Geothermal Energy Strategies: A Comparative Study of Austria, Finland, Iceland and New Zealand

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This thesis examines geothermal energy extraction methods in Austria, Finland, Iceland and New Zealand, comparing volcanic and non-volcanic environments to understand their efficiency and feasibility. Geothermal energy is an important component of sustainable energy strategies, providing a consistent energy supply with minimal environmental impact. The aim of the study is to explore the technical, environmental and political influences on different extraction methods and to address the following research questions How do geological conditions affect geothermal energy production? What are the environmental and policy implications of these methods?

Key concepts from the knowledge base include geothermal resource availability, high and low enthalpy extraction methods, and the role of policy and regulatory frameworks. The research methods include comparative analysis of geothermal technologies, data collection from case studies in the selected countries, and an assessment of environmental and policy factors influencing the use of geothermal energy.

The main findings indicate that volcanic regions such as Iceland and New Zealand effectively utilise direct steam and flash steam technologies due to their high-enthalpy geothermal fluids. In contrast, Austria and Finland, with non-volcanic environments, primarily use low-enthalpy resources through heat pumps and district heating, adapting to geological constraints. The thesis concludes that geothermal energy, supported by diverse extraction methods and robust policy frameworks, has an important role to play in the global transition to renewable energy. The findings underline the importance of technological advances and informed policy-making to improve the efficiency and sustainability of geothermal energy extraction.

Key words geothermal energy, sustainable energy, volcanic environments, non-volcanic environments, Austria, Finland, Iceland, New Zealand

CONTENTS

FOREWORD

I would like to express my sincere gratitude to the Lapland University of Applied Sciences for the invaluable resources provided, especially the extensive facilities and library services, which greatly assisted my research. Special thanks go to my supervisor, Ari Pikkarainen, whose guidance was vital. His willingness to answer any questions and his skilful handling of organisational and procedural issues were crucial to the successful completion of this thesis.

SYMBOLS AND ABBREVIATIONS

HDR	Hot Dry Rocks
GHP	Geothermal Heat Pumps: System using the earth’s consistent subsurface temperature for heating and cooling.
EGS	Enhanced Geothermal Systems: Technology to enhance or create geothermal reservoirs in non-volcanic areas.
EU	European Union
RED	Renewable Energy Directive: EU policy for increasing the use of renewable energy within the Union.
RMA	Resource Management Act: New Zealand law regulating geothermal development with sustainability considerations.

1 INTRODUCTION

In order to combat climate change and reduce our dependence on fossil fuels, finding renewable energy sources is becoming increasingly important. Among the various renewable energy sources, geothermal energy has attracted attention due to its potential for sustainability and constant power supply. This thesis examines how geothermal energy is extracted, focusing on the differences between volcanic and non-volcanic regions. These differences are explored in depth through case studies from Austria, Finland, Iceland, and New Zealand.

Geothermal energy, which utilises heat from the earth's interior, is a clean and sustainable energy source. However, the efficiency and feasibility of geothermal energy extraction methods vary greatly, depending on the geological conditions. The aim of this thesis is to compare and analyse these methods within specific regions, considering the technical, environmental, and political factors that influence their application and development.

Austria and Finland represent non-volcanic regions where the lack of natural heat sources of geothermal reservoirs poses a challenge for geothermal energy extraction. In contrast, Iceland and New Zealand are located in volcanic areas rich in geothermal resources, making them ideal for geothermal energy production. This thesis seeks to understand how these countries are utilising their geothermal potential and what impact their strategies have on the broader goal of transitioning to green energy.

It also examines the role of the policy and regulatory framework in the development of geothermal energy. The EU's Renewable Energy Directive (RED) and other policies provide the background for Austria and Finland's commitment to renewable energy, including geothermal energy. Iceland and New Zealand, on the other hand, have introduced independent policies that reflect their different approaches to energy sustainability.

This thesis contributes to the understanding of the role of geothermal energy in sustainable energy strategies through a comparative analysis of geothermal energy extraction methods and efficiency. It also looks at the regional specificities of geothermal energy utilisation and the global impact of geothermal energy on renewable energy development.

2 HISTORY OF GEOTHERMAL ENERGY EXTRACTION

The exploration and utilisation of geothermal energy span centuries, marking significant milestones in human innovation and engineering. This section delves into the historical progression of geothermal energy use, from ancient times to its role in the modern renewable energy landscape.

2.1 Ancient Utilisation

The use of geothermal resources can be traced back to ancient civilizations. The earliest known use of geothermal energy was by the Paleo-Indians, who settled in the hot springs areas in North America over 10,000 years ago. These springs served as a crucial resource for cooking, heating, and medicinal purposes. Similarly, the Romans, renowned for their engineering prowess, harnessed geothermal heat for bathing, space heating, and other domestic purposes in areas like Pompeii and Chaudes-Aigues in France, where the earliest known hot water heating systems were established around the 1st century AD. (Kępińska 2004, 2–3.)

2.2 Industrial Revolution to Early 20th Century

The industrial revolution brought about a paradigm shift in the way geothermal resources were viewed, transitioning from predominantly domestic and communal uses to industrial and commercial applications. The first attempt to produce electricity from geothermal steam occurred in Larderello, Italy, in 1904. Prince Piero Ginori Conti tested the first geothermal power generator, lighting four light bulbs and laying the groundwork for the first commercial geothermal power plant, which began operation in 1911. (Kępińska 2004, 2–3.)

2.3 Mid-20th Century to Present

The mid-20th century saw significant advancements in geothermal technology, spurred by the oil crises of the 1970s. Countries like the United States, New Zealand, Iceland, and the Philippines began to invest heavily in geothermal research and development, recognizing the potential for geothermal energy to contribute to their energy mix and reduce dependency on fossil fuels. The development of Enhanced Geothermal Systems (EGS) technology in the late 20th century represented a significant leap forward, enabling the exploitation of geothermal resources in areas without natural hydrothermal activity. (Tester et al. 2006, 6–7.)

2.4 Modern Context

Today, the significance of geothermal energy as a key part of the global mix of renewable energy is widely acknowledged. Developments in the technology used for drilling, the efficiency of power plants, and the sustainable management of geothermal resources have increased the use of this type of energy. It is now central to plans aimed at reducing carbon emissions and supporting a future with low carbon emissions. (Paulillo, Striolo & Lettieri 2019.)

The use of geothermal power is expanding, with countries such as Iceland depending on geothermal sources for a large share of their electrical power and almost all of their heating needs. The environmental impact of geothermal power, particularly studied at the Hellisheiði power station in Iceland, has shown that geothermal energy is a low-carbon technology with an environmental impact comparable to other renewable energies. (Paulillo et al. 2019.)

The history of geothermal energy is a testament to human ingenuity and adaptability, illustrating how people have harnessed this natural resource to meet our changing energy requirements. From ancient times to its current role in renewable energy strategies, geothermal energy remains a symbol of the continuous search for sustainable and reliable sources of energy.

3 FUNDAMENTALS AND IMPACTS OF GEOTHERMAL TECHNOLOGY

This chapter outlines the fundamental aspects and diverse applications of geothermal technology, a critical component of renewable energy strategies. It describes the basic principles of extracting heat from the Earth's subsurface and the technological advances that allow efficient energy use. It then explores the different sources of geothermal energy, its important role in sustainable energy production and the environmental and economic benefits it offers. Each section builds on an understanding of geothermal systems, from their natural formation and resource types to their strategic importance in achieving energy sustainability and reducing environmental impact. (Tester, Drake, Driscoll, Golay & Peters 2012, 816–819.)

3.1 Key Concept and Definition

Geothermal energy is a renewable energy source derived from the Earth's internal heat. This form of energy is harnessed by tapping into the thermal energy stored beneath the Earth's crust. Geothermal energy is generated from the heat generated during the earth's formation and the ongoing radioactive decay of minerals. It can be found in shallow ground, hot water, and rocks beneath the Earth's surface, and down deeper to the high temperatures of molten rock called magma. Herein, a comprehensive explanation is provided on the nature, sources, and significance of geothermal energy, which forms the theoretical backbone for understanding its potential as a sustainable energy resource. (Fridleifsson et al. 2008, 59, 62.)

3.2 Nature and Formation

Geothermal energy comes from the heat stored in the Earth's crust, which includes both solid rock and water in its pores and fractures. As depth increases, so does the temperature, creating a thermal gradient that is accessible for energy exploitation. This heat primarily comes from two sources: the residual heat from the planet's formation over 4.5 billion years ago and the continuous radioactive decay of elements like potassium, thorium and uranium in the Earth's mantle and crust. (Fridleifsson et al. 2008, 62–64.)

3.3 Sources of Geothermal Energy

Geothermal energy sources are identified based on their geological and physical characteristics, ranging from hydrothermal convection systems, where water circulates through heated rock masses, to geopressurized zones, hot dry rocks, and magma bodies. These diverse sources provide a broad spectrum for geothermal energy extraction, catering to direct heating applications and electricity generation. (Lund, Freeston & Boyd 2011, 162–163.)

Hydrothermal Convection Systems

Hydrothermal convection systems are the most commonly exploited geothermal resources. These systems consist of naturally occurring reservoirs of hot water and steam, found a few kilometres beneath the Earth's surface. Water in these systems is heated by the Earth's magma and rises to the surface through fractures in the rocks. When this hot water reaches the surface, the drop in pressure causes the water to convert into steam, which can be harnessed to drive turbines and generate electricity. The main advantage of hydrothermal systems is their relative accessibility and the straightforward method of electricity generation they offer. However, their location is geographically limited to areas with volcanic activity or tectonic plate boundaries. (Tester et al. 2006, 816–822.)

