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Unlocking the Potential of Geothermal Energy in Yemen: A Comparative Analysis with Global Trends

Abdulrahman Al-Fakih[1], Abbas Al-Khudafi[2]

[1]College of Petroleum Engineering and Geosciences, King Fahd University of Petroleum Minerals, Dhahran 31261, Saudi Arabia

[2]Hadhramout University, Mukalla, Yemen

Alja2014ser@gmail.com

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ABSTRACT

Geothermal energy, a sustainable and clean resource, has garnered significant global attention as an alternative to conventional energy sources. Its importance is particularly pronounced in the Middle East, a region traditionally reliant on fossil fuels. This study focuses on Yemen, a nation with untapped geothermal potential, largely due to its unique geological characteristics marked by tectonic boundaries and volcanic activity. This study assesses Yemen's geothermal resources, contrasting them with global practices to highlight the nation's potential. The aim is to shed light on Yemen's capacity to harness geothermal energy, contributing to both national energy sustainability and broader regional energy diversification. The study encapsulates the global significance of geothermal energy, highlights Yemen's unique potential, and outlines the study's purpose of placing Yemen's geothermal resources in a global perspective.

1. INTRODUCTION

The quest for sustainable and renewable energy sources has become increasingly crucial in the global energy landscape, particularly in light of climate change and the depletion of traditional fossil fuel resources (Nazarov et al., 2024; Akpan et al., 2023). Amidst this backdrop, geothermal energy emerges as a viable and environmentally friendly alternative, drawing attention for its low emissions and consistent supply (Alderson et al., 2023; Soltani et al., 2021). The global thrust towards geothermal energy, including in the oil-rich Middle East, underscores the shifting paradigms in energy sourcing (Axelsson et al., 2024; Sayed et al., 2023; Amoatey et al., 2021). In response to these global challenges, this study turns to Yemen, a nation whose geothermal potential represents an untapped asset in this emerging energy landscape.

Yemen stands at the crossroads of this energy transition. Its geothermal-rich geological setup, characterized by tectonic plate boundaries and active volcanic regions, is vividly depicted in the simplified geological map of Yemen (Albaroot et al., 2016). This map not only illustrates the regions with geothermal potential but also aligns with the nation's untapped energy prospects, which are significant for both Yemen's energy independence and the Middle East's energy diversification efforts (Chandrasekharam et al., 2016; Kubati et al., 2015; Albaroot et al., 2016; Al-Fakih et al., 2018; Al Kadasi et al., 2020; Al-Nabhani et al., 2022; Chauvet et al., 2023). However, the current exploitation of these resources is minimal, pointing to a gap between potential and actualized use, which this study aims to explore.

The potential economic and environmental benefits of geothermal development in Yemen could be transformative, offering a clean, sustainable, and locally-produced energy source (Qasem et al., 2018., 2022; Amoatey et al., 2021; Al-Wesabi et al., 2022; Ersoy et al., 2022; Sim et al., 2024). This study aims to bridge the existing knowledge gap by exploring Yemen's geothermal potential and drawing comparisons with global trends and best practices in geothermal energy utilization. Through this comparative analysis, we seek to underscore Yemen's untapped opportunities and propose strategic pathways for its development, contributing to the global narrative of renewable energy growth.

