Risk Assessment in Geothermal Energy Projects: Insights from the Literature

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ABSTRACT

This study examines risk management in geothermal energy projects, focusing on current and emerging trends in project risks. Using bibliometric methods and the Web of Science (WOS) database, 1580 academic documents were analyzed, narrowing the focus to 77 papers, including 12 specific to Switzerland. Network visualizations identified key authors, journals, and research themes, such as risks in resource exploration, drilling, financial challenges, environmental impacts, regulatory issues, and social acceptance. The findings underscore the multifaceted nature of risks in geothermal projects and offer insights for better risk management and sustainable development. A limitation of the study is its exclusive reliance on WOS documents. This is the first systematic review of geothermal project risks indexed in WOS, providing a foundation for future research in this area, particularly within Switzerland..

1. INTRODUCTION

Geothermal energy has gained increasing attention over the past two decades as a sustainable alternative in the global energy transition. However, the complexity and scale of modern geothermal projects have amplified the importance of effective risk management across their life cycle (Knoblauch & Trutnevyte, 2018; Gielen et al., 2019). Risks span technical, financial, environmental, regulatory, and societal domains, making their assessment critical to project success (Soltani et al., 2021; Dumas, 2019; Dowd et al., 2011).

Despite a growing body of literature, few studies systematically consolidate and analyse these risks, particularly within the Swiss context—a region characterized by strict regulations, societal scrutiny, and complex geology, especially in Enhanced Geothermal Systems (EGS). This study addresses this gap by conducting a systematic literature review, supported by bibliometric analysis, to map the thematic landscape of risk in geothermal energy projects.

The review aims to synthesise existing research, identify key risk factors, and inform future academic, policy, and industry efforts toward more resilient and sustainable geothermal development.

2. RESEARCH BACKGROUND

Geothermal energy has emerged as a key pillar in the transition to low-carbon energy systems, offering sustainable, baseload power with a relatively low environmental footprint (Gielen et al., 2019). Yet, the development of geothermal projects is inherently risky, with challenges spanning the entire project lifecycle—from exploration and drilling to energy production and resource management (Knoblauch & Trutnevyte, 2018).

Technical issues such as induced seismicity, reservoir uncertainty, and drilling complications are compounded by environmental risks, including groundwater contamination and biodiversity disruption. These are further influenced by regulatory complexity, societal acceptance, and economic uncertainty (Soltani et al., 2021; Dumas, 2019b; Dowd et al., 2011). While significant advances have been made in understanding individual risk categories, comprehensive, integrated analyses remain limited, particularly in underrepresented regions such as Africa and South America.

This study addresses these gaps by conducting a **systematic literature review and bibliometric analysis** of geothermal energy project risks, with a particular focus on Switzerland—a country characterized by complex geological conditions, stringent regulatory environments, and societal concerns regarding Enhanced Geothermal Systems (EGS).

2.1 Geothermal Energy Project Risk: A Multifaceted Landscape

Geothermal projects are uniquely exposed to a wide range of interrelated risks. At the **technical and geological level**, subsurface heterogeneity, uncertain reservoir behavior, and drilling risks remain major barriers (Jolie et al., 2021; Lukawski et al., 2016). **Regulatory and policy risks** vary by jurisdiction, where permitting delays and shifting energy policies can disrupt project timelines (Dumas, 2019b; Zong et al., 2018). **Financial and economic challenges**, including high capital costs, uncertain resource estimation, and volatile energy markets, further affect viability (Sigurdsson, 1997; Kepinska et al., 2021). Meanwhile, **technological risks** arise from the rapid evolution of geothermal technologies, often outpacing standard risk assessment protocols (Zheng et al., 2015).

Risk interdependencies are increasingly acknowledged, especially the connections between financial viability, regulatory certainty, and public acceptance. For example, debates around induced seismicity in EGS reflect both technological and social dimensions of risk (Sharmin et al., 2023; Johnston et al., 2011).

