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Exploration of Geothermal Resources as Sustainable Energy Alternative

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ABSTRACT
As the world continues to confront the pressing challenges of climate change and energy insecurity, the search for cleaner and more sustainable energy alternatives has become increasingly urgent. Among the various renewable options available, geothermal energy stands out due to its reliability, low environmental impact, and potential for long-term use. This paper explores geothermal energy as a viable and sustainable alternative to conventional fossil fuels and focuses on how it is discovered and developed. It also discusses key exploration methods such as geological surveys, geophysical techniques, geochemical analysis, and exploratory drilling, all of which are essential to identifying and harnessing subsurface heat. In examining the global relevance of geothermal energy, the paper highlights its environmental benefits, including reduced carbon emissions and minimal land disturbance. It also addresses the current limitations that hinder wider adoption, such as high initial costs and location-specific viability. The study found out that**,** viable geothermal systems require co-occurrence of heat, fluid, and permeability. It is therefore, recommended that governments, academic institutions, and private companies should prioritise funding for geothermal technologies, especially Enhanced Geothermal Systems (EGS) and hybrid systems, to improve efficiency and reduce costs. The dominant heat source is crustal radiogenic decay and mantle conduction, with magmatic intrusions critical for high-enthalpy volcanic systems (Moeck, 2014). Ultimately, the paper argues that with proper investment, policy support, and technological advancement, geothermal energy can play a significant role in the future global energy mix.

Keywords: Exploration, Geothermal Resources, Sustainable Energy Alternative, Geochemical, Fossil Fuels, Radioactive

INTRODUCTION

Geothermal energy is the heat that originates from the Earth's interior, stored in rocks and fluids beneath the surface (Manzella et al., 2018). This natural heat source can be harnessed to produce electricity or provide direct heating. The word "geothermal" comes from the Greek words *geo* (earth) and *therme* (heat), and the use of geothermal heat dates back to ancient times, when hot springs were used for bathing and heating in places like China, Italy, and Iceland (Lund & Freeston, 2001).

In today's world, where the effects of climate change are becoming more severe and fossil fuel resources are gradually depleting, the global energy sector is undergoing a significant transformation. Geothermal energy is increasingly viewed as an important part of this transition due to its low carbon footprint, constant availability, and potential for long-term sustainability. Unlike solar and wind, geothermal energy is not weather-dependent, which makes it a more stable energy source (DiPippo, 2012). In fact, according to the International Renewable Energy Agency (IRENA, 2020), geothermal power can play a critical role in achieving global climate goals by helping to reduce greenhouse gas emissions.

This paper explores how geothermal energy is discovered and developed, with a focus on the techniques used in its exploration. It also evaluates the potential of geothermal energy as a long-term, clean energy option in the context of the global energy transition. By examining the methods and technologies involved in geothermal exploration, the work contributes to a better understanding of how this energy source can support a more sustainable future.

Statement of the Problem

Global dependence on fossil fuels drives climate change, energy insecurity, and volatile electricity costs. While solar and wind capacity has expanded, both sources are intermittent and cannot reliably meet baseload demand without large-scale storage (IRENA, 2024). Geothermal energy offers firm, renewable, low-carbon power and direct heat, yet it accounts for less than 1% of global electricity generation (IEA, 2023). This underutilization persists despite estimates that the technical potential of geothermal could meet current global energy demand several times over (Tester et al., 2006).

The core problem is that geothermal resources remain poorly understood and underexploited. Six gaps prevent scaling:

