N. and Okumura, T. (2020) 'Country update of Japan', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-7. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 17 December 2022).

Zaborek, P. (2009) 'Application of multiple case study method in doctoral dissertation', in Strzyżewska, M. (ed.) *Selected methodological issues for doctoral students*. Warsaw: Warsaw School of Economics Publishing, pp. 83-98.

Zaidi, S. H. (2015) 'Economic growth and poverty reduction through geothermal development: integrated policy measures to rural development and economic sustainability', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-7. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 17 December 2020).

Zenginli, K. (2022) 'Gübre ve ilaç masrafı yok: Gıda krizine çözüm jeotermal seralar' [No fertilizer and pesticide cost: geothermal greenhouses the solution to the food crisis], *Türkiye Gazetesi*, 21 April. Available at: <https://www.turkiyegazetesi.com.tr/ekonomi/gubre-ve-ilac-masrafi-yok-gida-krizine-cozum-jeotermal-seralar-850962> (Accessed: 25 December 2022).

Zheng, K., Han, Z. and Zhang, Z. (2010) 'Steady industrialized development of geothermal energy in China country update report 2005-2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-11. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 December 2021).

Zheng, K., Dong, Y., Chen, Z., Tian, T. and Wang, G. (2015) 'Speeding up industrialized development of geothermal resources in China – country update report 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-7. Available at: <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/> (Accessed: 8 December 2021).

Appendix A

A structured web questionnaire with a five-point Likert scale, with interval-level response format.

The questionnaire was administered to 129 experts between 30 April – 14 May 2021.

Geothermal Energy: Government Support for Agri-Food Sector

Dear Contributor,

Thank you for taking part in this survey. Its purpose is to better understand the influence of government support on geothermal energy use in the agri-food sector.

This scale is developed from an extensive overview of major policies meant to positively impact geothermal adoption in the agri-food sector. Please assess them by stating how much you agree or disagree on their importance.

This questionnaire consists of two sections and should take less than 10 minutes.

Section 1. Geothermal Support: Policies (* required)

This section includes global, national, and local policies.

***Question 1:** For each of the following policies, please assess how much you agree or disagree on their importance for the adoption of geothermal energy in the agri-food sector:

1 = *Strongly disagree*

2 = *Somewhat disagree*

3 = *Neither agree nor disagree*

4 = *Somewhat agree*

5 = *Strongly agree*

	1	2	3	4	5
Global					
Paris Agreement: <i>legally binding international agreement on climate change</i>					
Nationally Determined Contributions (NDC): <i>mandatory action plan to comply with Paris Agreement</i>					
Long-Term Low Emission Development Strategies: <i>optional long-term vision plans for NDC</i>					
National Sustainable Development Strategy: <i>voluntary strategy for achieving Sustainable Development Goals</i>					
National					
Emissions Reduction Targets: <i>targets to cut emissions in specific sectors (housing, transport, agriculture, etc.)</i>					
Renewable Energy Action Plan, or similar: <i>targets for renewable energy development</i>					
Renewable Portfolio Standards: <i>obligation for companies to produce a certain amount of energy from renewables</i>					
Emissions Trading System: <i>permits issued to trade emissions. A form of carbon pricing.</i>					

Carbon Tax: <i>tax levy on carbon emissions. A form of carbon pricing.</i>					
Tax Rebate: <i>tax refund for renewable energy production</i>					
Tax Relief: <i>tax reduction for renewable energy producers</i>					
Tax Credit: <i>tax deduction for installing renewable energy system</i>					
Feed-in-Tariff: <i>long-term compensation for renewable energy producers</i>					
Feed-in-Premium: <i>premiums paid to renewable energy producers in addition to the wholesale price</i>					
Geothermal Energy Action Plan: <i>national plan for developing geothermal energy</i>					
Local					
Legal definition of geothermal resource					
Legally defined ownership rights of geothermal resource and its regulation					
Legally defined process for access to, and the use of geothermal resource					

Question 2: Please, include other impactful policies not mentioned in this list:

(Open answer)

Section 2. Personal Information (* required)

***Question 1:** Please, indicate the sector you are currently working in:

- Government agency
- Industry association, not-for-profit
- Industry company, for-profit
- Academic institution
- Independent consultant, or researcher
- Other *(open answer)*

***Question 2:** Could you please share with us a country you are currently working in?

(Open answer)

Question 3: If you would like to leave other comments or feedback, please type in below:

(Open answer)

Appendix B

Invitation email to participate in the questionnaire.

The invitation was sent out to 129 experts on 30 April, 3 May, and 12 May 2021. The deadline for contributions was set as 14 May 2021.

Dear «Name» «Surname»,

The International Geothermal Association (IGA) is conducting a survey to better understand the influence of government support on geothermal energy use in the agri-food sector. We are reaching out to you because we believe your work is important and would like to ask for your contribution.

The survey should take less than 10 minutes. We thank you in advance for your time and engagement, this is much appreciated. The participation in the survey is voluntary and anonymous.

The link to the survey can be found [here](#).

We accept contributions until 14 May 2021. Should you have any questions, do not hesitate to reach out to us.

Best regards,



Margaret Krieger

IGA Head of Research and Communication

Charles-de-Gaulle-Str. 5

D-53113 Bonn

Email: margaret@lovegeothermal.org

Website: www.lovegeothermal.org

Appendix C

Likert scale codebook, questionnaire answers and their analysis.

Likert scale codebook

A codebook contains the description of an independent variable, its measure, format, response scale and coded values.

Variable name	Policy incentives, independent
Variable definition	Relevant government instruments and measures directly or indirectly encouraging the use of geothermal energy
Measure	Likert scale
Format	Numeric
Response scale	Five-point interval-level
Coding anchors	
<i>Anchor number</i>	<i>Anchor name</i>
1	strongly disagree
2	somewhat disagree
3	neither agree nor disagree
4	somewhat agree
5	strongly agree

Scale items	
<i>Item code</i>	<i>Item name</i>
G1	Paris Agreement
G2	Nationally Determined Contributions
G3	Long-Term Low Emission Development Strategies
G4	National Sustainable Development Strategy
N1	Emissions Reduction Targets
N2	Renewable Energy Action Plan, or similar
N3	Renewable Portfolio Standards
N4	Emissions Trading System
N5	Carbon Tax
N6	Tax Rebate
N7	Tax Relief
N8	Tax Credit
N9	Feed-in-Tariff
N10	Feed-in-Premium
N11	Geothermal Energy Action Plan
L1	Definition
L2	Ownership rights and regulation
L3	Access and use

Questionnaire answers

All data are imported from MS Excel, where the complete analysis is performed.

Section 1. Geothermal Support: Policies.

Question 1: Expert responses on the importance of each scale item. Following the data accuracy check responses from expert judges 14, 26, and 27 were not included in the final analysis as they represent extreme response categories irrespective of content.

	Expert number and individual expert responses																															
Scale items	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
G1	4	4	4	3	4	5	5	3	3	4	3	4	5	5	5	4	4	3	4	5	2	5	4	3	5	5	5	5	5	3	4	2
G2	5	4	4	4	3	5	4	4	4	4	3	3	4	5	4	5	5	5	4	5	3	4	4	3	5	5	5	5	5	4	4	2
G3	4	4	5	3	3	5	5	4	4	4	3	5	5	5	3	3	4	3	5	5	2	3	3	3	5	5	5	5	5	3	3	4
G4	4	4	5	4	4	5	5	4	3	4	3	5	4	5	4	4	5	3	5	4	2	3	4	4	5	5	5	5	5	4	3	4
N1	5	4	4	3	4	5	4	4	3	2	5	5	5	5	5	4	5	5	5	4	4	4	5	4	5	5	5	5	5	4	4	5
N2	5	4	5	3	4	5	4	4	5	2	3	4	5	5	3	5	4	5	5	5	3	2	4	4	4	5	5	5	5	4	4	5
N3	5	4	4	2	4	2	5	4	5	3	3	2	5	5	5	5	3	5	2	3	4	3	3	3	4	5	5	5	5	4	3	4
N4	5	4	3	2	3	3	4	4	3	4	4	1	5	5	3	4	5	3	5	3	4	2	5	3	3	5	5	4	4	3	3	4
N5	5	4	3	3	2	3	4	3	4	4	4	5	4	5	4	4	5	5	3	4	4	2	4	3	5	5	5	5	5	3	4	4
N6	5	3	4	4	3	1	4	3	5	3	4	4	4	5	3	5	3	5	5	4	5	5	5	4	2	5	5	5	5	3	3	4
N7	5	5	3	4	3	1	5	3	5	3	4	5	4	5	4	5	3	5	5	5	5	5	5	4	2	5	5	5	5	3	3	4
N8	5	4	4	3	3	1	5	3	5	3	4	4	5	5	4	4	4	5	5	5	5	5	5	4	2	5	5	5	5	3	4	4
N9	5	3	4	5	2	5	4	3	5	4	3	1	5	5	3	5	4	5	5	3	5	2	4	4	1	5	5	5	5	3	4	4
N10	5	3	4	4	2	1	4	3	5	3	3	3	5	5	4	5	5	5	4	4	5	4	4	3	1	5	5	5	5	3	3	4
N11	5	5	5	3	4	4	5	5	5	4	5	5	4	5	5	5	5	5	5	3	3	5	5	4	5	5	5	5	5	5	4	5
L1	5	5	4	4	4	5	5	5	5	5	2	4	4	5	5	4	3	3	5	3	2	1	5	4	3	5	5	5	5	4	4	3
L2	5	5	4	4	4	4	4	5	5	5	2	5	5	5	5	3	3	5	5	2	5	5	3	3	5	5	4	5	4	4	4	
L3	5	5	4	3	4	4	5	5	5	4	2	5	5	5	5	2	3	4	5	2	5	1	3	3	5	5	5	5	4	2	3	

Question 2: Expert responses indicating other impactful policies not mentioned in Question 1.