2.2 Key Risks Across the Geothermal Project Lifecycle

Synthesis of existing literature highlights several critical risk areas:

- **Subsurface Uncertainty**: Geological variability affects reservoir performance and heat extraction (Monaghan, 2017).
- **Exploration and Resource Estimation**: Inaccurate assessments can result in costly delays (Zhu et al., 2023).
- **Drilling Risks**: Wellbore instability and unexpected formations often cause cost overruns (Blaz et al., 2023).
- **Regulatory Compliance**: Complex permitting processes and evolving standards can impact feasibility (Sedlar et al., 2022).
- **Economic Viability**: Fluctuations in energy prices and limited financial support mechanisms pose persistent barriers (Contini et al., 2019b).

2.3 Systematic Literature Review and Bibliometric Analysis

This study employs a **systematic literature review** combined with **bibliometric methods** to map the risk landscape of geothermal projects. Using the Web of Science database, 1,580 relevant documents were identified based on predefined inclusion/exclusion criteria. Co-occurrence and co-citation analyses were conducted to highlight thematic trends, key authors, and influential journals. This approach enables both a quantitative and qualitative understanding of the evolving discourse on geothermal risks.

Although regions like the U.S., Iceland, and Indonesia dominate geothermal research, countries such as Switzerland require **region-specific analyses** due to their unique geological and regulatory contexts. Furthermore, the lack of research from Africa and South America—despite their geothermal potential—highlights a pressing need for more geographically inclusive studies.

By consolidating risk dimensions across technical, financial, regulatory, and societal domains, this review provides a foundation for more effective and context-sensitive risk management in geothermal energy development.

3. RESEARCH METHODOLOGY

To achieve the objectives of this review, academic publications relevant to risks in geothermal energy projects were systematically collected from the Web of Science (WOS) online database. Given the vast scope of the field, a clearly defined methodological framework was necessary to establish the boundaries of the literature under investigation. A science mapping approach was adopted to facilitate bibliometric analysis, with the WOS database serving as the primary source due to its comprehensive coverage of peer-reviewed literature across disciplines pertinent to geothermal energy risk research.

A structured keyword selection process was employed, beginning with broad search terms such as *"geothermal," "risk,"* and *"risk management."* These terms were iteratively refined by examining keyword co-occurrence patterns and thematic relevance. The final keyword set was cross-checked to ensure the inclusion of studies addressing diverse risk dimensions—technical, financial, regulatory, and societal.

Inclusion criteria targeted peer-reviewed journal articles explicitly addressing risks in geothermal energy projects across the aforementioned domains. **Exclusion criteria** eliminated papers without a clear focus on risk management, including those centered on geothermal topics unrelated to project implementation, such as pure resource exploration or theoretical modeling without a risk component.

The initial search yielded 1,580 documents. The selection process followed a structured screening protocol, as illustrated in **Figure 1**, which outlines the methodology in a stepwise flowchart for transparency and reproducibility.

3.1 Screening Process and Rationale

Step 1: Initial Search and Retrieval (n = 1580) A comprehensive search was conducted in the WOS database using the predefined keywords. The search encompassed multiple subject areas, including *Geosciences*, *Environmental Sciences*, *Energy & Fuels*, and *Engineering*, to ensure interdisciplinary coverage. A total of 1,580 documents were initially retrieved.

