Vaasan yliopisto
UNIVERSITY OF VAASA

Talha Anis

Assessing Stakeholder Risk Perceptions and Their Impact on the Acceptance of Deep Geothermal Energy

School of Technology and Innovations
Master's thesis in Strategic Project Management

Vaasa 2025

UNIVERSITY OF VAASA
School of Technology and Innovations
Author: Talha Anis
Title of the Thesis: Assessing Stakeholder Risk Perceptions and Their Impact on the Acceptance of Deep Geothermal Energy
Degree: Master of Science in Strategic Project Management
Discipline: Master's Programme in Industrial Engineering and Management
Supervisor: Jouni Juntunen
Year: 2025 **Pages:** 86

ABSTRACT :

Climate change has emerged as one of the most significant global challenges necessitating an accelerated transition to renewable energy. Deep geothermal energy has emerged as a potential solution however successful deployment of deep geothermal projects depends heavily on stakeholder acceptance, which is influenced by their perceptions of economic, environmental, and social risks.
Existing research lacks studies on deep geothermal energy-specific risks, particularly the interplay between stakeholder risk perceptions and social acceptance. Additionally, only few studies explore how economic, environmental, and social risks interact, or include diverse stakeholder perspectives beyond single groups. Addressing this gap our research has investigated key risks of deep geothermal energy from the lens of stakeholders, analyzing how stakeholder risk perceptions impact their acceptance and support of deep geothermal energy projects across four European locations.
This study has utilized a qualitative research approach. Data was collected from workshops and interviews with diverse stakeholders including local communities, researchers, industry representatives, and developers. A thematic analysis conducted through NVivo 15 identified key risk themes including significant economic concerns such as high upfront costs environmental issues like seismicity and land use impacts, and social challenges including trust, transparency, and public disappointment. The findings highlight not all risks equally influence acceptance; the impact of risk perceptions varies across different risk types and stakeholder groups. This study also suggests implementing targeted risk mitigation strategies that address specific stakeholder concerns. To deepen the understanding of risk perceptions, future research should adopt a longitudinal approach to examine the evolution of stakeholder attitudes over time. Additionally, ensuring equal representation across diverse stakeholder groups for a comprehensive analysis.

KEYWORDS: Deep Geothermal Energy, Stakeholders, Economic Risks, Environmental Risks, Social Risks, Risk Perception, Social Acceptance

Contents

Figures

Tables

Abbreviations

DGE	Deep Geothermal Energy
BHEs	Borehole Heat Exchangers
REPs	Renewable Energy Projects

1 Introduction

The 2023 Global Climate Report (NOAA National Centers for Environmental Information, 2024) has revealed the accelerating climate change as the year 2023 marked the highest global temperatures recorded since measurements began in 1850, surpassing the previous record from 2016 by 0.15°C (0.27°F). The rapid pace of industrial growth significantly increased the energy demand, with fossil fuels being widely used as a primary source for this purpose. However, the widespread use of these non-renewable resources has contributed to the intensifying impacts of climate change and global warming, which are becoming increasingly visible each year. This is no longer an imminent threat but a present reality impacting the world by disrupting economies and destabilizing ecosystems. This highlights the need for urgent and decisive measures toward transitioning from fossil fuels to renewable sources. In this context, governments worldwide are looking towards several renewable energy sources for diversifying their energy portfolio and reducing greenhouse gases leading to a sustainable and green future for the coming generations.

Geothermal energy derived from the earth's inexhaustible internal heat makes it a reliable energy resource. Due to several benefits it offers like consistent energy supply, sustainable sources and higher thermal efficiency Deep Geothermal Energy has emerged as a potential energy source for driving the energy transition. However, the acceptance of geothermal energy projects especially those involving deep geothermal energy is impacted by their perceived risks like the environmental risks in the form of induced seismicity, economic uncertainties like high upfront costs, and social risks of affecting local communities. Due to the complex nature of the geothermal energy projects diverse stakeholders are involved in them and their acceptance of these projects plays an important role in their success. The risks play an important role in shaping the stakeholder perceptions, determining the social acceptance of these projects which is very important in the feasibility and success of such projects. Understanding how the stakeholders perceive different economic, social, and environmental risks associated with DGE (deep geothermal energy) changes is very important as it leads to understanding the reasons for opposition from these stakeholders which can be then addressed to foster trust among stakeholders ensuring the sustainable deployment of this technology.

Despite its potential to drive a successful energy transition, geothermal energy development requires acceptance from its diverse stakeholders which is impacted by different barriers. Building on (Freeman, 1984) foundational definition of stakeholders as people or groups of people that are interested in or impacted by the activities of an organization or a project (Gunnarsdóttir et al., 2021) expand this concept within energy studies, emphasizing stakeholders as the ones who affect or are affected by the energy system by either being directly involved in the value chain or influencing and enabling it. Despite its potential to drive a successful energy transition, geothermal energy development requires acceptance from its stakeholders. Previous studies have identified Citizens, Industry, Developers, Researchers and Policymakers as important stakeholder groups concerning geothermal energy development (Guðlaugsson et al., 2020; Metze et al., 2023).

Local communities play an important role in the success of geothermal energy projects. While they tend to have a higher level of acceptance for these projects, their limited technical knowledge about their risks and benefits can hinder acceptance (Pellizzone et al., 2017). Environmental and social risks, such as concerns about induced seismicity and a lack of transparency, are especially important for public acceptance. (Soltani et al., 2021) noted social risks largely arise due to the concerns of society about induced seismicity, compounded by a lack of transparency and community engagement from project developers. Addressing these concerns, especially during the initial phase of geothermal energy projects, leads to higher acceptance and success (Chavot et al., 2018a).

Industry and developers find economic risks as significant barriers to geothermal energy adoption. High initial investment costs and drilling expenses, which escalate with depth and the uncertainty of encountering suitable geothermal resources are a major concern for stakeholders (Agemar et al., 2014; Heidinger, 2010). Developers perceive the economic and financial risks as the main challenges, as they are interconnected with other barriers such as development issues, lengthy timelines and limited social acceptance (Kubota et al., 2013).

Researchers another key stakeholder in deep geothermal energy projects play a critical role in assessing and understanding the risks. Research around induced seismicity has focused on identifying reasons causing it identifying an increase in the pore pressure and introduction of cooler fluids into hot rocks causes thermal contraction as the main reasons causing earthquakes (Majer et al., 2007; Schmittbuhl et al., 2022).

(Ejderyan et al., 2019) found that ignoring concerns about the perceived risks of geothermal energy can reduce public trust, increase opposition, and reduce the social acceptability of projects, affecting important stakeholders including developers, authorities, and scientists. This highlights the importance of identifying and addressing the risks to align the projects with the stakeholder expectations.

Social acceptance of geothermal energy projects is closely tied to stakeholders' perception of risks. When stakeholders perceive risks associated with deep geothermal energy as substantial or inadequately managed, it can lead to resistance which reduces the acceptance of these projects. For instance, studies have found concerns regarding induced seismicity, a significant environmental risk linked to deep geothermal energy, have been shown to reduce public acceptance considerably (Balzan-Alzate et al., 2021). The lack of comprehensive information about geothermal energy and its implications further contributes to this reduced acceptance (Renoth et al., 2023; Vargas Payera, 2018). However, when risks are openly addressed and mitigated through transparent communication and stakeholder engagement, trust is developed which leads to greater support and acceptance (Kubota et al., 2013).

1.1 Problem Statement and Research Gaps

Regardless of the many benefits it offers the installation capacity and societal acceptance of deep geothermal energy is lower than other renewable energy sources like wind and solar (Li et al., 2015). Previous research on the development of DGE highlights that its advancement is not without challenges. Significant economic, social, and environmental risks emerge as critical barriers to its adoption. These risks not only shape how stakeholders perceive the technology but also directly influence its social acceptance.

Understanding how different stakeholders perceive these risks is crucial for gaining broader support for the technology. The review of the literature on societal acceptance and stakeholder's perception of renewable technologies reveals a gap in research specifically exploring the interplay between the stakeholder risk perception and social acceptance of deep geothermal energy.

Although some studies have explored the relationship between stakeholder perception and social acceptance of other renewable technologies like hydrogen energy (Emodi et al., 2021) revealing that prior knowledge, perceived risks, and environmental knowledge were the most influential factors in determining societal acceptance, very few studies exist on deep geothermal energy that could help understanding how risk perceptions shape its social acceptance something which this thesis aims to address.

Although many studies have investigated the economic, environmental, and social risks associated with geothermal in general, there is a noticeable lack of studies specifically addressing these risks in the context of deep geothermal energy. Deep geothermal energy differs substantially from traditional geothermal systems. DGE requires drilling to unprecedented depths, introducing unique challenges such as advanced, expensive tools to handle extreme depths leading to costly drilling and the chance of hitting dry wells, as well as greater risks of earthquakes from high-pressure fluid injections. These factors make deep geothermal energy inherently more challenging than the traditional systems requiring studies focusing on these unique risks. Moreover, the existing studies tend to focus on these risks in isolation rather than examining their interactions and collective impact on sustainable energy development, which limits a holistic understanding of how they influence public acceptance, policy-making, and effective risk mitigation strategies.

Another critical research gap lies in the limited number of studies exploring stakeholder engagement and acceptance of deep geothermal energy. Existing research is generally focused on specific stakeholder groups, such as local communities and policymakers (Pellizzone et al., 2015; Vargas Payera, 2018), without adopting a comprehensive approach that includes diverse stakeholder perspectives. Our research addresses this gap by including diverse stakeholders from a deep geothermal energy project, providing a comprehensive understanding of their engagement and acceptance.

1.2 Research Questions and Objectives

Our research will be guided by the following research questions:

1. What are the key social, economic, and environmental risks perceived by different stakeholders involved in deep geothermal energy projects?

2. How do stakeholder's perceptions of these risks influence their acceptance and support for deep geothermal energy projects?

Through these questions, our research aims to explore what are the main social, economic, and environmental risks associated with DGE projects and how different stakeholders perceive these risks. The primary objective is to identify the key risks as perceived by various stakeholders, including local communities, policymakers, developers, and research organizations. Additionally, through this study, we also try to understand whether these perceived risks influence stakeholder acceptance of deep geothermal energy, providing insights into the factors that impact support for geothermal energy projects.

1.3 Structure of the thesis

This thesis is organized into five main chapters:
It begins with the Introduction section which provides the background to the study, the problem statement, and the research gaps that made the necessity of this study, the research objective and research questions, and the thesis structure. A detailed literature review follows the introduction section which is done in the context of the risks associated with deep geothermal energy, stakeholders, and social acceptance.

To do this, the literature provides an overview of geothermal energy, an introduction to deep geothermal technology, and the stakeholders involved in these projects. The review further explores the concept of social acceptance and the various risks associated with deep geothermal energy. It also examines how these stakeholders perceive the role of deep geothermal energy in the energy transition. The methodology section details the qualitative research approach used for this study, which involved conducting four semi-structured interviews with stakeholders in a deep geothermal energy project. Additionally, data from three workshops was used to gather further insights. This section also details the stakeholder identification process and development of the interviews and workshops, as well as the strategies for data collection and ensuring the study's trustworthiness.

The fourth chapter includes results from the thematic analysis of interviews and workshop data using NVivo 15 to answer our research questions.

The final chapter concludes our research findings. This section also provides the study's limitations and future research recommendations.

2 Literature Review

2.1 Overview of Geothermal Energy

Geothermal energy, a widely utilized renewable energy resource, is derived from the Earth's internal heat. This heat in the Earth's crust is inexhaustible, making geothermal energy a reliable renewable energy resource. Although geothermal energy is generally classified as a renewable resource, its renewability depends on specific geological and operational factors. One of the major reasons why geothermal energy is termed sustainable is that Earth continuously replenishes the heat extracted from geothermal reservoirs so the rate of energy recharge is high for most of the geothermal energy resources. However, in some cases, such as hot dry rocks or certain sedimentary basin aquifers, the rate of energy recharge occurs significantly slower than the rate of extraction. This slower replenishment which is mainly reliant on thermal conduction, makes these resources finite and thus classifies them as non-renewable under such conditions (Stefansson, 2000).

Geothermal energy has several significant advantages when compared to other renewable energy sources such as wind and solar. Unlike wind and solar power, which are weather-dependent and can experience fluctuations in energy production, geothermal energy provides a consistent and reliable source of power, operating continuously for 24 hours making it a dependable base-load energy resource capable of meeting steady energy demands. Additionally, geothermal energy has a smaller ecological footprint compared to wind and solar installations. It has minimal land use as compared to the large space requirements of solar farms or the extensive land and visibility impacts of wind turbines. One more advantage is geothermal energy's high thermal efficiency as this technology is directly utilizing the Earth's heat (Li et al., 2015).

Discussions about climate change have recently brought geothermal energy into the spotlight. However, historical evidence indicates that humans have been utilizing geothermal energy for centuries, long before its adoption for commercial purposes. But at that time, geothermal energy was primarily utilized for its natural hot springs, which were mainly used for bathing and therapeutic purposes (Cataldi et al, 1999). The use of geothermal energy for electricity production and heating purposes began in the 19th century, following the Industrial Revolution. Before this, geothermal energy was primarily utilized for domestic activities such as cooking and bathing. The use of geothermal steam for electricity production was first pioneered in Tuscany, Italy in 1904. In 1928 Iceland started investigating the possibilities of geothermal energy usage for domestic heating purposes and introduced the first large-scale municipal district heating system in 1930. Since then the commercial use of geothermal energy has grown with more than 58 countries documented using geothermal energy (Fridleifsson, 2001).

There are various ways to use geothermal heat, including using it directly for heating buildings and industrial processes, converting it into electricity, and employing geothermal heat pumps for residential and commercial heating and cooling. The application of geothermal energy is categorized based on the temperature range. Low-temperature geothermal systems (below 150°C) are commonly used for direct applications such as district heating while High-temperature systems (above 150°C) are mainly used for electricity generation through geothermal power plants.

The geothermal power plants can be categorized into three main categories. Dry steam plants use geothermal heat directly from the earth to drive the turbines. More commonly used nowadays are the flash steam plants that take hot water from underground into a tank where pressure is lowered turning it into steam which drives the turbines to produce electricity. While Binary cycle plants use a more modern method where hot water from the earth passes through a heat exchanger heating the secondary fluid that has a lower boiling point and turning it into steam to run the turbine blades (Valdimarsson, 2011).

2.1.1 Introduction to Deep Geothermal Energy

Based on the depth of resources geothermal energy can be classified as deep and shallow geothermal energy. Shallow geothermal energy is stored at the approximate depths of 400-500 meters. Beyond these depths, temperature follows the geothermal gradient meaning the rate of temperature rises as we go deeper into the earth's surface.

Deep Geothermal energy on the other hand involves drilling exceeding depths of 5 km into hot aquifers or dry rock formations utilizing the earth’s natural geothermal gradient as temperature at such depths is sufficient to drive the turbines for the production of electricity. Deep geothermal systems are classified into hydrothermal and petrothermal systems. Hydrothermal systems use natural geothermal reservoirs with sufficient heat, permeability, and water recharge, dominating global geothermal energy production in both installations and power output. Petrothermal systems, by contrast, depend on artificial enhancement to create heat exchangers in low-permeability rocks, requiring external water injection for circulation. Although hydrothermal systems are more commonly used, petrothermal systems offer potential breakthroughs for the development of deep geothermal energy in areas without natural reservoirs but with high geothermal gradients (Falcone et al., 2018).

Deep geothermal energy is easily accessible across several countries providing countries with an alternate renewable energy option to diversify their energy portfolio. The process of extracting deep geothermal energy involves drilling wells into the geothermal reservoir to access hot water or steam. Through production wells, the geothermal fluid is brought to the surface, where it is either used directly for heating or, if sufficiently hot, to drive turbines for electricity generation. To ensure long-term sustainability and maintain reservoir pressure, the cooled fluid is reinjected into the reservoir via separate injection wells. This closed-loop system maximizes resource efficiency while minimizing environmental impact (Agemar et al., 2014; Kunze & Hertel, 2017).