Expert number	Expert response
1	Geothermal de-risking schemes; national resource mapping; local energy planning
6	Public Risk Scheme for geological uncertainties (RNES). Mining law, labour safety law and environmental law relations on logical chapters, leading to clear HSE mitigation by licence keepers being liable for all activities in one legal entity. Contract Management on integrated way, meaning that public and private agreements are in line (partly policy making, connected to professionalization of operator organizations). Market regulation on district heat systems and the connection with the mining law. Meaning that spatial ordering of both public environment and subsoil licences are connected to one another. In the Netherlands, you'll only get your mining licences as an exclusive right if you are able to show initial contracts that you can sell the heat, which in the end is both needed for the government as well for your financiers.
8	Public Risk Mitigation Systems to enable financing of explorational project development stage.
14	National data base with GSHP systems, required by central authorities and used for calculation of renewable energy coming from shallow geothermal; national data base with geothermal district heating systems; impact on energy price by the use of geothermal energy - effect on mitigating energy poverty; training and certification system for individuals and companies - effect on labour market at national and European level through mutual recognition of qualifications.
15	De-risking strategies for geothermal energy; standard procedures in Europe regarding geothermal energy definition, access and exploitation.
16	stable, predictable support system; legal certainty.
19	Turkish government supplies special incentives for geothermal greenhouse investments. These incentives are grants and appropriate loan possibilities for: 1. Geothermal greenhouses (agriculture section); 2. Geothermal district heating systems for agriculture section The technical modes have been determined by Orhan Mertoglu in terms of 3 systems. <i>System a</i> : individual greenhouse heating system (greenhouses own independently their production and reinjection wells). <i>System b</i> : geothermal greenhouses are using the return heat (reinjection heat) of geothermal district heating system (house heating). In this system the greenhouse heating system is integrated to geothermal district heating system. <i>System c</i> : reinjection heat; condensing surplus heat and waste steam heat of geothermal power plant is used for geothermal greenhouse heating. In this system the greenhouse heating system is integrated to geothermal power plant.
26	Public Risk-mitigation fund (Guarantee scheme) for Geothermal.
28	Liberalisation of data from all drilled wells for improving underground knowledge and improve geothermal resource assessment; policies to support co-production and cascade uses.
29	Liberalization of well data (for improving resource assessment) and of monitoring data (seismicity and other environmental information).

Section 2: Personal Information.

Question 1. Employment sector: Expert responses indicating their work sector (GA - Government agency; IA - Industry association, not-for-profit; IC - Industry company, for-profit; AI - Academic institution, ICR - Independent consultant, or researcher; OT – Other, open answer). Category “other” includes the following answers: Expert 3 – public body - consortium of municipalities and regional government; Expert 7 – scientific and research institute; Expert 32 – research centre and energy agency. The graph shows a breakdown of employment sectors.

		Individual expert responses																															
Sectors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	
GA									x		x						x			x	x				x	x	x				x		
IA	x			x														x						x				x					
IC																							x										
AI					x					x		x	x	x	x																		
ICR		x				x		x								x				x				x						x	x		
OT			x				x																										x



Question 2. Country of employment: Expert responses indicating their current country of work.

Country	Individual expert responses																																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	
Austria										x																							
Belgium																	x																
Cyprus					x																												
France		x																x															
Germany								x																									
Greece												x																					x
Hungary																x					x												
Iceland													x									x											
Italy			x	x																										x	x		
Netherlands						x																x				x							
Portugal															x																		
Romania														x																			
Serbia																							x										
Slovenia								x																							x		
Slovakia																																	x
Türkiye																				x													
Europe	x																									x							
No answer									x		x														x				x				

Question 3. Other comments and feedback: Expert responses indicating other comments and feedback.

Expert number	Expert response
1	Most of the policies identified in the questionnaire are quite relevant (especially binding policies and regulations that streamline and give certainty to geothermal project development). It is also quite important to focus on measures to reduce the risk of developing projects by implementing risk mitigation schemes and having some form of public mapping of geothermal resources. Finally, local heat planning is quite important in accelerating the uptake of geothermal projects, even for agricultural uses.
6	I'll mail you a Dutch Scheme the updated legislation for geothermal on an integrated way.
8	The combination of sustainable highly efficient agri-production in greenhouses, and geothermal nearby cities (reduced transport) can contribute substantially to climate protection and food security - elsewhere in the world. Let's do it!
14	Unfortunately, in spite of the efforts of geothermal professionals, no geothermal projects have been included in the Romanian National Resilience and Recovery Plan prepared for Brussels by the government representatives. The Romanian Geoexchange Society has sent numerous project proposals to the Romanian Minister for Investments and European Projects, including support schemes proposals. All these efforts were useless, so far - as they were for the last two decades. Geothermal energy is neglected by the Romanian government, in spite of existing resources and obvious benefits.
16	Develop a framework at European level.

Questionnaire analysis

All data are imported into MS Excel, where the complete analysis is performed.

The left table shows the values and scores for a *total sum*, *weighted mean*, and *standard deviation*. The *value* represents the actual calculated value for each item and the *score* is the attributed value based on a high or low actual value. The *composite score* is indicated in the last column and represents a sum of all scores. The items with the highest composite score are chosen as measurements for policy incentives. These are G2, G4, N1, N2, N11 and L2 items. The process for *calculation of attributed scores* is shown in the table on the right.

Items	Total sum		Weighted average		Standard deviation		Composite score
	value	score	value	score	value	score	
G1	93	0	3.8	0	0.90	1	1
G2	103	1	4.06	1	0.79	1	3
G3	80	0	3.8	0	0.93	1	1
G4	103	1	4.06	1	0.79	1	3
N1	120	1	4.3	1	0.77	1	3
N2	108	1	4.1	1	0.92	1	3
N3	85	0	3.7	0	1.05	0	0
N4	70	0	3.5	0	1	1	1
N5	91	0	3.8	0	0.86	1	1
N6	89	0	3.8	0	1.04	0	0
N7	97	0	4.06	1	1.10	0	1
N8	103	1	4.06	1	1.04	0	2
N9	93	0	3.8	0	1.23	0	0
N10	85	0	3.7	0	1.15	0	0
N11	124	1	4.5	1	0.69	1	3
L1	101	1	4	1	1.10	0	2
L2	110	1	4.2	1	0.94	1	3
L3	98	0	3.8	0	1.24	0	0

Calculation of attributed scores		
Total sum value	$\geq 70\%$	$< 70\%$
Attributed score	1	0
Weighted average value	≥ 4	< 4
Attributed score	0	1
Standard deviation value	≤ 1	> 1
Attributed score	1	0

Appendix D

The complete list of data sources per country.

All data sources can be found in the open-access International Geothermal Association (IGA) paper database at <https://www.lovegeothermal.org/explore/our-databases/conference-paper-database/>.

Worldwide reviews

Lund, J. W. and Freeston, D. H. (2000) 'World-wide direct uses of geothermal energy 2000', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-21.

Lund, J. W., Freeston, D. H. and Boyd, T. L. (2005) 'Worldwide direct uses of geothermal energy 2005', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-20.

Lund, J. W., Freeston, D. H. and Boyd, T. L. (2010) 'Direct utilization of geothermal energy 2010 worldwide review', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-23.

Lund, J. W. and Boyd, T. L. (2015) 'Direct utilization of geothermal energy 2015 worldwide review', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-31.

Lund, J. W. and Toth, A. (2020) 'Direct utilization of geothermal energy 2020 worldwide review', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-39.

Algeria

Fekraoui, A. and Kedaid, F. H. (2005) 'Geothermal resources and uses in Algeria: a country update report', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-8.

Fekraoui, A. (2010) 'Geothermal activities in Algeria', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-6.

Saibi, H. (2015) 'Geothermal resources in Algeria', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-10.

Abdelkader, A. O., Abdelhakim, A., Djamel, M., Abderrahman, I., Salima, O., Khadidja, B. and Khaled, I. (2020) 'Update of the most important Algerian geothermal provinces', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-8.

Argentina

Pesce, A. H. (2000) 'Argentina country update', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-11.

Pesce, A. H. (2005) 'Argentina country update', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-12.

Pesce, A. H. (2010) 'Argentina country update', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-12.

Pesce, A. H. (2015) 'Argentina country update', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-12.

Chiodi, A. L., Filipovich, R. E., Esteban, S. L., Pesce, A. H. and Stefanini, V. A. (2020) 'Geothermal country update of Argentina: 2015-2020', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-13.

Austria

Goldbrunner, J. (2005) 'State, possible future developments in and barriers to the exploration and exploitation of geothermal energy in Austria – country update', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-11.

Goldbrunner, J. (2010) 'Austria – country update', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-16.