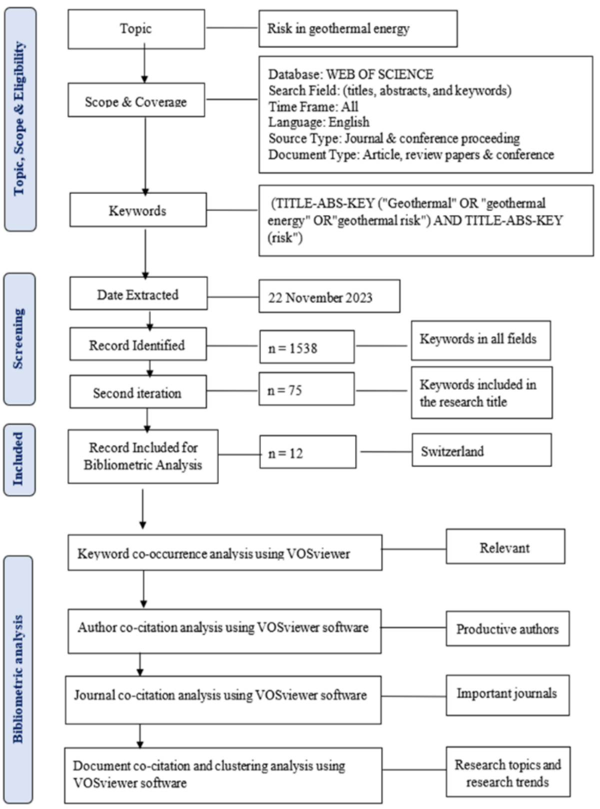

Figure 1. Flow diagram of the search methodology.

Step 2: First Filtering (n = 77)
Titles, abstracts, and keywords of the retrieved documents were reviewed to assess relevance. Papers were retained if they addressed geothermal energy risk—spanning technical, financial, regulatory, environmental, or societal aspects. Documents focusing solely on basic geothermal science or lacking a risk-oriented perspective were excluded. This filtering step reduced the dataset to 77 highly relevant articles.

Step 3: Second Filtering – Geographic Focus on Switzerland (n = 12)
To address regional disparities in geothermal research, the 77 selected papers were screened for geographic relevance to Switzerland. This manual review involved identifying references to Switzerland in the title, abstract, or keywords. The focus on Switzerland reflects a strategic aim to fill existing research gaps in geothermal risk studies in the region, given the unique geological, regulatory, and societal context. This step resulted in the selection of 12 papers.

Step 4: Final Dataset Formation
The 12 papers focusing on Switzerland were further examined for methodological rigor, relevance, and contribution to the broader discourse on geothermal risk. These papers constitute the core dataset for the region-specific analysis within this study.

3.2 Justification for Data Source

The Web of Science was chosen for its robust indexing of high-impact, peer-reviewed journals, ensuring a solid academic foundation for bibliometric and systematic review. However, we acknowledge the limitation of excluding gray literature and non-indexed academic sources, which may offer additional practical insights into geothermal project risk management. Future research will incorporate supplementary databases, such as Scopus and Google Scholar, to broaden coverage and include diverse publication types.

4. RESULTS AND DATA ANALYSIS.

This section presents the key findings from our systematic review and bibliometric analysis of geothermal energy project risks, based on a dataset of 1,580 academic articles indexed in the Web of Science (WOS) database. The analysis captures a wide spectrum of risk dimensions—technical, financial, regulatory, and societal—and highlights the geographical distribution and thematic focus of scholarly research in this field.

Using advanced bibliometric tools and visualization techniques, we identified the most influential authors, journals, and co-citation networks. The analysis also uncovers emerging research themes and reveals critical gaps that warrant further investigation, particularly in underrepresented geographic regions.

The results are structured as follows:

- First, we examine **publication trends over time**, identifying shifts in thematic focus and mapping the geographical distribution of research activity.
- Second, we explore the **intellectual structure** of the field through keyword co-occurrence and co-citation network analyses, which illustrate the interrelationships among different categories of risk.
- Finally, we discuss the **implications of geographic disparities**, especially the limited representation of geothermal risk studies in regions such as Africa and South America.

The insights presented here offer valuable implications for academics, policymakers, and industry stakeholders seeking to enhance geothermal project planning, risk mitigation, and regional collaboration.

Data Acquisition

The dataset for this study was obtained through a structured keyword-based search of the Web of Science (WOS) Core Collection, focusing on academic journal articles, reviews, and conference papers related to geothermal energy and risk management. The search strategy was designed to capture interdisciplinary literature across key risk categories and application areas within geothermal projects.

The WOS platform enabled categorization of the retrieved documents based on subject areas, which facilitated a deeper understanding of disciplinary contributions to geothermal risk research. As illustrated in **Figure 2**, the subject distribution shows that **42%** of the publications were categorized under *Geosciences Multidisciplinary*, followed by **19%** under *Energy & Fuels*. Other relevant subject areas included *Environmental Sciences*, *Engineering Geological*, and *Thermodynamics*, reflecting the cross-disciplinary nature of the research domain.