Geopressurized Zones

Geopressurized zones are deep underground reservoirs containing hot water under extremely high pressure, combined with methane gas. These zones are found at depths of 3,000 to 6,000 meters and can reach temperatures of up to 200 °C. The pressure in these reservoirs is significantly higher than the hydrostatic pressure at the same depth. Exploiting geopressurized zones involves drilling into these reservoirs to release the pressurized water and methane, which can then be used to generate electricity. Challenges include managing the extraction of both hot water and methane gas safely and efficiently, and the relatively high costs associated with drilling at such depths. (Tester et al. 2012, 825.)

Hot Dry Rocks

Hot Dry Rocks (HDR), also known as Engineered or Enhanced Geothermal Systems (EGS), involve creating geothermal reservoirs in areas where hot rock exists but is not naturally permeable or saturated with water. The process involves drilling into the rock, fracturing it hydraulically, and circulating water through the fractures. The water heats up as it passes through the hot rocks and is then pumped back to the surface, where its thermal energy can be used for power generation or heating. The main challenge of HDR/EGS lies in the engineering difficulties of fracturing the rock sufficiently to create an effective, permeable reservoir and managing the seismic activity that can be induced by the fracturing process. (Tester et al. 2012, 825–828.)

Magma Bodies

Magma bodies represent the most intense sources of geothermal energy, comprising molten or partially molten rock at temperatures exceeding 700 °C. These are found at significant depths and offer the potential for high-energy production. Directly tapping into magma for geothermal energy is a relatively new concept and poses significant technological and logistical challenges, including drilling to great depths, managing the extreme temperatures and pressures, and ensuring the durability of materials used in the extraction process. Despite these challenges, magma bodies present a significant potential for future geothermal energy due to their vast energy content. (Tester et al. 2012, 828.)

In summary, each of these geothermal energy sources offers unique opportunities and challenges. From the relatively accessible hydrothermal convection systems to the intense energy potential of magma bodies, the diversity of these sources highlights the versatility of geothermal energy as a renewable resource. Continued advancements in drilling technology, materials science, and reservoir management are key to unlocking the full potential of these geothermal resources.

3.4 Significance of Geothermal Energy

Geothermal energy's contribution to renewable energy extends beyond its sustainability and reliability. Its consistent availability and minimal environmental impact position it as a cornerstone for achieving a low-carbon energy future. Enhanced Geothermal Systems (EGS) advancements underscore geothermal energy's potential expansion, enabling exploitation in areas devoid of natural hydrothermal resources. (Tester et al. 2012, 172–176.)

3.5 Environmental and Economic Benefits

The environmental accolades of geothermal energy include significantly lower greenhouse gas emissions and a smaller land footprint when compared to conventional energy sources. Economically, the operational costs of geothermal power generation are competitively low once the initial setup is complete. This stability in operational costs offers a hedge against the volatility in fossil fuel prices, contributing to energy security. (Bertani 2012, 13–14, 17.)

4 DIFFERENT METHODS OF EXTRACTION

Geothermal energy extraction methods should be divided into 'volcanic' and 'non-volcanic' due to the different geological characteristics and thermal properties of these media. Volcanic areas typically offer resources with high enthalpy and higher temperatures, allowing direct steam extraction and power generation. On the other hand, non-volcanic areas typically have low-enthalpy resources suitable for direct heating or require the use of heat pumps to raise the temperature for various applications. This categorisation helps to match extraction methods and technologies to specific conditions, hence optimising the efficiency and sustainability of geothermal energy use.

4.1 Non-Volcanic Geothermal Energy Methods

Binary Cycle Power Plants

Binary cycle power plants (Figure 1) are designed to generate electricity from the earth's heat. These plants are best suited to geothermal reservoirs with low to moderate temperatures that are insufficient for direct steam generation. (Kamran 2023, 50–51.)

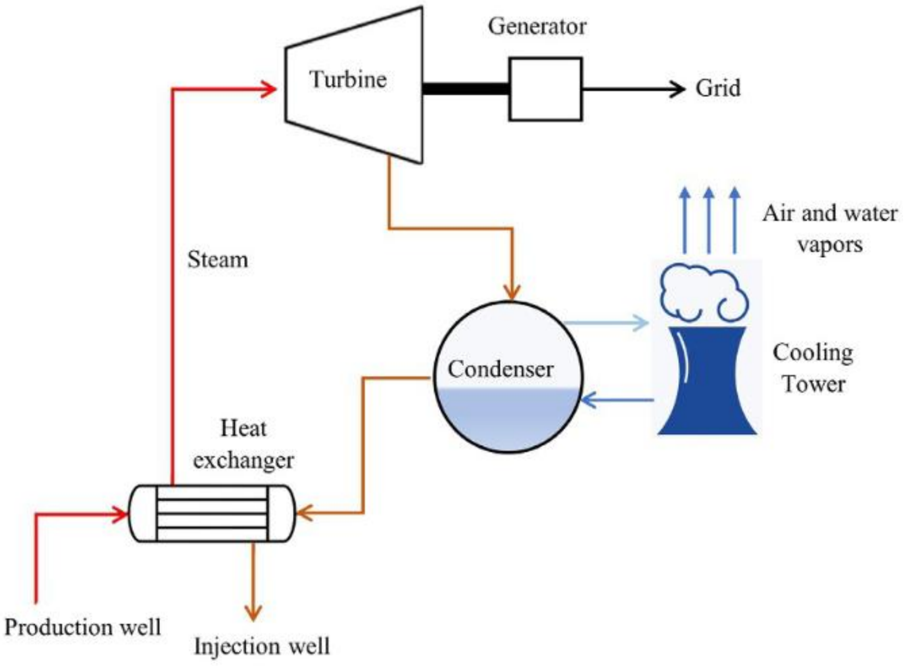

Figure 1. Binary Cycle Power Plants (Kamran 2023, 52)

They use a secondary fluid with a lower boiling point than water, which allows them to generate electricity from sources with temperatures between 85 °C and 180 °C. Hot water is extracted from the ground and passes through a heat exchanger where it heats the secondary fluid without direct contact, causing it to vaporise. This vapour drives a turbine which is connected to a generator to produce electricity. After heat exchange, the cooled geothermal water is injected back into the earth, maintaining the heat content of the reservoir. The secondary fluid vapour, after driving the turbine, is condensed back to a liquid and recirculated. This process allows for continuous power generation with minimal environmental impact, efficiently utilising low temperature geothermal resources and maintaining their sustainability. (Kamran 2023, 50–51.)

Geothermal Heat Pumps (GHPs)

GHPs (Figure 2) operate on the principle of exploiting the earth’s relatively constant subsurface temperature for heating and cooling purposes. This technology leverages the thermal stability found several feet below the Earth's surface, where temperatures remain consistent throughout the year, to achieve energy efficiency in heating and cooling systems within buildings. The system comprises a loop of pipes installed underground through which a water-antifreeze mixture is circulated.(Glassley 2010, 183–185.)

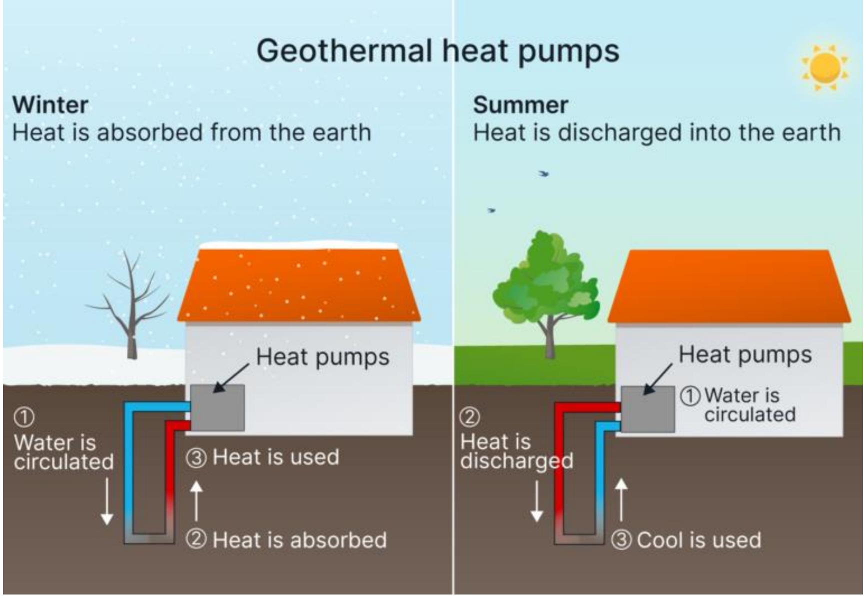

Figure 2. Geothermal Heat Pumps (Montana Renewable Energy Association 2022)

In the heating mode, the fluid absorbs ground heat and transports it indoors, where a heat pump unit elevates the temperature before distributing it throughout the building. Conversely, for cooling, the process is reversed; indoor heat is extracted and transferred to the ground loop, where it dissipates into the cooler earth. The central component of the GHP system is the heat pump unit, which adjusts the temperature of the circulating fluid depending on the heating or cooling needs. GHPs are distinguished by their efficiency, attributed to the movement of heat rather than its generation. This system offers a sustainable solution to heating and cooling by significantly reducing the electricity consumption typically associated with conventional HVAC systems. Through the strategic use of subsurface temperature stability, GHPs present an innovative approach to leveraging geothermal energy for residential and commercial applications, aligning with environmental sustainability goals and energy conservation efforts. (Glassley 2010, 183–185.)

4.2 Volcanic Geothermal Energy Methods

Dry Steam Power Stations

Dry Steam Power Stations (Figure 3) harness natural steam directly from the earth without the need for secondary fluids or heat exchangers. These systems drill into steam reservoirs, directing the steam through turbines to generate electricity. The efficiency of this process stems from its direct use of natural steam, minimizing energy loss. After powering turbines, steam is condensed into water and re-injected into the reservoir, ensuring resource sustainability. This method is recognized for its environmental friendliness and minimal surface impact, making it a preferred choice in suitable geothermal fields. (Kamran 2023, 49–50.)