Goldbrunner, J. (2015) 'Austria – country update', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-13.

Goldbrunner, J. (2020) 'Austria – country update', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-17.

Belgium

Loveless, S., Hoes, H., Petittelerc, E., Licour, L. and Laenen, B. (2015) 'Country update for Belgium', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-6.

Hoes, H., Dupont, N., Lagrou, D. and Petittelerc, E. (2020) 'Status and development on geothermal energy use in Belgium, a new momentum for the growth of deep geothermal energy production', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-9.

Bosnia and Herzegovina

Miošić, N., Samardžić, N. and Hrvatović, H. (2010) 'The current status of geothermal energy use and development in Bosnia and Herzegovina', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-10.

Miošić, N., Samardžić, N. and Hrvatović, H. (2015) 'The current status of geothermal energy research and use in Bosnia and Herzegovina', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-13.

Miošić, N., Samardžić, N. and Hrvatović, H. (2020) 'The current status of geothermal energy research and use in Bosnia and Herzegovina', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-16.

Bulgaria

Bojadgieva, K., Hristov, H., Hristov, V. and Benderev, A. (2000) 'Status of geothermal energy in Bulgaria', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-6.

Bojadgieva, K., Hristov, H., Hristov, V., Benderev, A. and Toshev, V. (2005) 'Geothermal update for Bulgaria (2000-2005)', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-11.

Bojadgieva, K., Hristov, H., Hristov, V., Benderev, A., Toshev, V. and Barokov, K. (2010) 'Bulgaria – geothermal update report', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-11.

Bojadgieva, K., Hristov, H., Berova-Andonov, A., Benderev, A. and Hristov, V. (2015) 'Geothermal update for Bulgaria (2010-2014)', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-10.

Hristov, V., Benderev, A., Stoyanov, N., Antonov, D., Trayanova, M. and Kolev, S. (2020) 'Geothermal update for Bulgaria (2014-2018)', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-11.

China

Zhen-guo, Z., Ji-yang, W., Xiang, R., Shi-bin, L. and Hua-zhou, Z. (2000) 'The state-of-the-art and future development of geothermal energy in China. Country update report for the period 1996-2000', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-3.

Zheng, K., Zhang, Z., Zhu, H. and Liu, S. (2005) 'Process and prospects of industrialized development of geothermal resources in China - country update report for 2000-2004', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-10.

Zheng, K., Han, Z. and Zhang, Z. (2010) 'Steady industrialized development of geothermal energy in China. Country update report 2005-2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-11.

Zheng, K., Dong, Y., Chen, Z., Tian, T. and Wang, G. (2015) 'Speeding up industrialized development of geothermal resources in China - country update report 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-9.

Tian, T., Dong, Y., Zhang, W., Wei, J., Jin, H. and Liu, Y. (2020) 'Rapid development of China's geothermal industry - China national report of the 2020 World Geothermal Conference', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-9.

Croatia

Jelić, K., Čubrić, S., Pavičić, H. and Bošnjak, R. (2000) 'Geothermal energy potential and utilization in the republic of Croatia', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-10.

Jelić, K., Kovačić, M. and Koščak-Kolin, S. (2005) 'State of the art of the geothermal resources in Croatia in the year 2004', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-9.

Jelić, K., Golub, M., Kolbah, S., Kulenović, I. and Škrlec, M. (2010) 'Croatia geothermal resources updates in the year 2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-9.

Kolbah, S., Živković, S., Golub, M. and Škrlec, M. (2015) 'Croatia country update 2015 and on', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-7.

Kolbah, S., Živković, S., Škrlec, M. and Tumara, D. (2020) 'Croatia country update 2020 – finally the start of power production', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-14.

Cyprus

Michopoulos, A. (2020) 'Geothermal developments in Cyprus – country update 2019', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-5.

Ecuador

Beate, B. and Salgado, R. (2005) 'Geothermal country update for Ecuador, 2000-2005', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-12.

Beate, B. and Salgado, R. (2010) 'Geothermal country update for Ecuador, 2005-2010', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-16.

Beate, B. and Urquizo, M. (2015) 'Geothermal country update for Ecuador: 2010-2015', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-14.

Beate, B., Urquizo, M. and Lloret, A. (2020) 'Geothermal country update of Ecuador: 2015-2020', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-13.

Egypt

Lashin, A. (2015) 'Geothermal resources of Egypt: country update', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-13.

Lashin, A. (2020) 'Review of the geothermal resources of Egypt: 2015-2020', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-7.

El Salvador

Rodríguez, J. A. (2000) 'Geothermal development in El Salvador – a country update', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-4.

Rodríguez, J. A. and Herrera, A. (2005) 'El Salvador country update', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-4.

Herrera, R., Montalvo, F. and Herrera, A. (2010) 'El Salvador country update', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-10.

France

Laplaige, P., Jaudin, F., Desplan, A. and Demange, J. (2000) 'The French geothermal experience review and perspectives', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-13.

Laplaige, P., Lemale, J., Decottegnie, S., Desplan, A., Goyeneche, O. and Delobelle, G. (2005) 'Geothermal resources in France – current situation and prospects', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-13.

Boissier, F., Desplan, A. and Laplaige, P. (2010) 'France country update', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-9.

Vernier, R., Laplaige, P., Desplan, A. and Boissavy, C. (2015) 'France country update', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-8.

Boissavy, C., Schmidlé-Bloch, V., Pomart, A. and Lahlou, R. (2020) 'France country update', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-19.

Georgia

Buachidze, G., Vardigorelli, O. and Tsertsvadze, N. (2000) 'Country update from Georgia', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-4.

Buachidze, G., Vardigorelli, O. and Tsertsvadze, N. (2005) 'Country update from Georgia', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-3.

Melikadze, G. (2010) 'Country update from Georgia', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-7.

Melikadze, G., Vardigoreli, O. and Kapandze, N. (2015) 'Country update from Georgia', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-6.

Melikadze, G., Tsertsvadze, N., Vardigoreli, O. and Kapanadze, N. (2020) 'Geothermal resource of Georgia', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-7.

Greece

Fytikas, M., Andritsos, N., Karydakos, G., Kolios, N., Mendrinou, D. and Papachristou, M. (2000) 'Geothermal exploration and development activities in Greece during 1995-1999', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-10.

Fytikas, M., Andritsos, N., Dalabakis, P. and Kolios, N. (2005) 'Greek geothermal update 2000-2004', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-8.

Andritsos, N., Arvanitis, A., Papachristou, M., Fytikas, M. and Dalambakis, P. (2010) 'Geothermal activities in Greece during 2005-2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-10.

Andritsos, N., Dalambakis, P., Arvanitis, A., Papachristou, M. and Fytikas, M. (2015) 'Geothermal developments in Greece – country update 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-11.

Papachristou, M., Dalampakis, P., Arvanitis, A., Mendrinos, D. and Andritsos, N. (2020) 'Geothermal developments in Greece – country update 2015-2020', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-14.

Hungary

Árpási, M., Kovács, L. and Szabó, G. (2000) 'Geothermal development in Hungary country update report 1995-1999', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-11.

Árpási, M. (2005) 'Geothermal update of Hungary 2000-2004', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-16.

Toth, A. N. (2010) 'Hungary country update 2005-2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-8.

Toth, A. N. (2015) 'Hungarian country update 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-8.

Toth, A. N. (2020) 'Country update for Hungary', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-10.

Iceland

Ragnarsson, A. (2000) 'Geothermal development in Iceland 1995-1999', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-13.

Ragnarsson, A. (2005) 'Geothermal development in Iceland 2000-2004', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-11.

Ragnarsson, A. (2010) 'Geothermal development in Iceland 2005-2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-12.

Ragnarsson, A. (2015) 'Geothermal development in Iceland 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-15.

Ragnarsson, A., Steingrímsson, B. and Thorhallsson, S. (2020) 'Geothermal development in Iceland 2015-2019', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-15.

Israel

Greitzer, Y. and Levitte, D. (2000) 'Geothermal update report from Israel 1999', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-4.

Levitte, D. and Greitzer, Y. (2005) 'Geothermal update from Israel 2005', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-5.

Italy

Cappetti, G., Passaleva, G. and Sabatelli, F. (2000) 'Italy country update report 1995-1999', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-8.

Borghetti, G. (2005) 'Direct uses of geothermal energy in Italy 2000–2004 update report', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-4.

Buonassorte, G., Rizzi, F. and Passaleva, G. (2010) 'Direct uses of geothermal energy in Italy 2005-2009: update report and perspectives', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-5.

Conti, P., Grassi, W., Passaleva, G. and Cataldi, R. (2015) 'Geothermal direct uses in Italy: country update for WGC2015', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-10.

Bargiacchi, E., Conti, P., Manzella, A., Vaccaro, M., Cerutti, P. and Cesari, G. (2020) 'Thermal uses of geothermal energy, country update for Italy', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-15.

Japan

Sekioka, M. and Yoshii, M. (2000) 'Country update report of geothermal direct uses in Japan', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-5.

Kawazoe, S. and Shirakura, N. (2005) 'Geothermal power generation and direct use in Japan', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-7.

Sugino, H. and Akeno, T. (2010) '2010 country update for Japan', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-7.

Yasukawa, K. and Sasada, M. (2015) 'Country update for Japan: renewed opportunities', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-6.