This subject distribution underscores the predominant focus on geological and engineering perspectives in geothermal risk studies, while pointing to potential underexplored areas such as social and policy-related dimensions.

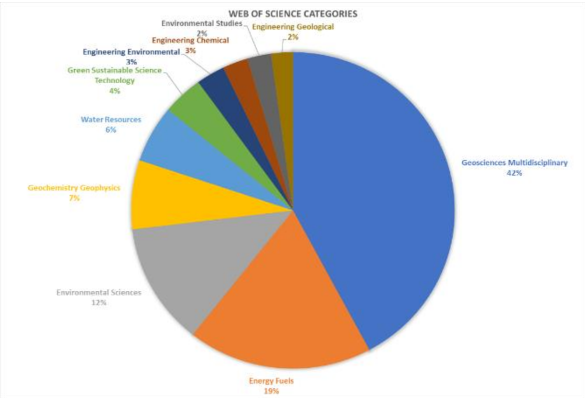

Figure 2. Categories by subject area.

Figure 3 illustrates the annual publication trends in the field of geothermal energy project risk management over the past three decades. The data indicate a consistent upward trajectory in the number of published studies, reflecting growing academic and industry interest in this area. Notably, the years **2021** and **2022** marked the peak of scholarly output, with **162** and **198** publications, respectively. Although the dataset for **2023** was still incomplete at the time of data collection, it already included approximately **135** documents, suggesting continued research momentum.

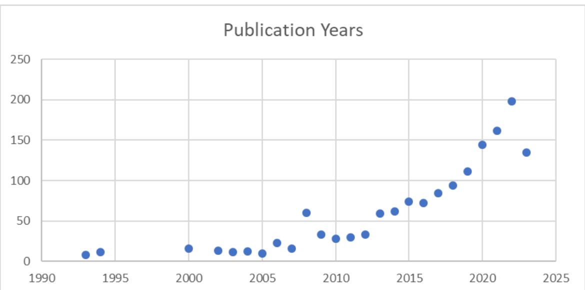

Figure 3. Annual distribution of publications on geothermal project risk management.

The geographical distribution of research activity is presented in **Table 2**, which display the publication output of the **top ten countries** contributing to this field. These figures highlight regional concentrations of expertise and may serve as a proxy for where geothermal risk management has garnered the most institutional and governmental support.

Table 2. Top publications per country.

Countries/Regions	Record Count	% of 1’538
USA	288	18.713
Italy	214	13.905
Germany	205	13.320
Peoples R China	196	12.736
England	159	10.331
New Zealand	149	9.682
France	122	7.927
Switzerland	111	7.212
Spain	80	5.198
Mexico	72	4.678
Australia	71	4.613
Japan	56	3.639
Netherlands	52	3.379
Scotland	52	3.379
Canada	49	3.184
Iceland	46	2.989
Chile	45	2.924
Turkey	37	2.469
South Korea	33	2.144
Indonesia	32	2.079

Keyword Co-Occurrence Analysis

Keywords serve as linguistic markers that encapsulate the thematic core of a document and delineate its conceptual boundaries within a specific research domain (Haustein & Larivière, 2015). In this study, a comprehensive keyword co-occurrence analysis was conducted using **VOSviewer**, a bibliometric mapping tool, based on data extracted from the **Web of Science (WOS)** database.

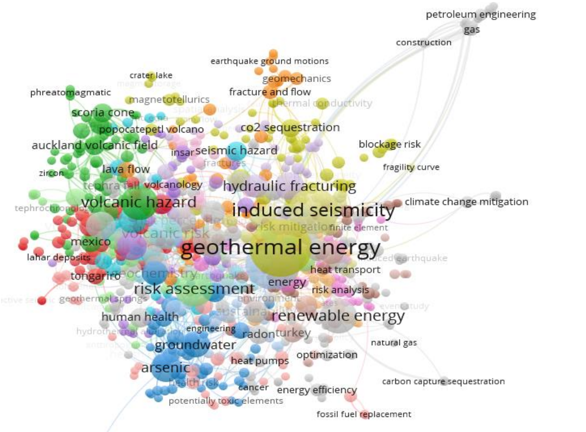

Figure 4. Keyword co-occurrence network.