The results from the analysis of several medium-deep geothermal energy systems in China indicate them to be significantly better for electricity production and commercial heating purposes (Deng et al., 2019). The exploitation of deep geothermal energy involves a number of complex steps, including conducting geological surveys, installing power plants, drilling wells, establishing reservoirs, circulating fluids, and operating systems to utilize the extracted energy (Zhang & Zhao, 2020). However, the costs and risks associated with deep geothermal energy drilling especially the seismic events caused by deep geothermal energy drilling are a big barrier in development (Falcone et al., 2018). Research is ongoing to develop advanced drilling technologies that can withstand the

extreme conditions encountered in deep geothermal environments, and reduce drilling costs with some researchers suggesting using a combination of mechanical drilling with laser or microwave technology (Zhang & Zhao, 2020).
Closed-loop systems particularly deep borehole heat exchangers (BHEs), offer a promising and sustainable approach to extract deep geothermal energy. A heat transfer medium is circulated within a coaxial pipe, absorbing heat from surrounding rock and returning it to the surface. These systems reduce the risk of induced seismicity and expand site suitability by eliminating the need for natural permeability or hydraulic stimulation. Operational examples in Germany, such as those in Arnsberg and Prenzlau, highlight the practical application of BHEs for heating (Agemar et al., 2014; Romanov & Leiss, 2022). Despite the technical challenges of the ongoing research on advanced drilling technologies, and investigations for using CO2 as an alternative heat transfer fluid, deep geothermal energy has the potential to expand its use and meet growing global energy demands sustainably.

2.2 Defining Stakeholders and Their Roles in Renewable Energy Projects

Stakeholders are defined as individuals or groups that can affect or be affected by an organization's decisions and actions. Their engagement is critical in various contexts, particularly in projects involving substantial social, economic, and environmental implications, such as renewable energy initiatives (Freeman, 1984).
Stakeholder theory initially put forward by Freeman holds that organizations and businesses should prioritize responsible conduct by addressing the interests of all stakeholders involved in a project or organization. This approach emphasizes that long-term and sustainable success can only be achieved when the needs and expectations of all stakeholders, including shareholders, are considered and integrated into decision-making processes. The theory advocates for a holistic perspective that balances profit generation with ethical and equitable stakeholder engagement (Freeman, 2010). However, a notable challenge is assessing the power and influence of different stakeholders in an organization or a project. (Mitchell et al., 1997) addressed this by proposing power, legitimacy,

and urgency as three attributes for guiding organizations in effectively allocating attention and resources and helping managers identify which stakeholders require greater attention and prioritization.

The inherent characteristics of renewable energy projects (REPs) make stakeholder engagement and satisfaction especially important for their successful implementation compared to traditional energy projects. This is evident from the study conducted by (Maqbool et al., 2020) which focused on medium and small-sized REPs and concluded that stakeholder satisfaction significantly influences project success. The increased sensitivity arises from the potential social and environmental impacts linked to REPs, including alterations in land use, visual disturbances, and possible disruptions to local economies and ecosystems (Martinez & Komendantova, 2020).

Local communities are recognized as the most critical stakeholders in renewable energy projects, as their support and acceptance can significantly influence the project's success or failure. The local community needs to be on board with the project otherwise it would lead to problems in the longer run as seen in the Na Pua Makani wind project in Hawai (Susskind et al., 2022) where despite the general support for renewable energy the particular wind energy project was opposed due to the potential health and environmental impacts and the lack of local involvement in the decision-making process.

Securing stakeholder acceptance is crucial for addressing renewable energy development's complex social, economic, and environmental challenges. Successfully managing social impacts and engaging with local communities is essential to ensure the project's feasibility and long-term sustainability. However, this engagement is often complicated by factors such as community dynamics, willingness to participate, and notably, the level of trust among stakeholders (Kalkbrenner & Roosen, 2016; Segreto et al., 2020). Trust, in particular, is a recurring theme across studies, influencing how communities perceive and engage with renewable energy projects. Adopting a collaborative and inclusive approach that acknowledges the diverse interests and values of local citizens is essential for the success of renewable energy projects. When communities are actively engaged, they can play a crucial role in driving the energy transition forward, helping to build a more sustainable and fair energy future (Mihailova et al., 2022).

NGOs and environmental organizations are important stakeholders in renewable energy projects, advocating for sustainable practices and raising awareness of environmental impacts (Martinez & Komendantova, 2020). However, their influence is often constrained by limited resources and a lack of formal decision-making power compared to government and private sector stakeholders. The research by (Guðlaugsson et al., 2020) on Iceland's energy system highlights that NGOs, despite being active stakeholders, have limited power in renewable energy decisions due to their classification as "Crowd" in a power-interest matrix, indicating low influence compared to government and industry players who hold dominant decision-making roles. Despite having relatively low power, NGOs are generally more trusted by the public than other key actors in renewable energy projects (Huijts et al., 2007). This finding suggests that although NGOs may lack significant influence in decision-making, their public credibility can be crucial in fostering support and legitimacy for renewable energy initiatives. Engaging NGOs could therefore enhance stakeholder trust and improve project acceptance, bridging the gap between developers and local communities.

Moreover, as the world advances towards sustainable energy solutions, the role of government organizations and regulatory frameworks becomes increasingly significant in facilitating effective energy transitions. Although the development of renewable energy requires significant technological advancements the role of government organizations remains important in creating a supportive environment. As argued by (Wüstenhagen et al., 2007) governments play a crucial role as stakeholders in REPs by shaping policies that build investor confidence and market acceptance. Their consistent commitment to renewable energy goals encourages private-sector investment, which is another key stakeholder in the transition to sustainability through their financial backing and funding of green projects. The scale of investment required for widespread renewable energy adoption necessitates significant private-sector involvement. An illustrative example of this private sector engagement is the Powering Australian Renewables Fund (PARF), established by AGL Energy in partnership with the Queensland Investment Corporation. With a financial commitment of $2-3 billion, PARF seeks to unlock investments in large-scale renewable energy projects by reducing financing costs and diversifying associated risks (Taghizadeh-Hesary & Yoshino, 2020).

2.3 Risk Associated with Deep Geothermal Energy Projects

Several definitions of risk exist in the literature however (Aven, 2010) offers a broader perspective, defining risk as the potential for adverse outcomes originating from events, their consequences, and the associated uncertainties. This comprehensive approach emphasizes the importance of considering uncertainties explicitly, moving beyond traditional probability-based definitions. Like other projects involving natural resources, risks associated with Deep Geothermal Energy are one of the main barriers to its development. How people perceive risk plays a crucial role in shaping individual behaviour, as well as their acceptance of and commitment to specific technologies, policies, and societal norms (Siegrist & Árvai, 2020). The stakeholder acceptance depends on deep geothermal energy's perceived benefits and risks. Risk perception shapes the social acceptance of renewable energy projects as it directly impacts stakeholder opinion, impacting project acceptance and ultimately determining the feasibility of geothermal energy development.

As highlighted by (Ejderyan et al., 2019) downplaying the concerns regarding the perceived risks of geothermal energy can have detrimental consequences for project developers, political authorities, and scientists as it not only impacts the public trust but also leads to higher opposition towards projects reducing their social acceptability. While previous studies have established a link between trust and risk perception, this relationship has been explored primarily in the context of traditional energy sources, with limited attention given to geothermal energy or other renewable technologies. This gap highlights the need for further investigation into how trust influences risk perception and social acceptance in the renewable energy sector. In this context, the study by (Bronfman et al., 2012) revealed that in contrast to traditional energy sources, social acceptance of renewables like geothermal energy is less connected with trust in regulatory authorities and more influenced by uncertainties about social and environmental risks. This signifies the importance for developers to engage directly with stakeholders, addressing their concerns transparently and collaboratively to improve acceptance.

Although deep geothermal energy is being recognized for its potential to help with the transition to clean energy, there are several barriers to its development. The concerns by stakeholders are mainly due to the economic, environmental, and social risks and their perceptions of these risks play a critical role in shaping public support and project deciding its acceptance.

Economic Risks

Although deep geothermal energy offers many economic benefits like job creation, local economic development and energy savings, there are several risks associated with its development. A significant barrier to developing DGE is the higher initial investment costs associated with developing geothermal power plants (Agemar et al., 2014). These are considerably higher compared to other renewable technologies like solar and wind (Pan et al., 2019). The 5–7-year payback period for geothermal plants poses a significant challenge in attracting investors. This coupled with high initial investment is a big risk for financial investors.

Drilling costs are another major economic risk factor for deep geothermal energy projects as beyond the high expense and advanced technology required, there is substantial uncertainty, including the risk of encountering dry wells or achieving insufficient temperatures for viable electricity production. Achieving the optimal temperature for electricity production often requires drilling to unprecedented depths, significantly escalating costs. Research on drilling costs at the Soultz-sous-Forêts geothermal power plant showed that these costs rise exponentially with the depth of the drilling. This finding highlights the economic challenges of deep geothermal projects, emphasizing the need for innovative cost-reduction technologies and strategies to enhance project feasibility (Heidinger, 2010).

Deep geothermal energy is highly dependent on favourable geographical conditions meaning areas with lower subsurface temperatures or less accessible geothermal reservoirs would require drilling at greater depths to reach the required temperature for electricity production increasing drilling costs. This deeper drilling increases both the complexity and cost of exploration and development. In their study of deep geothermal energy potential in Canada (Majorowicz & Minea, 2015) highlighted drilling costs as a significant financial risk in exploration and development making electricity production economically unfeasible in regions like Northern Québec with lower geothermal activity. The cost of drilling for geothermal energy is usually higher than the drilling costs for oil and gas exploration ranging between 2.5 and 50 million USD depending on the size of the geothermal plant (Soltani et al., 2021). The risk of dry wells or encountering temperatures insufficient for electricity or direct heating not only leads to significant financial losses but also reduces the trust of the stakeholders in this novel technology as the true financial potential of a geothermal resource can only be determined after the drilling process so the risk is significant.

Environmental Risks

Although deep geothermal energy is being positioned as a clean, renewable energy source with significant potential to lead the energy transition, some of the environmental risks associated with it especially the seismic risks raise serious doubts about its successful implementation. The induced seismicity in deep geothermal energy projects occurs due to several reasons including the increase in the pore pressure which reduces the friction holding pre-existing fractures together causing a seismic slip. Another reason is the decrease in temperature due to the introduction of cooler fluids in hot rocks causing thermal contraction. As the heat extraction process from underground involves injecting and withdrawing the fluids a volume change occurs destabilizing the surrounding geological formations and leading to small earthquakes (Majer et al., 2007). Many studies have found that the risk of seismicity not only results in public opposition but also leads to project failures. Several geothermal energy explorations have been closed down after the reported incidents of seismic activities including the deep geothermal project in Strasbourg which was halted after the induced earthquake with a 3.6 magnitude on the Richter scale (Schmittbuhl et al., 2022). (Maurer et al., 2020) reported that the geothermal field development in Rittershoffen, France was associated with instances of

1300 earthquakes reported. In Switzerland, one of the deep heat mining projects was suspended following many small seismic activity reports (Häring et al., 2008). The Pohang earthquake in South Korea (2017), linked to geothermal drilling activities, is a case example of environmental risks associated with geothermal exploration as such events have long-lasting impacts on the stakeholder perception of the technology.
Another risk with deep geothermal energy is the water quality and water usage. Geothermal energy drilling and operation requires a significant amount of water between 0 to 17 cubic meters of water per megawatt-hour (MWh). This normally comes from local streams or reservoirs and impacts local resources. The geothermal fluids contain several harmful substances like arsenic, mercury, boron, or hydrogen sulphide. Any leakage presents a serious environmental concern for the drinking water, local crops and marine population (Pan et al., 2019). Although some solid waste is produced like mud mostly due to drilling it is not significant enough to cause any environmental degradation (Soltani et al., 2021).

Social Risks

Historically, the social dimensions of renewable energy projects have received limited attention. However, a growing body of research is now focusing on the social aspects and public acceptance of deep geothermal energy projects. Social acceptance has emerged as one of the key barriers to the successful development of these projects. However, this is largely dependent on managing perceived social risks and demonstrating clear benefits. Addressing these concerns and effectively demonstrating the benefits of geothermal energy is critical to building trust and fostering support among stakeholders and local communities.
Several studies found that the resistance from the local community towards deep geothermal energy projects is mostly due to their concerns about the risk of induced seismicity (Knoblauch et al., 2019; Soltani et al., 2021; Stauffacher et al., 2015). A lack of transparency and effective communication with local stakeholders by project developers significantly reduces social acceptance. This creates scepticism about the project's intentions and potential impacts, often leading to delays or even the complete failure of the

initiative (Chavot et al., 2018). Concerns regarding land acquisition, property values, and resistance when communities perceive an unequal distribution of benefits, such as electricity or profits, compared to the risks they bear, such as seismic activity or disruptions, are other social risks that must be addressed.

2.4 Stakeholder Risk Perception in Deep Geothermal Energy Projects

How people evaluate the likelihood and severity of potential harm or loss caused by a technology is termed as risk perception. These judgments are shaped by personal beliefs and interpretations about the nature and intensity of a risk. How an individual perceives risk depends upon several factors including their attitudes towards taking risk. An individual's approach to risk can also be influenced by various factors, including self-perception and the subjective interpretation of a situation (Vasvári, 2015).

As the global energy transition accelerates, countries are increasingly exploring a diverse range of renewable sources to build sustainable, resilient energy portfolios for the future. Each renewable technology brings unique advantages, and geothermal energy is gaining attention due to its consistent baseload power generation, low emissions, and minimal land footprint. Compared to other renewable sources like wind and solar, geothermal energy stands out for its efficiency and reliability, making it a promising technology for advancing a low-carbon, sustainable future (Li et al., 2015).

A successful transition to renewable energy requires the development of diverse energy sources and the acceptance and support of various stakeholders. However, the advancement of innovative technologies like deep geothermal energy is now also heavily dependent on how people perceive the risks associated with them (Arning et al., 2017). Geothermal energy's potential to contribute towards energy security and sustainability attracts interest from diverse stakeholders. A previous study on stakeholder acceptance of geothermal energy in Japan by (Kubota et al., 2013) revealed that, despite geothermal energy's stability and independence from weather fluctuations, several significant barriers hinder its development, with stakeholder acceptance being a primary challenge. The findings emphasize that for geothermal energy to become more socially accepted, it is important for all stakeholders ranging from local communities to policymakers and industry players to have access to clear, accurate information about both the risks and the realistic benefits of geothermal technology. The insights from the study on the failure of the Tolhuaca exploration geothermal energy project in Chile by (Vargas-Payera et al., 2020) validate the significance of stakeholder engagement and perception in the success of geothermal energy projects. The project faced resistance from the stakeholders especially the environmental NGOs and Indigenous communities due to concerns about potential impacts on the landscape, protected forests, and culturally significant sites as they perceived these risks to significant enough to oppose the technology despite many benefits it offers. Ineffective and delayed engagement and poor communication about potential risks led to growing concerns, mistrust, and a lack of collaboration. This ultimately resulted in increasing opposition, despite the initial positive outlook toward the project. The study also reveals that stakeholders within the same geothermal energy project can have differing perspectives on its environmental sustainability. This is often influenced by their stakes in the project and the financial benefits they are getting from it. Another important conclusion is that stakeholder perceptions about geothermal energy are dynamic and they keep on evolving with time. These perceptions are influenced by factors such as project progress, risk mitigation efforts, and the extent to which anticipated benefits are realized as the project advances.

Despite its limitations, Stakeholders worldwide view geothermal energy as a potential technology to address both energy demand and sustainability goals. In their study about Societal acceptance of Geothermal energy by stakeholders involved in hot springs (Kubota et al., 2013) , hot spring managers recognize that geothermal energy offers an advantage by reducing greenhouse gas emissions, a key concern in the transition to a sustainable energy system**.** They do not oppose the development of geothermal power plants themselves, and they even recognize that geothermal energy has the advantage of reducing greenhouse gas emissions. However, some managers perceive the benefits of geothermal development, such as job creation or infrastructure improvements, as insufficient to outweigh the perceived risks to their livelihoods and the cultural value of hot springs. However various companies involved in geothermal power plant development see it as a great business opportunity as the world moves towards renewable energy and the calls for decarbonization grow.

The findings from studies by (Vargas-Payera et al., 2020) and (Kubota et al., 2013) provide an overview of how financial perspectives positively shape the stakeholder risk perception of geothermal energy projects. However, a comparative analysis of both studies provides a more nuanced view revealing that while financial gains positively impact the stakeholder acceptance of geothermal energy, ineffective engagement and poor risk communication can drive opposition even among initially supportive stakeholders.