Yasukawa, K., Nishikawa, N., Sasada, M. and Okumura, T. (2020) 'Country update of Japan', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-7.

Kenya

Mwangi, M. (2000) 'Country update report for Kenya 1995-1999', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-9.

Mwangi, M. (2005) 'Country update report for Kenya 2000-2005', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-10.

Simiyu, S, M. (2010) 'Status of geothermal exploration in Kenya and future plans for its development', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-11.

Omenda, P. and Simiyu, S. (2015) 'Country update for Kenya 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-11.

Omenda, P. (2020) 'Country update report for Kenya 2015-2019', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-16.

Mexico

Quijano-León, J. L. and Gutiérrez-Negrín, L. C. A. (2000) 'Geothermal production and development plans in Mexico', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-7.

Gutiérrez-Negrín, L. C. A. and Quijano-León, J. L. (2005) 'Update of geothermics in Mexico', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-10.

Gutiérrez-Negrín, L. C. A., Maya-González, R. and Quijano-León, J. L. (2010) 'Current status of geothermics in Mexico', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-11.

Gutiérrez-Negrín, L. C. A., Maya-González, R. and Quijano-León, J. L. (2015) 'Present situation and perspectives of geothermal in Mexico', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-10.

Gutiérrez-Negrín, L. C. A., Canchola Félix, I., Romo-Jones, J. M. and Quijano-León, J. L. (2020) 'Geothermal energy in Mexico: update and perspectives', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-13.

Mongolia

Bignall, G., Dorj, P., Batkhishig, B. and Tsuchiya, N. (2005) 'Geothermal resources and development in Mongolia: country update', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-7.

Dorj, P. (2015) 'Geothermal development in Mongolia: country update', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-6.

Dorj, P., Samrock, F. and Erdenechimeg, B. (2020) 'Update of geothermal development in Mongolia', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-5.

Netherlands

van Heekeren, E. V., Snijders, A. L. and Harms, H. J. (2005) 'The Netherlands country update on geothermal energy', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-3.

van Heekeren, E. V. and Koenders, M. (2010) 'The Netherlands country update on geothermal energy', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-7.

van Heekeren, E. V. and Bakema, G. (2015) 'The Netherlands country update on geothermal energy', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-6.

Bakema, G., Provoost, M. and Schoof, F. (2020) 'Netherlands country update', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-8.

New Zealand

Thain, I. A. and Dunstall, M. (2000) '1995-2000 update report on the existing and planned use of geothermal energy for electricity generation and direct use in New Zealand', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-9.

Dunstall, M. G. (2005) '2000-2005 New Zealand country update', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-10.

Harvey, C. C., White, B. R., Lawless, J. V. and Dunstall, M. G. (2010) '2005-2010 New Zealand country update', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-10.

Carey, B., Dunstall, M., McClintock, S., White, B., Bignall, G., Luketina, K., Robson, B., Zarrouk, S. and Seward, A. (2015) '2015 New Zealand country update', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-18.

Daysh, S., Carey, B., Doorman, P., Luketina, K., White, B. and Zarrouk, S. J. (2020) '2015-2020 New Zealand country update', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-17.

North Macedonia

Dimitrov, K., Gorgieva, M. and Popovski, K. (2000) 'Geothermal energy resources and their use in the Republic of Macedonia', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-7.

Popovski, K., Micevski, E. and Popovska Vasilevska, S. (2005) 'Macedonia – country update 2004', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-8.

Popovska Vasilevska, S., Popovski, K. and Micevski, E. (2010) 'Macedonia – country update 2010', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-7.

Popovska Vasilevska, S. and Armenski, S. (2015) 'Macedonia – country update 2015', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-7.

Popovska Vasilevska, S. and Armenski, S. (2020) 'Macedonia – country update 2020', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-17.

Poland

Kepinska, B., Bujakowski, W. and Ney, R. (2000) 'Geothermal energy country update report from Poland', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-7.

Kepinska, B. (2005) 'Geothermal energy country update report from Poland, 2000-2004', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-10.

Kepinska, B. (2010) 'Geothermal energy country update report from Poland, 2005-2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-8.

Kepinska, B. (2015) 'Geothermal energy country update report from Poland, 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-11.

Kepinska, B. (2020) 'Geothermal energy country update report from Poland, 2015-2019', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-13.

Portugal

Aires-Barros, L. and Marques, J. (2000) 'Portugal country update', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-6.

Carvalho, J. M., Monteiro da Silva, J. M., Bicudo da Ponte, C. A. and Cabeças, R. M. (2005) 'Portugal geothermal country update 2005', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-11.

Cabeças, R., Carvalho, J. M. and Nunes, J. C. (2010) 'Portugal country geothermal update 2010', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-10.

Carvalho, J. M., Coelho, L., Nunes, J. C., Carvalho, M. R., Garcia, J. and Cerdeira, R. (2015) 'Portugal country update 2015', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-11.

Nunes, J. C., Coelho, L., Carvalho, J. M., Carvalho, M. R. and Garcia, J. (2020) 'Portugal country update 2020', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-12.

Romania

Cohut, I. and Bendea, C. (2000) 'Romania update report for 1995-1999', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-6.

Rosca, M., Antics, M. and Sferle, M. (2005) 'Geothermal energy in Romania: country update 2000-2004', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-8.

Rosca, M., Antal, C. and Bendea, C. (2010) 'Geothermal energy in Romania: country update 2005-2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-9.

Bendea, C., Antal, C. and Rosca, M. (2015) 'Geothermal energy in Romania: country update 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-9.

Gavriliuc, R., Rosca, M., Bendea, C., Antal, C. and Cucueteanu, D. (2020) 'Geothermal energy in Romania – country update 2015-2019', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-12.

Russia

Kononov, V., Polyak, B. and Kozlov, B. (2000) 'Geothermal development in Russia: country update report 1995-1999', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-6.

Kononov, V. and Povarov, O. (2005) 'Geothermal development in Russia: country update report 2000-2004', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-7.

Povarov, K. O. and Svalova, V. B. (2010) 'Geothermal development in Russia: country update report 2005-2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-4.

Svalova, V. and Povarov, K. (2015) 'Geothermal energy use in Russia. Country update for 2010-2015', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-5.

Svalova, V. and Povarov, K. (2020) 'Geothermal resources and energy use in Russia', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-9.

Serbia

Milivojevic, M. and Martinovic, M. (2000) 'Geothermal energy possibilities, exploration and future prospects in Serbia', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-8.

Milivojevic, M. and Martinovic, M. (2005) 'Geothermal energy possibilities, exploration and future prospects in Serbia', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-11.

Martinovic, M. and Milivojevic, M. (2010) 'Serbia country update', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-11.

Oudech, S. and Djokic, I. (2015) 'Geothermal energy use, country update for Serbia', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-10.

Oudech, S. and Djokic, I. (2020) 'Geothermal energy use, country update for Serbia', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-11.

Slovakia

Benovsky, V., Drozd, V., Halas, O., Vana, O. and Vranovska, A. (2000) 'Geothermal energy utilisation in Slovakia and its future development', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-6.

Fendek, M. and Fendekova, M. (2005) 'Country update of the Slovak Republic', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-9.

Fendek, M. and Fendekova, M. (2010) 'Country update of the Slovak Republic', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-10.

Fendek, M. and Fendekova, M. (2015) 'Country update of the Slovak Republic', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-8.

Fričovský, B., Černák, R., Marcin, D., Blanárová, V., Benková, K., Pelech, O., Fordinál, K., Bodiš, D. and Fendek, M. (2020) 'Geothermal energy use – country update for Slovakia', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-19.

Slovenia

Kralj, P. and Rajver, D. (2000) 'State-of-the-art of geothermal energy use in Slovenia (country update)', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-9.

Rajver, D. and Lapanje, A. (2005) 'The current status of geothermal energy use and development in Slovenia', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-9.

Rajver, D., Lapanje, A. and Rman, N. (2010) 'Geothermal development in Slovenia: country update report 2005-2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-10.

Rajver, D., Rman, N., Lapanje, A. and Prestor, J. (2015) 'Geothermal development in Slovenia: update report 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-14.

Rajver, D., Rman, N., Lapanje, A. and Prestor, J. (2020) 'Geothermal country update report for Slovenia, 2015-2019', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-16.

South Korea

Yum, B. W. (2000) 'The present status of Korean geothermal research and investigations', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-6.

Song, Y. (2005) 'Direct use geothermal development in Korea: country update 2000-2004', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-7.

Song, Y., Kim, H-C. and Lee, T. J. (2010) 'Geothermal development in Korea: country update 2005-2009', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-11.

Song, Y. and Lee, T. J. (2015) 'Geothermal development in the Republic of Korea: country update 2010-2014', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-8.

Song, Y. and Lee, T. J. (2020) 'Geothermal development in the Republic of Korea: country update 2015-2019', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-9.

Spain

Sanchez-Guzman, J. and Garcia de la Noceda-Marquez, C. (2005) 'Geothermal energy development in Spain – country update report', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-10.

Sanchez-Guzman, J. and García de la Noceda, C. (2010) 'The evolution of geothermal energy in Spain – country update (2005-2009)', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-8.