The resulting co-occurrence network is **distance-based**, wherein the spatial proximity of nodes reflects the **strength of the association** between respective keywords (Mansury & Shin, 2015). In this representation, keywords with stronger relationships are positioned closer together, and **node size** corresponds to the frequency of occurrence. VOSviewer applies **clustering algorithms** to group related keywords into clusters, each visually distinguished by a unique color (Van Eck & Waltman, 2010).

To enhance visual clarity and analytical focus, a **threshold of at least five occurrences** was set for keyword inclusion. This filtering process yielded **337 keywords** from an initial pool of **5,501**. Figure **4** illustrate both the **co-occurrence network** of keywords, comprising 337 nodes and 6,612 links. The cumulative **total link strength** for the top 20 keywords was calculated at **20,876**.

As summarized in **Table 3**, "geothermal energy" emerged as the most frequently occurring author keyword in the dataset. "Induced seismicity" ranked third in frequency, emphasizing its growing relevance in geothermal risk discourse. It is also important to note that the keyword "geothermal" appears in multiple contexts—such as *project risk*, *energy models*, and *renewable energy*—contributing to a **cumulative total of 610 occurrences** within the top 20 keywords. Meanwhile, the keyword **"risk"** was identified as the **fourth most frequent**, underscoring its central role in the literature.

Table 3. Top 20 keywords occurrences and links.

keyword	occurrences	total link strength
geothermal energy	93	210
geothermal	70	204
induced seismicity	61	142
risk assessment	35	99
renewable energy	34	64
volcanic hazard	33	85
risk	28	86
volcanic risk	26	59
arsenic	23	56
hydraulic fracturing	22	43
volcanic hazards	22	57
Volcano	22	78
uncertainty	21	60
Hazard	20	76
groundwater	19	46
risk perception	19	41
geochemistry	16	50
permeability	16	44
enhanced geothermal system	15	31
gis	15	42

Citation Trends and Research Impact (2000–2023)

The **Web of Science (WOS) citation report analysis**, depicted in **Figure 5**, provides a comprehensive overview of the evolving academic landscape in the field of **geothermal energy and risk research** over the period **2000–2023**. The analysis reveals a **marked and consistent increase** in both the number of published documents and the corresponding annual citations, culminating in a **peak in 2022**. This surge underscores the growing relevance and scholarly engagement with risk-related dimensions of geothermal energy.

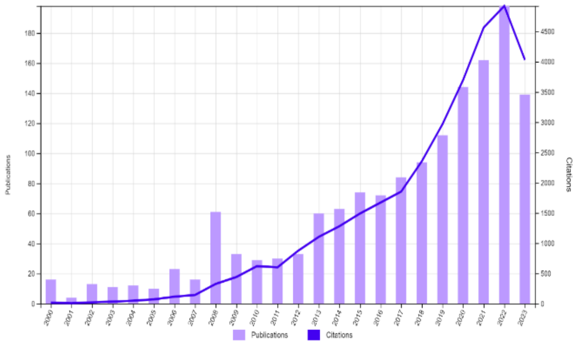

Figure 5. Documents and Citation Record Count (2000–2023)

The **upward trajectory** in publication volume over the last two decades indicates a sustained and intensifying academic interest in the intersection between **geothermal technologies** and **risk management**. This pattern likely reflects several converging factors, including the **rising global emphasis on sustainable energy solutions**, the **deployment of geothermal systems in diverse geographical contexts**, and the **need for robust risk assessment frameworks** to ensure safe and efficient implementation.

In parallel, the **growing number of citations per year** suggests that the literature in this domain is not only expanding but also exerting **increasing scholarly influence**. The citation peak in **2022** may be interpreted as the result of cumulative efforts in research, technological innovation, and heightened policy and public interest in **energy transition strategies**. This trend also reflects the **centrality of risk discourse** in ongoing conversations about geothermal project viability, public acceptance, and regulatory frameworks.