1. Limited understanding of sources and nature: Stakeholders and policymakers often lack clarity on how geothermal energy is formed, where it occurs, and how subsurface heat, fluid, and permeability interact. This knowledge gap restricts investment and public acceptance.
2. Inconsistent classification and targeting: Geothermal resources are classified by temperature as low, medium, and high enthalpy, yet exploration strategies are not always matched to the appropriate temperature class and end use. Misalignment leads to wasted drilling and failed projects.
3. High exploration risk and technical barriers: Exploration relies on indirect geological, geochemical, and geophysical techniques. Drilling success rates for new fields range from 20% to 60%, creating significant financial risk (IGA, 2022). Without improved, cost-effective exploration techniques, capital flows to lower-risk renewables.
4. Infrastructure and technology constraints: Development of geothermal resources requires specialized drilling, reservoir engineering, and power plant technologies. Enhanced Geothermal Systems show promise for non-volcanic regions but face challenges with induced seismicity, reservoir creation, and long-term sustainability (Breede et al., 2013). Infrastructure costs and technical complexity deter adoption, especially in developing regions.
5. Undervalued benefits and externalities: The environmental and economic benefits of geothermal, including low lifecycle emissions, small land footprint, and baseload reliability, are not fully quantified or integrated into energy planning. This undervaluation weakens the business case compared to subsidized solar and wind.
6. Persistent challenges in development: Regulatory delays, social concerns about seismicity and water use, high upfront costs, and lack of risk mitigation instruments continue to limit geothermal deployment. These challenges are compounded by insufficient data sharing and limited workforce capacity.

Therefore, there is a need to systematically examine the sources and nature of geothermal energy, classify resources by temperature, evaluate exploration techniques, assess technological approaches and infrastructure, quantify environmental and economic benefits, and identify challenges in exploration and development. Addressing these six areas is critical to reduce uncertainty, lower costs, and position geothermal as a viable sustainable energy alternative for baseload power and heating.

Aim and Objectives of the Study

This study explored geothermal energy as a viable and sustainable alternative to conventional fossil fuels. Specifically, the study:

1. Examined the primary geological and geophysical sources of geothermal energy.
2. Explored how geothermal resources are classified by temperature.
3. Investigated techniques that are currently used to identify and evaluate geothermal reservoirs.
4. Assessed the technological approaches and infrastructure that are required to develop geothermal systems.
5. Evaluated the measurable environmental and economic benefits of geothermal energy.
6. Examined the challenges and limitations in geothermal exploration and development.

Research Questions

Based on the objectives of the study, the following research questions guided the study:

1. What are the primary geological and geophysical sources of geothermal energy?
2. How are geothermal resources classified by temperature?
3. What exploration techniques are currently used to identify and evaluate geothermal reservoirs?
4. What technological approaches and infrastructure are required to develop geothermal systems?
5. What are the measurable environmental and economic benefits of geothermal energy?
6. What are the major challenges limiting geothermal exploration and development?

Significance of the Study

This study is significant for theory, practice, and policy:

1. Theoretical significance: The paper integrates geoscience, engineering, economics, and environmental science to present a holistic framework of geothermal development. It clarifies how temperature classification, exploration risk, and technology choice interact to determine resource viability. This contributes to energy resource theory by linking subsurface characteristics to surface outcomes.
2. Practical significance: For developers and energy planners, the study provides a consolidated review of exploration techniques, technology options, and cost structures. Understanding which methods reduce drilling risk and which infrastructure suits specific temperature classes helps de-risk investment and improve project success rates.
3. Policy significance: Governments and regulators need evidence to design incentives, risk mitigation funds, and regulatory frameworks that scale geothermal. By quantifying environmental and economic benefits and identifying barriers, the study supports data-driven energy transition policies. This is critical for countries seeking baseload renewable alternatives to meet 2030 and 2050 decarbonization targets.
4. Social significance: Geothermal provides stable electricity and heat with low emissions and minimal land use. Expanding its role improves energy access, reduces air pollution, and creates skilled jobs in drilling, engineering, and plant operations. Clarifying social concerns around seismicity and water use supports informed community engagement.

Scope and Limitations of the Study

Scope

1. Thematic scope: The study covers six domains: sources and nature, temperature classification, exploration techniques, technology and infrastructure, benefits, and challenges.
2. Technology scope: Includes conventional hydrothermal systems, binary cycle plants, flash steam plants, direct-use applications, and Enhanced Geothermal Systems.
3. Geographic scope: Global review with emphasis on regions with high geothermal potential, including the Kenya, Iceland, and Philippines. Case comparisons are used to illustrate context.

4. Methodological scope: Desk research using systematic review of peer-reviewed journals, industry reports from IGA, IRENA, and IEA, and technical databases. No primary field data or new modeling is conducted.