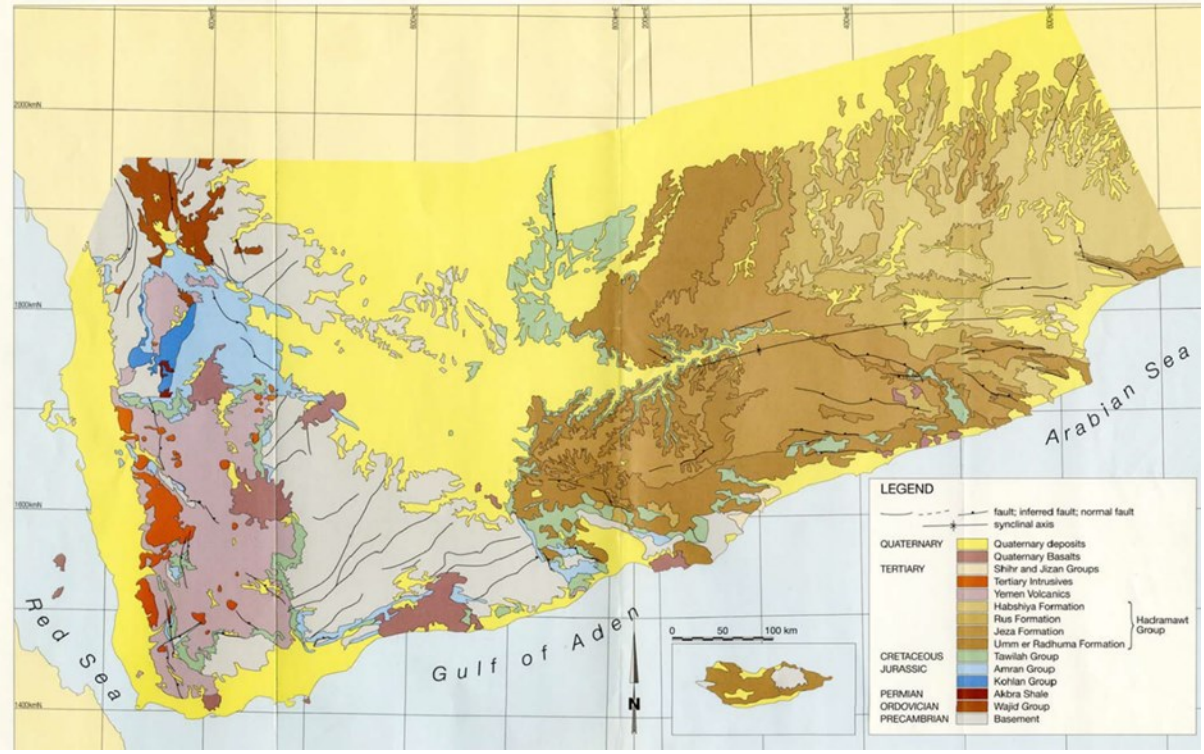

Figure 1: The Simplified Geological Map of Yemen, which forms a cornerstone visual of this study, delineates the country's diverse geological formations, providing clues to its geothermal wealth. The map color codes various geological periods, from the ancient Precambrian to the more recent Quaternary, indicating a complex and varied geologic history. Notably, the map pinpoints the fault lines and volcanic areas, particularly in the west, suggesting regions of heightened geothermal activity. Such geological features are critical indicators of geothermal potential, as they often correlate with increased heat flow and the presence of geothermal reservoirs. (after Van der Gun & Ahmed 1995 and Albaroot et al., 2016). Source: (Ministry of Water and Environment of the Republic of Yemen).

2. METHODOLOGY

This study employs a multifaceted approach to evaluate Yemen's geothermal potential. The methodology encompasses:

- Data Collection: The research begins with a thorough collection of chemical composition data from various thermal springs across Yemen, which serves as a primary indicator of geothermal activity.
- Comparative Analysis: Utilizing this data, we perform a comparative analysis against regional and global geothermal energy benchmarks. This involves examining the temperature ranges, flow rates, and estimated geothermal capacities documented in the existing literature.
- Geological Assessment: We also incorporate geological surveys and existing maps to identify geothermal manifestations and assess the subsurface geothermal conditions. This includes analyzing geological structures such as faults and volcanic features that are conducive to geothermal activity.
- Technological Review: The current state of geothermal technology and its applicability to Yemen's context is reviewed, taking into account the technological advancements in geothermal exploration and exploitation worldwide.
- Synthesis of Findings: By synthesizing the collected data and comparative studies, the research aims to create a comprehensive picture of Yemen's geothermal resources, highlighting areas with high potential and suggesting optimal locations for future geothermal plants.

3. YEMEN'S GEOTHERMAL RESOURCE

3.1 Geological Overview

Yemen's dynamic geothermal potential is deeply rooted in its complex geological history, marked by active tectonic plate interactions and prolific volcanic activity (Abdelrahman et al., 2023; Al-Kohlani et al., 2008). Figure 2 shows that Bir Ali Caldera Lake exemplifies the significant geothermal features present, nestled within the expansive Balhaf–Bir Ali volcanic field that covers an area of approximately 500 km² in southeastern Yemen (Heikal et al., 2014). This field, with its characteristic cinder cone complexes and lava flows interspersed with ultramafic xenoliths, points to a substantial underlying geothermal gradient, which is primed for energy exploitation (M inissale et al., 2013). Mapping the sensitivity of regions to volcanism and tectonics, particularly in Yemen and extending into Eastern Africa, reveals a belt of heightened geothermal activity (Barahim et al., 2017). The sensitivity of the region to volcanism and tectonics, as illustrated in Figure 3, underscores Yemen's potential in a belt of heightened geothermal activity, attributed to a thinner Earth's crust. Figure 4 offers a satellite perspective, reinforcing the diversity and complexity of Yemen's geological makeup, indicative of substantial geothermal reservoirs.

Figure 2:" Bir Ali Caldera Lake in Balhaf, Yemen: A Natural Geothermal Wonder" The Bir Ali crater lake, situated within one of Yemen's largest volcanic fields, serves as a compelling visual for the country's geothermal potential. The presence of geological formations such as cinder cones and vesicular lava flows indicates active geothermal processes below the surface that are ripe for exploration (Heikal et al., 2014). Source: (Ministry of Water and Environment of the Republic of Yemen).