The trajectory captured in this citation analysis highlights the field's emergence as a **critical area for interdisciplinary research**, drawing contributions from engineering, geosciences, environmental studies, economics, and social sciences. Moreover, the 2022 citation apex demonstrates that geothermal risk research has achieved not only **quantitative growth** but also **qualitative recognition**, becoming increasingly integral to broader energy research agendas.

5. DISCUSSION AND FINDINGS

This study examined the **geographical distribution of innovation** in geothermal research, focusing on publication trends by organizations and individuals. The analysis revealed a strong concentration of research outputs in **North America, Europe, China, and Australia**, with **Africa and South America (excluding Chile)** notably underrepresented. This aligns with the findings of Elbarbary et al. (2022), who noted that **adoption challenges**, rather than innovation gaps, are more pronounced in many African countries with respect to geothermal energy.

Switzerland emerged among the **top ten countries** contributing to geothermal research, as shown in Figure 5. This reflects the country's growing engagement in the field, particularly in addressing **project risk and sustainability challenges**. The study has successfully captured both historical and recent advances in geothermal energy research, establishing connections between **technological innovations** and the **persisting challenges** associated with project risk. The overarching aim is to **demystify technical terminology**, detect thematic patterns, and improve understanding of breakthrough developments in the literature. These insights are critical for stakeholders in the **construction and energy sectors**, providing a comprehensive map of the **intellectual landscape** and highlighting **future research priorities**.

Bibliometric analysis serves a pivotal role in evaluating the **performance of a research field**, guiding **policy decisions**, informing **funding allocation**, and assessing both scientific inputs and outputs (Ellegaard, 2018). Furthermore, bibliometric findings are instrumental in identifying **key research drivers** and enhancing the efficiency of future investigations (Akhavan et al., 2016; van Eck & Waltman, 2010).

This review employed a refined query to retrieve **1,580 documents** from the **Web of Science (WOS)** database relating to geothermal project risk. **Statistical classification** of these documents reveals that **51.4%** are associated with **Geology**, while **22.2%** fall under **Energy Fuels**. The analysis of temporal trends shows a **steady increase in publications** over the past three decades, with **publication peaks in 2021 and 2022**.

The first research objective focused on identifying the **most frequently used keywords** in the field, which were analyzed using **VOSviewer** through co-occurrence mapping. The top 20 keywords are presented in Table 2 and provide insights into dominant themes such as **“geothermal energy,” “induced seismicity,” and “risk.”** The second objective sought to identify **influential contributors**, both individual authors and academic journals. Among the most cited authors, **Franck Lavigne** leads with **647 citations**, followed by **Surono** (535 citations), **Nemeth & Karoly** (529 citations), and **Stefan Wiemer** (524 citations). The most cited journals include the *Journal of Volcanology and Geothermal Research*, *Geothermics*, *Renewable & Sustainable Energy Reviews*, *Earth-Science Reviews*, and *Applied Energy* (see Figure 9 and Table 3).

A focused examination of **research titles** revealed only **77 studies** explicitly addressing **risk in geothermal energy**, with **Switzerland contributing just 12**. Given the wide spectrum of risk categories—ranging from exploration and drilling to operations, environmental, and financial issues—this finding highlights a **notable research gap**. Addressing this gap is particularly relevant for Switzerland, which forms a key case study in this long-term project assessing geothermal risk.

The risk classification developed in this study encompasses a **comprehensive typology**, including **technical, environmental, financial, regulatory, social, legal, and climate-related risks**. Table 4 presents this categorization alongside **potential mitigation strategies**. While the current framework does not explore the **hierarchical relationships** among these risk types, future work could employ **system dynamics or influence diagrams** to reveal interdependencies and relative weights.