Limitations

1. Data availability: Subsurface data are proprietary. The study relies on published success rates and case studies, which may not represent all geologic settings.
2. No economic modeling: While economic benefits are reviewed, the paper does not produce new levelized cost of energy models or project-specific financial analysis.
3. Technology maturity: EGS and closed-loop systems are still emerging. Performance data are limited and may change as pilots scale.
4. Generalizability: Geological conditions vary widely. Findings on exploration techniques and challenges may not transfer directly across all regions without site-specific studies.
5. Exclusion of non-energy uses: The study focuses on electricity and direct heat. Mineral extraction from geothermal brines is acknowledged but not analyzed in detail.

LITERATURE REVIEW

CONCEPTUAL FRAMEWORK

Conceptual Framework: Geothermal Resource Development Pathway

This study adopts a systems-based conceptual framework that links subsurface resource characteristics to surface outcomes through six sequential but interacting stages. The framework reflects the six specific objectives and shows how technical, economic, and policy factors determine whether geothermal potential is realized.

The framework is a six-stage oval with feedback loops.

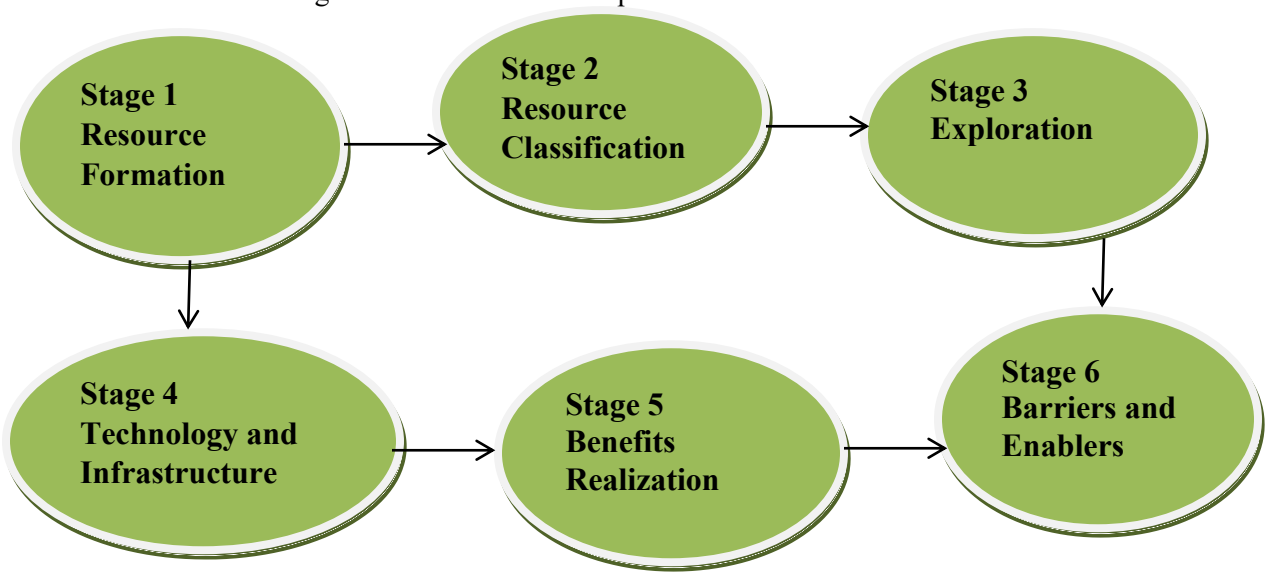

Figure 1: Geothermal Resource Development Pathway

1. Stage 1: Resource Formation: Earth's heat, fluid, and permeability create geothermal systems. Key constructs: tectonic setting, heat flow, lithology, fault networks. Maps to Objective 1.
2. Stage 2: Resource Classification: Systems are categorized by temperature and enthalpy to determine application. Key constructs: low enthalpy <90°C, medium 90–150°C, high >150°C; direct use vs. electricity. Maps to Objective 2.

3. Stage 3: Exploration: Geological, geochemical, and geophysical methods reduce subsurface uncertainty. Key constructs: magnetotellurics, seismic, remote sensing, conceptual modeling, drilling risk. Maps to Objective 3.
4. Stage 4: Technology and Infrastructure: Resource type dictates plant design. Key constructs: flash steam, binary cycle, EGS, direct-use networks, well design, and reservoir management. Maps to Objective 4.
5. Stage 5: Benefits Realization: If developed, geothermal delivers outcomes. Key constructs: lifecycle emissions, capacity factor, LCOE, job creation, energy security. Maps to Objective 5.
6. Stage 6: Barriers and Enablers: Technical, economic, regulatory, and social factors filter development. Key constructs: upfront cost, induced seismicity, permitting, risk mitigation, social license. Maps to Objective 6.