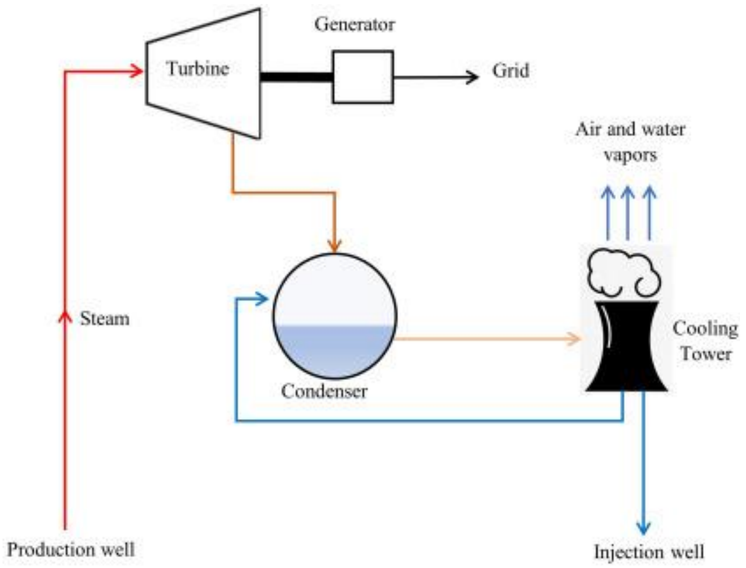

Figure 3. Dry Steam Power Stations (Kamran 2023, 50)

Flash Steam Power Stations

Flash Steam Power Stations (Figure 4) are versatile, capable of operating with lower temperature resources. These stations utilise hydrothermal fluids, extracting them under high pressure. Upon reaching the surface, the sudden pressure drop causes some hot water to vaporize or “flash” into steam, which then drives turbines to produce electricity. The process's adaptability to a range of geothermal fluid temperatures makes it widely applicable. Unutilised water and condensed steam are re-injected to preserve the geothermal source. (Glassley 2010, 167–169.)

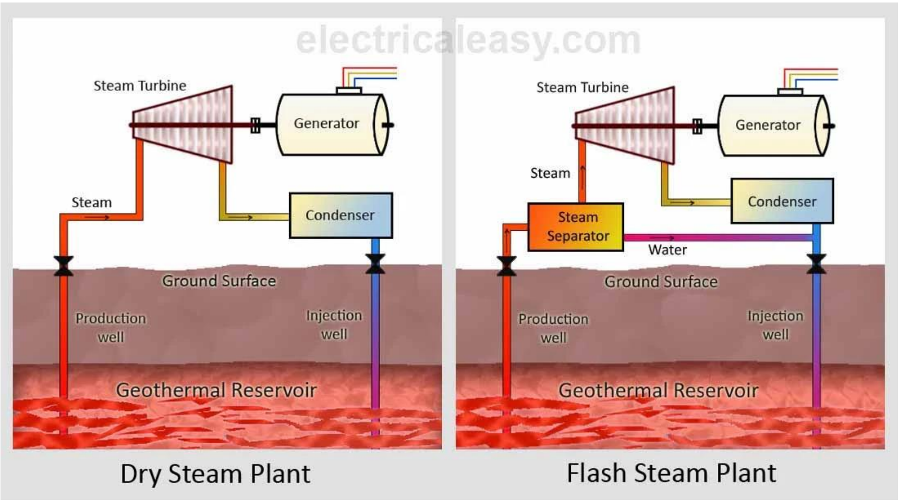

Figure 4. Dry- versus Flash Steam Plant (Daware 2021)

Enhances Geothermal Systems (EGS)

EGS (Figure 5) push the boundaries of geothermal energy extraction by creating or enhancing geothermal reservoirs in areas lacking natural steam or hydrothermal fluids. This technology involves injecting water into deep underground fractures to absorb heat from surrounding rocks. The heated water is then extracted and used for electricity generation, akin to conventional geothermal methods but with artificially created pathways for water circulation. EGS technology heralds a significant expansion in geothermal energy's potential, promising access to sustainable power across diverse geographical landscapes. (Tester et al. 2006, 6–7.)

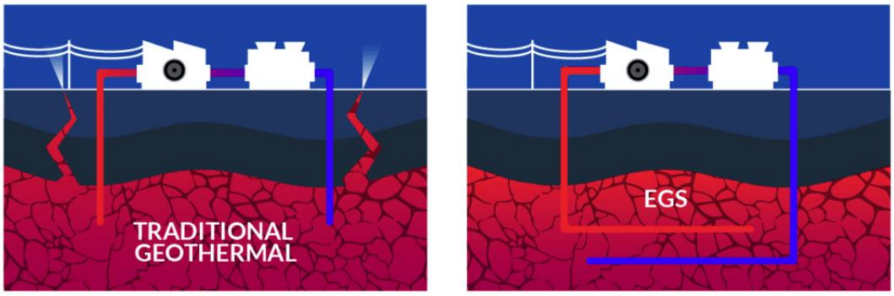

Figure 5. Enhances Geothermal Systems (Hector 2021)

5 ADVANCES AND CHALLENGES IN VOLCANIC GEOTHERMAL TECHNOLOGY

Advances and challenges in volcanic geothermal technology have been key in shaping the current renewable energy landscape. Each extraction method, including dry steam power plants, flash steam power plants and enhanced geothermal systems (EGS), has evolved through years of innovation and faced unique challenges.

5.1 The different Power Stations

Dry Steam Power Stations

The oldest form of geothermal power generation, Dry Steam Power Stations (Figure 6), have seen significant advancements in turbine technology and reservoir management. Early implementations, such as the one in Larderello, Italy, laid the groundwork for utilising steam directly from the ground. Over the years, improvements in drilling techniques have allowed for deeper and more efficient access to steam reservoirs, increasing the potential energy output. However, the challenge with dry steam reservoirs lies in their rarity and geographical limitation. Moreover, overexploitation can lead to diminished steam production over time, necessitating careful management of the reservoirs to ensure sustainability. (DiPippo 2012, 141–148.)

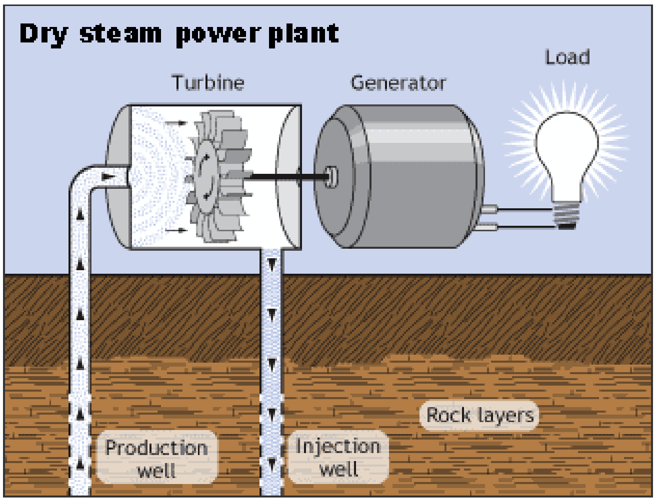

Figure 6. Dry Steam Power Plant (U.S. Energy Information Administration (EIA) 2022)

Flash Steam Power Stations

Flash Steam Power Stations (Figure 7) have benefited from advancements in materials science and engineering, allowing for more efficient heat exchangers and turbines capable of handling the rapid vaporization of pressurized hot water. The introduction of binary cycle technology has further enhanced the efficiency of flash steam systems by allowing lower temperature resources to be exploited more effectively. Despite these advancements, flash steam stations face challenges in managing the balance between extracting sufficient heat without cooling the geothermal reservoir too rapidly, which can reduce the system's longevity and efficiency. (Glassley 2010, 167–169.)

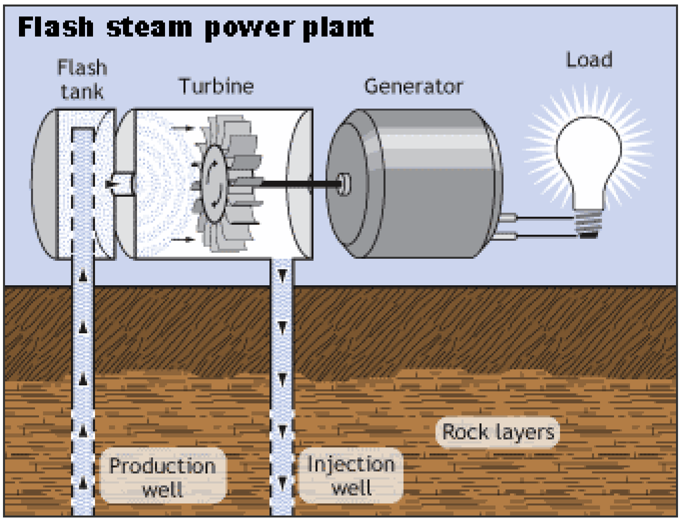

Figure 7. Flash Steam Power Plant (U.S. Energy Information Administration (EIA) 2022)

Enhanced Geothermal Systems (EGS)

Enhanced Geothermal Systems (Figure 8) represent a significant leap forward in geothermal technology, offering the promise of creating geothermal reservoirs where none naturally exist. Advances in hydraulic fracturing and 3D seismic imaging have enabled more precise creation and monitoring of fractures in hot dry rock formations, significantly expanding the potential locations for geothermal energy production. However, EGS faces challenges related to the induced seismicity from fracturing operations, and the high costs associated with drilling and stimulation of deep geothermal wells. These factors present barriers to widespread adoption and require ongoing research to mitigate. (Tester et al. 2006, 5–7.)