Arrizabalaga, I., de Gregorio, M., García de la Noceda, C., Hidalgo, R. and Urchueguía, J. F. (2015) 'Country update for the Spanish geothermal sector', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-9.

Arrizabalaga, I., de Gregorio, M., de Santiago, C., García de la Noceda, C., Pérez, P. and Urchueguía, J. F. (2020) 'Country update for the Spanish geothermal sector', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-10.

Tunisia

Mohamed, M. B. (2010) 'Geothermal direct application and its development in Tunisia', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-8.

Mohamed, M. B. (2015) 'Geothermal energy development: the Tunisian experience', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-8.

Türkiye

Batik, H., Koçak, A., Akkus, I., Simsek, S., Mertoglu, O., Dokuz, I. and Bakir, N. (2000) 'Geothermal energy utilisation development in Turkey. Present geothermal situation and projections', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-7.

Simsek, S. (2005) 'Geothermal energy utilisation, development and projections – country update report (2000-2004) of Turkey', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-10.

Mertoglu, O. (2010) 'Geothermal country update report of Turkey (2005-2010)', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-9.

Mertoglu, O., Simsek, S. and Basarir, N. (2015) 'Geothermal country update report of Turkey (2010-2015)', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-9.

Mertoglu, O., Simsek, S. and Basarir, N. (2020) 'Geothermal energy use: projections and country update for Turkey', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-11.

United Kingdom

Batchelor, T., Curtis, R. and Ledingham, P. (2005) 'Country update for the United Kingdom', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-5.

Batchelor, T., Curtis, R. and Ledingham, P. (2010) 'Country update for the United Kingdom', *World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April, pp. 1-4.

Batchelor, T., Curtis, R., Ledingham, P. and Law, R. (2015) 'Country update for the United Kingdom', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-7.

Batchelor, T., Curtis, R. and Busby, J. (2020) 'Geothermal energy use, country update for United Kingdom', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-10.

United States of America

Lund, J. W. and Boyd, T. L. (2000) 'Geothermal direct use in the United States update: 1995-1999', *World Geothermal Congress 2000*. Kyushu-Tohoku, Japan, 28 May-10 June, pp. 1-9.

Lund, J. W., Bloomquist, R. G., Boyd, T. L. and Renner, J. (2005) 'The United States America country update', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-19.

Lund, J. W., Gawell, K., Boyd, T. L. and Jennejohn, D. (2010) 'The United States of America country update 2010', *World Geothermal Congress 2005*. Antalya, Turkey, 22-29 April, pp. 1-18.

Boyd, T. L., Sifford, A. and Lund, J. W. (2015) 'The United States of America country update 2015', *World Geothermal Congress 2015*. Melbourne, Australia, 19-25 April, pp. 1-12.

Lund, J. W., Sifford, A., Hamm, S. G. and Anderson, A. (2020) 'The United States of America direct utilization update 2019', *World Geothermal Congress 2020+1*. Reykjavik, Iceland, April-October 2021, pp. 1-16.

Appendix E

Sampling process table with raw data.

The table contains an initial sampling pool with 39 countries using geothermal energy for greenhouse agriculture purposes. It shows the *greenhouse agriculture capacity* (in MWt) for each country for every five-year period – 2010, 2015 and 2020. The values in parenthesis () signify the data from IGA Worldwide Reviews, while values without parenthesis indicate the data from IGA Country Updates. When data didn't match between the two sources, Country Updates were given priority as they represent original submissions from industry experts.

The dataset was analyzed for data *integrity*, *trend*, and *consistency*. These stages are represented in the table together with a *final sampling pool* consisting of twelve countries. The *yes* in the *decision* column indicates the country being included in the final sampling pool together with its *energy development tendency*. The tendency is identified as growth, with a continuous increase in capacity (Austria, Greece, Hungary, Iceland, the Netherlands, Spain, and Türkiye) and decline, with a continuous decrease in capacity (Italy, Japan, Kenya, Serbia, and the USA).

All numbers in the table are rounded. The changes of 1 MWt or less are considered rounding errors and are disregarded.

№	Country	Greenhouse agriculture capacity, MWt			Data analysis			Final sampling pool	
		2010	2015	2020	Integrity	Trend	Consistency	Decision	Tendency
1	Algeria			1	•				
2	Argentina	20	21	21		•			
3	Austria	2	2	22				yes	growth
4	Belgium	(1)			•				
5	Bosnia & Herzegovina	1			•				
6	Bulgaria	6	1	1		•			
7	China	147	154	346			•		
8	Croatia		7	2	•				
9	Cyprus			0,07	•				
10	Ecuador			(0,05)	•				
11	Egypt		1		•				
12	El Salvador	(0,5)	(0,5)	(0,5)		•			
13	France	9	8	8		•			
14	Georgia	2	20	18			•		
15	Greece	34	34	38				yes	growth
16	Hungary	196	271	358				yes	growth
17	Iceland	45	45	57				yes	growth
18	Israel	(27)	(27)	(27)		•			
19	Italy	69	69	67				yes	decline
20	Japan	37	(37)	25				yes	decline
21	Kenya	16	16	5				yes	decline

22	Mexico	0,004	0,004		•				
23	Mongolia	(2)			•				
24	Netherlands	10	(100)	230				yes	growth
25	New Zealand	24	24	24		•			
26	North Macedonia	3	3	3		•			
27	Poland	(0,5)			•				
28	Portugal	1	1	(1)		•			
29	Romania	4	15	15		•			
30	Russia	160	160	160		•			
31	Serbia	19	13	5				yes	decline
32	Slovakia	17	15	45		•			
33	Slovenia	13	15	10			•		
34	South Korea	0,17	0,17	0,17		•			
35	Spain	15	15	(22)				yes	growth
36	Tunisia	(42)	(42)	(42)		•			
37	Türkiye	483	612	820				yes	growth
38	United Kingdom	0,25			•				
39	United States of America	97	97	80				yes	decline

Appendix F

Content and thematic analysis codebook and record sheet.

Content analysis codebook

Content codebook contains the *policy items* and their *names* separated by *level*. *Units of analysis*, *predefined categories*, and *values* for each policy item are also shown.

Policy level	Policy item	Policy name	Unit	Categories	Value
Global	G2 and N1	Nationally Determined Contributions (NDC) and Emissions Reduction Targets	words phrases sentences	geothermal thermal geothermal energy geothermics	total number of context relevant references in a document
	G4	National Sustainable Development Strategy			
National	N2	Renewable Energy Action Plan			
	N11	Geothermal Energy Action Plan			
Local	L2	Legally defined ownership rights of geothermal resource and its regulation	ownership regulation status	factual presence count	

Thematic analysis codebook

Thematic codebook contains *main recurring themes*, their *types* per sector and topic and *corresponding codes* for each identified national policy mention.

Each national policy mention can cover one or more themes. If a mention covers one theme, it is represented by two letters: one for *sector* (heating and cooling, electricity, or other) and one for the *topic* (general, financial, or policy). Sometimes the theme is not straightforward, e.g., the mention can cover both heating and cooling and electricity sectors. In this case, three or more letters are used for coding, for instance a financial instrument that influences both electricity and heating and cooling sectors, such as “co-financing scheme by federal government to support test drilling” in Austria is coded as H/EF.

Type of theme	Main themes	Code
Sector	Heating and cooling	H
	Electricity	E
	Other	O
Topic	General	G
	Financial	F
	Policy	P

Content and thematic analysis record sheet

A record sheet below shows the data values and mentions counted for each policy document per country. Each country includes six policy items with their values per policy and level indicated as numbers in parenthesis (). (*N/a*) indicates the lack of a certain policy document and value zero (0) shows there are no relevant references in a document. *Asterisk superscript* (*) signifies the explicit connection between geothermal energy and greenhouse agriculture in a policy. The relevance of these values should only be assessed relative to each other and not as absolute.

When geothermal energy is mentioned in a policy a table with specific mentions is attached. *Unit* stands for a specific phrase or sentence that references geothermal energy. *Page* indicates specific page number in a document (for global and national policies) or a specific article/paragraph in the law (for local policies) where the reference can be found. Some local level references (ownership and status of geothermal energy) are identified as *implicit*, which means they are not legally defined in the law but rather implied through a broader legal framework. Column *value* shows whether a certain mention is considered for the final count. *Value 1* stands for mentions that advocate and encourage the use of geothermal energy, introducing certain targets, goals and plans for its expansion. References with value 1 are included in the final count. *Value 0* identifies so-called “unaccounted references”, which are aimed at specific markets (electricity, district heating and cooling, etc.) not relevant for the hypotheses. These can also represent simple factual statements about energy development or negative references about barriers and issues impeding energy expansion. Implicit local mentions are also unaccounted. References with value 0 are not included in the final count. *Asterisk superscript* (*) next to the value signifies the explicit connection between geothermal energy and greenhouse agriculture in a policy. The *code* in the final column indicates the coded theme for national policy mentions.

AUSTRIA

Global level (0)

G2 and N1 (0)

G4 (n.a.)