Cross-cutting moderators: Policy support, financing mechanisms, and data availability influence movement between stages. Feedback loops show that benefits and challenges inform new exploration and technology choices.

The Source and Nature of Geothermal Energy

Geothermal energy comes from the natural heat stored beneath the Earth's surface. This heat originates from two main sources: the residual heat left over from the Earth's formation about 4.5 billion years ago, and the continuous heat produced by the radioactive decay of elements such as uranium, thorium, and potassium in the Earth's mantle and crust (Dickson & Fanelli, 2004). Over time, this heat builds up in underground reservoirs, where it can be accessed through wells and used to generate electricity or provide direct heating.

The deeper one goes beneath the Earth's surface, the hotter it becomes. This phenomenon is known as the geothermal gradient, which typically increases by about 25 to 30°C per kilometre of depth in most regions (Hochstein, 1990). In areas with volcanic activity or tectonic plate boundaries, such as the Rift Valley in East Africa or parts of the Pacific Ring of Fire, the geothermal gradient is much higher, making it easier to access geothermal heat at shallower depths. What makes geothermal energy unique is its reliability. Unlike solar or wind energy, which depends on weather and time of day, geothermal energy is available 24/7, all year round. This continuous availability makes it a very attractive option for base-load electricity generation.

Types of Geothermal Systems

Geothermal systems are classified based on how heat is stored and transferred in the subsurface. The two main types are hydrothermal systems and Enhanced Geothermal Systems (EGS).

1. **Hydrothermal Systems:** These are the most commonly used geothermal systems. They consist of naturally occurring hot water or steam trapped in porous rocks beneath the Earth's surface. Hydrothermal resources are usually found in areas with active tectonics, where faults allow water to circulate deep into the Earth and return to the surface as hot springs, geysers, or steam vents. Power plants can tap into these systems by drilling wells to bring the hot fluid to the surface and convert it into electricity (DiPippo, 2012).
2. **Enhanced Geothermal Systems (EGS):** Unlike hydrothermal systems, EGS are engineered. They are used in areas where the rocks are hot but lack enough natural water or permeability to carry heat to the surface. In EGS, water is injected into deep, hot rock formations to create artificial reservoirs. The water is then heated by the rocks and returned to the surface to generate electricity. Though still in its early stages, EGS has the potential to significantly expand geothermal use in areas where traditional hydrothermal systems are absent (Tester et al., 2006).

Table 2: Characteristics of Major Geothermal System Types

System Type	Heat Source	Fluid Source	Permeability Control	Global	Examples Typical Temp
Volcanic hydrothermal	Magmatic intrusion	Meteoric water	Faults, fractures	Iceland, Indonesia, Kenya	>200°C
Crystalline EGS	Radioactive decay, conduction	Engineered injection	Induced fractures	Soultz, France; Utah FORGE	150–300°C
Geopressured	Compaction, high pressure	Formation brine	Overpressured sands	Gulf Coast, USA	90–200°C

Temperature Classifications of Geothermal Resources

Geothermal resources are also classified by temperature, which affects how they can be used. These classifications are generally divided into low, medium, and high enthalpy resources:

1. **Low Enthalpy (Less than 90°C):** These are typically used for direct heating purposes, such as space heating, greenhouse agriculture, fish farming, and spa tourism. They are common in many parts of the world and are often the first step toward geothermal development in emerging regions (Lund et al., 2005).
2. **Medium Enthalpy (90°C to 150°C):** These resources can be used for both direct heating and power generation, typically through binary cycle power plants, which can operate efficiently at moderate temperatures.
3. **High Enthalpy (Above 150°C):** These are suitable for large-scale electricity generation. They are usually found in volcanically active regions and are the target of most geothermal power projects around the world, such as those in Iceland, the Philippines, and Kenya (Bertani, 2016).