As the previous studies have indicated the development of geothermal energy involves a diverse group of stakeholders including local communities, governments, environmental organizations, and industry leaders all playing important roles in shaping the trajectory of geothermal energy initiatives. Their perspectives and acceptance of geothermal energy are shaped by their interests, knowledge, and potential benefits. The research on the acceptance of geothermal energy development in Central Italy by (Pellizzone et al., 2017) highlighted the varied risk perceptions of geothermal energy among different stakeholder groups. Although the local citizens have a higher level of support towards geothermal energy, however their limited technical knowledge about its risks and benefits reduces overall acceptance. In contrast, environmentalist groups possess a deeper understanding of geothermal energy but emphasize the necessity of creating public awareness. They advocate for a long-term vision through comprehensive and transparent information campaigns to educate and actively engage the public. These efforts are seen as essential to building informed support and addressing concerns effectively across all stakeholder groups. Although the levels of knowledge and focus, are different both groups have shared a common distrust toward key decision-makers, particularly politicians. This is due to the lack of transparency and consistent decision-making. The perceptions of politicians on the other hand are influenced by various factors including the political agenda and the challenge of balancing economic interests with environmental sustainability (Meller et al., 2018). However previous studies suggest that the projects where the decision makers actively engage in dialogue with operators and local communities have higher acceptance as evidenced by the success of the geothermal energy development in Illkirch-Graffenstaden, France(Chavot et al., 2018).

The growing climate change concerns mean that Governments and Policymakers are looking keenly at the development of geothermal energy due to its ability to meet base-load energy demands, contribute to carbon reduction goals, and diversify national energy portfolios. This is evident in the growing use of geothermal energy for electricity production in recent years (Gutiérrez-Negrín, 2024). Despite its numerous risks including higher initial costs requiring substantial government subsidies leading Policymakers view geothermal resources as a strategic asset as they can support energy independence and long-term sustainability, especially in regions where they are easily accessible.

2.4.1 Communication Strategies for Mitigating Perceived Risks of Deep Geothermal Energy Projects

As evident from the previous literature, risks surrounding deep geothermal energy are multifaceted, so effective risk communication and management strategies are required to mitigate these risks and address the stakeholders' risk perception to improve social acceptance. Globally, various projects and programs have emerged to address the challenges of risk perception in geothermal energy. One notable example is GeoLaB, a project designed to address key scientific challenges and enhance public transparency concerning geothermal energy systems. Negative public perception is mostly due to concerns about environmental impacts such as induced seismicity and potential groundwater contamination. To mitigate these risks, GeoLaB focuses on conducting controlled high-flow experiments, developing smart stimulation technologies, and ensuring borehole safety to minimize adverse environmental effects. Not only this Geo-LaB will be providing a platform for open dialogue between scientists, industry, policymakers, and the public to address these concerns and build trust. The project plan to increase social acceptance included offering educational opportunities, including guided tours, summer schools, and online resources, to enhance public understanding of geothermal energy and build capacity among stakeholders (Meller et al., 2018).

Early and consistent engagement of the public in decision-making serves as an important strategy for addressing the risks and concerns of deep geothermal energy, as delayed communication regarding risks leads to a decline in acceptance (Cousse, 2021). (Kubota et al., 2013) highlight that effective risk management strategies for the development of geothermal energy often involve a combination of technical and social measures, including risk avoidance through careful planning and mitigation before development. (Metze et al., 2023) propose participatory repertoires as an effective multifaceted communication strategy to mitigate perceived risks associated with deep geothermal energy. These include open discussions to explore public values, joint efforts to gather facts about technical risks, and involving diverse groups ranging from local communities to national policymakers. Such communication strategies enhance trust by involving diverse participants supporting a more inclusive energy transition.

The role of traditional and social media is also very important in communicating strategies for mitigating the perceived risks of deep geothermal energy. Traditional media has been used for years to communicate the benefits and risks associated with geothermal energy. The negative framing of risks around geothermal energy especially induced seismicity leads to a negative perception of the technology impacting how people view the technology (Cousse, 2021). The media study regarding the perceived benefits and risks of geothermal energy in Australia revealed that economic feasibility and technological uncertainty are the most prominently mentioned risks (Romanach et al., 2015). Additionally, social media resources like Facebook serve as an effective tool for mitigating perceived risks of deep geothermal energy by facilitating targeted engagement, transparency, and dialogue. Not only helping stakeholders reach specific demographics but also sharing project updates and addressing concerns by proactively communicating potential risks (Wirtz-Bruckner et al., 2015). These insights provided by the media can be strategically used to develop proactive communication strategies. Through educational campaigns providing accurate and balanced information, the media can help educate the public about the challenges of geothermal energy.

2.5 Social Acceptance and Geothermal Energy Risks

Despite its numerous advantages, the total installed capacity of geothermal electricity remains much lower compared to that of wind and solar energy (Li et al., 2015). These results show that the success of renewable energy projects extends beyond technical feasibility and economic viability. Social acceptance has now emerged as an important factor in determining the realization and long-term sustainability of such projects. (Wüstenhagen et al., 2007) contributed towards the understanding of social acceptance by providing a structured framework distinguishing it into three key dimensions including socio-political acceptance, community acceptance, and market acceptance. These dimensions collectively form what is often referred to as the social acceptance triangle, as shown in Fig 1.

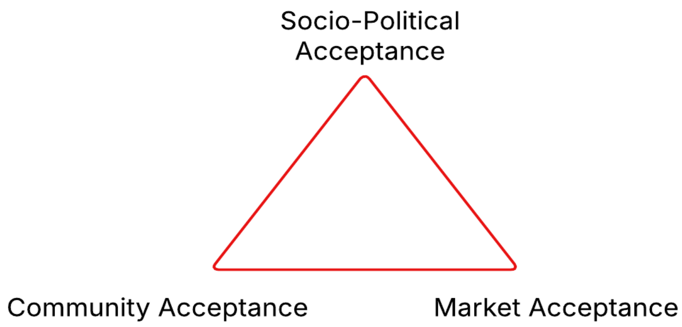

Figure 1. Social Acceptance Triangle adapted from (Wüstenhagen et al., 2007)

Deep geothermal energy projects around the world have received varying levels of social acceptance reflecting diverse societal attitudes and priorities. The risks associated with DGE, particularly the issue of induced seismicity, are among the most prominent concerns raised by the public reducing its acceptance significantly (Balzan-Alzate et al., 2021; Stauffacher et al., 2015). Several studies have identified a lack of information about geothermal energy and its implications as an important contributor to its reduced acceptance (Renoth et al., 2023; Vargas Payera, 2018). Further studies emphasize the importance of ensuring that all stakeholders, including the general public, are well-informed about the risks, technical aspects, and realistic benefits of the technology (Kubota et al., 2013). The social acceptance of deep geothermal energy is highly dynamic, often evolving as public awareness increases and specific project details emerge. A study by (Malo et al., 2019) in Québec, Canada, revealed low initial awareness, with only 17% distinguishing between shallow and deep geothermal systems. After an informational intervention, support rose to 67% for electricity production and 64% for local pilot projects. However, the mention of hydraulic stimulation reduced support to 56% and 52%, respectively, highlighting how perceived risks can significantly impact public attitudes. Media plays an important role in shaping public opinions about any technology. Unfavourable media coverage can significantly reduce the public acceptance of deep geothermal energy by amplifying concerns about risks such as induced seismicity and environmental impacts, often overshadowing its benefits (Dowd et al., 2011).

Past studies on social acceptance of geothermal energy highlight that the most important factor for increasing social acceptance is trust in key actors, a trend consistent with other energy projects. Trust in developers, policymakers, and regulators plays a pivotal role in shaping public perceptions and support for deep geothermal energy initiatives (Renoth et al., 2023).

Social acceptance of deep geothermal energy is not a unified concept as it can vary significantly between countries and even within different regions of the same country. Local contexts, cultural differences, and specific regional concerns influence this variation. The investigation of social acceptance of deep geothermal energy in Germany and Switzerland revealed despite having higher acceptance towards the technology the Swiss public is more accepting even of the projects with higher seismicity concerns than the German public, partly due to a higher willingness to take risks, reflecting cultural and societal differences as well as indicating how varying risk perceptions among different populations can lead to the subsequent higher or lower acceptance of the technology (Knoblauch et al., 2019).

2.6 Government Policy and Regulations

While the availability of geothermal energy resources presents its challenges, an even bigger challenge associated is the complex process of exploring and developing these resources for energy production which require effective government policies and regulations. The stakeholder analysis conducted by (Guðlaugsson et al., 2020) on the Icelandic sustainable energy development system revealed the national government as the key player with high interest and decision-making powers.

One significant way governments shape the development of geothermal energy is through policies on land ownership and management (Koon Koon et al., 2021). Land-ownership policies vary around the world offering insight into how regulations can shape the development and acceptance of geothermal energy as part of the worldwide energy transition. In New Zealand, the management of geothermal resources evolved from a government-only model to a shared management system with public and private stakeholders (Malafeh & Sharp, 2015). However, Iceland which is one the global leaders in the development of geothermal energy thanks to its energy policies has taken a contrasting route where geothermal resource ownership is assigned based on land ownership, but extraction rights are strictly regulated through state-issued licenses. This way not only the private owners' interests are protected leading to higher acceptance, while also allowing the government to maintain control over enforcing its energy policies (Ketilsson et al., 2021). Despite their contrasting approaches, both countries have developed comprehensive policy guidelines for geothermal energy development, highlighting that effective policies are those that reflect each region's legal, environmental, and societal context. These findings provide a valuable lesson for the developing geothermal markets to balance resource protection, ownership rights, and local conditions to stimulate sustainable geothermal energy development.

The German government considers geothermal energy as an important part of its future energy transition scenarios. It has been included in the feed-in tariff (FiT) for renewable energies (Kunze & Hertel, 2017). Geothermal energy has been incentivized by including the projects under the mining law meaning they no longer fall under the local parliament decisions and Environmental Impact Assessments (EIAs). However, the results from research by (Kunze & Hertel, 2017) reveal that following a series of induced seismic events in Germany and Switzerland, public concern grew, sparking new environmental protests and local citizen initiatives (LCIs) that have increasingly opposed geothermal projects suggesting the regulatory support and policies by the government do not guarantee the project's success. The government's policies should incorporate the stakeholders' views and must be carefully designed to address the stakeholder concerns.

The regulatory framework for deep geothermal energy in the UK presents a contrasting picture to Germany as the government's absence of reliable policies and a lack of specific financial incentives and risk-sharing mechanisms discourage private investment resulting in the underutilization of this renewable energy source (McClean & Pedersen, 2023). The two contrasting policy cases highlight that firstly for the success of geothermal energy incentives, the government needs to have a consolidated policy and regulatory process, secondly the policy needs to be inclusive to build local trust, attract investment, and have sustainable growth.

The research on Geothermal energy projects in France by (Chavot et al., 2018) highlights the problems of creating effective government policies that not only promote the development of geothermal energy but also ensure the acceptance of local stakeholders. The contrasting response to the different deep geothermal energy projects in Alsace demonstrates how a one-size-fits-all approach in government policy-making is insufficient for such context-dependent energy projects. (Chavot et al., 2018) found that the projects that were developed after detailed early-stage consultation and partnerships with local government and operators as well as facilitating the local public faced very little resistance. Conversely, projects initiated without prior stakeholder involvement encountered notable opposition, despite aligning with France’s national energy transition goals. The results from this research indicate that while consistent policies regarding the development of deep geothermal energy sources can provide a good foundation they must be adaptable to the needs and priorities of the local stakeholders which can vary substantially in different areas depending upon the local culture, values, climate and other relevant factors.

Although the research on stakeholder communication strategies has been increasing only a few studies are effective in providing strategies that not only align with government policy but also reflect societal needs. (Metze et al., 2023) have addressed this gap by focusing on the province of North Brabant in the Netherlands, which entered a Green Deal with industrial and societal partners to explore deep geothermal energy at five sites. Local municipalities, provincial authorities, industry, citizen groups, and others invested in sustainable energy were the stakeholders involved. Stakeholders have different expectations for timing, scope, and organization of engagement, highlighting the need for flexible approaches which is in line with the findings from the previous research by (Chavot et al., 2018). Through their study (Metze et al., 2023) identified ways to coordinate society and policy through the following participatory storylines:

1. Local Dialogue: Discuss the usefulness of DGE in a specific area.
2. Local Fact-Finding: Experts gather technical information locally to address uncertainties.
3. Societal Fact-Finding: National-level experts share general DGE information.
4. Societal Dialogue: A national conversation led by the government about DGE's role in the energy mix.

The decision regarding the approach to use would depend on the specific uncertainties and preferences of the people involved. To ensure more inclusive energy transitions, it is essential to implement the appropriate process at the right time.

The national energy policy of countries can provide a great opportunity for developing geothermal energy resources. Despite being a small country Iceland has been able to utilize its geothermal energy resources efficiently thanks to the long-standing commitment and sustained support of the government towards renewable energy and consistent policy actions. The National Renewable Energy Action Plan (NREAP) announced in 2012 set out a clear roadmap and ambitious targets for the development of geothermal energy in Iceland up to 2020. With strong government support, Iceland achieved its electricity production targets from geothermal energy by 2018 well ahead of the scheduled timeline. This success highlights how strong national policies and strategic roadmaps can accelerate the development of geothermal energy, showing the crucial role that government energy policy plays in utilizing renewable resources effectively (Ketilsson et al., 2021).

Iceland's experience underscores the potential for other countries to unlock geothermal energy development through focused policy initiatives and long-term planning however China's geothermal sector reveals how a lack of clarity in policy and regulations related to geothermal energy can hinder growth despite abundant resources. A centralized legal framework is lacking as different regions have different policies. The lack of effective financial incentives, long-term research support, and a unified exploration and planning system is also impacting the growth rate of geothermal technology. The researchers have identified the 13th Five-year Plan period of the Chinese Government as an opportunity to advance geothermal energy development. In this light (Wang et al., 2020) have provided the following policy recommendations:

1. Establishing a clear legal definition to streamline management and regulatory processes, drawing inspiration from countries like the U.S., New Zealand, and Japan.
2. Implementing financial incentives such as tax breaks, subsidies, and preferential resource access to attract investment and lower development costs, similar to solar and wind energy support.
3. Develop a unified, nationwide system for assessing geothermal resources, and identifying priority development areas.

3 Data and Methodology

This chapter details the methodology used to drive this research, including an introduction to the research approach, data collection method including the stakeholder identification process and stakeholder mapping, followed by an introduction to the tools used for data analysis. The chapter concludes by addressing the measures taken to ensure the research's integrity and trustworthiness.

3.1 Research Approach

Depending on the nature of the study researchers employ different research approaches offering distinct ways of collecting and interpreting data. The three most commonly used research approaches include quantitative, qualitative, and mixed methods (Taherdoost, 2022). Although all three research methodologies have their strengths however the correct choice of methodology based on the research objectives and goals is very important for conducting successful research.

Quantitative research is a systematic investigation through numerical data to study phenomena and their relationships. The data is analyzed using mathematical methods commonly statistics. Researchers use this approach to explore how different measurable factors are connected. The goal is to explain these relationships, predict outcomes, and sometimes manage or influence the phenomenon being studied (Mohajan, 2020). Qualitative research on the other hand refers to a range of methodologies that explore phenomena by examining experiences, behaviors, and relationships. Unlike quantitative research, which relies on numerical data or statistical analysis qualitative research focuses on understanding the underlying meanings, motivations, and patterns within human interactions and contexts (Basias & Pollalis, 2018).

Although quantitative research is valuable for its ability to generalize results from large sample sizes leading to objective insights, and offer standardized, replicable methods. However, reliance on numerical data means this approach is limited in explaining complex social realities and human emotions. This limitation is particularly important in studies focused on social acceptance like ours, where understanding subjective experiences and contextual factors is crucial. Despite the disadvantages of qualitative research like lack of concentration on contextual sensitivities and lack of generalizability of findings due to small sample spaces in comparison to quantitative studies, the possibility of providing in-depth information, especially regarding emotions and discovering the individual experiences through interacting with the participants during the data collection procedures makes this research method very valuable (Taherdoost, 2022).

A third type of research methodology that addresses the concerns of both qualitative and quantitative methods by combining both is termed mixed method research. (Creswell & Vicki, 2018) have described the process of the mixed methods approach as one in which the researcher collects and analyzes both qualitative and quantitative data to answer research questions. The two forms of data and their results are then combined and organized these procedures into a clear research plan that provides the logic and procedures for conducting the study.