Table 4. Risk Categorization Framework

Category	**Examples**	**Potential Mitigation Strategies**
Technical Risks	Drilling challenges, reservoir issues	Advanced drilling tech, reservoir modeling
Environmental Risks	Induced seismicity, contamination	Seismic monitoring, groundwater protection
Financial and Economic	High capital cost, market volatility	Subsidies, long-term PPAs
Regulatory and Policy	Permitting delays, unclear rules	Streamlined approvals, clear policies
Social	Community opposition, land conflicts	Stakeholder engagement, transparent communication
Health and Safety	High-temp fluids, H_2S gas	Safety protocols, gas treatment systems
Market	Competitiveness issues	Cost innovation, policy integration
Legal	Contract disputes, liability	Sound contracts, insurance mechanisms
Climate Change	Precipitation changes, sustainability	Adaptive management, climate modeling

The thresholds applied in the bibliometric analysis (e.g., co-occurrence count, link strength) were calibrated in accordance with standard practices to balance **cluster visibility** and **network interpretability**. While this review employs **descriptive statistics** to reveal key trends, future research could incorporate **regression analysis** or **machine learning techniques** to explore **causal relationships** and trend significance.

Importantly, the analysis confirmed the **limited representation of African and South American (excluding Chile) studies**. As suggested by prior work (e.g., Elbarbary et al., 2022), this may reflect systemic barriers to **geothermal adoption**, such as infrastructure, policy support, and financing. Understanding and addressing these challenges requires a **multi-scalar approach**—one that includes **local case studies**, comparative policy analysis, and broader economic assessments.

Although this review focused on **quantitative bibliometric indicators**, future studies could include **qualitative comparative assessments** of methodological approaches employed in geothermal risk literature. A **temporal bibliometric analysis** could also reveal the **evolution of themes**, distinguishing between emerging and declining areas of research—a next step we intend to pursue.

Finally, **Switzerland-specific results** were contextualized globally, highlighting both contributions and gaps. Swiss research, especially in the area of **risk mitigation strategies**, provides valuable insights for international scholars. Conversely, findings from other regions—particularly on seismicity and regulatory frameworks—could benefit Swiss geothermal development.

6. COMMON RESEARCH TOPICS IN GEOTHERMAL ENERGY PROJECT RISK

This section highlights key research topics on geothermal energy project risks, based on a systematic review of recent literature.

1. **Resource Exploration and Assessment**: Resource exploration is crucial for identifying subsurface geothermal reservoirs. Techniques such as seismic surveys, geochemical analysis, and drilling are used to assess reservoir size, depth, and temperature. Accurate data integration supports sustainable resource management and risk mitigation (Piña-Varas et al., 2023).

2. **Drilling and Reservoir Engineering**: Drilling and reservoir management are essential for accessing and maintaining geothermal energy sources. Key risks include wellbore stability, fluid dynamics, and induced seismicity. Advanced techniques like directional drilling improve efficiency and reduce risks (Blaz et al., 2023).

3. **Technological Risks**: Technological risks span drilling, reservoir engineering, and power plant operations. Uncertainties in fluid flow, induced seismicity, and equipment wear impact project success. Emerging technologies, such as Enhanced Geothermal Systems (EGS), introduce additional risks and require ongoing innovation (Zheng et al., 2015).

4. **Operational Performance and Maintenance**: Operational risks involve plant efficiency, scaling, corrosion, and equipment wear. Proactive maintenance, including predictive techniques, is critical for minimizing downtime and ensuring long-term operational success (Daniilidis et al., 2020).

5. **Environmental Impact and Mitigation**: Geothermal projects must address environmental risks like ecosystem disruption and water quality. Mitigation strategies focus on minimizing ecological impacts and ensuring sustainable development (Alayi and Aylar, 2024).

6. **Financial and Economic Risks**: Economic assessments examine investment risks, financing, and cost-benefit analyses, offering insights into the financial feasibility and long-term sustainability of geothermal projects (Taghizadeh-Hesary et al., 2020).

7. **Regulatory and Policy Risks**: Regulatory risks involve the complexity of laws and policies affecting geothermal projects. Research focuses on the impact of regulatory changes and offers strategies for navigating legal uncertainties (Wang et al., 2020).

8. **Community Engagement and Social Risks**: Social risks concern community opposition, cultural impacts, and socioeconomic consequences. Effective engagement strategies are essential for fostering positive relationships and ensuring project acceptance (Chiu et al., 2015).

9. **Market Dynamics and Competitiveness**: Market risks include volatility, shifting demand, and competitive pressures. Understanding market dynamics helps stakeholders navigate uncertainties and improve geothermal energy's competitiveness (Gong et al., 2023).