Table 3: Temperature Classes, Technologies, and Applications

Class Temperature	Typical Technology Efficiency	Primary Uses LCOE Range	USD per MWh
High enthalpy >150°C	Dry steam, single/double flash	10–23% n Grid electricity	50-90
Medium enthalpy 90–150°C	Binary cycle ORC	8–12% Electricity, industrial heat	70–130
Low enthalpy <90°C	Heat exchangers, heat pumps COP 3–6	District heat, greenhouses, balneology	20–60 thermal

Sources: DiPippo, 2016; IRENA, 2024; Lund & Toth, 2021.

Binary plants extended geothermal to 38 countries by 2023, yet average capacity factors are 75% versus 85% for flash plants due to lower resource temperatures (Bertani, 2016). Studies show 32% of failed projects cited "resource temperature lower than predicted" (IGA, 2022). Direct-use is under-reported in energy statistics despite 107 GWth installed globally, indicating undervaluation in policy (Lund & Toth, 2021).

Geothermal Resource Exploration Techniques

Before geothermal energy can be harnessed, the presence, depth, and quality of the resource must be thoroughly assessed. This involves a combination of surface investigations, subsurface imaging, fluid analysis, and test drilling. These exploration techniques help determine whether a geothermal system is viable and sustainable over time. Though the methods resemble those used in petroleum exploration, they are tailored to the specific properties of geothermal systems, such as heat distribution, water-rock interaction, and permeability zones (Dickson & Fanelli, 2013). The exploration process is typically carried out in phases, starting with broad regional surveys and narrowing down to detailed site-specific studies.

1. **Geological Surveys:** The first step in geothermal exploration often involves geological mapping and surface reconnaissance. This includes the identification of surface manifestations such as hot springs, fumaroles, altered rocks, and sinter deposits, which are natural indicators of subsurface heat (Hochstein, 1990). Tectonic settings are also studied since geothermal activity is commonly

associated with plate boundaries, volcanic arcs, and rift zones. By understanding the geology of the area, geoscientists can infer the presence of geothermal reservoirs and estimate their potential.

2. **Geophysical Methods:** Once promising surface indicators are observed, geophysical techniques are used to probe the subsurface without physical drilling. Seismic surveys help map fault structures, fractures, and the depth of potential reservoirs. Magnetotellurics (MT) and electrical resistivity methods are particularly valuable in geothermal exploration, as they can detect changes in rock conductivity due to the presence of hot fluids and hydrothermal alteration (Ussher et al., 2000). Low-resistivity zones often correlate with geothermal reservoirs, guiding further exploration efforts.
3. **Geochemical Analysis:** Geochemical methods involve sampling and analysing thermal waters and gases at the surface to infer subsurface conditions. The concentration of certain elements and isotopes (e.g., silica, sodium, potassium, and stable isotopes like $\delta^{18}O$ and δD) provides clues about the temperature and origin of the geothermal fluids (Giggenbach, 1988). Geothermometers are used to estimate reservoir temperatures based on these chemical compositions, offering a non-invasive way to understand the system before drilling.
4. **Exploratory Drilling:** The most definitive way to confirm a geothermal resource is through exploratory drilling. This involves sinking core holes or temperature gradient wells to directly measure subsurface temperatures and obtain rock samples. These early wells help assess the thermal gradient, reservoir permeability, and fluid content (Tester et al., 2006). While expensive, exploratory drilling provides the crucial data needed to decide whether full-scale development is feasible.

Technological Approaches and Infrastructure for Geothermal Development

Developing a geothermal resource goes beyond exploration. It requires the application of technology that can efficiently extract, convert, and deliver heat or electricity to end users. These technologies differ based on the type of geothermal system and the temperature of the resource. Just like in petroleum geology, careful infrastructure planning is crucial to ensure the long-term sustainability and economic viability of a geothermal project.

Power Generation Technologies

There are three main types of geothermal power plants, each suited for different resource conditions:

1. Dry Steam Plants: These are the oldest and simplest form of geothermal power technology. They directly use steam from the reservoir to turn turbines. Dry steam plants are only suitable in areas where the geothermal fluid is mostly steam, such as The Geysers in California (DiPippo, 2012).
2. Flash Steam Plants: These systems pump high-pressure hot water from deep underground and release it at surface pressure, causing it to vaporise or "flash" into steam. The steam drives turbines, and the remaining liquid can often be reinjected (DiPippo, 2012).
3. Binary Cycle Plants: Ideal for medium- to low-temperature resources, these plants use geothermal fluid to heat a secondary fluid with a lower boiling point (like isobutane). The vapour from the secondary fluid drives the turbine. Binary systems are closed-loop and environmentally friendly, releasing little to no emissions (Zarrouk & Moon, 2014).