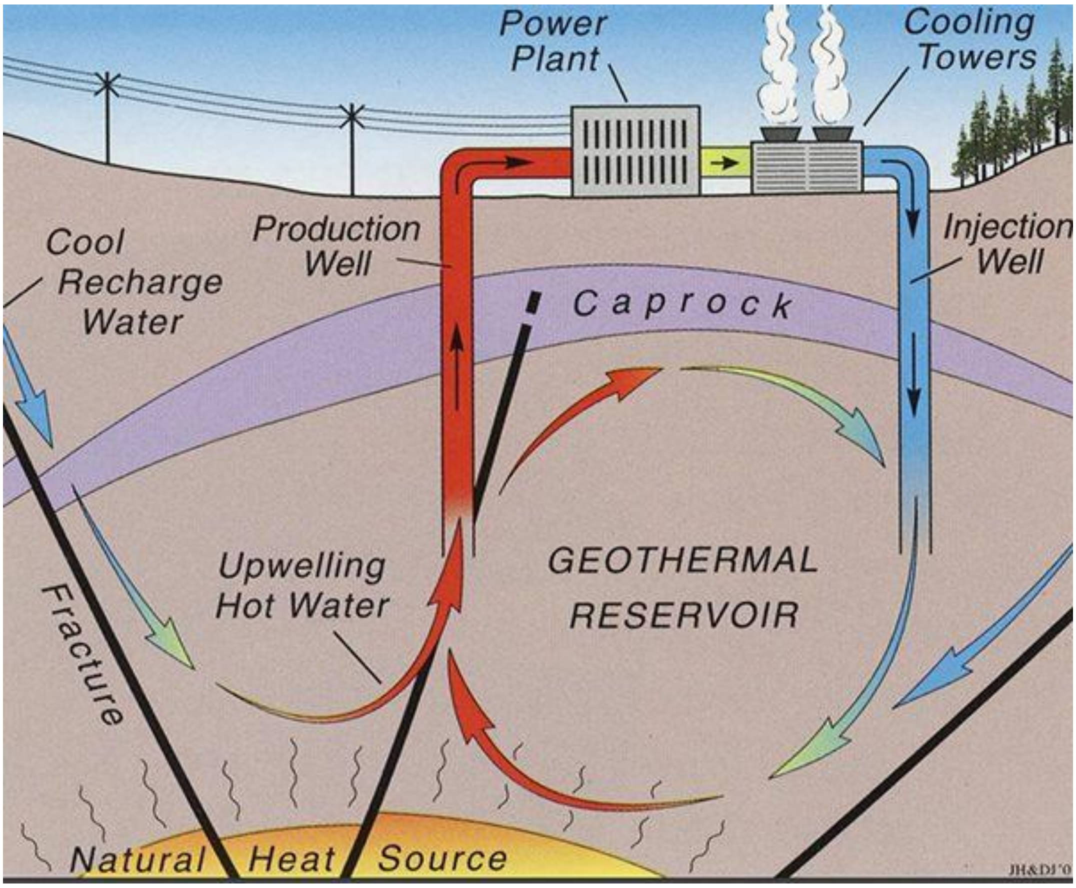

Figure 8. Enhanced Geothermal Systems (Patel 2022)

5.2 Overall Challenges and Outlook

For all volcanic geothermal extraction methods, progress has been accompanied by environmental and technical challenges. The fine balance between energy production and conservation of geothermal resources is an ongoing challenge. Innovations in drilling technologies, power plant efficiency and environmental mitigation strategies are crucial. The development of sustainable reservoir management practices remains a priority to ensure the long-term viability of geothermal energy as a major contributor to the global energy mix. As technology advances, addressing these challenges head-on will be essential to unlocking the full potential of volcanic geothermal energy for future generations. (Thain, Reyes, Hunt, Climo & Milicich 2006, 5.)

6 POLITICAL AND REGULATORY INFLUENCES ON GEOTHERMAL DEVELOPMENT

Geothermal energy, as a key renewable energy source, is greatly influenced by political and regulatory frameworks, which can vary widely between countries. These frameworks are shaped by a nation's geological profile—whether it is volcanic or non-volcanic—and political factors like membership in the European Union (EU). The section will compare and contrast the policy and regulatory environments for geothermal development in Austria and Finland, which are non-volcanic, with those in Iceland and New Zealand, which are volcanic. This comparison highlights the role of policies, regulations, and funding mechanisms in shaping the development of geothermal energy, focusing on the broader political and regulatory context without delving into the technical details of geothermal energy extraction. (Dumas 2019, 20–25.)

6.1 Non-Volcanic Countries: Austria and Finland within the EU framework

6.1.1 Austria and Finland: National Policies and EU Influence

Austria and Finland, as EU member states, adhere to EU-wide regulations and directives that significantly influence their national energy policies. The Renewable Energy Directive (RED), which sets ambitious targets for the EU to increase its share of energy from renewable sources, is a key policy framework both countries follow. Austria's national policies strongly support renewable energy, including geothermal, as part of its commitment to reducing greenhouse gas emissions and increasing energy efficiency. Finland, with its colder climate and focus on heating needs, also integrates geothermal energy within its national strategy for renewable energy, leveraging EU funding and technological support to develop its geothermal resources. (Brodny, Tutak & Bindzár 2021, 19–27.)

Both countries benefit from EU funding mechanisms such as the European Regional Development Fund, which supports geothermal projects aimed at increasing the use of renewable energy. However, the specific national policies, incentives and regulatory frameworks of Austria and Finland reflect their unique geographical and economic contexts, emphasising the tailored approach within the common EU regulatory environment.

6.2 Volcanic Countries: Iceland's and New Zealand's Independent Policies

6.2.1 Iceland: A World Leader in Geothermal Energy

Iceland, not an EU member but closely associated through the European Economic Area (EEA), has unique national policies that have established it as a global leader in geothermal energy utilisation. Iceland's approach to geothermal policy is characterized by significant government support, investment in research and development, and an emphasis on sustainability. The country's regulatory framework facilitates geothermal development by streamlining the permitting process and providing incentives for both exploration and exploitation. While Iceland adheres to many EU standards due to its EEA affiliation, it maintains autonomy over its energy policies, which allows for tailored approaches to geothermal development. (Orkustofnun 2024.)

6.2.2 New Zealand: Policies and Regulatory Framework

New Zealand, isolated geographically and politically from the EU's influence, has developed its own comprehensive policy and regulatory framework to support geothermal energy. The Resource Management Act (RMA) serves as the cornerstone of New Zealand's environmental management and regulates geothermal energy development by ensuring sustainability and mitigating environmental impacts. New Zealand's approach to geothermal energy is also characterized by partnerships with indigenous Maori communities, recognizing their traditional rights and integrating them into the development process. (Ministry for the Environment 2023, 27, 73.)

6.3 Comparative Analysis and Global Implications

While Iceland is a leader in geothermal development due to its abundant volcanic resources and supportive policies, New Zealand provides a model of inclusive and sustainable development. The comparison between EU and non-EU countries highlights the importance of tailored national policies in a global context.

Iceland's position as a leader in geothermal energy has the potential to indirectly influence EU policies through knowledge sharing and best practice. Similarly, New Zealand's successful integration of indigenous rights into geothermal development provides a model that could inspire policies in other regions.

The global geothermal energy landscape highlights the importance of political and regulatory frameworks in exploiting this renewable resource. As countries navigate their unique geological, economic and political contexts, the exchange of knowledge and experience will be critical in shaping a sustainable energy future.

7 METHOD EFFICIENCY AND TECHNOLOGICAL ADVANCEMENTS

7.1 Efficiency and Technological Comparisons

Geothermal energy extraction has advanced significantly, with technology improving the efficiency of these systems. These advancements are crucial for maximizing the energy harnessed from geothermal sources, optimizing the cost-effectiveness of operations, and minimizing environmental impacts. (Tester et al. 2006, 7–9.)

Advancements in Drilling Techniques

Developments in drilling techniques such as Enhanced Geothermal Systems (EGS) have allowed for the access of heat resources at greater depths with higher efficiency. The adoption of directional drilling, originally pioneered for oil and gas extraction, has also been adapted for geothermal applications, allowing for precise targeting of hotspots and minimizing surface disruption. (DiPippo 2012, 44–51.)

Binary Cycle Power Plants

Binary cycle power plants have transformed the exploitation of geothermal resources, particularly in regions with lower temperature gradients. These systems enable electricity production from geothermal reservoirs with temperatures as low as 100 °C, which were previously not viable, thus expanding geothermal development's potential. (Glassley 2010, 166, 168.)

Heat Extraction Enhancements

The introduction of advanced working fluids in binary cycle plants has considerably improved the efficiency of heat extraction. Using fluids with lower boiling points than water has increased the conversion efficiency, making the process more productive and economically feasible. (DiPippo 2012, 163–164.)

7.2 Impact of Geological Conditions on Method Selection

Geological conditions greatly influence the choice of geothermal extraction methods. These conditions dictate the accessibility of geothermal resources and the type of technology that can be used most effectively.

High-temperature Fields

In high-temperature fields, typically found in volcanic regions such as Iceland, traditional flash steam power plants are prevalent. The high enthalpy of these systems allows direct utilisation of steam to drive turbines, offering high efficiency in electricity generation. (Bertani 2012, 10.)

Low-temperature Fields

Conversely, in low-temperature fields such as those in Austria and Finland, binary cycle power plants are more suitable due to their ability to operate efficiently at lower temperatures. Here, the geological formations do not provide the intense heat necessary for flash steam plants, and thus, the binary cycle technology is a suitable alternative. (Lund et al. 2011, 177–178.)

Hydrothermal Convection Systems

Areas with natural hydrothermal convection systems, often associated with high permeability and water content, are ideal for direct-use applications and conventional power generation methods. The presence of natural aquifers and reservoirs can provide a consistent supply of geothermal fluids. (Fridleifsson et al. 2008, 63–65.)