National level (7)

N2 (7)

Unit	Page	Value	Code
Certification schemes for shallow geothermal systems and heat pumps	40	1	HP
Environmental Assistance in Austria (UFI): funding support for companies and individuals for installation of geothermal applications	63	1	H/EF
Financial support for geothermal heating plants and heat pumps	66, 69, 98, 102	1	HF
Financial support for geothermal projects e.g., the reuse of existing oil wells, drilling, underground injection, distribution grids	67, 98	1	H/EF
Co-financing by federal states to support test drilling	67	1	H/EF
Projected final energy consumption from geothermal heating and cooling: 40 ktoe by 2020	87	1	HG
Projected final energy consumption from geothermal heat pumps: 26 ktoe by 2020	87	1	HG
Feed-in-tariffs for geothermal small-scale eco-electricity plants	55, 57, 61	0	EF
Projected gross electricity production from geothermal energy: 1 MW by 2020	84, 103	0	EG
Green electricity ordinance 2010: fixed price of 7.50 c/kWh for geothermics	149	0	EF

N11 (n.a.)

Local level (0)

L2 (0) Water Rights Acts 1959

Unit	Page	Value
Geothermal energy is regulated as a groundwater resource	implicit	0
Ownership rights of geothermal energy are based on the landownership	implicit	0

GREECE

Global level (1)

G2 and N1 (0)

G4 (1)

Unit	Page	Value
Geothermal energy is a resource with high potential	70	1

National level (8)

N2 (8)

Unit	Page	Value	Code
Greece has promising geothermal potential	7	1	O
To support the heat production and district heating and cooling from geothermal energy	10, 64 70, 79	1	HG
Law 3175/2003: exploitation of the geothermal potential	30, 31	1	H/EP
Ministerial Decree OG 1249/B/2009: utilization of geothermal energy for personalized heating and cooling use	46	1	HP
Fiscal incentives for shallow geothermal applications	64	1	HF
To support the co-generation of electricity and heating and cooling	79	1	H/EG
Projected final energy consumption from geothermal heat pumps: 50 ktoe by 2020	87, 103	1	HG
Projected final energy consumption from geothermal heating and cooling: 51 ktoe by 2020	103	1	HG
17 ktoe was produced from geothermal energy in 2008	7	0	O
Projected gross electricity production from geothermal energy: 120 MW by 2020	9, 11, 54, 79, 99	0	EG
Permitting and licencing for geothermal power plants	33, 40, 41	0	EP
Law 3851/2010: promotion of feed-in tariffs for geothermal plants	70, 73	0	EF/P
Remuneration for electricity production from geothermal energy: 73 €/MWh for mainland and 84.5 €/MWh for non-interconnected islands	72	0	EF

N11 (n.a.)

Local level (2)

L2 (2) Legislative Decree 210/1973, or Mining Code 1973

Unit	Page	Value
Geothermal potential is regulated as a mineral resource	Art. 2	1
Ownership rights of geothermal potential belong to the state	Art. 3, Art. 143	1

HUNGARY

Global level (1)

G2 and N1 (0)

G4 (1)

Unit	Page	Value
Hungary has good geothermal potential	30	1

National level (8)

N2 (8)

Unit	Page	Value	Code
The use geothermal energy represents one of the pillars of the green economy	15	1	O
Geothermal energy is a natural treasure of Hungary	39, 201	1	O
National Energy Saving Programme: preferential loans, tariffs and non-refundable aid for geothermal electricity and heat	39, 41 52, 95, 121, 133, 135, 201	1	H/EF
Investment and third-party financing support to promote the use of geothermal energy	41, 134	1	H/EF
Requirements for ground source heat pump installations	82	1	HP
To increase the capacity and efficiency of the existing geothermal heat supply systems	159	1	HG
Projected final energy consumption from geothermal heating and cooling: 357 ktoe by 2020	209	1	HG
Projected final energy consumption from geothermal heat pumps: 107 ktoe by 2020	209	1	HG
Limiting factors for geothermal energy: development costs	39	0	O
Installation and renewal of power grid connections using geothermal energy	134	0	EG
Projected gross electricity production from geothermal energy: 57 MW by 2020	202	0	EG

N11 (n.a.)

Local level (1*)

L2 (1*)

Act XLVIII of 1993 on Mining

Unit	Page	Value
Geothermal energy is regulated as a mining activity	para. 49	0
Ownership rights of geothermal energy below 2500m belong to the state	para. 3	0.5

Act LVII of 1995 on Water Management

Unit	Page	Value
Geothermal energy above 2500m is regulated as thermal water	implicit	0
Ownership rights of thermal waters above 2500m are based on the landownership	para. 6	0.5
Geothermal energy water usage for agricultural production is covered in the law	para. 10	*

ITALY

Global level (0)

G2 and N1 (0)

G4 (0)

National level (9)

N2 (9)

Unit	Page	Value	Code
Energy efficiency credit scheme for geothermal heat pumps	6, 53, 56, 58, 139	1	HF
Data record sheets for low temperature geothermal heat	52	1	H/EG
Projected final energy consumption from geothermal heating and cooling: 300 ktoe by 2020	167	1	HG
Law 9/1991: introduction of a new National Energy Plan including the development of geothermal energy	176	1	H/EP
Legislative Decree 22/2010: reorganization of legislation relating to search for and mining of geothermal resources	179	1	H/EP
Apulia Regional Law 19/2000: administrative procedures relating to geothermal resources	198	1	H/EP
Tuscany Regional Executive Decision 933/2008: division of geothermal funds	202	1	H/EP/F
Projected final energy consumption from geothermal heat pumps: 522 ktoe by 2020	209	1	HG
Aid scheme for experimental operations of high-temperature geothermal energy	228	1	H/EP
Promotion and development of geothermal district heating and cooling with tax relief measures for users connected to such networks: 25,8 €/MWht	6, 26, 31, 56, 60, 99, 139, 143	0	HF
Community Support Framework 2007-2013: funding support for geothermal power plants	12	0	EF
Integration of geothermal energy into buildings	31, 58, 65	0	HG
Law 99/2009: requirements for the installation of geothermal heating and cooling systems in buildings	41	0	HP
Geothermal tariffs of 20 euroCent/kWh	123	0	EF
Projected gross electricity production from geothermal energy: 920 MW by 2020	164	0	EG

Local level (2)

L2 (2) Legislative Decree No. 22, of February 11, 2010

Unit	Page	Value
Geothermal resource is regulated as a mineral resource	Art. 1.6	1
Ownership rights of geothermal resources belong to the state	Art. 1.6	1

NETHERLANDS

Global level (0)

G2 and N1 (0)

G4 (0)

National level (21*)

N2 (5)

Unit	Page	Value	Code
Certification schemes for shallow geothermal systems and heat pumps	45	1	HP
Expected increase from deep geothermal energy: 11 PJ by 2020 compared to 1.6 PJ in 2010	106	1	O
Projected final energy consumption from geothermal heating and cooling: 259 ktoe by 2020	110	1	HG
Projected final energy consumption from geothermal heat pumps: 242 ktoe by 2020	110	1	HG
Implementation program: geothermal energy is a part of comprehensive renewable energy regional strategies – Climate Energy and Space 2010	113	1	H/EP
Use of geothermal for large scale district heating networks	55	0	HG

N11 (16*)

Unit	Page	Value	Code
To increase the contribution of geothermal to 50 PJ by 2030 and 200+ PJ by 2050	9, 30	1	O
CO ₂ reductions from geothermal: three mton in 2030 and 12 mton by 2050	9	1	O
Geothermal energy to become a baseload energy source	9, 10	1	O
Geothermal energy is the most economical sustainable solution	9, 12	1	O
To develop greenhouse horticulture as a priority sector: to meet 50% of the demand from geothermal energy	9, 12	1*	HG
Ultra Deep Geothermal pilot projects	10, 12, 22	1	H/EG
To increase direct and indirect jobs in geothermal industry	12	1	O
To promote research, innovation, and information about geothermal energy	14, 49, 54	1	O
To optimize and adapt policies for geothermal sector e.g., amendment of the Mining Act	14, 39, 42	1	H/EP
Expansion of subsidy schemes such as SDE+	15	1	H/EF
To generate models for public participation and monitoring	15, 50, 54	1	O
Geothermal data collection and data management system	35, 47	1	H/EG
Cost reduction through asset management and innovation	37	1	H/EF
To establish predictable price policies	38	1	H/EP/F
Implementation of industry standards and guidelines	40	1	H/EP
To improve geothermal energy safety management systems	45	1	H/EG
Use of geothermal in the urban environments in district heating networks	11	0	HG

Use of geothermal for industrial uses e.g., breweries, milk factories	12	0	HG
---	----	---	----

Local level (0)

L2 (0)

Mining Act 2002

Unit	Page	Value
Geothermal energy below 500m is regulated as terrestrial heat	implicit	0
Ownership rights of terrestrial heat below 500 m belong to the state	implicit	0

Water Act 2009

Unit	Page	Value
Geothermal energy above 500m is regulated as groundwater	implicit	0

SPAIN

Global level (0)

G2 and N1 (0)

G4 (0)

National level (11)

N2 (11)