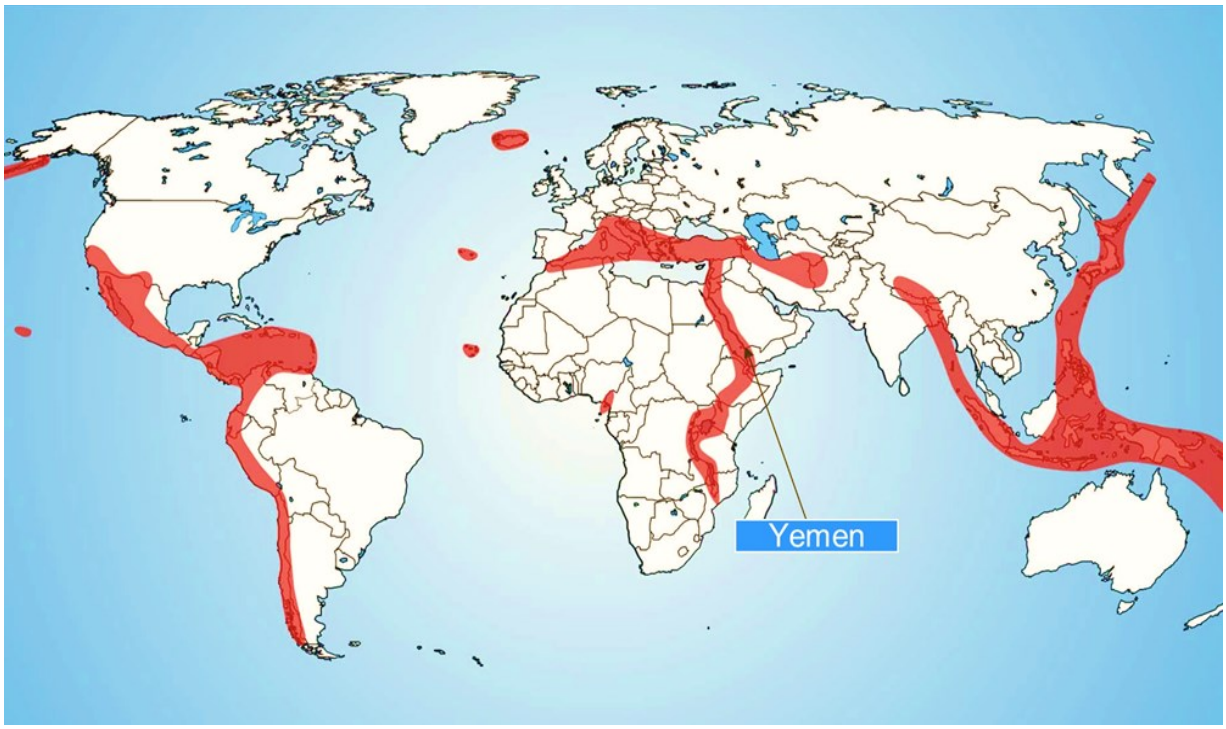

Figure 3: Volcanism and Tectonics Zones. This map highlights regions sensitive to volcanism and tectonics, including Yemen and Eastern Africa. Such zones are often associated with high geothermal potential due to the Earth's crust being thinner, allowing for easier access to geothermal energy. Source: (Ministry of Water and Environment of the Republic of Yemen).