EGS Implementation

Regions with hot dry rock formations, where natural water content is insufficient, are potential candidates for EGS. This method involves artificially creating permeability to circulate water through the hot rocks and extract the heat. (Tester et al. 2006, 4–7.)

In conclusion, technological advancements in geothermal energy extraction have significantly increased the scope and efficiency of this renewable energy source. However, geological conditions remain a determining factor in the selection of the most appropriate and efficient extraction method, with different technologies suited to the specific characteristics of each geothermal field.

8 COMPARATIVE ANALYSIS OF GEOTHERMAL RESOURCE UTILISATION

This chapter provides a comparative analysis of the use of geothermal resources in different countries. It focuses on the use of geothermal resources from a geological, technological, regulatory and sustainability perspective.

8.1 Geological Comparisons: Austria vs. Finland

The geothermal landscapes of Austria and Finland are shaped by distinct geological features, influencing the potential and methods for geothermal energy extraction in both countries. Neither country is characterized by volcanic activity; instead, their geothermal potential is defined by their unique tectonic and bedrock conditions.

8.1.1 Austria’s Geothermal Profile

Austria's geothermal resources (Figure 9) are closely linked to the tectonic settings of the Eastern Alps, with geothermal manifestations such as hot springs and deep sedimentary basins prevalent, especially in the Vienna Basin where the crust is relatively thinner (Lund 2005). These conditions are favourable for geothermal district heating, tapping into the available lower-enthalpy resources. (Haenel, Stegena & Rybach 2012, 288–293.)

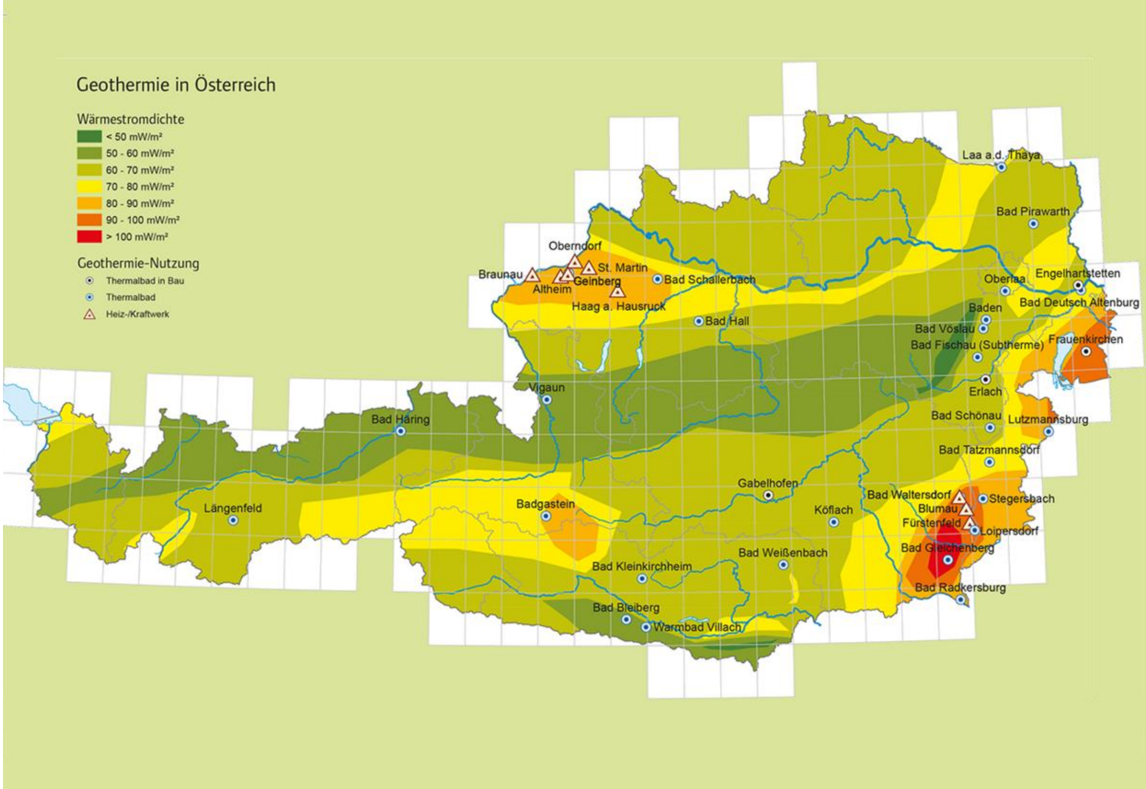

Figure 9. Austria Heat Flow Map (GeoSphere Austria 2024)

8.1.2 Finland’s Geothermal Landscape

Finland's geothermal characteristics (Figure 10) are dominated by the Fennoscandian Shield, with its crystalline bedrock providing a stable but challenging environment for high-enthalpy geothermal energy extraction (Kukkonen 2000, 277–279). Finnish geothermal solutions have predominantly been tailored to this setting, with ground-source heat pumps used extensively for heating. (Lund et al. 2011, 160–161, 170.)

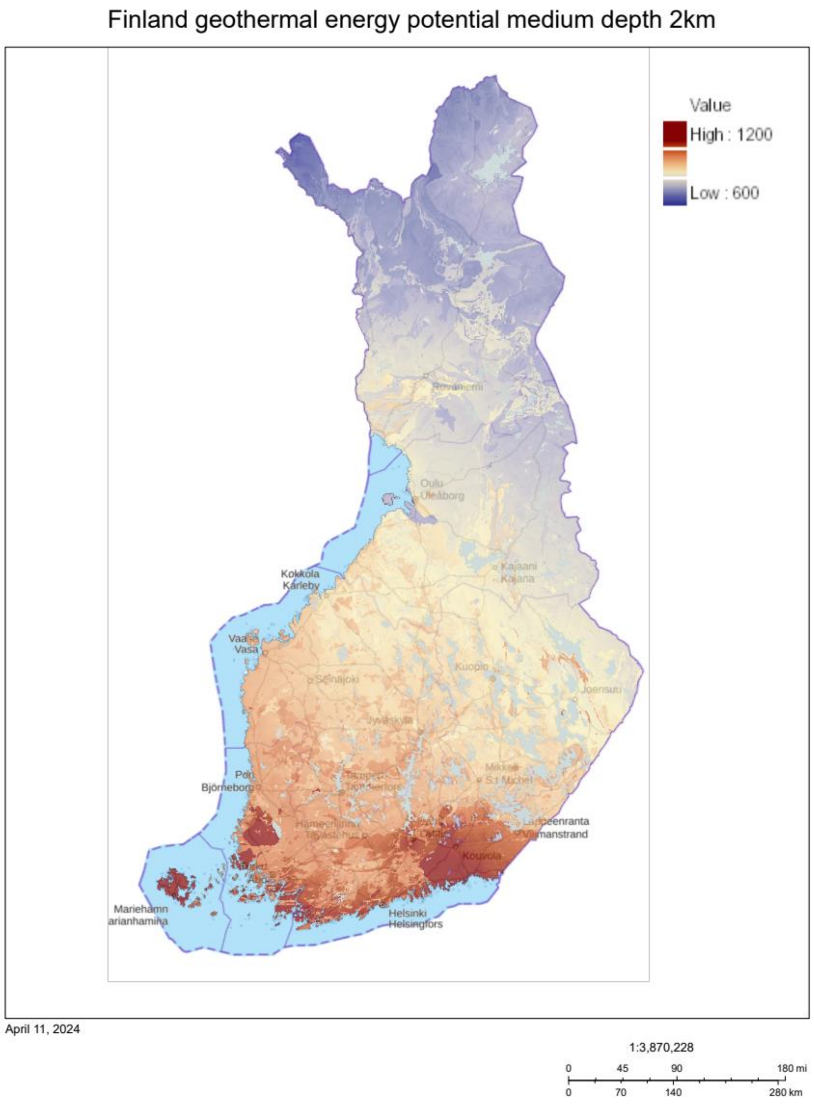

Figure 10. Finland Geothermal Energy Potential (GTK - Hakku 2024)

8.1.3 Comparative Insights

The comparison between Austria and Finland illustrates how geological conditions dictate the development of geothermal energy technologies adapted to each country’s unique environment. Austria has leveraged its geothermal features for direct heating, while Finland's stable bedrock has guided it towards the use of ground-source heat pumps for heat extraction. Both nations are also exploring EGS to expand their geothermal capacity, demonstrating a shared interest in technological advancements to overcome geological limitations. (Bloomquist 2003, 514, 520; Lund et al. 2011, 159–180; Tester et al. 2006, 7–9.)

In conclusion, Austria and Finland exemplify how non-volcanic regions can harness geothermal energy by adapting to their specific geological circumstances. This analysis underscores the necessity for tailored geothermal strategies and the potential for technological innovations such as EGS in regions lacking traditional high-temperature geothermal resources. (Lund 2005; Bloomquist 2003, 514; Kukkonen 2000, 279.)

8.2 Technological Applications

The technological applications of geothermal energy in different countries vary considerably due to unique geological contexts. This section explores the tailored technologies adopted in each country's geothermal energy sector, reflecting their geological features.

8.2.1 Austria

In Austria, geothermal energy applications predominantly focus on district heating, capitalizing on the geological features such as the Eastern Alps and the Vienna Basin. These areas provide significant geothermal potential due to their tectonic settings, facilitating the use of low-enthalpy geothermal systems. Such systems, less intensive than high-enthalpy counterparts, are optimal for sustained heat extraction used in residential and commercial heating. Enhanced Geothermal Systems (EGS) are also under exploration to expand potential applications by artificially creating geothermal reservoirs where natural conditions are less favourable. (Lund et al. 2011, 169, 177.)