Unit	Page	Value	Code
Geothermal energy is considered new and unknown	38	1	O
Certification model for geothermal energy installations	53, 91, 95, 97	1	H/EP
To promote knowledge of geothermal potential as regulatory measure	53	1	H/EP
To develop financial aid and risk reduction programs	53	1	H/EP
Analysis of the equipment and application of technical specifications for geothermal drilling	75	1	H/EG
Law 22/1973 of July 21, 1973 on Mines: regulation of geothermal resources	107	1	H/EP
Emerging geothermal heat pumps market	143	1	HG
Projected final energy consumption from geothermal heating and cooling: 9.5 ktoe by 2020	155	1	HG
Projected final energy consumption from geothermal heat pumps: 40.5 ktoe by 2020	155	1	HG
Total employment generated by geothermal in 2010 is 577 people, forecast for 2015 - 641, for 2020 - 430	158	1	O
Forecasted cumulative CO ₂ emissions prevented by 2020 with the use of geothermal energy: 201 636 for electricity tCO ₂ /year and 74 358 tCO ₂ /year for heating and cooling	161	1	H/EG
No local ordinance for geothermal energy	82	0	O
Non-manageable geothermal electricity plants with 50 MW or lower	99	0	EG
Contributions made from geothermal for heating and cooling will not be significant	103	0	HG
Implementation of district heating projects	103, 119, 143	0	HG
Remuneration for electricity generation from geothermal: regulated tariff for the first 25 years is 7.2 eurocent/kWh and thereafter is 6.8 eurocent/kWh	113	0	EF
Pilot financing programme GEOCASA for geothermal heating and cooling installations in buildings	120	0	HF
Regulation on thermal installations in buildings	120	0	HP
Development of a high-temperature geothermal power project in Tenerife and other Canary Islands	142	0	EG
Pilot projects for EGS for electricity generation	143	0	EG

Current use of geothermal spas and greenhouses is stable and is not expected to grow	143	0	HG
Feasibility studies for geothermal electricity in deep sedimentary basins	143	0	EG
Projected gross electricity production from geothermal energy: 50 MW by 2020	154	0	EG

Local level (2)

L2 (2) Law 22/1973, of July 21, 1973 on Mines

Unit	Page	Value
Geothermal resources are classified as mineral deposits	Art. 3	1
Ownership rights of geothermal resources belong to the public	Introduction	1

ICELAND

Global level (5)

G2 and N1 (0)

G4 (5)

Unit	Page	Value
Export of Icelandic knowledge with regards to geothermal energy to other countries	41, 55, 107, 109	1
Grants to support geothermal exploration	53	1
Low costs of geothermally energy in Iceland	54	1
Training of young professionals via United Nations University Geothermal Training Programme	55, 61, 66, 85, 110	1
CarbFix: carbon dioxide research in geothermal fluids	66	1
Grants to support the construction of new geothermal district heating systems	53	0
Geothermal energy (electricity and/or heat) is used in 90% of buildings	53	0
Air quality studies from geothermal power plants	75	0
Reykjavik city geothermal district heating project	87	0

National level (12*)

N2 (12*)

Unit	Page	Value	Code
Iceland has big reserves of geothermal energy	3	1	O
To encourage the use of geothermal plants industrial parks, horticulture stations, recycling	4	1*	HG
The Nature Conservation Act No 44/1999 on special protection for geothermal resources: to formulate protective approach for geothermal energy use	4, 37	1	H/EP
Geothermal energy is very economical in Iceland	7	1	O
National Energy Fund: grants and loans to increase the use of geothermal in “cold areas”, where geothermal heat has not yet been detected	17, 25, 28, 43, 47	1	H/EF
Act No 48/2011 on the Master Plan for Hydro and Geothermal Energy Resources in Iceland	19	1	EP
Grants and state subsidies to use geothermal for space heating and to change the supply from oil to geothermal	24, 36, 43	1	HF
Orkusetur, government agency: to promote the rational use of geothermal space heating	27	1	HG
Financial support for geothermal research and drilling	43	1	H/EF
Geothermal Research and Utilization Scheme: geothermal-specific targets for research and utilization	44, 45	1	O
Potential of joint projects and knowledge export in the field of geothermal	56	1	O

Projected final energy consumption from geothermal heating and cooling: 805 ktoe by 2020	155	1	HG
Geothermal energy is used in 90% of buildings for heating and cooling and 27% for electricity	3, 5, 7, 23, 32, 34, 25, 28, 36, 41, 44, 57	0	H/EG
Energy Act 58/1967: concessions for geothermal district heating systems	18	0	HP
Projected gross electricity production from geothermal energy: 715 MW by 2020	59	0	EG

N11 (0)

Unit	Page	Value	Code
Scope includes geothermal high temperature areas of 200 °C or higher with depth of 1000 m or less for electricity generation	Article 2	0	EG
Preparation of a Master Plan on the utilisation of hydroelectric power and geothermal energy	Article 13	0	EP

Local level (1*)

L2 (1*) Act on Survey and Utilization of Ground Resources 1998 No 57 of 19 June, or Natural Resource Act

Unit	Page	Value
Geothermal resources are classified as ground resources	implicit	0
Ownership rights of geothermal resources are based on the landownership	Article 3	1
Use of geothermal energy for agricultural purposes is covered in the law	Article 10	*

JAPAN

Global level (0)

G2 and N1 (0)

Unit	Page	Value
Geothermal energy to amount to approx. 1% of total power generation by 2030	8	0

G4 (0)

National level (3)

N2 (3)

Fourth Strategic Energy Plan 2014 (3)

Unit	Page	Value	Code
Japan has the world's third largest amounts of geothermal resources	24	1	O
Combined heat-power use of geothermal energy is anticipated	45	1	H/EG
Support for heat supply facilities using geothermal energy	45	1	HG
Geothermal is considered "base-load powerhouse": it provides electricity in a stable manner	22, 45	0	EG
Geothermal energy has low power generation cost	22, 45	0	EG
Geothermal power development requires long time and high investments	43	0	EG
To streamline safety regulations, accelerate environmental assessment and mitigate investment risks under Electricity Business Act	44	0	EF/P
Current use: geothermal provides warm water for hotels and greenhouses	45	0	HG
Challenges with regulation, coordination with regions and environmental assessment of geothermal	45	0	O
Research activities for appropriate use and evaluation of geothermal power generation	46, 85	0	EG

Fifth Strategic Energy Plan 2018 (0)

Unit	Page	Value	Code
Measures to make geothermal an independent, competitive major power source	50, 110, 123	0	EG
Power grid constraints: geothermal resources are located in only some regions	50	0	EG
Japan has 70% share of global market for geothermal power equipment manufacturing	51	0	EG
To promote global expansion of geothermal power as a decarbonization technology	51, 120	0	EG

N11 (n.a)

Local level (0)

L2 (0)

Industrial Water Law No. 146 of 1956

Unit	Page	Value
Geothermal resources are regulated as industrial water	implicit	0

Civil Code Act No. 89 of 1896

Unit	Page	Value
Ownership rights of geothermal resources are based on the landownership	implicit	0

KENYA

Global level (2)

G2 and N1 (2)

Unit	Page	Value
Expansion of geothermal energy as a climate mitigation strategy	1, 2	1
Revised business-as-usual projection for geothermal deployment to reflect current trends	4	1

G4 (0)

National level (12)

N2 (12)

National Climate Change Action Plan 2013 (10)

Unit	Page	Value	Code
Geothermal Development Company, Ministry of Energy: to facilitate the use of secure and geothermal energy source	13	1	H/EG
Geothermal energy is one of the most promising, low carbon priority actions: it should be the baseload energy source	31, 36, 61, 66, 110, 117, 147, 162	1	O
Energy Policy Act: to promote geothermal energy	116	1	H/EP
To scale up resource mapping and data availability of geothermal resource	119	1	H/EG
Company KenGen acquired innovative geothermal energy technologies	126	1	O
Geothermal energy can improve energy security	147, 162	1	O
Projected investment costs for geothermal energy by 2030: 877 – 1115 billion KSh	151	1	H/EP
Knowledge import and geothermal development cooperation: formulate bilateral initiatives	162, 184		O
Analysis of the remaining gaps and barriers for geothermal development in Kenya	163	1	O
Education and training activities for geothermal energy	210	1	O
Feed-in-Tariffs for the generation of electricity from geothermal energy	11	0	EF
To promote and expand the use of geothermal power generation	16, 66, 119	0	EG
Electricity supply in Kenya is dominated by geothermal energy	66	0	EG
Geothermal power is the key enabler for Kenya's economic growth, it is cost-competitive on a life cycle basis	66, 162	0	EG
Geothermal power has the largest CO ₂ abatement potential	67	0	EG
To develop an additional 2,257 MW of geothermal power capacity by 2030 by encouraging private sector investments via grants, access to loans, risk mitigation schemes, etc.	80, 162	0	EF
List of communication techniques for geothermal power	111	0	EG

Lack of supportive networks for installation and maintenance of geothermal technologies	112	0	O
The use of directional, deep drilling, well-head technologies in geothermal power development	119	0	EG
Water shortages for local communities by unsustainable use of geothermal	138	0	O
Un-recycled water demand from geothermal power generation	139	0	EG
Geothermal power generation has up to 10 000 MW potential in Kenya	147, 162	0	EG
Geothermal power is clean, reliable, renewable, and large-scale domestic source	147	0	EG
High initial costs and resource exploration risks slow down geothermal power development	162	0	EG
Kenya's Updated Least Cost Power Development Plan: to prioritize geothermal power development	162	0	EP

National Climate Change Action Plan 2018 (2)

Unit	Page	Value	Code
To reduce emissions by 9.2. MtCO ₂ by 2020 through the development of geothermal and other energy sources	86, 129	1	O
To train 60 participants per year at the United Nation University Geothermal Training Programme	90	1	O
44% of Kenya's electricity was produced with geothermal in 2016/2017	13, 24, 85	0	EG
To develop captive geothermal plants to power boilers and dryers	88	0	EG

N11 (n.a.)