10. **Legal and Contractual Risks**: Legal risks involve land rights, permitting, and compliance with contractual agreements. Research highlights areas of legal vulnerability and strategies to ensure regulatory compliance (Azmi et al., 2021).

11. **Health and Safety Risks**: Health and safety risks focus on worker and community well-being. Research emphasizes hazard identification, mitigation techniques, and adherence to safety standards to protect stakeholders (Tonka and Ekmekci, 2022).

12. **Climate Change and Geopolitical Risks**: Climate change and geopolitical issues, such as regulatory shifts and energy market dynamics, can influence project viability. Understanding these risks helps in adapting geothermal projects to changing environmental and political landscapes (Xiao et al., 2022).

This ongoing research deepens our understanding of the risks associated with geothermal energy projects across their lifecycle, supporting better risk management strategies.

7. CONCLUSION

This systematic literature review, "Navigating Risk in Geothermal Energy Projects," provides a comprehensive examination of the diverse risks encountered in geothermal energy development. Drawing on 1580 articles from the Web of Science, we identified major research trends, influential authors, and key journals. Critical risk areas include resource exploration, technological challenges, financial and economic hurdles, regulatory and policy issues, community engagement, market dynamics, legal concerns, health and safety, and the effects of climate change and geopolitical factors.

Geographically, geothermal innovation is concentrated in North America, Europe, China, and Australia, with regions like Africa and South America underrepresented. This highlights the need for targeted research in these areas, where geothermal potential remains largely untapped. Our findings underscore the importance of addressing regional barriers to maximize geothermal energy's global impact.

Theoretical Implications

Our study contributes to the theoretical understanding of geothermal risk management by presenting a cohesive framework that integrates technical, financial, regulatory, and social risks across the project lifecycle. This framework offers a basis for future theoretical models that can better address the complexities of geothermal energy, while also contributing to the broader renewable energy discourse.

Practical Implications

For policymakers and industry practitioners, the findings provide practical insights on prioritizing risk mitigation strategies. Addressing public acceptance and regulatory challenges, particularly in countries like Switzerland, is crucial for project success. Additionally, recognizing financial and operational risks can guide the development of robust economic models and encourage technological innovation to enhance project viability. These insights offer a roadmap for integrating geothermal energy into the global energy mix sustainably.

Future Research Directions in Switzerland

We recommend several future research directions specific to Switzerland's geothermal landscape, including:

1. **Seismic Risk Assessment**: Investigate induced seismicity in Swiss geothermal projects, focusing on fault activity and mitigation strategies.

2. **Environmental Impact**: Assess the ecological impact of geothermal projects on Switzerland's alpine ecosystems and biodiversity.

3. **Market Dynamics**: Analyze financial risks and competitive positioning in Switzerland's geothermal energy market.

4. **Energy System Integration**: Explore the integration of geothermal energy with Switzerland's energy grid, focusing on synergies with hydroelectric and solar power.

5. **Technological Innovation**: Evaluate new geothermal technologies, such as advanced drilling techniques, and their associated risks.

6. **Enhanced Geothermal Systems (EGS)**: Study the feasibility of cold EGS in Switzerland's alpine regions, addressing challenges like low temperatures and complex geology.

7. **Heat Utilization Strategies**: Investigate the potential for geothermal heat applications, such as district heating and industrial uses.

8. **Hybrid Systems**: Explore the integration of geothermal energy with solar, wind, or hydropower to enhance sustainability.

9. **Climate Change Resilience**: Study how climate change may impact the performance and sustainability of Swiss geothermal projects.

Critical Assessment of Study's Limitations

1. **Geographical Limitation**: The focus on Switzerland limits the generalizability of the findings to other regions with different geothermal conditions or regulatory environments.

2. **Database Limitation**: Relying solely on the Web of Science database may exclude valuable studies from other sources, such as gray literature or non-academic publications.

3. **Risk of Bias**: Potential biases exist in the selection of studies, as the review was limited to those explicitly addressing geothermal risk management.

These limitations suggest avenues for future research to expand the scope and deepen the understanding of geothermal energy risks globally.

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