8.2.2 Finland

Finland's geothermal technology adoption aligns with its geological composition, dominated by the Fennoscandian Shield. The crystalline bedrock here presents challenges for high-enthalpy geothermal exploitation, thus guiding Finland towards the extensive use of geothermal heat pumps (GHPs). These pumps leverage the stable subsurface temperatures for heating applications, providing a significant portion of residential heating across the country. Finnish strategies also include the potential development of EGS technologies to enhance geothermal output in regions where natural activity is minimal. (Tester et al. 2006, 1–3.)

8.2.3 Comparative Analysis

The contrast between Austria and Finland in the utilisation of geothermal technologies underscores the influence of geological conditions on technological choices. Austria utilises direct-use geothermal applications due to its tectonic activity, while Finland, with its challenging geological environment, relies on technology such as GHPs to harness geothermal energy. Both countries are exploring EGS to overcome geological limitations and enhance their geothermal capability, indicating a trend towards technological innovation in response to geothermal resource characteristics (Bloomquist 2003, 514–516.)

In conclusion, the tailor-made technology applications in the geothermal sectors of Austria and Finland demonstrate adaptive strategies adapted to their unique geological characteristics. This approach not only maximises geothermal potential, but also paves the way for future advances in geothermal technology.

8.3 Regulatory Influence and EU Policy

The impact of European Union (EU) policies on the development of non-volcanic geothermal energy in Austria and Finland demonstrates how international regulations can shape national energy strategies. This analysis builds on previous discussions of EU policies, in particular the Renewable Energy Directive (RED), which sets ambitious targets for the uptake of renewable energy in the European Union.

8.3.1 Impact on Austria

Austria's geothermal development is heavily influenced by EU energy policies. As discussed in section 6.1, the country's compliance with the EU's directives fosters a supportive environment for renewable energy, including geothermal heating projects. These projects are often integrated into broader district heating systems that are prevalent across Austria, taking advantage of the EU's funding mechanisms, such as the European Regional Development Fund. This funding supports the infrastructure needed to harness geothermal energy efficiently, particularly in areas like the Vienna Basin, where geothermal resources are abundant but require significant upfront investment to develop. (Lund et al. 2011, 169, 177.)

8.3.2 Impact on Finland

In Finland, the influence of EU policies is manifested through national strategies that align with the goals of increasing renewable energy usage. As previously noted in section 6.1, Finland's geothermal strategy utilises geothermal heat pumps extensively to meet the heating demands of its colder climate. The EU's policy frameworks support technological innovation and deployment of these systems by providing access to technological and financial resources. This is crucial for Finland, where the geological conditions do not naturally support high-enthalpy geothermal activities. The support from the EU facilitates the adoption of low-enthalpy systems, which are more suitable for the Finnish geological environment. (Tester et al. 2006, 1–3.)

8.3.3 Comparative Analysis

The regulatory impact of EU policies on Austria and Finland highlights different aspects of geothermal development based on the geological and economic context of each country. While Austria focuses on integrating geothermal systems into the existing district heating infrastructure, Finland prioritises the use of geothermal heat pumps as the primary method for exploiting its geothermal potential. Both approaches are supported by EU directives, which not only mandate the development of renewable energy, but also support it through financial and technical assistance. This tailored approach within the EU framework allows each country to effectively exploit its geothermal resources while meeting the common goal of increasing the use of renewable energy and reducing carbon emissions.

In conclusion, the EU regulatory framework has played a crucial role in shaping the geothermal landscapes of Austria and Finland. By providing both the legislative mandate and the necessary support mechanisms, the EU is enabling these countries to adapt and innovate within their specific geological contexts, thereby enhancing their renewable energy portfolios.

8.4 Sustainable Energy Contribution

The integration of geothermal energy into the renewable energy portfolios of Austria and Finland reflects their commitment to sustainability and renewable energy diversification. This section explores how each country is using geothermal resources to enhance their sustainable energy strategies.

8.4.1 Austria's Geothermal Integration

Austria's geothermal energy contribution primarily focuses on heating applications, complementing its broader renewable energy portfolio, which includes significant hydroelectric and wind energy components. Geothermal energy is particularly integrated into district heating networks in regions with geothermal potential, such as the Vienna Basin. This integration not only helps in reducing the dependency on fossil fuels but also supports Austria's goals under the EU's climate and energy framework, aiming for a substantial reduction in greenhouse gas emissions by 2030. The strategic use of geothermal heating helps in achieving these targets by providing a stable, low-carbon heat source, especially during the colder months when heating demand peaks. (Haenel et al. 2012, 288–296.)

8.4.2 Finland's Geothermal Practices

In Finland, geothermal energy is integrated into the national energy system primarily through the widespread use of geothermal heat pumps (GHPs). These systems are utilised to harness the stable geothermal conditions afforded by the Fennoscandian Shield, providing heating and cooling solutions across residential and commercial properties. This method aligns with Finland's sustainability strategy, which emphasizes energy efficiency and the reduction of environmental impact. The use of GHPs significantly contributes to Finland's renewable energy targets, as outlined in the EU's Renewable Energy Directive, by increasing the share of renewables in the energy mix and decreasing energy consumption in the heating sector. The strategic deployment of GHPs across Finland showcases an effective use of geothermal energy adapted to the local geological conditions, thereby supporting the country's commitment to sustainable and energy-efficient solutions. (Kukkonen 2000.)

8.4.3 Comparative Insights

Both Austria and Finland have effectively integrated geothermal energy into their renewable energy strategies, though their approaches reflect their distinct geological and climatic conditions. Austria utilises geothermal resources for direct heating in regions with accessible geothermal potential, enhancing its renewable energy capacity and reducing carbon emissions. Conversely, Finland’s approach, heavily reliant on geothermal heat pumps, addresses its climatic challenges and geological characteristics by providing an efficient, sustainable heating solution widespread across the country. These strategies not only align with the EU’s energy and climate goals but also highlight the adaptability of geothermal technology to meet specific national needs.

In conclusion, the integration of geothermal energy into the renewable energy portfolios of Austria and Finland demonstrates a commitment to sustainable energy development. Each country's unique approach to harnessing geothermal resources illustrates the versatility of geothermal technology and its potential to significantly contribute to the EU's renewable energy and sustainability objectives.

8.5 Volcanic Geothermal Potential: Iceland vs. New Zealand

The volcanic geothermal resources of Iceland and New Zealand are central to the energy landscapes of both countries. Located in areas of significant geological activity, they exploit geothermal energy for a range of uses, from electricity generation to district heating and industrial applications.

8.5.1 Iceland’s Geothermal Dominance

Iceland is exceptional in its geothermal energy use, situated on the geologically active Mid-Atlantic Ridge. It utilises high-temperature geothermal fields (Figure 11) to produce around 30% of its electricity and meet nearly 90% of its housing heating needs with geothermal sources. The country's energy policy and advancements in geothermal systems are evident in its substantial geothermal infrastructure and capacity. (Fridleifsson 2001, 302–305.)

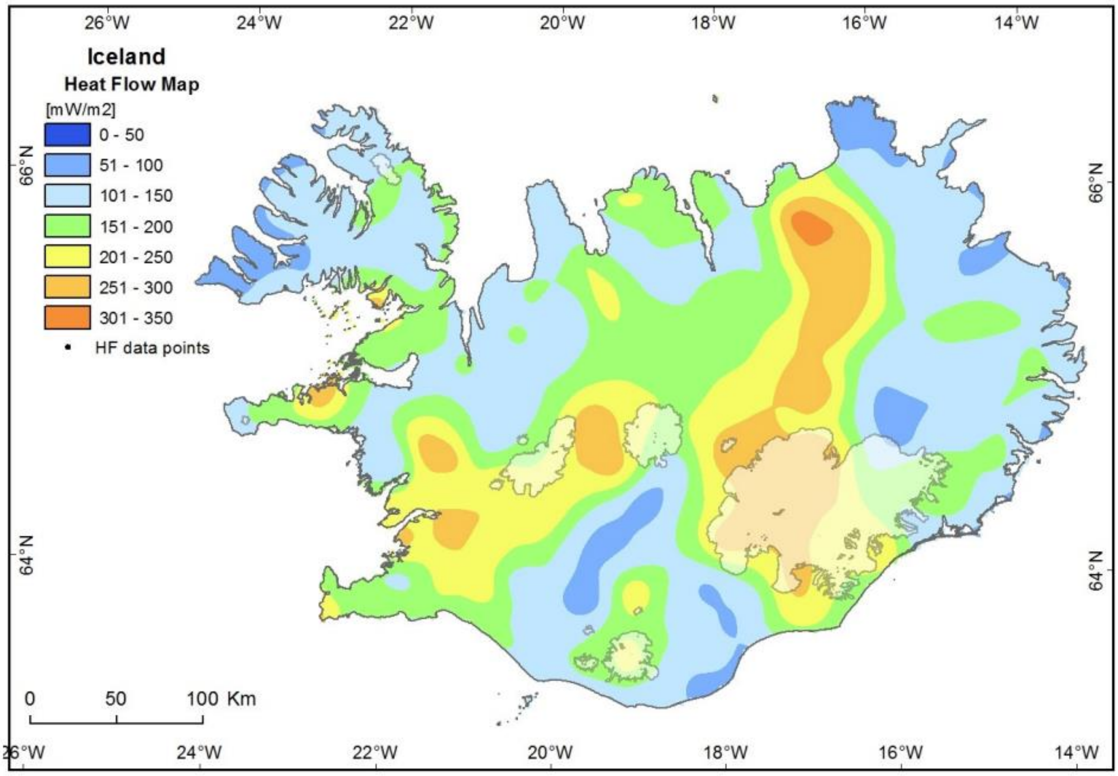

Figure 11. Iceland Heat Flow Map (Hjartarson 2015, 3)

The map shows high values, especially adjacent to or within the volcanic zones, with variations from less than 40 mW/m² to over 300 mW/m², with an average heat flow for Iceland of about 175 mW/m². These high heat flow values underline Iceland's geothermal wealth and support the extensive use of this renewable energy source. Notably, the map has been corrected from previous versions where the unit of heat flow was incorrectly displayed, ensuring accurate representation in milliwatts per square metre.