Local level (1)

L2 (1) Geothermal Resource Act 1982

Unit	Page	Value
Geothermal energy is regulated as a natural resource	implicit	0
Ownership rights of unextracted geothermal resources belong to the state	Article 3	1

SERBIA

Global level (0)

G2 and N1 (0)

G4 (0)

National level (8)

N2 (8)

Unit	Page	Value	Code
In Serbia, geothermal potential per year accounts for 0.2 Mtoe	7	1	O
Balance of geothermal energy is available since 2009	10	1	O
Projected final energy consumption for geothermal heating and cooling: 10 ktoe by 2020	19, 131	1	HG
Law on Mining and Geological Explorations: covers exploitation and use of geothermal resources	32, 35, 150	1	H/EP
Guide for investors covers construction of plants and generation of heat and electricity from geothermal energy	50	1	H/EF
To define the procedure for the certification of equipment installations for geothermal plants	70	1	H/EP
Estimated financial investment for geothermal heat production by 2020: 1500 € / kWt	126	1	HF
Rulebook on the Content of Mining Design Documentation: covers geothermal design	151	1	H/EP
Geothermal accounts for 3% of all renewable energy sources	7	0	O
Projected gross electricity production from geothermal energy: 1 MW by 2020	18, 130	0	EG
To consider geothermal energy as an energy source in buildings	60	0	HG
To use geothermal energy as a replacement of fossil fuels in district heating systems	87	0	HG
Estimated financial investment for geothermal electricity production by 2020: 4115 € / kW	126	0	EF

N11 (n.a.)

Local level (1)

L2 (1) Law on Mining and Geological Explorations 2015

Unit	Page	Value
Geothermal energy is regulated as a mining resource	implicit	0
Ownership rights of geothermal resources belong to the state	Article 4	1

TÜRKIYE

Global level (0)

G2 and N1 (n.a.)

G4 (0)

Voluntary National Report 2016 (0)

Voluntary National Report 2019 (0)

Unit	Page	Value
Purchase guarantee tariffs for generation of electricity from geothermal are 10.5 USD cents/kWh	77	0
Geothermal generation in 2013 was 1.4 TWh and 6.1 TWh in 2017	78	0
Energy generation through geothermal energy is one of the key components of the policy framework	79	0

National level (14*)

N2 (14*)

Unit	Page	Value	Code
The use of geothermal energy is among the key contributors to the renewable energy mix	8	1	O
Strategies to protect geothermal resources during utilization	10	1	H/EG
Geothermal Law No: 5686: rules for search, exploration, development, production, and protection of geothermal resources	11, 13, 75	1	H/EP
The existence of big geothermal potential in Türkiye	27, 56	1	O
Risk-sharing mechanism, or mitigation of capital risk to support geothermal drilling and exploration by private investors	27, 30, 56	1	H/EF
Financial investment support to promote the development of Hot Dry Rock geothermal	27	1	H/EF
Introduction of feed-in-tariff premium for early-stage geothermal development projects for private sector, for instance the use of waste heated water in greenhouses	30, 51	1*	HF
Licence for geothermal exploration activities	34, 36	1	H/EP
Information support for the investors regarding access to the geothermal resource	36	1	O
Introduction of certification schemes for shallow and heat pump geothermal systems	41, 43	1	HP
Distinction between small-scale biomass, solar thermal and geothermal systems	43	1	O
Opportunity cost: if Türkiye will not use available geothermal resources, their potential will be wasted	53, 58, 61	1	O
Projected final energy consumption from geothermal heating and cooling: 485 ktoe by 2023	57, 69	1	HG
Projected final energy consumption from geothermal heat pumps: 2440 ktoe by 2023	57	1	HG

Projected gross electricity production from geothermal energy: 1000 MW or higher by 2023	8, 18, 22, 51-52, 67, 68	0	EG
Geothermal energy production increased from 1 million toe in 2007 to 2.2. million toe in 2012	9	0	O
To open up areas for geothermal electricity development to accelerate private sector participation	10	0	EG
Law No: 5346 on the utilization of renewable energy resources for the purpose of generating electrical energy	12	0	EP
Geothermal installed power capacity was 310 MW in 2013	18	0	EG
Administrative procedures to install geothermal power capacities	33	0	EP
The potential to use geothermal in district heating and cooling systems: proven geothermal capacity 31 500 MWt	48, 69	0	HG
Feed-in-tariff scheme for the sale of geothermal electricity: 10.5 USD cent/kWh	54, 55	0	EF

N11 (0)

Local level (1)

L2 (1) Law No. 5686 on Geothermal Resources and Mineral Waters 2007

Unit	Page	Value
Ownership rights of geothermal resources belong to the state	Article 4	1

UNITED STATES OF AMERICA

Global level (0)

G2 and N1 (0)

G4 (n.a.)

National level (1)

N2 (1)

Unit	Page	Value	Code
Negotiations for free global trade in geothermal energy technologies	19	1	O
The use of geothermal energy for electricity production has doubled in the USA	4, 6	0	EG
Deploying additional potential from geothermal energy for military installations by 2025	7	0	H/EG
Since 2009 new 11 geothermal power plants were approved	7	0	EG

N11 (n.a.)

Local level (2)

L2 (2)

Ottobonie vs. the United States of America 1977

Pariani vs. State of California 1980

Unit	Page	Value
Geothermal energy is regulated as a mineral resource	court order	1
Ownership rights of geothermal resources belong to the state	court order	1

Appendix G

Python code used for computing leave-one-out cross-validation (LOOCV).

```
#importing libraries

import pandas as pd
import seaborn as sns
import matplotlib.pyplot as plt

#setting seaborn plotting style
sns.set_style("whitegrid", {"grid.color": ".6", "grid.linestyle": ":"})
binarycolor = np.array([1,1,1,0,1,1,1,0,0,0,1,0]) #Capacity change binary marker 1=growing,
0=declining (for plotting marker colors)
df= data#.append(color)
spec = sns.color_palette("coolwarm", as_cmap=True)

#Function to place labels in readable locations
def Countplot(df, spec):

def plotlabel(xvar, yvar, label):
    if label == 'USA':
        plt.text(xvar-1.7, yvar+8.2, label, size=14)
    elif label == 'Greece':
        plt.text(xvar-0.2, yvar+9.6, label, size=14)
    elif label == 'Serbia':
        plt.text(xvar-1.2, yvar-19.4, label, size=14)
    elif label == 'Austria':
        plt.text(xvar-0.6, yvar+15.9, label, size=14)
    elif label == 'Italy':
        plt.text(xvar-0.1, yvar-24.9, label, size=14)
    elif label == 'Japan':
        plt.text(xvar+0.2, yvar+20.9, label, size=14)
    elif label == 'Netherlands':
        label = 'Netherlands*'
        plt.text(xvar-0.9, yvar+12, label, size=14)
    elif label == 'Kenya':
        plt.text(xvar+.4, yvar-6, label, size=14)
    elif label == 'Iceland':
        label = 'Iceland*'
        plt.text(xvar-.4, yvar+9, label, size=14)
    elif label == 'Spain':
        plt.text(xvar+.2, yvar, label, size=14)
    elif label == 'Turkiye':
        label='Türkiye*'
        plt.text(xvar+0.3, yvar+5, label, size=14)
    elif label == 'Hungary':
        label='Hungary*'
        plt.text(xvar+0.5, yvar+5, label, size=14)
    else:
        plt.text(xvar+0.5, yvar+.2, label, size=14)

#Matplotlib plotting properties
```

```

plt.rcParams["font.family"] = "serif"
plt.rcParams["font.serif"] = ["Times New Roman"]
plt.rcParams["font.weight"] = "normal"
plt.rcParams["legend.title_fontsize"] = "x-large"
plt.rcParams["legend.fontsize"] = "large"
plt.figure(figsize=(12,6))
plt.xlim(0,25)
plt.ylim(-70, 390)

plt.legend(loc=2,prop={'size':12})

# The magic starts here: dropping one input and evaluating linear trend for the remaining
data
for i in range(len(df)):

    if str(df['Country'][i])=='Turkiye':
        label='Türkiye'
    else :
        label=str(df['Country'][i])

    sns.regplot(x='Policy Value', y='Capacity Change', truncate=False, ci=0, data = df.drop(i),
label=label, scatter=False,
                line_kws=dict(alpha=0.7, linewidth=2))

    df.apply(lambda x: plotlabel(x['Policy Value'], x['Capacity Change'], x['Country']), axis=1)

# Axis labels nad title
plt.title('Leave-one-out cross-validation', size=14, fontname="Times New Roman",
fontweight="bold")
plt.ylabel('Capacity change (MWt) 2010-2020', size= 14, fontname="Times New Roman",
fontweight="bold")
plt.xlabel('Policy incentives', size=14, fontname="Times New Roman", fontweight="bold")

#computing function and plotting
Countplot(df, spec)
sns.scatterplot(x='Policy Value', y='Capacity Change', data = df, marker='o', color='grey')

plt.savefig('LOO_cross_validation.svg')

```