This study has used a qualitative research approach. The decision was made based on the nature of the research questions and the objectives. This research will involve an in-depth exploration of the risks associated with deep geothermal energy as identified by stakeholders and how their perceptions of these risks influence social acceptance. A qualitative research methodology supports this approach, allowing in-depth data collection and analysis of complex and context-specific issues (Basias & Pollalis, 2018). Additionally, understanding the relationship between perceived risks and social acceptance requires exploring feelings, values, and context, for which qualitative research is well suited as identified by the previous studies (Taherdoost, 2022). This approach offers a deeper understanding of how people interact with and perceive this technology. Given that deep geothermal energy projects involve different stakeholder groups that have unique concerns depending on their involvement and interest in the project, qualitative methods like interviews can provide rich insights into these varied viewpoints.

3.2 Data Collection

This study is a part of the HOCLOOP project, which is a circular by-design project that uses an environmentally friendly geothermal energy solution based on a horizontal closed loop to extract heat from shallow rock formations. It employs a horizontal closed-loop system and innovative CO2-based fluids to harness geothermal power from both deep and shallow rock formations. This method promises to extend geothermal energy's reach beyond traditional hotspots, reducing costs and environmental impacts while enhancing power production and reliability. The project involves collaboration across different European countries.

3.2.1 Overview of Research Sites

Belgium site: Vito Geothermal energy development site at Balmatt

As a part of the research four different pilot sites were chosen to investigate how the stakeholder's risk perceptions and acceptance vary across different deep geothermal energy locations. One of the sites selected was Balmatt Belgium which was already at advanced development stages of deep geothermal energy. The Balmatt geothermal project began in November 2019 when VITO, a leading research center driving sustainability with innovative, scalable technologies, launched a geothermal exploration and development initiative. The project resulted in construction of the Balmatt geothermal plant in Mol (Belgium). Operated in collaboration with VITO and other stakeholders, the site uses advanced technologies, including a fractured limestone reservoir at depths between 3200 and 3400 meters. It employs horizontal closed-loop systems to extract geothermal heat. The facility features three wells: a vertical production well, an injection well, and a monitoring well. Operational since 2021, the site supplies heat to nearby research institutions, such as VITO and SCK, and supports district heating and electricity generation through an organic Rankine cycle unit. This innovative approach aims to enhance the scalability and sustainability of geothermal energy in the region. Local actors are committed to explore the potential use of the third well for implementing the HOCLOOP solution, and HOCLOOP project can utilize comprehensive subsurface data available for thermal simulations. One of the key research angles of this project involves exploring the social acceptance of deep geothermal energy. By examining stakeholder perceptions of various social, economic, and environmental risks, this study aims to understand how these risks influence the social acceptance of deep geothermal projects at the Belgium site.

Finland site

The workshop in Vaasa, Finland, was unique among the other sites as the region does not currently host any active deep geothermal energy exploration projects as part of HOCLOOP. However, Finland has potential for geothermal energy and the country has had deep geothermal drilling in the past. As the Finnish Government is aiming to become climate-neutral by 2035 reducing its carbon emissions it was a good time to strategically engage the stakeholders. Vaasa, known as the energy capital of Finland, was an ideal location to assess the potential for future DGE development. The workshop aimed to create awareness about the technology while exploring the current level of knowledge, perceptions, and apprehensions regarding deep geothermal energy among local research stakeholders providing a platform to explore the readiness and openness to adopt the technology.

Germany site

The Darmstadt site in Germany is a key contributor to the HOCLOOP project, led by the Technical University of Darmstadt (TUD). At this site in Darmstadt, TUD is collaborating to explore optimal geological conditions and evaluate heat extraction potential. The research by TUD also involves data collection, underground simulations, and techno-economic feasibility studies.

Poland site

The government of Poland is actively investing in Geothermal energy development. Deep geothermal energy research by AGH University of Science and Technology in Krakow is aimed at assessing the possibility of heating homes, buildings, and agricultural sites. The extensive research confirming the presence of geothermal energy by AGH has led to the drilling of a well with a planned depth of 2,500 meters in August 2023 in Gluszyca, Poland. Laboratory tests would be conducted as part of the HOCLOOP project to analyze the properties of advanced working fluids, tailoring the results according to the Polish sites conducting environmental assessments. The citizen acceptance and engagement at these sites will also be researched.

3.2.2 Key Stakeholders: Belgium example

Based on the prior media analysis of the articles about the project and project documentation, the following active stakeholders as shown in Table 1 were identified who were involved in or influenced the deep geothermal energy development at the pilot site in Mol.

Table 1. Overview of Stakeholder Groups.

Name of the Stakeholder	Stakeholder Group	Description
Vito	**Research**	Vito is an independent research organization based in the Flemish region working on cleantech and sustainable development. Vito is the primary stakeholder actively involved with developing the first deep geothermal plant in Flanders and researching the potential of deep geothermal energy in the region.
Hita	**Developers**	Hita is a VITO spin-off that is actively involved with the development of geothermal energy projects in the region.
Flemish Government	**Policymakers**	Another key stakeholder is the Flemish government which provides critical regulatory support, policies, and financial support to the deep geothermal energy projects in the region.
Local Residents of Mol and Dessel	**Local Citizens**	The biggest stakeholders of the project are the residents as deep geothermal energy extraction will impact their environment and the benefits of geothermal energy will impact their quality of life, so their interest is high, even if their influence is lower.
Janssen Pharmaceutica	**Industry**	Janssen Pharmaceutica is a key stakeholder as it is investing in a deep geothermal project that aims to significantly reduce CO2

		emissions by using geothermal energy to heat Janssen pharmaceutical premises.
European Union	**Policymakers**	The EU is providing substantial financial backing by investing and co-funding 5 million euros in the HOCLOOP Deep geothermal energy project. It also provides funding and policy oversight through programs like the European Regional Development Fund (ERDF)
Smet	**Industry**	As one of the major concerns with deep geothermal energy is the drilling at such unprecedented depths, drilling companies involved like Smet group play a technical role in the project with drilling expertise but have limited interest beyond their contract fulfilment.
Vocational or Educational Institutions	**Research**	(European School in Mol, Thomas More in Geel) The deep geothermal energy project brings more jobs and learning opportunities for the students in the region.

Diverse stakeholders are involved in renewable energy projects, making stakeholder identification and analysis crucial for the effective development of natural resources. One of the methods used for stakeholder analysis is the Interest-Power Matrix method, which categorizes the stakeholders in different matrices based on their interest in the project and the power they have. According to (Reed et al., 2009) who evaluated various stakeholder analysis methods in natural resource management, the Interest-Power Matrix emerged as the most effective and efficient approach. The main strength of this method is that it does not require a lot of resources as it can be implemented either through focus group discussions or by the researcher independently. For this study firstly, the potential stakeholders were identified, including Local Citizens, Researchers, Developers, Policymakers, and industry. Each stakeholder's level of interest in the project and their power to influence its direction, funding, or public perception was assessed, and using the interest and power axes the stakeholders were categorized into a matrix as visualized in Fig 2.

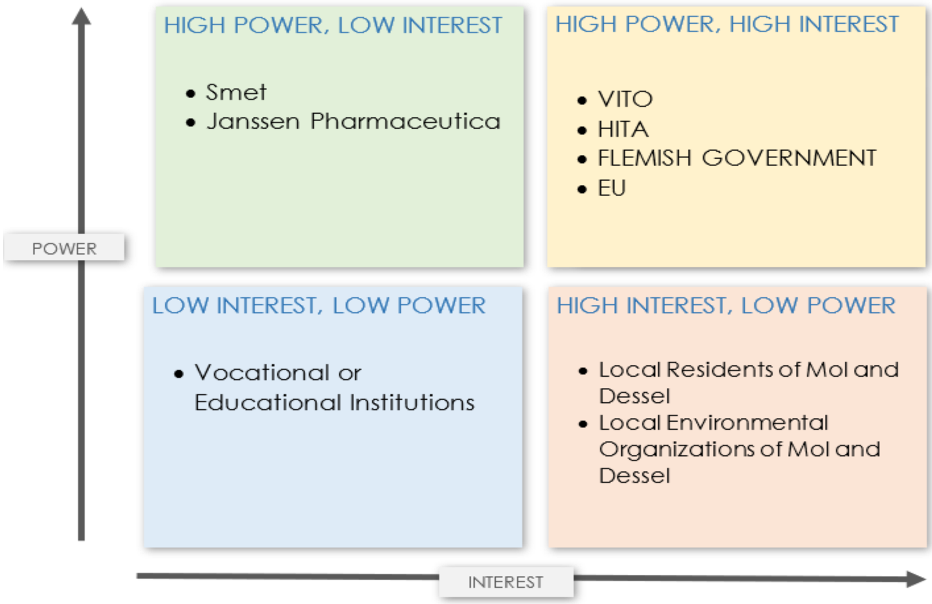

Figure 2. Stakeholder Power-Interest Matrix

3.2.3 In-depth Interviews and Workshop Design

The primary data sources include the semi-structured interviews conducted by the researcher and the data collected from previous project workshops. Semi-structured interviews provide flexibility by combining closed and open-ended questions with the possibility of follow-up questions allowing deeper insights and thoughts from the respondent (Adams, 2015). The use of a semi-structured interview approach allowed for more flexibility and the use of open-ended questions allowed the participants to share their thoughts, feelings, and experiences about deep geothermal energy.

Table 2. Summary of the Interview Process.

Interviewee ID	Role	Organization	Date	Dura-tion	Interview Mode	Pages Transcribed
Interviewee 1	Research Co-ordinator	Vito	26.10.2022	58 mins	Face to face	15
Interviewee 2	Citizen En-gagement	Vito	5.11.2024	51 mins	Online	34
Interviewee 2	Citizen En-gagement	Vito	12.12.2024	47 mins	Online	33
Interviewee 3	Project Engi-neer	Hita	12.12.2024	44 mins	Online	25

This study's sample size includes four interviews conducted with three different stakeholders, along with data gathered from three workshops held at various locations as shown in Table 2 above.

A purposive sampling strategy guided the selection of interview participants. Purposive sampling is an effective technique employed to choose participants who are most likely to provide relevant and valuable insights (Kelly, 2010). Given the study's focus on understanding risks associated with deep geothermal energy and stakeholder risk perceptions, purposive sampling allowed us to prioritize participants who have significant involvement, expertise, and influence in the development of deep geothermal energy projects in the region. Due to the limited research resources and time, a power-impact matrix was used to identify stakeholders with high interest and influence over the technology's development. This ensured that the selected interviews would result in-depth, nuanced information about the risks and challenges associated with deep geothermal energy, as well as the perceptions and attitudes shaping stakeholder acceptance.

One of the stakeholders, responsible for communication with local residents about deep geothermal energy technology, was interviewed twice to capture the evolving dynamics of local engagement and perceptions. The first interview focused on their role and strategies for engaging the community, during which an upcoming local engagement session related to the technology was mentioned. A second interview was conducted after this session to incorporate insights from that event and explore how the engagement influenced their understanding of local's perceptions of risks and acceptance of deep geothermal energy. This added depth to the study's look at risk perceptions and social acceptance. An outline of the questions was prepared to guide the interview process.

Workshop participant selection, on the other hand, was based on collaboration with local research organizations. The local organizations used their expertise to draft a list of participants, including all the potential and relevant stakeholders for possible project implementation. The invitations for the stakeholders were sent by the local organization. The final participant list was a subset of the recognized participants (those who accepted the invitation). Table 3 summarizes the key characteristics of the workshops used for data collection.

Table 3. Overview of Key Workshop Features.

Workshop ID	Location	Date	Total Participants	Stakeholder Groups
WS-1	Vaasa, Finland	10.08.2023	18	Researchers, Industry
WS-2	Darmstadt, Germany	11.12.2023	17	Researchers
WS-3	Krakov, Poland	08.10.2024	21	Researchers, Industry, Citizen Groups

3.3 Data Analysis

After the data was collected through interviews and workshops the interview transcripts and workshop notes were used for the analysis. This study used NVivo 15, a software used for Qualitative Data Analysis. Thematic analysis is a method used to find, examine, and present patterns or themes within data. Through thematic analysis qualitative data can be organized and described in a clear and detailed manner, providing rich insights (Braun & Clarke, 2006). As this study aimed to examine the stakeholder risks related to deep geothermal energy and identify how stakeholders perceive risks and their influence on acceptance, which involves interpreting deeper insights. Thematic analysis was used primarily to identify and interpret patterns and themes.

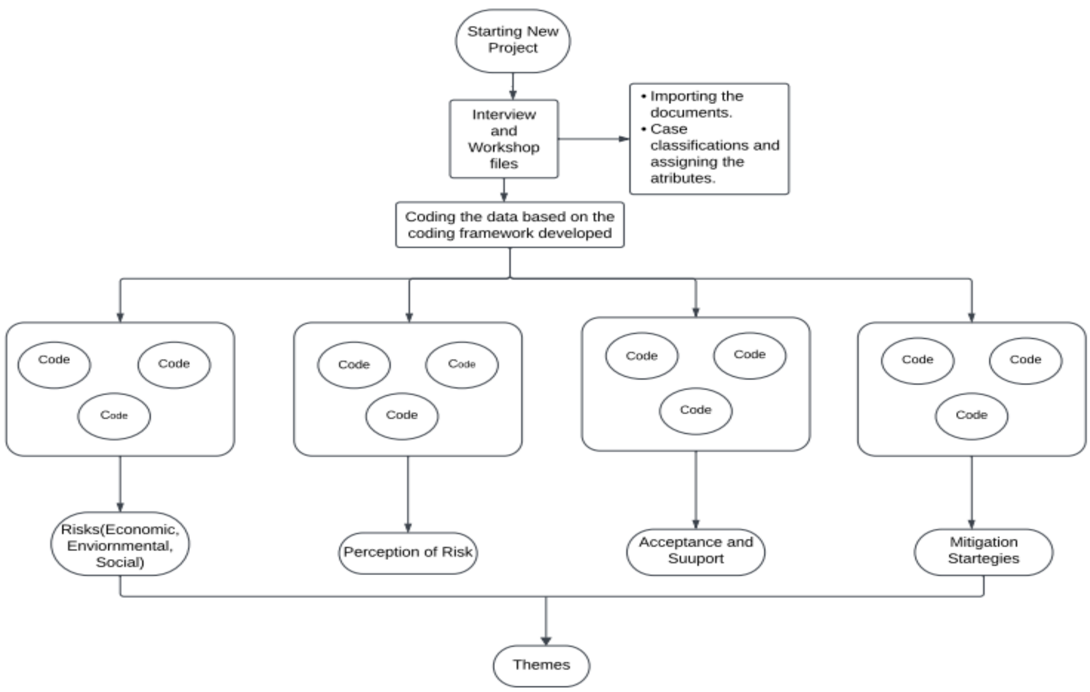

Figure 3. Stepwise Guide to Thematic Analysis process in NVivo adapted from (Pradhananga & ElZomor, 2023)

A coding framework was developed guided by the research questions and relevant literature and the data was coded in the predefined codes in NVivo based on this coding scheme. Six main codes were identified initially including social risks, environmental risks, economic risks, risk perceptions, acceptance and support, and mitigation strategies. Fig 3 shows the step-by-step process followed for the thematic analysis in NVivo. The transcripts and notes from interviews and workshops were first imported into NVivo. Data from interviews and workshops was carefully coded to the relevant themes in NVivo. The different stakeholders were classified based on the attributes including stakeholder groups to analyze the variations in perceptions across different stakeholder groups. After carefully reviewing the coding process, the relevant codes were grouped into different themes, providing insights relevant to our research objectives.

3.4 Trustworthiness of the Research

The concepts of reliability and validity are commonly used to assess the quality and integrity of research. The move away from conventional approaches to reliability and validity in qualitative research due to the problems with their applicability led to the development of alternative concepts. (Lincoln & Guba, 1985) introduced the concept of trustworthiness ensuring rigor in qualitative research, focusing on credibility, transferability, dependability, and confirmability as the key aspects.

Triangulation is using multiple data sources to develop a comprehensive understanding of the research problem which is also seen as one of the methods to improve the reliability and validity of the research by converging the information from more than one source ensuring the richness and rigor of the qualitative studies (Patton, 1999). Data Triangulation was one of the strategies used by this study to enhance the credibility of the research. This approach involved utilizing multiple data sources, including stakeholder interviews and workshop data, to develop a comprehensive understanding of the research problem. Confirmability is the extent to which the study results are unbiased and based on the data, rather than the researcher's personal opinions(Lincoln & Guba, 1985). The research supervisor was also involved in the interview process providing an objective perspective, which helped enhance the confirmability of the study. The interviews were recorded after getting permission from the participants. The audio recordings and full transcripts of the stakeholder interviews were carefully reviewed to ensure credibility and confirmability as well as allowing for a detailed analysis and a transparent method of checking the accuracy of the data collected. Transferability of research is defined as the degree to which its results apply to other contexts, times, and situations (Drisko, 2025) while dependability in qualitative study is defined as the research consistency (Janis, 2022). This study has provided detailed information about the research methodology including a clear description of how data was collected, the interview selection process, how the analysis was carried out and the tools used, as well as the reasoning behind decisions made throughout the research process which has enhanced the transferability and dependability of the research.