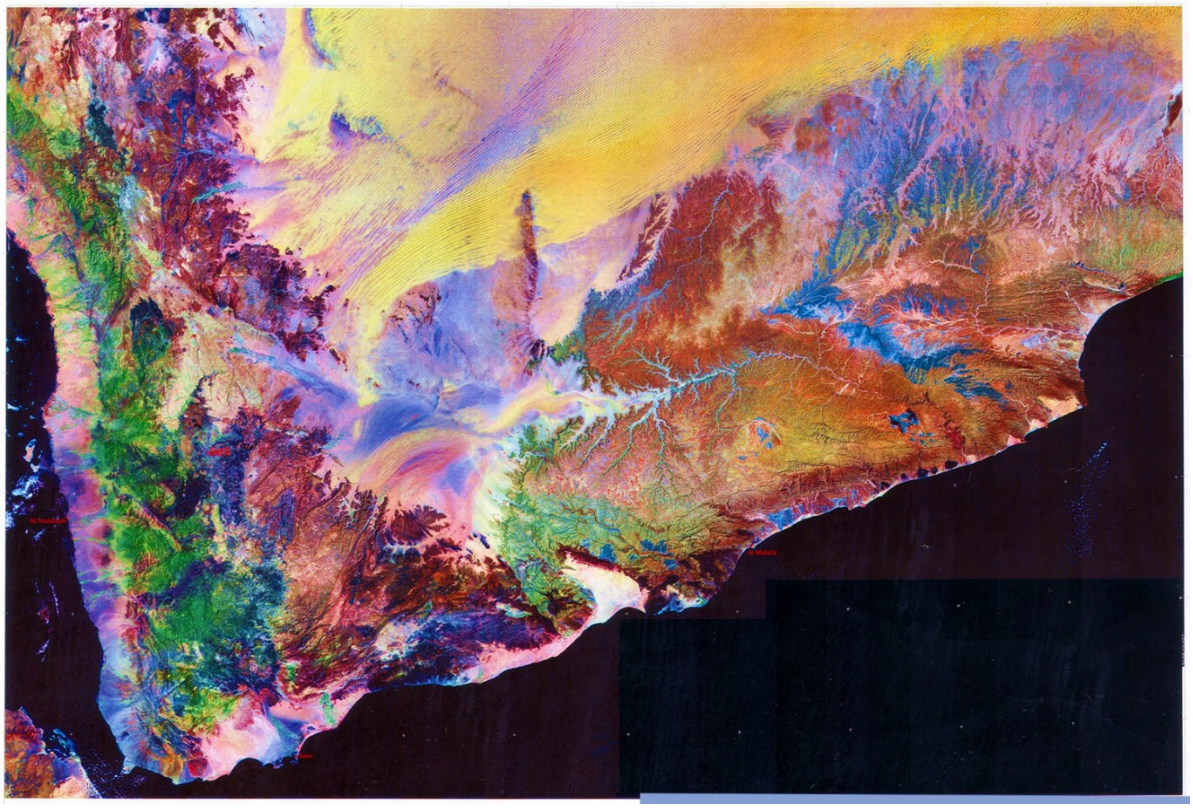

Figure 4: A satellite image of Yemen provides a macro-perspective of the terrain. Variations in color and texture illustrate a diverse geological landscape, which, upon closer inspection, could reveal areas with geothermal prospects. Source: (Ministry of Water and Environment of the Republic of Yemen).

3.2 Thermal Spring Analysis

Yemen's thermal springs, highlighted in Figure 5, offer invaluable insights into the country's geothermal activity. These hot springs are essential indicators for mapping geothermal energy potential, serving as surface evidence of the extensive heat available beneath.