Heat Extraction and Conversion

In addition to electricity production, geothermal energy can also be used directly for heating purposes. This is common in residential heating systems, greenhouses, aquaculture, and industrial processes. Direct-use systems extract hot water and deliver it via pipelines without converting it to electricity, making the process more energy-efficient in some contexts (Lund & Freeston, 2001). Another important technology is the ground-source heat pump (GSHP). These systems use shallow geothermal energy for heating and cooling buildings. Though widely used in countries like Sweden and the United States, GSHPs are still relatively new in many developing nations.

Infrastructure and Operational Considerations

Developing geothermal energy requires more than drilling and turbines—it involves a full-scale infrastructure that includes:

- Production wells to extract geothermal fluids
- Injection wells to return used fluids back to the reservoir
- Pipelines for fluid transport
- Power stations with turbines, condensers, and cooling systems
- Monitoring equipment to track temperature, pressure, and reservoir health over time

Long-term productivity depends on how well this infrastructure is maintained. Proper reinjection of fluids is especially important to sustain pressure in the reservoir and minimise environmental risks like ground subsidence or induced seismicity (Axelsson, 2008).

Environmental and Economic Benefits of Geothermal Energy

Geothermal energy has gained attention not only because it is renewable but also due to its minimal environmental footprint and long-term economic potential. Compared to fossil fuels, geothermal systems offer cleaner, more stable, and often more locally sourced energy solutions; key traits in the global shift toward sustainability.

- **Environmental Benefits**

One of the most compelling advantages of geothermal energy is its low greenhouse gas emissions. While fossil fuel plants emit significant amounts of carbon dioxide (CO_2) and other pollutants, geothermal plants emit only a fraction, or sometimes none at all in closed-loop systems. According to the U.S. Environmental Protection Agency (EPA), binary geothermal plants release virtually zero emissions during operation (EPA, 2021).

Also, geothermal power requires a relatively small land footprint. Unlike solar or wind farms, which need large surface areas, geothermal installations, especially those built vertically, take up much less space, preserving surrounding ecosystems (IRENA, 2017).

Another environmental benefit is its reliability. Unlike solar or wind power, geothermal energy is not weather-dependent. It offers consistent base-load energy 24/7, which reduces the need for fossil fuel backup and helps stabilize the electricity grid (Tester et al., 2006).

- **Economic Advantages**

From an economic standpoint, geothermal energy provides long-term cost savings. Although initial investment costs, especially for drilling and infrastructure, can be high, operational and maintenance costs are relatively low over time. Once a geothermal system is established, it can produce energy for decades with minimal fuel input (Lund & Boyd, 2016).

Geothermal projects also promote energy independence, particularly in countries that rely heavily on imported fossil fuels. Local geothermal resources can help diversify the energy mix, boost national energy security, and reduce vulnerability to global oil price shocks.

In addition, geothermal development can spur job creation. It requires geologists, drilling specialists, engineers, environmental scientists, plant operators, and skilled technicians, creating opportunities across multiple sectors (Gehringer & Loksha, 2012).

Challenges and Limitations in Geothermal Exploration and Development

Despite its many benefits, the exploration and development of geothermal resources come with distinct challenges. These issues can hinder project success, especially in regions where the technology or infrastructure is still developing. Primary challenges include:

1. **High Initial Costs and Financial Risk:** There is a high upfront cost associated with geothermal exploration. Drilling, which is essential to confirm the presence of a viable resource, is both technically complex and financially demanding. According to DiPippo (2012), drilling can account for over 40% of the total cost of a geothermal project. Because success is not guaranteed, the financial risk is substantial, particularly for private investors or in developing countries.