4 Results

4.1 Risks in Deep Geothermal Energy Development: Stakeholder Views

One of the primary aims of this study was to investigate different risks associated with deep geothermal energy development. Our analysis of stakeholder perspectives on deep geothermal energy development revealed a range of perceived risks that influence acceptance and support for the technology. These risks can be categorized into three main areas: economic, environmental, and social risks. Fig 4 illustrates the number of different risk types mentioned by each stakeholder group.

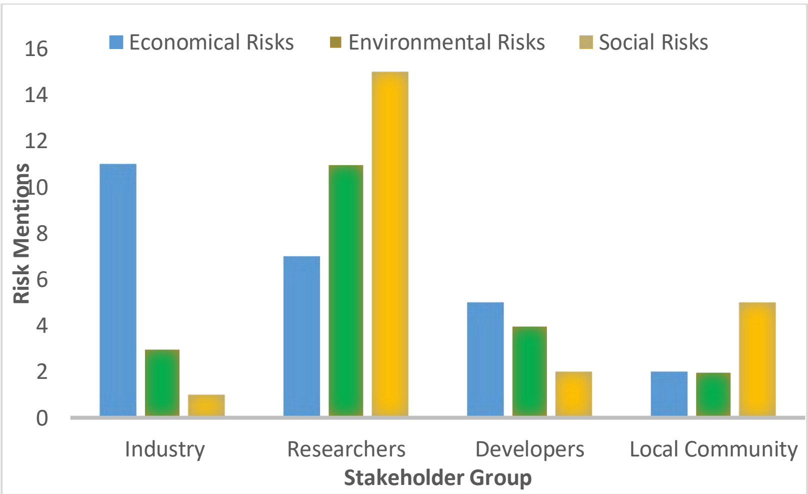

Figure 4. Stakeholder Frequency of Risk Mentions in Deep Geothermal Energy

Different stakeholder groups, including Industry, Researchers, Developers, and the Local Community, identified shared and distinct risks depending on their level of involvement and knowledge of the technology and their influence on its development. Through the thematic analysis, the different risks mentioned by the stakeholders were examined and categorized into various themes and subthemes presented in the following subsections for a detailed explanation.

4.1.1 Economic Risks of Deep Geothermal Energy

The development and deployment of deep geothermal energy face several challenges and one of the significant challenges is economic considerations relating to the technology. The results from the data analysis revealed several economic risks as viewed by the stakeholders. These risks were grouped into four major themes including High Initial Investment and Financial Barriers, Market and Economic Uncertainty, Policy and Regulatory Challenges Leading to Costs, Integration and Operational Costs. The exemplary data presenting direct stakeholder quotes regarding these risks is shown in Table 4

Table 4. Key Economic Risks in Deep Geothermal Energy Identified by Stakeholders.

Economic Risks	Subthemes	Exemplary Quotes by the stakeholders
High Initial Investment and Financial Barriers	1. High capital cost. 2. Long Return-on-Investment Timelines. 3. Drilling Costs and Risks. 4. Cost Competitiveness	Higher investment costs, and not possible for small communities to arrange such massive amounts of investments. (Finland Workshop) Drilling risks, long and deep drilling – higher in risk as not enough drilling information exist before, drilling costs a significant amount and dry wells lead to significant financial losses. (Germany Workshop) We have clients disconnected from our network because cheaper is heating by gas, not green energy. (Poland Workshop)
Market and Economic Uncertainty	1. Uncertainty in Market Size and Demand. 2.Attracting Investors.	It's hard to forecast market size and volume due to geological conditions and variability in demand. (Poland Workshop) The main struggle that we have now to find companies and to find partners in this set up that we have that are willing to sign for multiple years. (Interviewee 3)

Operational and Infrastructure Costs	1. Integration into district heating networks. 2. Maintenance costs.	The integration of geothermal systems into existing district heating networks was highlighted as a complex task requiring significant planning and investment. (Poland Workshop) Maintaining of structure is also a barrier for the industry and developers towards the development of deep geothermal energy. (Poland Workshop)
Policy and Regulatory Challenges	1. Lack of subsidies from the government. 2. Regulatory delays.	Indeed, the high initial cost, but also the lack of support from government and support from subsidy programs. (Interviewee 3) Delays caused due to permits required related to environmental regulations leading to high costs. (Interviewee 3)

High Initial Investment and Financial Barriers

High Initial Investment and Financial Barriers emerged as the major concerns among stakeholders including Local citizens, researchers, and industry frequently mentioning the high initial costs of Deep Geothermal energy projects. The higher investment costs lead to the exclusion of smaller communities due to affordability. All interviewees cited high investment costs as a major barrier. Also, the difficulties of smaller developers in securing long-term investment partners were brought up.

Long return-on-investment timelines also reduce the commercial appeal of this technology as well as discourage investors despite the many benefits it offers. Although industrial stakeholders acknowledged deep geothermal energy as a useful solution however high return on investment timeframes were a concern for them. Despite growing investments in clean energy, investors are likely to favor technologies like solar and wind, which offer lower ROI timeframes and faster over deep geothermal energy, which has higher upfront costs and longer development periods.

Another major economic concern that also leads to higher costs for deep geothermal energy projects is the drilling costs and associated challenges. Deep geothermal energy requires highly sophisticated and advanced drilling equipment for deep drilling and the risks of dry wells or insufficient geothermal resources can lead to significant financial risks.

Drilling costs represent a significant challenge particularly for new startups and entrepreneurs, as they are often the largest expense and pose considerable risks for businesses operating with limited resources. Finally cost competitiveness of deep geothermal energy as compared to other established energy sources is another barrier to its widespread acceptance.

Market and Economic Uncertainty

The energy produced by deep geothermal energy can also differ due to the geological variability associated with geothermal resources. It's hard to forecast market size and volume due to geological conditions and variability in demand. Although not debated as frequently compared to the risks concerning high costs, stakeholders including research and industry, discussed the unpredictable market conditions for deep geothermal energy and economic uncertainty as economic risks.

As deep geothermal energy projects have higher costs, investments and funding are required to keep them running in addition to the uncertainty of drilling leading to cold wells. These financial and technical uncertainties make it challenging for developers to secure long-term partners.

Operational and Infrastructure Costs

Another economic barrier hindering the successful deployment of deep geothermal energy technology identified by the stakeholders was the costs associated with operating the geothermal energy plants and the finances required to integrate deep geothermal energy infrastructure with already existing district heat networks. Integration of geothermal systems into existing networks is a complex task requiring significant planning and investment. In some cases, it would not be possible to integrate the resources which would mean developing new heat networks increasing the costs significantly. One of the Interviewee also mentioned that some local citizens were concerned about the distribution costs of deep geothermal energy. Additionally, concerns have been raised about the distribution costs of deep geothermal energy for local citizens.

Some stakeholders focused on the maintenance costs of the infrastructure for geothermal energy projects including geothermal energy plants as well as heat networks and pipelines requires significant resources. The cost increases due to the involvement of people, money, and technology in the production and maintenance process.

Policy and Regulatory Challenges

Policy and regulatory challenges were another key challenge contributing to the economic risks of deep geothermal energy identified from the data analysis. The significant costs associated with deep geothermal energy require substantial government support and subsidies to make this technology attractive to investors and developers. However, the lack of subsidies from the government is making the widespread usability of deep geothermal energy difficult. Deep geothermal energy developers look for funding from local governments to support their projects while highlighting that support is there for the companies but it is very limited. Many companies are waiting just to have this government support, which is then financial support for them to make the switch to geothermal energy. Meanwhile, some stakeholders mentioned that incentives would be needed to get the technology taken into use referring to the need for steps from the government especially in terms of finances to support the development.

Regulatory delays can also result in the projects exceeding their estimated budgets, as geothermal developers have experienced setbacks due to permitting issues, leading to additional financial challenges. Although the regulatory delays are directly related to uncertain government policies regarding deep geothermal energy, the resulting project delays lead to increased costs, thereby linking them to economic risks.

4.1.2 Environmental Risks of Deep Geothermal Energy

Despite deep geothermal energy's potential as a green and sustainable energy source, some concerns exist regarding its environmental downsides. Our analysis revealed themes capturing stakeholder concerns and highlighting potential environmental challenges that need attention which are summarized in Table 5 alongside relevant subthemes and direct quotes by the stakeholders as evidence.

Table 5. Environmental challenges in Deep Geothermal Energy development.

Economic Risks	Subthemes	Exemplary Quotes by the stakeholders
Seismicity and Geological Concerns	1. Induced seismicity and Public concerns about seismicity. 2. Seismic risks near sensitive locations. 3. Geological variability	Mostly the public has a problem is a big word but they are concerned about the seismicity (Interviewee 3) There was this seismic risk and they're (Locals) more worried because there is also a nuclear storage. (Interviewee 2) Environmental variability - Geological conditions determine how much power the system can sustain without efficiency losses. (Poland Workshop)
Water Contamination and Emissions Risks	1. Groundwater pollution. 2. Corrosion and Environmental Impacts. 3. Emissions Concerns.	It's hard to forecast market size and volume due to geological conditions and variability in demand. (Poland Workshop) The main struggle that we have now to find companies and to find partners in this set up that we have that are willing to sign for multiple years. (Interviewee 3) Emissions of nitrogen are a little bit of a concern for the government right now, so we need to make a lot of calculations about those. (Interviewee 3)
Land use and Sustainability concerns	1. Land-use conflicts and ecological disruptions. 2. Public skepticism.	Sometimes Deep geothermal energy development leads to cutting of the trees. (Interviewee 3) End users are concerned about the carbon footprint of the heat they are using. (Poland Workshop)

Seismicity and Geological Concerns

Deep geothermal energy extraction unlike shallow geothermal energy necessitates drilling to unprecedented amplifying the risk of seismic activity. Seismicity emerged as a significant concern among majority of stakeholders particularly the risks associated with minor earthquakes and induced seismicity due to drilling activities. For example, one of the project sites had to temporarily shut the geothermal plants after a minor earthquake, reinforcing concerns raised in all the workshops and interviews. For some stakeholders, this concern was heightened when geothermal projects were planned near sensitive or critical areas, such as regions with pre-existing geological vulnerabilities or facilities with unique safety considerations. Stakeholders raised concerns about the presence of sensitive nearby mines that already compromise ground stability. There were also specific worries about seismic activity near nuclear storage facilities. Additionally, industrial stakeholders highlighted the risks posed by environmental variability, as geological conditions determine how much power the system can sustain without efficiency losses.

Water Contamination and Emissions Risks

The risks of emissions and contamination are closely tied to the drilling and operation of deep geothermal energy systems. Alongside seismicity, stakeholders mentioned soil and water contamination as a considerable environmental risk. Although the performance of geothermal systems increases as we drill deep into the earth's surface, drilling this deep increases the risk of polluting the water and soil. Several stakeholders underscored that there is a possibility of drilling resulting in groundwater and soil pollution. In particular participants in Germany Workshop highlighted risks related to groundwater pollution, radiation, and other ecological drawbacks. As fluids are used for drilling purposes there is always a risk of leakage and some of the participants from the Finland workshop mentioned that the release of potentially dangerous liquids in the event of leaks or critical system failures was a major concern they had with the technology. But also other concerns were raised such as corrosion and its subsequent environmental impacts due to drilling. Emissions such as nitrogen release during the operation of geothermal plants are a major concern for government representatives.

Land use and Sustainability concerns

Stakeholders raised concerns about the land-use impacts of deep geothermal energy, particularly deforestation and ecosystem disruption. Developers identified site preparation, including tree removal, as a major challenge. Similarly, some stakeholders highlighted the loss of green spaces near parks and community areas, as well as difficulties integrating geothermal projects into densely populated regions. While not a direct environmental risk of deep geothermal energy, public concerns about potential issues such as drilling impacts, seismicity, and contamination can influence the success of a project. As identified by the industrial stakeholders the users have concerns about how environmentally friendly deep geothermal energy is.

4.1.3 Social Risks of Deep Geothermal Energy

Like any other technology, deep geothermal energy projects present various social challenges that can significantly impact public acceptance, particularly within local communities. These challenges are crucial to identify and address to ensure successful implementation. Unfortunately, the social risks associated with deep geothermal energy are often overlooked. This study has highlighted several key themes and subthemes that contribute to the social barriers preventing widespread technology adoption. Table 6 contains illustrative data featuring direct stakeholder quotes concerning these risks.

Table 6. Key Social Risk Themes Recognized by Stakeholders.

Social Risks	Subthemes	Exemplary Quotes by the Stakeholders
Lack of Equality and Inclusivity	1.Fair distribution. 2. Benefit sharing with local communities. 3. Exclusion of marginalized groups	Smaller-scale consumers are seen as financially less viable, indicating a potential barrier to widespread implementation. This gives rise to the question of Inclusivity and Fair Access. (Poland Workshop) Distribution of the benefits of the deep geothermal energy projects to the local community**.** (Interviewee 2) People in rural areas not getting benefits of technology or benefits of subsidies. (Finland Workshop)
Community Concerns and Challenges	1. Earthquakes 2. Drilling-related impacts.	There were some people with that reported cracks in their houses due to earthquakes. (Interviewee 2) Hard to convince people for drilling around their living areas. (Germany Workshop)
Building Trust and Awareness	1 Creating awareness 2. Transparency and engagement 3. Managing expectations.	Lack of knowledge about deep geothermal energy among the local people. Lack of understanding about what is happening from the local government and surrounding companies. (Interviewee 3) After about two years of pure scientific development, we certainly noticed, okay, without reaching out to our neighbors, to our citizens over here, this project is never going to fly. (Interviewee 1) The previous CEO he made like big promises. That all households would have would benefit. And since the third well was dry and everything is scaled down again. There is still this narrative, and there's a disappointment. (Interviewee 2)

Lack of Equality and Inclusivity

Deep geothermal energy offers a number of financial as well as environmental benefits however, this also brings the challenge of ensuring these benefits are distributed equitably. If the resources are not shared fairly, it can create resistance towards the technology from within the society. The importance of equality in benefit sharing emerged as a key theme for fostering local support and ensuring the long-term success of geothermal projects. The concentration of benefits in specific groups like industry or even the policymakers can lead to social divisions. Unequal distribution of benefits among community members can create friction and impact project development. Ensuring inclusivity and fair access to deep geothermal energy remains a significant challenge. Another social challenge concerning deep geothermal energy interlinked with fair distribution of resources was the risk of marginalized groups like rural communities and small households getting excluded from these projects. The economic and social advantages provided by geothermal development such as jobs, energy access, or infrastructure improvements might not be accessible to these groups. It was noted that the potential exclusion of rural communities or small households from benefits resulted in widening the social gap across various social groups. Similarly, higher investment costs would mean small communities can't arrange such massive amounts of investments, excluding them from benefitting from this technology. Although some stakeholders pointed out the importance of getting an outside perspective to ensure fairness in decision-making, however the Local stakeholders stressed the importance of transferring the benefits of the technology directly to the local people. This approach would not only encourage community engagement but would also contribute to a positive relationship between project developers and the local citizens.

Community Concerns and Challenges

Several community concerns were identified by different stakeholders that led to the lack of social acceptance of deep geothermal energy. Not only does deep geothermal energy development have an impact on the surroundings. Local People feel the deep geothermal energy projects put a burden on the area. One of the most discussed environmental risks of deep geothermal energy is seismicity and earthquake concerns. The safety concerns due to the occurrence of earthquakes have a significant impact on the overall acceptability of the technology, especially from the local people. If there are earthquakes, it is going to be a problem for social acceptability in the long term. The risk of these small earthquakes was significant, with the earthquake causing damage to nearby houses at one of the sites. These seismic events are not only hazardous to the environment but also undermine the social viability of the project. The resulting loss of public support makes it more challenging to ensure the project's success. Deep geothermal energy extraction involves drilling to great depths, which not only demands advanced technology and skilled labor but also has a range of associated risks. One such risk is Noise pollution caused by geothermal drilling. Drilling activities generate significant noise, particularly affecting areas near project sites, according to some stakeholders. Although this might not be a big concern for the other stakeholders however for the local communities this causes disruptions to their daily life.