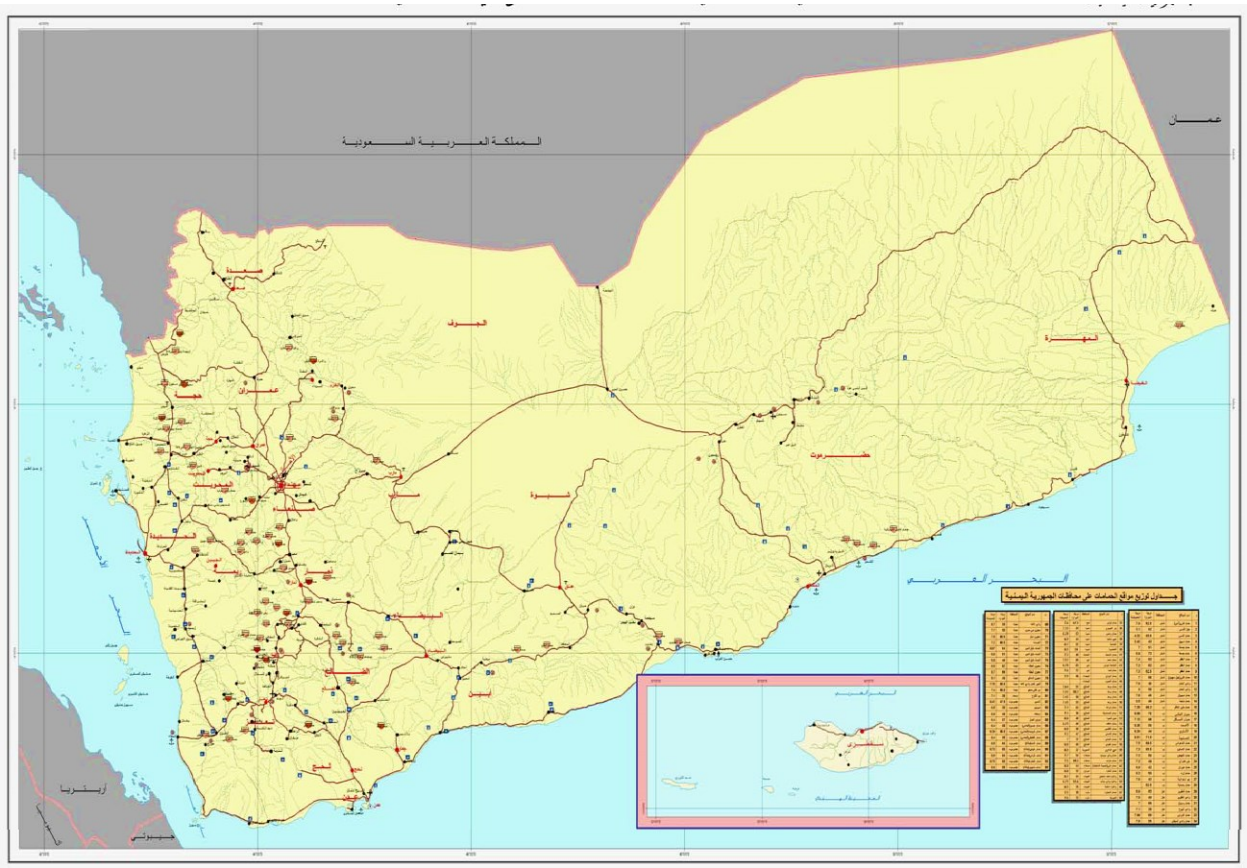

Figure 5: Yemen Hot Springs: This image, likely marking the locations of hot springs, can be correlated with geothermal activity. Hot springs are surface expressions of geothermal heat and are key indicators when mapping out geothermal energy potential. Source: (Ministry of Water and Environment of the Republic of Yemen).

3.3 Areas of High Potential

The volcanic highlands and rift zones of Yemen, shown in Figure 6, are identified as regions with significant geothermal activity. The geological cross-section provided aids in targeting potential sites for geothermal wells. The hydrogeological map of the Dhamar area, depicted in Figure 7, is integral for understanding the interactions between aquifers and geothermal systems, crucial for direct-use applications and sustainable resource management.

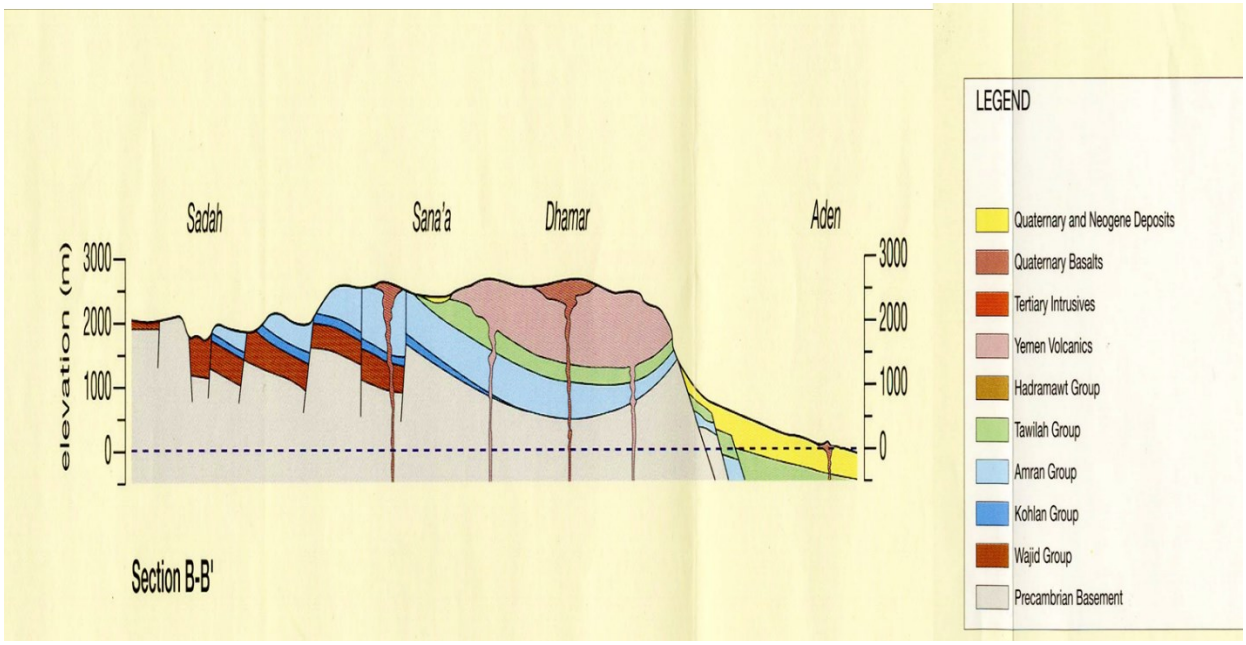

Figure 6: Geological Cross-Section of Yemen: The cross-section offers insight into the geological layers of Yemen. Identifying layers associated with geothermal activity, such as volcanic deposits, could guide the location of potential geothermal wells. Source: (Ministry of Water and Environment of the Republic of Yemen).