8.5.2 New Zealand’s Varied Geothermal Features

New Zealand shares Iceland's richness in geothermal resources, attributed to its position on the Pacific Ring of Fire. The Taupo Volcanic Zone in the centre of the North Island (Figure 12) is especially noteworthy for its geothermal activity, hosting substantial power stations like Wairakei and Ngatamariki. These installations are vital to New Zealand's energy grid and underscore the country's innovative approach to incorporating geothermal power within a diverse renewable energy mix. Advancements in technology and regulatory frameworks are evident from the recent report, indicating progress in geothermal energy exploitation and integration. (International Energy Agency 2023, 103–104.)

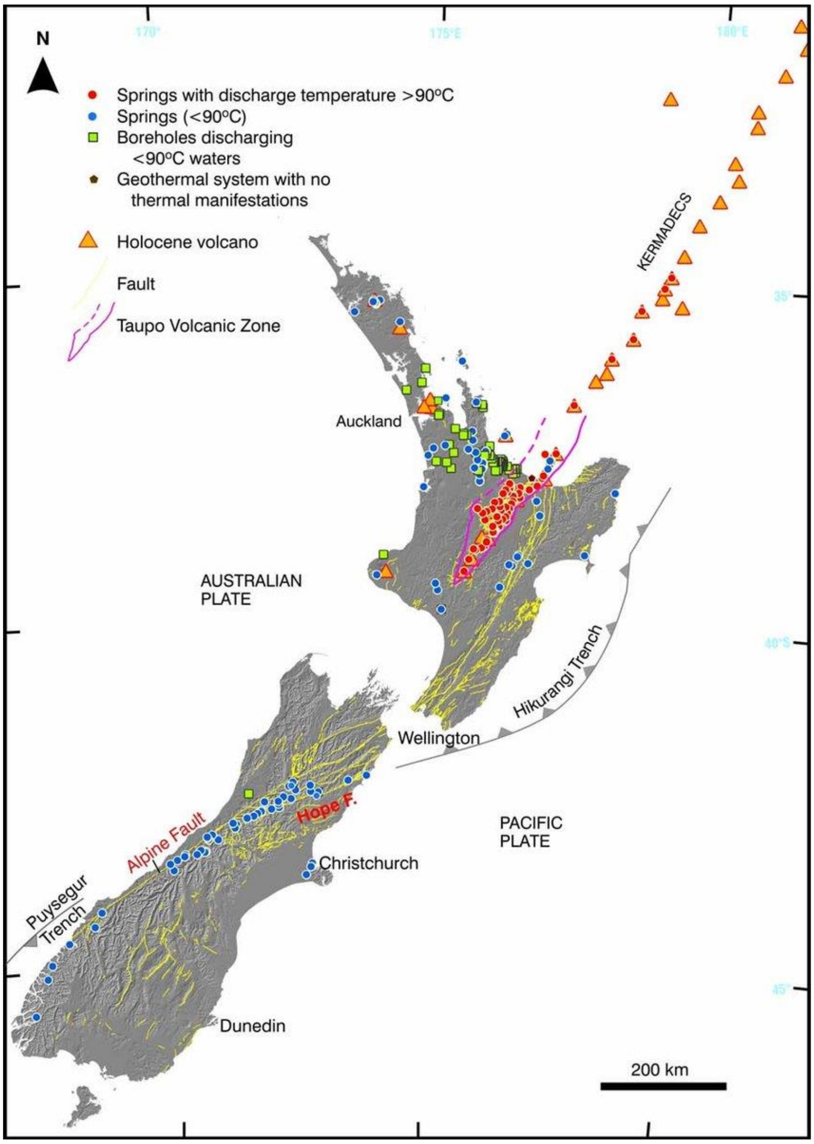

Figure 12. Distribution of hot springs in New Zealand (Thain et al. 2006, 4)

8.5.3 Comparative Insights

Iceland and New Zealand both make effective use of their volcanic geothermal resources, but their utilisation strategies differ. Iceland's focus remains on heating and electricity, exploiting the intensity of its geothermal fields. Conversely, New Zealand's strategy includes the versatile use of geothermal energy in various industrial processes, reflecting a multi-faceted approach to its energy policy. These differences illustrate the adaptive use of geothermal resources, shaped by each country's unique geological conditions and policy frameworks.

The volcanic geothermal resources of Iceland and New Zealand not only form an integral part of their respective energy systems but also demonstrate the significant potential of geothermal energy globally. This potential is amplified when supported by conducive policy environments and ongoing technological innovations. Iceland's geothermal capacity is world-renowned, underpinned by its location on the Mid-Atlantic Ridge. The nation utilises high-temperature geothermal fields to produce about 30% of its electricity and provides nearly 90% of its housing heating needs. Iceland's extensive use of geothermal energy is reflected in its energy policy and technological innovation in geothermal systems. (Fridleifsson 2001, 301–306.)

8.6 Technological Synergies and Differences

This section evaluates the technological approaches used to harness high-enthalpy geothermal systems in volcanic regions, focusing on the synergies and differences between the methods employed. High-enthalpy geothermal resources, typically found in volcanic areas, offer substantial energy potential due to their high temperatures and pressures. The examination here builds upon earlier discussions of geothermal technology in volcanic settings (cf. Section 5) and contrasts these with specific implementations in different volcanic regions.

Technological Synergies

In volcanic regions, the primary technological synergy lies in the use of conventional high-enthalpy extraction methods, such as dry steam and flash steam power stations. Both technologies are designed to exploit the natural steam and high-temperature fluids available in volcanic geothermal fields.

Dry Steam Power Stations are one of the oldest and most direct methods of geothermal energy extraction, where steam extracted directly from geothermal reservoirs is used to drive turbines. This method is highly efficient in regions with naturally occurring steam, such as at The Geysers in California, which is one of the largest dry steam fields in the world. (DiPippo 2012, 154–158.)

Flash Steam Power Stations are more versatile and can handle a broader range of reservoir conditions. These systems take advantage of the high pressure and temperature of geothermal fluids. Upon reaching the surface and experiencing a pressure drop, the hot water 'flashes' into steam, which then drives a turbine to generate electricity. This technology is prevalent in places like Iceland and the Philippines, where geothermal conditions vary but generally include high temperatures. (Fridleifsson et al. 2008, 74–75.)

Technological Differences

While the basic principles of high-enthalpy geothermal energy extraction remain consistent, regional differences in geological conditions necessitate adaptations in technology and operational practices.

Adaptations in Flash Steam Technology: Depending on the specific geothermal reservoir characteristics, modifications in the design of flash steam plants are necessary. For instance, in New Zealand, flash steam facilities are often designed with advanced condensing systems to handle the variable fluid qualities and to optimize the energy conversion efficiency given the local geothermal properties. (Glassley 2010, 161–165.)

Integration with Binary Cycle Systems: In some volcanic regions, particularly where the geothermal fluid contains a mix of steam and liquid at lower temperatures, integrated systems that combine flash steam technology with binary cycle processes are used. These hybrid systems ensure that even the lower-temperature heat is utilised efficiently, significantly enhancing the overall efficiency of the geothermal power plant. (Tester et al. 2012, 824.)

Customization Due to Environmental and Operational Constraints

Environmental considerations also drive technological differences. For example, in Iceland, geothermal plants are designed with particular attention to minimizing environmental impacts on the local landscape and ecosystems, which are typically fragile. The technology employed often includes reinjection techniques to sustain the pressure in geothermal reservoirs and to prevent land subsidence and reduced emissions of geothermal gases. (Paulillo et al. 2019.)

Conclusion

The technological approaches to harnessing high-enthalpy geothermal energy in volcanic regions demonstrate both significant synergies and necessary differences. While the fundamental technologies like dry steam and flash steam power stations provide a common framework, regional adaptations are crucial to address the specific geological, environmental, and operational challenges encountered in different volcanic settings. These adaptations not only optimize the energy extraction processes but also align with sustainable energy development goals, showcasing the dynamic nature of geothermal technology in responding to diverse conditions.

8.7 Independent Policies and Their Impact

This section investigates and contrasts how independent policies, external to the European Union (EU) regulatory framework, influence the geothermal energy sector in Iceland and New Zealand. Both countries, with significant geothermal resources due to their volcanic geologies, have developed unique policy frameworks that drive the development and utilisation of geothermal energy.

8.7.1 Iceland's Geothermal Policies

Iceland, not a member of the EU but part of the European Economic Area (EEA), has developed its geothermal energy policies based on its abundant geothermal resources, facilitated by its location on the Mid-Atlantic Ridge. The Icelandic government has established a supportive policy environment that includes incentives for geothermal exploration, development, and the export of geothermal expertise and technology. Significant emphasis is placed on sustainability and the minimization of environmental impact, reflecting the country's commitment to maintaining its pristine natural environments.

One of the key aspects of Iceland’s policy framework is the integration of geothermal energy into the national energy strategy, aiming to achieve energy independence and export surplus electricity through green data centres and hydrogen production. These initiatives are supported by government-funded research and development programs focusing on enhancing geothermal technology and minimizing ecological disturbances. The Icelandic policies are tailored to capitalize on the high-enthalpy resources available, facilitating extensive use of geothermal energy for both electricity generation and district heating. (Fridleifsson 2001, 304.)