Building Trust and Awareness

Deep Geothermal Energy is a relatively new technology as compared to other renewable resources like solar and wind energy which are more often talked about in the context of sustainable energy transitions. Lack of understanding of technology leads to assumptions and risks about the technology which might not be true, like some people showed concerns regarding having enough heat, especially in winter. Similarly, a lack of familiarity and knowledge about deep geothermal energy technology among the local people leads to resistance to change. Lack of trust is another major social risk. Building public trust would require transparency about risks, uncertainties, and benefits from the responsible stakeholders like industry, researchers and policymakers. The researchers pointed to the need for Transparency and information at an early stage, both regarding the risks and the possibilities to be very important. Another important social risk to manage is public disappointment and managing the expectations of people from the project. Lack of effective communication between the local community and industry is another social risk hindering the success of the project.

4.2 Risk Perception as a Barrier and Enabler for Deep Geothermal Energy Acceptance

This section will explore the interplay between the perception of risks and acceptance of deep geothermal energy, focusing on insights from various stakeholder groups. Fig 5 provides an overview of how stakeholders perceive different types of deep geothermal energy risks including economic, environmental, and social risk as well as linking these risk perceptions with the acceptance and support of the technology.

Figure 5. Connection between Stakeholder Risk Perception and Deep Geothermal Energy Acceptance

4.2.1 Economic Risk Perceptions and Acceptance

Our analysis revealed multiple themes exploring different types of economic risks identified by different stakeholder groups. The most significant of them was the high initial investment cost. Throughout the study, multiple stakeholders identified the high upfront investment costs as a significant barrier to the adoption of deep geothermal energy. The risk perception regarding the higher upfront costs was very high among the stakeholders.

Industrial stakeholders perceive the high upfront investment required for deep geothermal energy projects as a significant barrier. This perception also affects their willingness to invest, as noted by Interviewee 3:

“Private investors fund smaller geothermal energy developers. The geothermal energy development companies see attracting funding for deep geothermal energy projects as a major barrier to their development currently. Companies shy away due to the perception of higher costs”.

They reluctance of private investors makes it very difficult to find partners and companies that want to use geothermal energy or who want to help with the development. They struggle a lot to find companies and partners that have enough money and are willing to invest in deep geothermal energy projects as well as signing up to be on board for multiple years. Interviewee 3 further added how due to the perception of high costs companies don’t even want to talk without realizing that they would not be alone in investing and there will be other partners. This leads to major barriers in attracting more investments. However, the stakeholders did point out how different subsidies from the government reduce the risk perception of higher costs leading to higher acceptance. Participants from Poland Workshop belonging to both the research community and industry emphasized the role of subsidies in lowering the cost of geothermal energy, making it more economically viable for the stakeholders. Subsidy programs were discussed as pivotal for supporting geothermal development. Interviewee 3 also discussed how the companies view government support, particularly in the form of subsidies, as a crucial factor in overcoming the high initial costs and long-term investment barriers associated with deep geothermal energy. Many companies are waiting for top-down initiatives or a push from higher levels of authority to make the transition economically viable. Such subsidies directly lead to higher acceptance of deep geothermal energy projects for the industrial stakeholders.

The research and industrial stakeholders were concerned about the unknown maintenance costs and Long Return-on-Investment Timelines. The Finland Workshop participants expressed apprehensions about the uncertainty surrounding the maintenance costs of the system, fearing that unforeseen expenses could make it a more expensive solution than existing alternatives raising doubts about the system's overall financial viability. Poland Workshop participants also raised similar issues about the lack of a clear timeline for return on investments making it difficult for the industrial players find it difficult to attract investments. However, despite these concerns, researchers were very accepting of the technology focusing on its potential to become cost-effective over time. Participants from the Finland Workshop particularly noted that as the technology matures, costs are expected to decrease, enhancing its financial appeal over time. For local communities, the promise of positive long-term low-cost energy, as highlighted by Germany Workshop participants, contributed to higher acceptance levels.

Despite the shared recognition of high economic risks associated with deep geothermal energy, the acceptance levels varied significantly across stakeholder groups. Researchers one hand showed strong acceptance of the technology. Despite acknowledging the challenges of higher costs their support was driven by the belief that deep geothermal energy offers substantial long-term benefits, including enhanced energy security and reduced environmental impacts. In contrast the acceptance levels of the industrial players and developers were more negatively affected by their risk perceptions regarding cost competitiveness. One of the industrial stakeholders from the Poland Workshop said:

“We have clients disconnected from our network because cheaper is heating by gas, not green energy”.

This statement also shows how local citizen's acceptance of deep geothermal energy is shaped by the risk of high costs. The participants from Poland Workshop further discussed that how cost considerations outweigh green heat as primary motivators for users. Although people consider the environmental benefits of deep geothermal energy however it is secondary as cheap energy is the primary dominant factor.

Regulatory barriers, particularly delays in obtaining permits also emerged as a key factor influencing the economic risk perception of the stakeholders, especially the developers. Interviewee 3 expressed their frustration detailing how the permits required to carry out geothermal development activities have a big impact on the project planning phase. Some of the permits take longer time than anticipated. Bureaucracy requirements and small things like missing documents or the need for further explanations cause delays.

In case the permit is declined the whole process needs to be started again adding a couple of months each time for permitting. The project delays caused due to the permit issue disrupted the project timeline and led to increased costs. This directly decreases the acceptance of deep geothermal energy projects for developers. Interviewee 3 pointed out how one of their deep geothermal energy projects fell off and is still on hold despite securing funding for drilling costs. The primary reason was the prolonged waiting period for obtaining the necessary permits. These delays not only reduce the acceptance among the industry but also make it difficult to attract investors already concerned with the return on investment timelines.

4.2.2 Environmental Risk Perceptions and Acceptance

From the thematic analysis, concerns about seismicity and earthquakes emerged as the most prominent environmental risks associated with deep geothermal energy. The frequent mentions of this issue by multiple stakeholder groups during their discussions highlighted the significant risks perceptions associated with it. Industrial stakeholders identified seismicity as a major barrier to the development of deep geothermal energy, while research stakeholders highlighted the risks of earthquakes during drilling as a key challenge to public acceptance. The publics risk perception of earthquakes and seismicity is particularly high, as these are viewed as significant safety concerns. According to Interviewee 2:

"People often worry about safety and whether these projects might harm the environment or their properties".

The way local communities perceive seismicity risks varies considerably depending on their prior experiences and the regional context. For instance, participants in the Finland Workshop highlighted how past familiarity with earthquakes can influence acceptance:

"The risk with minor earthquakes can be seen very differently in different locations, based on if you are used to that or not."

This shows how communities with prior exposure to induced seismicity and minimal resulting damage may demonstrate higher acceptance. However, regions unfamiliar with seismic activity may express nervousness about the environmental consequences of such earthquakes even drawing comparisons with incidents in other areas. This was noted by Interviewee 2 during one of the local engagement sessions that Local people compare the earthquake incidents with those that have happened around the world or nearby, indicating their concern. One of the local people from the engagement session was worried about the possibility of this happening in their area.

The proximity of deep geothermal energy projects to sensitive infrastructure significantly amplifies risk perceptions. At a deep geothermal energy project site in Mol, Belgium, where a minor earthquake occurred, local communities expressed concerns about the potential impact on nearby nuclear storage facilities and the possibility of future seismic events. Similarly, the participants from the Poland Workshop were concerned by the possibility of earthquakes due to the presence of mines in the area fearing considerable environmental damage. These heightened risk perceptions negatively influenced social acceptance of deep geothermal energy. However, industrial stakeholders emphasized ongoing efforts to address these concerns. They pointed out that companies are actively conducting seismic research and implementing safety measures to improve public trust and acceptance.

Despite the concerns surrounding seismicity, local engagement efforts revealed a surprising willingness among some communities to support deep geothermal energy for its environmental benefits. Interviewee 2, who facilitated local engagement sessions, highlighted this finding mentioning how people wanted to learn more about the impact of earthquakes indicating proper information about the risks can lead to an improved level of acceptance as currently they were uncertain about the impacts of these earthquakes leading to a lack of support. As Interviewee noted:

“Local People are generally curious about the technology and what is happening and how it will impact their lives”.

Deep geothermal energy development sometimes necessitates site preparation activities, such as cutting trees, which can lead to environmental degradation. According to Interviewee 3 geothermal developers do not see this as a significant risk as they have already strategies to derisk this environmental concern by planting an equal number of trees in some other location. Other stakeholders including Local citizens, Policymakers and environmental groups generally perceive this risk as manageable as long as the trees are planted in other areas without significant plantation. The proper handling of this risk meant that it did not have any impact on the acceptance or resistance towards technology. While geothermal development involves risks related to emissions and water contamination, these risks are generally perceived as low-impact. For example, concerns about nitrogen emissions exist primarily at the governmental level, where companies must maintain records of their nitrogen outputs. However according to Interviewee 3:

"Although the government is concerned about nitrogen emissions and requires companies to keep a record of their nitrogen emissions leading to companies having to make a lot of calculations but it is not a big risk for the industrial players and developers If they can show that they don't have any nitrogen emissions it is okay and the nitrogen emissions by geothermal energy plants are very negligible so not a big concern".

Another emissions-related risk is the end user's concerns about the carbon footprint of the heat they are using. However industrial heat users see geothermal energy as an opportunity to reduce their carbon footprint and align with decarbonization goals. The participants from the Germany Workshop also agreed that deep geothermal energy can significantly reduce CO2 emissions increasing the acceptability of the technology. The perception of geothermal energy as a low-emission, environmentally friendly solution contributes positively to its acceptance. Concerns about groundwater contamination from deep geothermal operations were discussed by stakeholders but found to be less impactful on acceptance. Researchers emphasized that closed-loop systems, a common design in deep geothermal projects, significantly reduce risks compared to open-loop systems. Geological conditions and environmental variations emerged as another area of concern, as they influence how much power the system can sustain without efficiency losses. Participants from the Poland Workshop noted that while these uncertainties do not directly deter acceptance, they shape perceptions about the reliability and scalability of geothermal systems, especially in regions with less predictable geological characteristics. Minor concerns, such as corrosion due to drilling, were raised but did not significantly influence acceptance. According to Interviewee 2, the concern from one of the locals about corrosion due to drilling was not very high and was more from the lack of knowledge about the technology and curiosity to learn how deep geothermal energy drilling works having no impact on their acceptance.

4.2.3 Social Risk Perceptions and Acceptance

Although social risks are less frequently discussed compared to economic or environmental concerns, they play a pivotal role in shaping public perception and acceptance of deep geothermal energy. One key risk identified by researchers during the Finland Workshop was the issue of fairness and inclusivity. The participants highlighted the potential of deep geothermal energy to enable a just energy transition by focusing on the working and middle class, who often reside in blocks of buildings closer together compared to individuals living in personal villas or mansions. However, as noted by the researcher's higher investment costs make it impossible for small communities to arrange such massive amounts of investments. This indicates a significant social risk, as small communities may feel excluded from the benefits of geothermal energy. Interviewee 1 stressed the importance of local inclusion, recounting how the failure to involve locals in the decision-making process led to the failure of an earlier deep geothermal energy project. However, the support and acceptance significantly increased once the locals were made part of the decision-making process. Locals made it clear that continued support was conditional on consistent updates and opportunities to express concerns showing the direct influence of inclusivity on the acceptance of technology. Another considerable risk was benefit sharing with local communities as according to Interviewee 2:
"Local people want to ensure that the benefits of deep geothermal energy also reach their region alongside its burdens".
When locals perceive that they are bearing the environmental or social burdens of geothermal energy development without receiving enough benefits, resistance to the projects increases, leading to decreased acceptance. Ensuring that benefits such as job creation, infrastructure improvements, or access to affordable energy reach the local community is important. Similarly concerns about the impacts on surroundings, particularly

those caused by earthquakes and drilling, also emerged as significant social risks. In some areas, properties were damaged by small earthquakes, leading to the closure of geothermal power plants. This not only generated negative perceptions but also significantly reduced public support for the technology. As the researcher stakeholders from the Germany Workshop noted that Seismicity-related events directly impact social acceptance. Interviewee 2 further elaborated on public concerns regarding property safety: “People were greatly worried about the safety of their properties due to the risks of earthquakes.”

The workshop participants from both Poland and Germany identified Transparency as a significant risk influencing the acceptance of deep geothermal energy projects. Transparency was a big concern for the local stakeholders, especially the citizens and the end users. They felt transparency is very important and information at an early stage, both regarding the risks and the possibilities. The communication should consider the fears of the public such as risks regarding groundwater pollution, earthquakes, radiation, ecological drawbacks etc. According to Interviewee 3

“Early communication and transparency as well as efforts to reduce risk like seismicity campaigns have a positive impact on the social acceptance of deep geothermal energy projects of local stakeholders. This shows how addressing the risks surrounding transparency leads to higher acceptance levels”.

This highlighted the importance of having proactive communication strategies, coupled with efforts to mitigate risks and address concerns for higher levels of acceptance.

Lack of results after drilling often leads to public disappointment which reduces the trust of the people in the technology. Interviewee 1, who was involved in deep geothermal energy development in the Mol and Dessel region, recounted a case where a dry well-hindered progress in setting up district heating networks:

“And then of course, looking at your dry well as being the source of heat for these networks, and then after testing the dry well, we had to say, sorry, we can’t deliver the heat. So, it was quite a setback and something that people in the community, I did live here. So, I often still get questions, when do we get the geothermal heating? “

The inability to provide heat from geothermal drilling as a result of dry wells led to disappointment among the people, reducing the support for the technology. Interviewee 2 also echoed similar sentiments, stating:

"Although big promises were made earlier the lack of immediate results led to disappointment replacing the initial curiosity about the technology it takes so long for your energy bill to go down. So, they have these expectations and you promised that there would be warm water coming from my tap and it's not happening".

Such unmet expectations undermine public confidence and create uncertainty about the prospects and feasibility of the technology bringing down the acceptance levels significantly. The Poland Workshop participants highlighted another critical challenge: stakeholders unfamiliar with geothermal systems often fear managing new responsibilities and associated risks. This lack of understanding creates apprehension among both local communities and industrial stakeholders.

The participants from the Poland Workshop pointed out that, Stakeholders unfamiliar with geothermal systems express fear of managing new responsibilities and the associated risks, reflecting a need for capacity-building and technical education. Industrial experts also find it difficult to explain the efficiency of this system to people who are afraid of using the technology. This gap in technical knowledge furthers public uncertainty, hindering broader acceptance of the technology.

4.3 Risk Mitigation Strategies for Deep Geothermal Energy Projects

This section presents some mitigation strategies identified during stakeholder interviews and workshops to address the perceived risks of deep geothermal energy projects. Fig 6 shows a framework consisting of different actions and steps that can lead to improved social acceptance of deep geothermal energy.

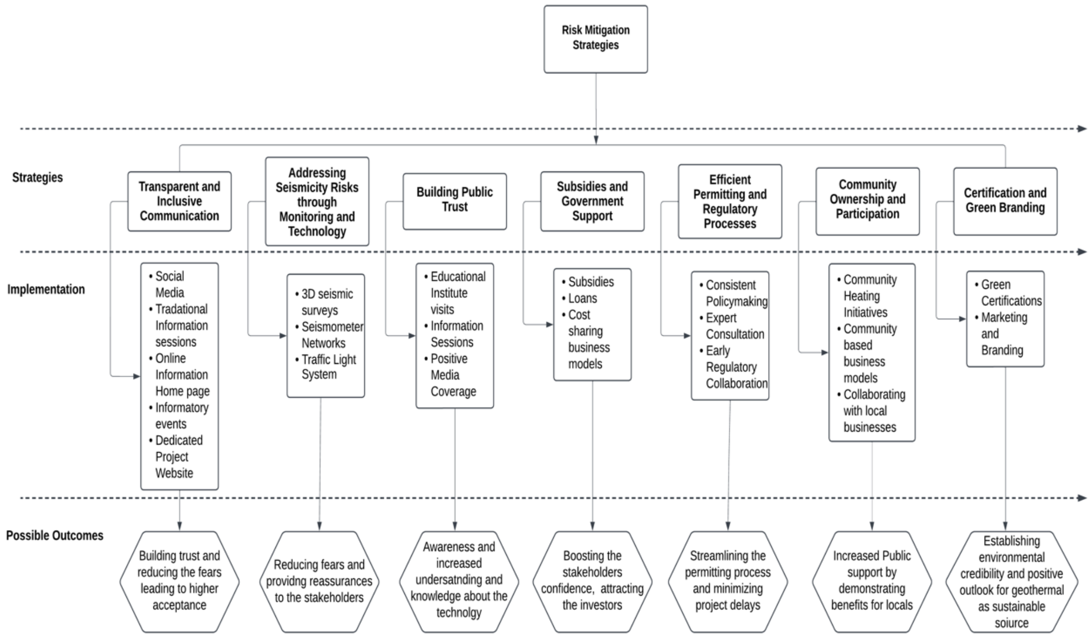

Figure 6. Risk Mitigation Strategies for Enhanced Acceptance

1. Transparent and Inclusive Communication

Our analysis revealed Transparency and clear communication as significant factors influencing stakeholder confidence. A lack of easily accessible information heightened public fears leading to resistance, especially regarding complex risks like seismicity.