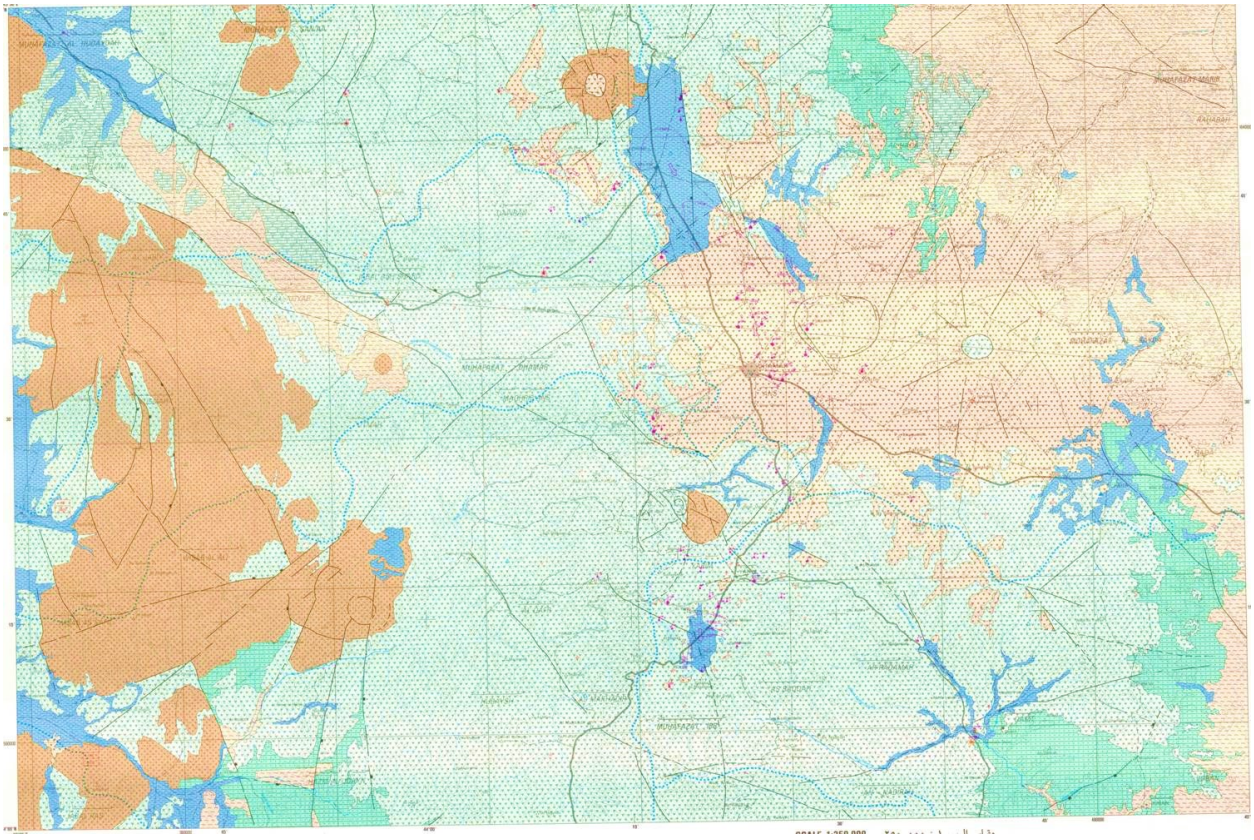

Figure 7: Hydrogeological Map of Dhamar Area:Hydrogeological maps provide critical information about the water table and aquifers, which are essential components in geothermal energy extraction, especially for direct-use applications and for understanding the recharge of geothermal reservoirs. Source: (Ministry of Water and Environment of the Republic of Yemen).

3.2 Regional Context of Geothermal Resources

In examining the Middle Eastern geothermal landscape, a discerning analysis up to the year 2021 underscores Yemen as a regionally significant contender in geothermal richness. This distinction is grounded in the substantial projections of geothermal capacity, highlighted by the country's extensive volcanic topography and the variety of thermal gradients. However, juxtaposed against this natural wealth is the relative paucity of developmental initiatives, especially when contrasted with Saudi Arabia, whose burgeoning geothermal sector reflects a strategic pivot towards renewable energies. Figure 8 graph elucidates the disparate geothermal capacities across Middle Eastern nations, quantified in megawatts. The visualization draws from the latest research to contrast Yemen's vast, yet underutilized, geothermal resources against the active and emergent projects within the region. Contained within the appendix is a meticulously compiled dataset articulating the geothermal energy estimates, encompassing energy capacity, geographic expanse, thermal characteristics, and the nature of enthalpy for pertinent sites across the Middle East. This repository is instrumental for a granular understanding of each locale's geothermal profile and paves the way for a nuanced comparison of regional resources.(Amoatey et al. 2021).