8.7.2 New Zealand's Geothermal Framework

New Zealand’s geothermal policies are shaped by its position on the Pacific Ring of Fire, which provides it with substantial geothermal potential. Unlike Iceland, New Zealand has developed a comprehensive regulatory framework that promotes the development of geothermal resources and ensures the involvement of indigenous communities, particularly the Maori, in the management and benefits derived from geothermal activities.

The Resource Management Act (RMA) plays a crucial role in New Zealand's geothermal policy, requiring any geothermal development to consider environmental effects and the rights of indigenous peoples. This act ensures sustainable management of natural resources, including geothermal, by integrating cultural, economic, and environmental considerations into the planning and consent processes. New Zealand’s approach is characterized by a balance between exploitation for energy production and maintaining the ecological and cultural integrity of geothermal sites. (Ministry for the Environment 2023, 73.)

8.7.3 Comparative Analysis

The independent policies of Iceland and New Zealand reflect their unique geological, cultural, and economic contexts. While both countries focus on sustainable development and environmental conservation, Iceland’s policies are more directed towards maximizing energy production and export, leveraging its geothermal abundance. In contrast, New Zealand’s policies emphasize the protection of cultural heritage and the equitable sharing of resources, which is critical given the significant role of indigenous communities.

The difference in policy focus and implementation demonstrates how independent policies can shape the development trajectories of the geothermal sectors in these countries. Iceland’s approach has made it a leader in geothermal technology on a global scale, whereas New Zealand’s policies have set a standard for the integration of indigenous rights and environmental stewardship in geothermal development.

In conclusion, the independent policies outside of the EU regulatory framework significantly impact how Iceland and New Zealand harness their geothermal resources. These policies not only influence the technological and economic aspects of geothermal development but also integrate broader societal and environmental goals, demonstrating the multifaceted impacts of policy on renewable energy sectors.

8.8 Strategic Energy Role

This section analyses the strategic significance of geothermal energy in the national energy strategies of Iceland and New Zealand, particularly in the context of the global shift towards renewable energy. Both countries are renowned for their substantial geothermal resources and have integrated these into their national energy systems, albeit in ways that reflect their unique geographic, economic, and cultural contexts.

8.8.1 Iceland's Strategic Use of Geothermal Energy

Iceland's geothermal energy plays a pivotal role in its national energy strategy, primarily due to its abundant geothermal resources that are a direct result of its geological position on the Mid-Atlantic Ridge. Geothermal energy in Iceland is not just a component of the national energy mix; it is a cornerstone of the country's energy independence and sustainability goals. It accounts for approximately 66% of the country's primary energy use, with nearly 90% of household heating derived from geothermal sources. (Fridleifsson 2001, 304.)

The strategic significance of geothermal energy in Iceland extends beyond energy security to encompass economic benefits through the export of geothermal expertise and technology. This has positioned Iceland as a global leader in geothermal technology, contributing to international projects and consultations on geothermal development. Furthermore, Iceland's commitment to renewable energy aligns with global climate goals, showcasing a successful transition from fossil fuels to renewables, and setting a benchmark for other nations.

8.8.2 New Zealand's Geothermal Framework

In New Zealand, geothermal energy is a key element of the national strategy to increase renewable energy sources and reduce carbon emissions. Geothermal energy provides about 19% of New Zealand's electricity generation, making it a significant contributor to the country's goal of achieving 100% renewable electricity by 2035. (International Energy Agency 2023, 116.)

New Zealand's strategic approach to geothermal energy also emphasizes sustainability and the involvement of indigenous communities. The integration of Maori perspectives and rights in geothermal developments not only aligns with the country's principles of environmental stewardship but also ensures that the benefits of geothermal energy support local communities. This dual focus on renewable energy development and cultural integrity reflects a comprehensive strategy that considers both environmental and societal dimensions.

8.8.3 Comparative Insights

The comparison of Iceland and New Zealand's strategic use of geothermal energy illustrates diverse approaches to integrating this renewable resource into national energy strategies. Iceland’s strategy is driven by geothermal abundance and involves a high degree of technological export and international cooperation, while New Zealand’s strategy focuses on balancing energy production with cultural and environmental sustainability.

Both countries, however, share a common recognition of the strategic importance of geothermal energy in achieving renewable energy targets and contributing to global climate objectives. Their successful integration of geothermal resources into their energy systems provides valuable insights into the potential of geothermal energy as a stable, reliable, and sustainable energy source on a global scale.

In conclusion, the strategic roles of geothermal energy in Iceland and New Zealand not only underscore its importance in national energy strategies but also highlight the adaptability of geothermal technology to meet both local and global energy needs. As the world shifts towards renewable energy, the experiences of Iceland and New Zealand offer important lessons on leveraging geothermal energy for sustainable development.

9 CONCLUSIONS

This chapter summarises the findings of the comparative analysis carried out throughout the thesis, focusing on the differences and similarities in geothermal development strategies, the factors influencing technological and policy decisions, and the wider geopolitical and economic contexts shaping geothermal development.

Comparative Insights Synthesis

The comparative analysis across different geological settings has revealed both distinct and shared strategies in geothermal energy exploitation. Countries like Iceland and New Zealand, with abundant high-enthalpy resources, predominantly employ direct steam and flash steam technologies to maximize their geothermal output (Sections 8.6, 8.7). In contrast, non-volcanic regions like Austria and Finland focus on low-enthalpy systems, utilising heat pumps and district heating solutions adapted to their more limited geothermal environments (Section 8.1.3).

Despite these differences, a common theme is the commitment to integrating geothermal energy within national renewable energy portfolios, enhancing energy security and sustainability. This is evident in both the volcanic and non-volcanic regions, where geothermal energy forms a critical part of the renewable energy strategy, albeit through different technological pathways (Sections 8.1.3, 8.8).

Decision-Making Analysis

The choice of geothermal technologies and policies is heavily influenced by geological conditions. High-enthalpy resources in volcanic regions allow for technologies that can directly use steam for power generation, while in non-volcanic regions the prevalence of low-enthalpy resources requires technologies that can operate efficiently at lower temperatures. (Section 8.1.2).

Policy decisions are similarly influenced by these geological distinctions, but also by the economic and environmental priorities of each country. For instance, Iceland’s policy framework supports extensive development and export of geothermal technology, driven by its vast high-enthalpy resources (Section 8.7).

Finland’s approach, meanwhile, is tailored to harness low-enthalpy resources efficiently within its colder climate, reflecting a strategic adaptation to its geological constraints (Section 8.1.3).

Geopolitical and Economic Influences

Geothermal energy development is not only a technical or environmental issue but also a geopolitical and economic one. The ability of a country to develop its geothermal resources is often tied to its geopolitical positioning, economic stability, and access to international technology and markets.

Countries like Iceland benefit from their geopolitical stability and economic policies that encourage investment in geothermal technology, both domestically and for export (Section 8.7). In contrast, New Zealand's approach to geothermal energy is significantly shaped by its commitment to indigenous rights and sustainable management practices, which influence both policy and economic decisions regarding resource exploitation (Section 8.7).

The economic implications of geothermal energy are profound, offering long-term benefits such as energy security, reduction in carbon emissions, and potential revenue from technology export. However, these benefits are contingent on the geopolitical environment that can either facilitate or hinder access to necessary technologies and markets.

10 DISCUSSION

10.1 Comprehensive Overview

The exploration of geothermal energy extraction methods in Austria, Finland, Iceland, and New Zealand provides a comprehensive view of how geological, technological, and policy factors are interwoven to influence the development and implementation of geothermal energy strategies. In volcanic regions like Iceland and New Zealand, high-enthalpy resources facilitate the use of technologies such as dry steam and flash steam power stations, which are capable of harnessing the intense energy directly from the earth’s subsurface (Sections 8.6, 8.7). These technologies align with the countries' abundant geothermal resources, allowing them to capitalize on their geological advantages.

Conversely, non-volcanic regions like Austria and Finland utilise technologies suited to their lower-enthalpy resources, such as geothermal heat pumps and district heating systems. These technologies are adapted to the less intense geothermal activity available, providing sustainable heating solutions that are integrated into the broader renewable energy frameworks of these countries (Section 8.1.3). The policy frameworks in each country further tailor these technological implementations to meet national energy goals, reflecting both local and international energy policies (Sections 8.1.3, 8.7).

10.2 Geothermal Energy’s Future Outlook

Looking ahead, the role of geothermal energy in the sustainable energy transition appears promising, but it also faces several challenges. The increasing global emphasis on renewable energy sources positions geothermal energy as a critical player due to its reliability and ability to provide baseload power. However, expanding the use of geothermal energy will require continued technological innovation, especially in regions with less favourable geological conditions.

For countries like Iceland and New Zealand, the future challenge is to balance energy production with environmental and cultural preservation. As these countries continue to develop their geothermal resources, they will need to manage the environmental impacts and ensure that the benefits of geothermal development are shared equally, particularly with indigenous people in New Zealand. (Section 8.7).

In non-volcanic regions such as Austria and Finland, the challenge is to improve the efficiency and usability of low-enthalpy geothermal technologies. This will likely involve advances in heat pump technology and the exploration of hybrid systems that can more effectively integrate geothermal energy into the national renewable energy mix (Section 8.1.3).

Overall, the strategic importance of geothermal energy is clear across the studied countries. Each country's approach to geothermal energy not only reflects its unique geological setting but also its technological capabilities and policy priorities. As the world moves towards a more sustainable energy future, the experiences of Austria, Finland, Iceland, and New Zealand offer valuable lessons on the integration of geothermal energy into diverse energy systems. The continued evolution of geothermal technology and policies will play a crucial role in shaping the future landscape of renewable energy globally.

In conclusion, geothermal energy stands as a testament to the innovation and adaptability required to harness the earth's natural resources responsibly. The insights garnered from these countries underscore the potential of geothermal energy to contribute significantly to global renewable energy goals, provided that technological and policy developments continue to address the inherent challenges of this sustainable resource.

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