Clarity and Accessibility: Effective communication channels tailored to stakeholder groups are needed as pointed by Germany Workshop participants suggesting:

"Different communication channels for different stakeholder groups"

Using social media for younger audiences and traditional information sessions for older generations. An online platform for two-way communication, such as a city homepage, can serve as a centralized information hub.

Engaging the Public: Deep geothermal energy is a relatively lesser known technology as compared to other renewable sources so Large-scale events like the Night of Arts or Night of Research could help reach a broad audience and creating awareness about the positive impacts of the technology. Similarly, school and site visits along with interactive workshops featuring visuals of seismic activity and subsurface structures as already employed at Mol site could be very effective.

Dedicated Online Resources: Interviewee 3 mentioned the use of a Website with FAQs in simple language for one of their projects leading to effective information sharing with the public about the project. Similar practices can be used at other deep geothermal sites to ensure that even individuals without prior technical knowledge feel informed, directly enhancing acceptance.

Ongoing Dialogues: Regular sessions with communities allow for addressing fears and emphasizing benefits, improving trust and alignment with stakeholder expectations.

2. Addressing Seismicity Risks Through Monitoring and Technology

Seismicity is among the most prominent risks, with fears of earthquakes significantly impacting public and industrial stakeholder confidence. However, use of the latest technology and further research could be a possible way to reduce these risks.

Real-time data collection on underground changes via seismometers demonstrates active monitoring, reducing public fears of unmanaged seismic risks. Similarly, a Traffic Light System currently in use by one of the research institutions in Mol provides actionable thresholds for earthquake monitoring, assuring stakeholders that risks are being actively managed. This builds confidence among citizens and local authorities. Public demonstrations, such as trucks used for creating vibrations for collecting seismic data, were previewed by the locals as tangible evidence of safety measures, fostering acceptance.

3. Building Public Trust Through Education and Media

Another common risk is the misconceptions and lack of knowledge about deep geothermal energy elevating resistance among local communities. People often get afraid about the risks due to their limited understanding of the technology so engagement methods similar to the ones used by Interviewee 2 during local engagement sessions could be used

“We used visuals to explain complex concepts like seismic activity and subsurface structures. Our team designed workshops to make the discussions as interactive and informative as possible”

Educational Campaigns: Community-based education initiatives emphasizing the long-term environmental and cost benefits address misconceptions and build confidence. Some of the deep geothermal energy projects are already conducting school visits to the sites and open sessions to educate people.

Media Engagement: In the past year’s media especially, social media has become a primary source of information for people shaping their attitudes about important issues including emerging technologies. Positive media coverage can create a supportive narrative, countering negative perceptions and creating a favorable public opinion.

4. Subsidies and Government Support

A number of investors and developers stay away from deep geothermal energy due to high costs. Government and Policymakers can play an important role in mitigating this risk by providing support and financial assistance through subsidies, loans, and cost-sharing models. Shared responsibility between public authorities and private companies could ensure equitable risk and benefit distribution, improving acceptance.

5. Efficient Permitting and Regulatory Processes

Regulatory delays due to lack of certainty in Policymaking sometimes disrupt project timelines, increasing costs. However, based on the stakeholder comments some of the strategies that can help reduce this risk include:

Policy Reforms: A consistent and clear regulatory framework tailored for geothermal energy which could expedite permitting process.

Proactive Engagement and Expert Consultation: Based on the learnings from one of the projects involving one of the stakeholders we interviewed a possible strategy to overcome permitting issue is collaborating with government regulators early in the process, supplemented by the expertise of consultants, ensuring submissions are both compliant and credible. This approach minimizes the risk of rejections and delays by addressing regulatory requirements and compliance risks effectively from the outset.

6. Promoting Community Ownership and Participation

It is important to make the benefits of the technology visible to the locals to create a sense of ownership.

Important to create a good image locally, e.g. via local collaborations, such as heating the local football stadium and get visibility in this way reaching a large number of citizens. (Germany Workshop)

Similarly building new business models which encourage community ownership and shared responsibility model with the government can contribute to the success of the projects especially when interest of locals gets aligned with the project. Collaborating with locally respected businesses could also strengthen the legitimacy of projects and draw public and political support.

7. Certification and Green Branding

Some of the stakeholders are concerned about the environmental benefits of deep geothermal energy and the lack of clear certification can undermine their confidence in it.

“Certification of green energy is important for the viability of the business model i.e. can be enforced by the need for going greener”. (Poland Workshop)

Certifying deep geothermal energy projects as green projects and marketing it as a green and sustainable energy source aligns the technology with global decarbonization goals, improving its viability and appeal for citizens.

5 Discussion and Conclusions

One of the aims of this study was to identify various risks associated with deep geothermal energy through the lens of different stakeholders. We explored how these risks are perceived and examined the relationship between risk perception and acceptance providing a deeper insight into the concerns and expectations of different stakeholder groups influencing their support or opposition to deep geothermal energy. The thematic analysis of stakeholder interviews and workshops revealed a range of economic, environmental, and social risks that serve as key barriers to acceptance. We categorized these risks into overarching themes and corresponding subthemes, helping understand how they influence stakeholder perceptions and concerns answering other part of our research.

The key economic risks identified by the stakeholders from our study can be divided into four main themes: High Initial Investment and Financial Barriers, Market and Economic Uncertainty, Operational and Infrastructure Costs, and Policy and Regulatory Challenges. Significant Environmental risks include Seismicity and Geological Concerns, Water Contamination and Emissions, and Land use and Sustainability concerns. While the most discussed social challenges of deep geothermal energy are Lack of Equality and Inclusivity, Community Concerns and Challenges, and Building Trust and Awareness.

Our research found that deep geothermal energy development encounters multiple challenges that shape stakeholder risk perceptions. While economic, environmental, and social risks were all widely discussed, economic risks emerged as the most frequently mentioned and actively managed concern across different stakeholder groups. However, rather than a single dominant factor influencing acceptance, the perceived severity and importance of risks varied depending on stakeholder priorities, knowledge levels, and involvement in geothermal projects.

Previous studies have consistently identified high initial investment costs and long return-on-investment timelines as major economic barriers to the adoption of deep geothermal energy (Agemar et al., 2014; Soltani et al., 2021). Consistent with the literature our findings confirm that economic feasibility remains a primary challenge as one of the constant concerns among stakeholders across all locations was higher costs. The different stakeholder groups including researchers from all four workshop locations as well as developers and Local communities shared similar sentiment. However, a key contribution of our study is in revealing how the risk perception and acceptance levels vary across different stakeholder groups, despite their shared recognition of economic risks. Industry stakeholders and end users including Local communities were highly concerned viewing economic feasibility as a primary determinant of acceptance, researchers on the other hand although recognized the financial burden still maintained higher acceptance levels. Although all the stakeholders identified this risk however their risk perceptions varied impacting their acceptance. Unlike industry and users, who required immediate economic benefits, researchers viewed deep geothermal energy as an investment in long-term sustainability and energy security rather than a short-term cost burden.

Economic concerns varied across stakeholder groups due to the priorities and risk preferences. Local communities and end users were mainly worried about higher energy costs, while industrial players and developers struggled with high upfront investment and long return-on-investment (ROI) timelines, making it difficult to attract investors. Researchers discussed about the drilling costs which would require technological advancements. Drilling, operational, and maintenance costs were a common concern across all groups, with end users fearing bearing financial burden and developers hesitating due to complexity however these risks had a very low impact on the stakeholder acceptance. Interestingly, developers were the only group to highlight permitting delays and inconsistent policymaking as major economic risks, emphasizing how certain risks are prominent for specific stakeholder categories depending on their role and involvement with the technology. Although subsidies and government support emerged as mechanism to offset these financial risks with Industrial players, developers, and researchers all emphasizing the need for subsidies to mitigate the financial burden of high initial investment and operational costs increasing their acceptance levels. The local communities however did not express any strong opinions about subsidies, suggesting that while financial incentives are critical for developers and industry, they do not directly influence public acceptance.

Although many consider deep geothermal as a green energy source with the potential to drive energy transition however our findings suggest that for most stakeholder groups including local communities, developers, and industry stakeholders, cost considerations outweigh the environmental benefits. The holistic approach this study has taken exploring different risk types reveals these risk dimensions are interconnected as economic feasibility cannot be separated from environmental and social concerns because a weak business case is further complicated by permitting delays, environmental issues resulting in public resistance, or regulatory uncertainty. However, for developers and industrial stakeholders economy of the projects needs to be tight before the other risks are even considered.

The findings of our study compliment the previous research confirming that seismicity and earthquakes are among the most significant environmental risks associated with deep geothermal energy, leading to heightened risk perceptions and impacting stakeholder acceptance (Balzan-Alzate et al., 2021; Knoblauch et al., 2019; Manzella et al., 2018). Our results also highlight how risk perceptions vary across different countries based on local context. In locations with sensitive infrastructure near geothermal sites, such as nuclear storage facilities and mines, local communities tend to express greater safety concerns, amplifying their resistance to the technology leading to reduced social acceptance levels. While citizens are mostly worried by the seismicity, other stakeholder groups are also worried about emissions (CO2, Nitrogen) and groundwater contamination from drilling leaks however their impact on acceptance is low.

The results from this study build on the findings of (Chavot et al., 2018) who found that early engagement and transparent communication contribute to higher social acceptance of geothermal projects. Our research further emphasizes that while seismicity is a major environmental risk, we observed a significant shift in local community attitudes from opposition toward support and acceptance when effective and transparent communication strategies were implemented suggesting this might enable higher acceptance even during the development stages of projects. Overall sentiment from people participating in the engagement sessions was positive towards deep geothermal energy hoping it will bring a more sustainable future. Also highlighting the interplay between environmental risks, economic benefits and social factors in deep geothermal energy projects.

Existing literature on the social acceptance of geothermal energy has identified Trust and transparent communication as major barriers (Kubota et al., 2013; Vargas Payera, 2018). Our research not only support these findings but it also expands them by suggesting that the social risk of public disappointment although unexplored is very significant as it has a great impact on the long-term public acceptance of the technology. The existing literature has not focused much on unique risks associated with deep geothermal energy. Our findings address this gap by demonstrating how the unpredictability of deep drilling which can sometimes fail to yield the expected heat output due to dry wells lead to skepticism among local communities about the future of technology. This significantly reduces their support and acceptance towards the technology. This is connected with another risk identified by the developers and industry as the lack of communication between local community and industry creating misunderstandings about the real potential of DGE. This points out towards the need for expectation management strategies in DGE projects.

Our study shows not all risks impact acceptance equally, risk perception and its impact vary across risk types and stakeholder groups. Deep geothermal energy projects can be made more successful by reducing stakeholder risk perceptions and enhancing stakeholder acceptance through targeted risk mitigation strategies. Based on the insights from the stakeholders and already proven methods a few risk mitigation strategies that can effectively handle these risks include government subsidies as key to addressing economic concerns, while transparent communication via dedicated websites, tailored outreach, and educational visits builds public trust and mitigates social risks. For environmental risks, proactive measures (3D seismic surveys and traffic light systems) and transparent risk communication can help manage seismicity concerns leading to higher acceptance.

Our study has some potential limitations. Due to time and availability constraints, some stakeholder groups particularly policymakers and local communities were underrepresented in the study. This may reduce the comprehensiveness of the findings, as policymakers play a critical role in shaping regulatory frameworks, and local communities are central to social acceptance. Future studies should aim for a balanced representation of different stakeholder groups increasing the breadth of results.

Another limitation of this study is that the research focuses on four European countries, limiting the generalizability of the findings beyond the regional context. Since the stakeholder risk perceptions are influenced by a number of factors like government policies, economic conditions and socio-political contexts, there would be variations across regions. Although our study contributes to understanding of challenges faced by deep geothermal energy and the acceptance levels in Europe, further studies with diverse geographical settings are needed for generalized understanding of these concepts. A quantitative approach with large sample size can further address the generalizability issues.

Finally, our study lacks a longitudinal perspective as we have captured stakeholder perceptions at a specific point in time. The stakeholder risk perceptions are dynamic and they evolve as the deep geothermal energy projects progress and are influenced by the factors such as benefits and outcomes, regulatory changes and possible setbacks. Studies in future with longitudinal approach can add to understanding of risk perceptions and acceptance by tracking evolving stakeholder attitudes.

References

Adams, W. C. (2015). Conducting Semi-Structured Interviews. In K. E. Newcomer, H. P. Hatry, & J. S. Wholey (Eds.), *Handbook of Practical Program Evaluation* (1st ed., pp. 492–505). Wiley. https://doi.org/10.1002/9781119171386.ch19

Agemar, T., Weber, J., & Schulz, R. (2014). Deep Geothermal Energy Production in Germany. *Energies*, *7*(7), 4397–4416. https://doi.org/10.3390/en7074397

Arning, K., Van Heek, J., & Ziefle, M. (2017). Risk Perception and Acceptance of CDU Consumer Products in Germany. *Energy Procedia*, *114*, 7186–7196. https://doi.org/10.1016/j.egypro.2017.03.1823

Aven, T. (2010). On how to define, understand and describe risk. *Reliability Engineering & System Safety*, *95*(6), 623–631. https://doi.org/10.1016/j.ress.2010.01.011

Balzan-Alzate, D., López-Sánchez, J., Blessent, D., Raymond, J., Dezayes, C., Portela, J. P., Restrepo, E. R., Rendón, D. M., Malo, M., Goderniaux, P., Daniele, L., & Le Borgne, T. (2021). An online survey to explore the awareness and acceptance of geothermal energy among an educated segment of the population in five European and American countries. *Geothermal Energy*, *9*(1), 9. https://doi.org/10.1186/s40517-021-00188-x

Basias, N., & Pollalis, Y. (2018). Quantitative and Qualitative Research in Business & Technology: Justifying a Suitable Research Methodology. *Review of Integrative Business and Economics Research, 7*, 91–105.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Bronfman, N. C., Jiménez, R. B., Arévalo, P. C., & Cifuentes, L. A. (2012). Understanding social acceptance of electricity generation sources. *Energy Policy*, *46*, 246–252. https://doi.org/10.1016/j.enpol.2012.03.057

Cataldi et al. (1999). *Stories from a heated earth: Our geothermal heritage (No. 19)*. Nicholson.

Chavot, P., Heimlich, C., Masseran, A., Serrano, Y., Zoungrana, J., & Bodin, C. (2018a). Social shaping of deep geothermal projects in Alsace: Politics, stakeholder attitudes and local democracy. *Geothermal Energy*, *6*(1), 26. https://doi.org/10.1186/s40517-018-0111-6

Chavot, P., Heimlich, C., Masseran, A., Serrano, Y., Zoungrana, J., & Bodin, C. (2018b). Social shaping of deep geothermal projects in Alsace: Politics, stakeholder attitudes and local democracy. *Geothermal Energy*, *6*(1), 26. https://doi.org/10.1186/s40517-018-0111-6

Cousse, J. (2021). Still in love with solar energy? Installation size, affect, and the social acceptance of renewable energy technologies. *Renewable and Sustainable Energy Reviews*, *145*, 111107. https://doi.org/10.1016/j.rser.2021.111107

Creswell, J. W., & Vicki, L. P. C. (2018). *Designing and Conducting Mixed Methods Research* (Third, pp. 5–6). Sage.