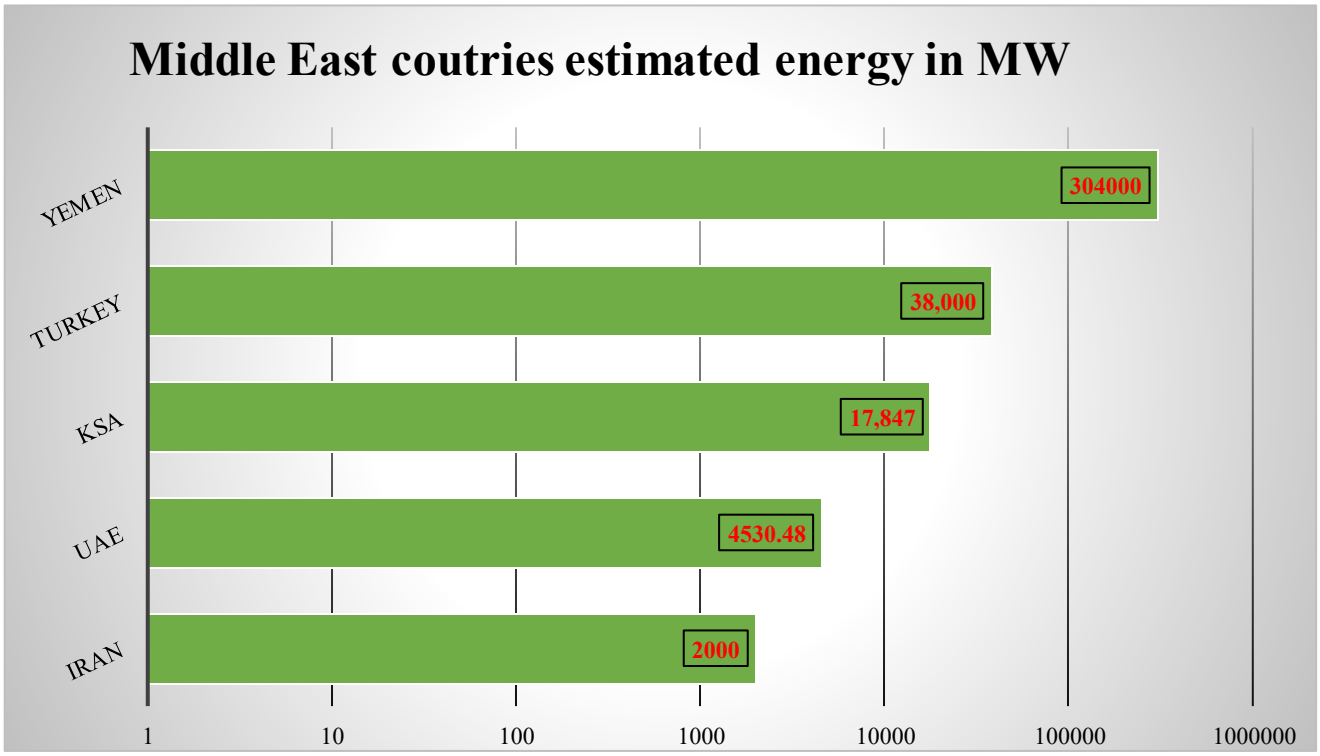

Figure 8: Disparities in Geothermal Energy Capacities of Middle Eastern Countries"This illustration quantitatively represents the geothermal energy potential across the Middle East. Yemen's superior estimated capacity starkly contrasts with neighboring nations, signaling vast untapped resources. The figure serves as a clarion call for intensified exploration and utilization strategies within the Yemeni border. Data extracted from (Amoatey et al. 2021)

3.5 Challenges and Opportunities

The development of geothermal resources in Yemen faces challenges such as technological limitations, infrastructure needs, and political stability. However, the opportunities for sustainable energy production and economic growth provide strong incentives to overcome these challenges.

3.2 Current Developments

The Yemen Geothermal Development Project, under GEF Project ID 3474, was a collaborative initiative involving the United Nations Environment Programme and Yemen's Ministry of Water and Environment. It aimed to advance geothermal exploration and development in Yemen, targeting the discovery of high enthalpy geothermal reservoirs to improve energy access and decrease dependency on fossil fuels. However, the project, which received approval in 2008 and was expected to contribute significantly to climate change mitigation, was eventually canceled in 2018. For detailed information, please refer to the project's page at https://www.thegef.org/projects-operations/projects/3474.

4. GLOBAL GEOTHERMAL TRENDS AND YEMEN'S POSITION

The global shift toward sustainable energy solutions has seen a pronounced increase in the installed capacity of geothermal energy, with a recorded total of 16,335 MW by the end of 2023. Leading the charge are countries like the U.S., Indonesia, and the Philippines, each harnessing their geothermal resources to meet a substantial portion of their energy demands. This global perspective, as presented in Figure 9, highlights the significant strides in geothermal energy production and sets a benchmark for countries with untapped geothermal potential. In contrast, Yemen, despite its placement in a geothermally promising region, remains underrepresented in this global narrative. The study aims to project Yemen's geothermal prospects onto this global canvas, suggesting that with appropriate investment and development, Yemen could leverage its rich geothermal resources to join the ranks of these leading nations. Figure 9 serves as a visual cue for the immense possibilities that lie within Yemen's geothermal landscapes and underscores the need for a strategic approach to unlock this potential. Integrating Yemen into the global geothermal market could provide a significant boost to the nation's energy independence and contribute to a sustainable energy future (Richter et al., 2023).