Deng, J., Wei, Q., He, S., Liang, M., & Zhang, H. (2019). What Is the Main Difference between Medium-Depth Geothermal Heat Pump Systems and Conventional Shallow-Depth Geothermal Heat Pump Systems? Field Tests and Comparative Study. *Applied Sciences*, *9*(23), 5120. https://doi.org/10.3390/app9235120

Dowd, A.-M., Boughen, N., Ashworth, P., & Carr-Cornish, S. (2011). Geothermal technology in Australia: Investigating social acceptance. *Energy Policy*, *39*(10), 6301–6307. https://doi.org/10.1016/j.enpol.2011.07.029

Drisko, J. W. (2025). Transferability and Generalization in Qualitative Research. *Research on Social Work Practice*, *35*(1), 102–110. https://doi.org/10.1177/10497315241256560

Ejderyan, O., Ruef, F., & Stauffacher, M. (2019). Geothermal Energy in Switzerland: Highlighting the Role of Context. In A. Manzella, A. Allansdottir, & A. Pellizzone (Eds.), *Geothermal Energy and Society* (Vol. 67, pp. 239–257). Springer International Publishing. https://doi.org/10.1007/978-3-319-78286-7_15

Emodi, N. V., Lovell, H., Levitt, C., & Franklin, E. (2021). A systematic literature review of societal acceptance and stakeholders' perception of hydrogen technologies. *International Journal of Hydrogen Energy*, *46*(60), 30669–30697. https://doi.org/10.1016/j.ijhydene.2021.06.212

Falcone, G., Liu, X., Okech, R. R., Seyidov, F., & Teodoriu, C. (2018). Assessment of deep geothermal energy exploitation methods: The need for novel single-well solutions. *Energy*, *160*, 54–63. https://doi.org/10.1016/j.energy.2018.06.144

Freeman, R. E. (1984). *Strategic Management: A Stakeholder Approach.*

Freeman, R. (2010). *Strategic management: A stakeholder approach.* Cambridge university press.

Fridleifsson, I. B. (2001). Geothermal energy for the benefit of the people. *Renewable and Sustainable Energy Reviews*, *5*(3), 299–312. https://doi.org/10.1016/S1364-0321(01)00002-8

Guðlaugsson, B., Fazeli, R., Gunnarsdóttir, I., Davidsdottir, B., & Stefansson, G. (2020). Classification of stakeholders of sustainable energy development in Iceland: Utilizing a power-interest matrix and fuzzy logic theory. *Energy for Sustainable Development*, *57*, 168–188. https://doi.org/10.1016/j.esd.2020.06.006

Gunnarsdóttir, I., Davíðsdóttir, B., Worrell, E., & Sigurgeirsdottir, S. (2021). It is best to ask: Designing a stakeholder-centric approach to selecting sustainable energy development indicators. *Energy Research & Social Science*, *74*, 101968. https://doi.org/10.1016/j.erss.2021.101968

Gutiérrez-Negrín, L. C. A. (2024). Evolution of worldwide geothermal power 2020–2023. *Geothermal Energy*, *12*(1), 14. https://doi.org/10.1186/s40517-024-00290-w

Häring, M. O., Schanz, U., Ladner, F., & Dyer, B. C. (2008). Characterisation of the Basel 1 enhanced geothermal system. *Geothermics*, *37*(5), 469–495. https://doi.org/10.1016/j.geothermics.2008.06.002

Heidinger, P. (2010). Integral modeling and financial impact of the geothermal situation and power plant at Soultz-sous-Forêts. *Comptes Rendus. Géoscience*, *342*(7–8), 626–635. https://doi.org/10.1016/j.crte.2009.10.010

Huijts, N. M. A., Midden, C. J. H., & Meijnders, A. L. (2007). Social acceptance of carbon dioxide storage. *Energy Policy*, *35*(5), 2780–2789. https://doi.org/10.1016/j.enpol.2006.12.007

Janis, I. (2022). Strategies for Establishing Dependability between Two Qualitative Intrinsic Case Studies: A Reflexive Thematic Analysis. *Field Methods*, *34*(3), 240–255. https://doi.org/10.1177/1525822X211069636

Kalkbrenner, B. J., & Roosen, J. (2016). Citizens' willingness to participate in local renewable energy projects: The role of community and trust in Germany. *Energy Research & Social Science*, *13*, 60–70. https://doi.org/10.1016/j.erss.2015.12.006

Kelly, S. E. (2010). Qualitative Interviewing Techniques and Styles. In I. Bourgeault, R. Dingwall, & R. De Vries, *The SAGE Handbook of Qualitative Methods in Health Research* (pp. 307–326). SAGE Publications Ltd. https://doi.org/10.4135/9781446268247.n17

Ketilsson, J., Petursdottir, H. T., Gudmundsdottir, M., Johannesson, J. A., Gudmundsson, J. R., Oddsdottir, A. L., Eggertsson, V., Stefandsdottir, D. B., & Johannesson, G. A. (2021). *Legal Framework and National Policy for Geothermal Development in Iceland*.

Knoblauch, T. A. K., Trutnevyte, E., & Stauffacher, M. (2019). Siting deep geothermal energy: Acceptance of various risk and benefit scenarios in a Swiss-German cross-national study. *Energy Policy*, *128*, 807–816. https://doi.org/10.1016/j.enpol.2019.01.019

Koon Koon, R., Shah, K., Ashtine, M., & Lewis, S. (2021). A Resource and Policy Driven Assessment of the Geothermal Energy Potential Across the Islands of St. Vincent and the Grenadines. *Frontiers in Energy Research*, *9*, 546367. https://doi.org/10.3389/fenrg.2021.546367

Kubota, H., Hondo, H., Hienuki, S., & Kaieda, H. (2013). Determining barriers to developing geothermal power generation in Japan: Societal acceptance by stakeholders involved in hot springs. *Energy Policy*, *61*, 1079–1087. https://doi.org/10.1016/j.enpol.2013.05.084

Kunze, C., & Hertel, M. (2017). Contested deep geothermal energy in Germany—The emergence of an environmental protest movement. *Energy Research & Social Science*, *27*, 174–180. https://doi.org/10.1016/j.erss.2016.11.007

Li, K., Bian, H., Liu, C., Zhang, D., & Yang, Y. (2015). Comparison of geothermal with solar and wind power generation systems. *Renewable and Sustainable Energy Reviews*, *42*, 1464–1474. https://doi.org/10.1016/j.rser.2014.10.049

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic Inquiry*. Sage Publications.

Majer, E. L., Baria, R., Stark, M., Oates, S., Bommer, J., Smith, B., & Asanuma, H. (2007). Induced seismicity associated with Enhanced Geothermal Systems. *Geothermics*, *36*(3), 185–222. https://doi.org/10.1016/j.geothermics.2007.03.003

Majorowicz, J. A., & Minea, V. (2015). Shallow and deep geothermal energy potential in low heat flow/cold climate environment: Northern Québec, Canada, case study. *Environmental Earth Sciences*, *74*(6), 5233–5244. https://doi.org/10.1007/s12665-015-4533-1

Malafeh, S., & Sharp, B. (2015). Role of royalties in sustainable geothermal energy development. *Energy Policy*, *85*, 235–242. https://doi.org/10.1016/j.enpol.2015.06.023

Malo, M., Malo, F., Bédard, K., & Raymond, J. (2019). Public Perception Regarding Deep Geothermal Energy and Social Acceptability in the Province of Québec, Canada.

In A. Manzella, A. Allansdottir, & A. Pellizzone (Eds.), *Geothermal Energy and Society* (Vol. 67, pp. 91–103). Springer International Publishing. https://doi.org/10.1007/978-3-319-78286-7_7

Manzella, A., Bonciani, R., Allansdottir, A., Botteghi, S., Donato, A., Giamberini, S., Lenzi, A., Paci, M., Pellizzone, A., & Scrocca, D. (2018). Environmental and social aspects of geothermal energy in Italy. *Geothermics*, *72*, 232–248. https://doi.org/10.1016/j.geothermics.2017.11.015

Maqbool, R., Deng, X., & Rashid, Y. (2020). Stakeholders' satisfaction as a key determinant of critical success factors in renewable energy projects. *Energy, Sustainability and Society*, *10*(1), 28. https://doi.org/10.1186/s13705-020-00259-0

Martinez, N., & Komendantova, N. (2020). The effectiveness of the social impact assessment (SIA) in energy transition management: Stakeholders' insights from renewable energy projects in Mexico. *Energy Policy*, *145*, 111744. https://doi.org/10.1016/j.enpol.2020.111744

Maurer, V., Gaucher, E., Grunberg, M., Koepke, R., Pestourie, R., & Cuenot, N. (2020). Seismicity induced during the development of the Rittershoffen geothermal field, France. *Geothermal Energy*, *8*(1), 5. https://doi.org/10.1186/s40517-020-0155-2

McClean, A., & Pedersen, O. W. (2023). The role of regulation in geothermal energy in the UK. *Energy Policy*, *173*, 113378. https://doi.org/10.1016/j.enpol.2022.113378

Meller, C., Schill, E., Bremer, J., Kolditz, O., Bleicher, A., Benighaus, C., Chavot, P., Gross, M., Pellizzone, A., Renn, O., Schilling, F., & Kohl, T. (2018). Acceptability of geothermal installations: A geoethical concept for GeoLaB. *Geothermics*, *73*, 133–145. https://doi.org/10.1016/j.geothermics.2017.07.008

Metze, T. A. P., Van Den Broek, J., Van Est, R., & Cuppen, E. H. W. J. (2023). Participatory repertoires for aligning policy and society: An analysis of Dutch stakeholder views on deep geothermal energy. *Energy Research & Social Science*, *98*, 103019. https://doi.org/10.1016/j.erss.2023.103019

Mihailova, D., Schubert, I., Burger, P., & Fritz, M. M. C. (2022). Exploring modes of sustainable value co-creation in renewable energy communities. *Journal of Cleaner Production*, *330*, 129917. https://doi.org/10.1016/j.jclepro.2021.129917

Mitchell, R. K., Agle, B. R., & Wood, D. J. (1997). Toward a Theory of Stakeholder Identification and Salience: Defining the Principle of Who and What Really Counts. *The Academy of Management Review*, *22*(4), 853. https://doi.org/10.2307/259247

Mohajan, H. K. (2020). Quantitative Research: A Successful Investigation in Natural and Social Sciences. *Journal of Economic Development, Environment and People*, *9*(4). https://doi.org/10.26458/jedep.v9i4.679

NOAA National Centers for Environmental Information. (2024). *Annual 2023 Global Climate Report.* Noudettu osoitteesta retrieved on December 4, 2024 from https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202313

Pan, S.-Y., Gao, M., Shah, K. J., Zheng, J., Pei, S.-L., & Chiang, P.-C. (2019). Establishment of enhanced geothermal energy utilization plans: Barriers and strategies. *Renewable Energy*, *132*, 19–32. https://doi.org/10.1016/j.renene.2018.07.126

Patton, M. Q. (1999). Enhancing the quality and credibility of qualitative analysis. *Health Sciences Research*.

Pellizzone, A., Allansdottir, A., De Franco, R., Muttoni, G., & Manzella, A. (2015). Exploring public engagement with geothermal energy in southern Italy: A case study. *Energy Policy*, *85*, 1–11. https://doi.org/10.1016/j.enpol.2015.05.002

Pellizzone, A., Allansdottir, A., De Franco, R., Muttoni, G., & Manzella, A. (2017). Geothermal energy and the public: A case study on deliberative citizens' engagement in central Italy. *Energy Policy*, *101*, 561–570. https://doi.org/10.1016/j.enpol.2016.11.013

Pradhananga, P., & ElZomor, M. (2023). Revamping Sustainability Efforts Post-Disaster by Adopting Circular Economy Resilience Practices. *Sustainability*, *15*(22), 15870. https://doi.org/10.3390/su152215870

Reed, M. S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., Quinn, C. H., & Stringer, L. C. (2009). Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management*, *90*(5), 1933–1949. https://doi.org/10.1016/j.jenvman.2009.01.001

Renoth, R., Buchner, E., Schmieder, M., Keim, M., Plechaty, M., & Drews, M. (2023). Social acceptance of geothermal technology on a global view: A systematic review. *Energy, Sustainability and Society*, *13*(1), 49. https://doi.org/10.1186/s13705-023-00432-1

Romanach, L., Carr-Cornish, S., & Muriuki, G. (2015). Societal acceptance of an emerging energy technology: How is geothermal energy portrayed in Australian media? *Renewable and Sustainable Energy Reviews*, *42*, 1143–1150. https://doi.org/10.1016/j.rser.2014.10.088

Romanov, D., & Leiss, B. (2022). Geothermal energy at different depths for district heating and cooling of existing and future building stock. *Renewable and Sustainable Energy Reviews*, *167*, 112727. https://doi.org/10.1016/j.rser.2022.112727

Schmittbuhl, J., Lambotte, S., Lengliné, O., Grunberg, M., Jund, H., Vergne, J., Cornet, F., Doubre, C., & Masson, F. (2022). Induced and triggered seismicity below the city of Strasbourg, France from November 2019 to January 2021. *Comptes Rendus. Géoscience*, *353*(S1), 561–584. https://doi.org/10.5802/crgeos.71

Segreto, M., Principe, L., Desormeaux, A., Torre, M., Tomassetti, L., Tratzi, P., Paolini, V., & Petracchini, F. (2020). Trends in Social Acceptance of Renewable Energy Across Europe—A Literature Review. *International Journal of Environmental Research and Public Health*, *17*(24), 9161. https://doi.org/10.3390/ijerph17249161

Siegrist, M., & Árvai, J. (2020). Risk Perception: Reflections on 40 Years of Research. *Risk Analysis*, *40*(S1), 2191–2206. https://doi.org/10.1111/risa.13599

Soltani, M., Moradi Kashkooli, F., Souri, M., Rafiei, B., Jabarifar, M., Gharali, K., & Nathwani, J. S. (2021). Environmental, economic, and social impacts of geothermal energy systems. *Renewable and Sustainable Energy Reviews*, *140*, 110750. https://doi.org/10.1016/j.rser.2021.110750

Stauffacher, M., Muggli, N., Scolobig, A., & Moser, C. (2015). Framing deep geothermal energy in mass media: The case of Switzerland. *Technological Forecasting and Social Change*, *98*, 60–70. https://doi.org/10.1016/j.techfore.2015.05.018

Stefansson, V. (2000). *THE RENEWABILITY OF GEOTHERMAL ENERGY*. World Geothermal Congress.

Susskind, L., Chun, J., Gant, A., Hodgkins, C., Cohen, J., & Lohmar, S. (2022). Sources of opposition to renewable energy projects in the United States. *Energy Policy*, *165*, 112922. https://doi.org/10.1016/j.enpol.2022.112922

Taghizadeh-Hesary, F., & Yoshino, N. (2020). Sustainable Solutions for Green Financing and Investment in Renewable Energy Projects. *Energies*, *13*(4), 788. https://doi.org/10.3390/en13040788

Taherdoost, H. (2022). What are Different Research Approaches? Comprehensive Review of Qualitative, Quantitative, and Mixed Method Research, Their Applications, Types, and Limitations. *Journal of Management Science & Engineering Research*, *5*(1), 53–63. https://doi.org/10.30564/jmser.v5i1.4538

Valdimarsson, P. (2011). GEOTHERMAL POWER PLANT CYCLES AND MAIN COMPONENTS. *Proceedings of the Short Course on Geothermal Drilling, Resource Development and Power Plants.*

Vargas Payera, S. (2018). Understanding social acceptance of geothermal energy: Case study for Araucanía region, Chile. *Geothermics*, *72*, 138–144. https://doi.org/10.1016/j.geothermics.2017.10.014

Vargas-Payera, S., Martínez-Reyes, A., & Ejderyan, O. (2020). Factors and dynamics of the social perception of geothermal energy: Case study of the Tolhuaca exploration project in Chile. *Geothermics*, *88*, 101907. https://doi.org/10.1016/j.geother-mics.2020.101907

Vasvári, T. (2015). Risk, Risk Perception, Risk Management – a Review of the Literature. *Public Finance Quarterly*.

Wang, Y., Liu, Y., Dou, J., Li, M., & Zeng, M. (2020). Geothermal energy in China: Status, challenges, and policy recommendations. *Utilities Policy*, *64*, 101020. https://doi.org/10.1016/j.jup.2020.101020

Wirtz-Bruckner, S., Jakobs, E.-M., Kowalewski, S., Kluge, J., & Ziefle, M. (2015). The potential of Facebook® for communicating complex technologies using the example of deep geothermal energy. *2015 IEEE International Professional Communication Conference (IPCC)*, 1–10. https://doi.org/10.1109/IPCC.2015.7235811

Wüstenhagen, R., Wolsink, M., & Bürer, M. J. (2007). Social acceptance of renewable energy innovation: An introduction to the concept. *Energy Policy*, *35*(5), 2683–2691. https://doi.org/10.1016/j.enpol.2006.12.001

Zhang, Y., & Zhao, G.-F. (2020). A global review of deep geothermal energy exploration: From a view of rock mechanics and engineering. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, *6*(1), 4. https://doi.org/10.1007/s40948-019-00126-z