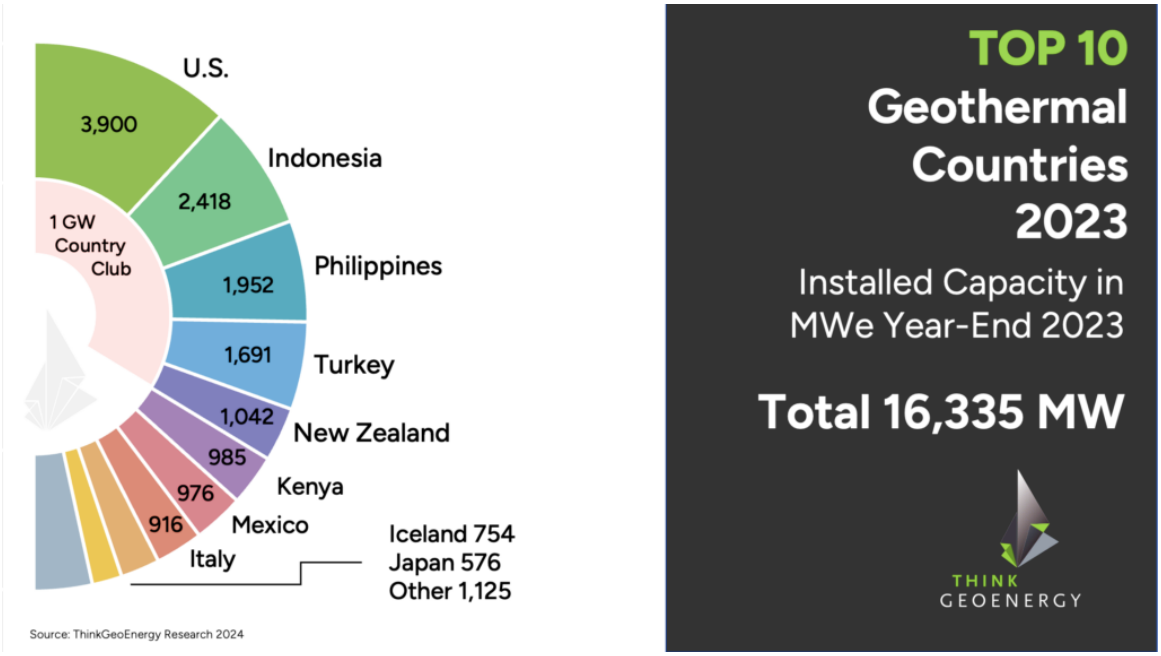

Figure 9: Top 10 Geothermal Countries by Installed Capacity in 2023 (Richter et al., 2023)

5. STRATEGIC RECOMMENDATIONS

For Yemen to capitalize on its geothermal resources, it is recommended to adopt a multi-tiered strategy. This would involve:

- Infrastructure Development: Prioritize the construction of geothermal plants and associated infrastructure with international investment and expertise.
- Policy Framework: Establish a robust legal and regulatory framework that incentivizes renewable energy investments and provides clear guidelines for geothermal development.
- Technology Transfer: Collaborate with leading geothermal countries to adopt cutting-edge technologies suited to Yemen's geothermal characteristics.
- Capacity Building: Invest in local workforce development to create a skilled pool of professionals in geothermal exploration and plant operation.
- Regional Cooperation: Enhance regional energy stability by integrating geothermal energy into the broader Middle Eastern energy network.

By implementing these strategies, Yemen could not only improve its national energy security but also contribute to regional energy stability and sustainability

6. CONCLUSION

This study has presented a comprehensive analysis of Yemen's geothermal potential, placing it within the broader context of regional and global renewable energy trends. Yemen's unique geological features, particularly its volcanic regions and tectonic settings, have been established as fertile ground for geothermal energy production. Despite this, current exploitation remains minimal, particularly when juxtaposed with the active developments in other Middle Eastern countries.

The analysis underscores the substantial, yet untapped, geothermal capacity of Yemen, which if harnessed, could significantly contribute to national energy needs and regional energy security. Strategic recommendations for Yemen include developing infrastructure, establishing supportive policies, and fostering technological and knowledge transfer.

Continued research and investment in Yemen's geothermal sector are imperative for realizing this renewable energy's full potential. The insights provided by this study aim to catalyze such advancements, suggesting a path forward not only for Yemen but also for the Middle East, to pivot towards a more sustainable and secure energy future.

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