2. **Geological Uncertainty:** Even with modern exploration tools, subsurface conditions can be unpredictable. Accurate mapping of geothermal reservoirs is challenging due to the complexity of rock formations, variations in temperature, and the presence of faults or fractures. Mistakes in interpreting geological or geophysical data can lead to drilling failures and wasted resources (Glassley, 2014).
3. **Technological Limitations:** While technology has advanced in areas like Enhanced Geothermal Systems (EGS), the field still faces limitations. EGS involves artificially creating reservoirs in hot dry rock, but maintaining permeability and avoiding induced seismicity remain ongoing concerns. Moreover, some geothermal systems may contain corrosive fluids or gases that require expensive materials and maintenance to prevent damage to infrastructure (MIT, 2006).
4. **Environmental and Social Concerns:** Though geothermal energy is relatively clean, it is not entirely free from environmental concerns. Improperly managed geothermal plants can cause land subsidence, noise pollution, or minor earthquakes, especially in EGS projects. Additionally, the release of trace gases such as hydrogen sulfide, if not properly controlled, can pose health and environmental hazards (Bertani, 2015).
5. **Limited Accessibility and Infrastructure:** In many developing countries, promising geothermal sites are located in remote areas with poor infrastructure. Building access roads, transmission lines, and drilling platforms can significantly increase project costs. Furthermore, the lack of skilled labour, technical know-how and policy frameworks can slow down development (World Bank, 2014).

Case Studies of Successful Geothermal Projects around the World

Geothermal energy has seen successful deployment across various countries, demonstrating its viability and long-term benefits.

- Iceland is a global leader, with nearly 90% of homes heated using geothermal energy. Its success is due to favourable geology and strong government support (Orkustofnun, 2022).
- Kenya stands out in Africa. The Olkaria Geothermal Plant provides over 40% of the country's electricity, making Kenya a model for geothermal development on the continent (IRENA, 2020).
- The Philippines ranks among the top geothermal producers globally, with long-standing projects like the Leyte Geothermal Production Field contributing significantly to its energy mix (DOE Philippines, 2021). These examples show that with the right investment, policy, and geological conditions, geothermal energy can play a central role in sustainable power generation.

Geothermal Potential in Nigeria and Other Oil-Producing Nations

Although oil-rich countries have traditionally focused on fossil fuels, many are beginning to explore geothermal energy as a complementary and sustainable resource.

Nigeria, for instance, sits within regions of tectonic and volcanic interest, such as the Benue Trough and parts of the Jos Plateau, which may possess untapped geothermal potential (Onyewuchi et al., 2017). Studies have indicated the presence of hot springs and elevated geothermal gradients in certain areas, suggesting promising conditions for low- to medium-enthalpy applications like direct heating, agricultural processing, and possibly electricity generation in remote communities. Other oil-producing nations are making more progress. Indonesia, for example, is leveraging its volcanic geography to become the second-largest geothermal power producer globally, with more than 2 GW of installed capacity (World Bank, 2021). Similarly, Saudi Arabia has initiated preliminary research into geothermal potential, aligning with its broader Vision 2030 goals to diversify its energy mix (Al-Sharif et al., 2020). The growing interest in geothermal exploration by fossil-fuel-dependent countries highlights a shift toward more resilient and cleaner energy futures.

Future of Geothermal Energy

The future of geothermal energy looks promising, driven by rapid technological advancements and increasing global demand for clean and stable energy sources. One of the most significant innovations is the development of Enhanced Geothermal Systems (EGS). Unlike conventional hydrothermal systems that rely on naturally occurring water and permeability, EGS can create artificial reservoirs by injecting

fluid into hot dry rock formations deep beneath the surface (Tester et al., 2006). This approach expands geothermal potential beyond volcanic or tectonically active regions. Another promising direction is the emergence of hybrid energy systems, which combine geothermal with solar or biomass to improve efficiency and reduce intermittency. These integrated systems offer a steady energy output, especially in areas where one resource alone may be insufficient or variable.

Geothermal energy is also expected to play a growing role in the future energy mix, especially for countries seeking to decarbonize their grids while maintaining a base-load electricity supply. Unlike solar or wind, geothermal can operate continuously, thereby providing a reliable source of clean power regardless of weather or time of day. Moreover, there is an increasing push to integrate geothermal exploration with petroleum geology. Since oil and gas reservoirs and geothermal systems share similar subsurface characteristics, such as heat, rock structure, and fluid flow, existing oilfield data, tools, and expertise can be adapted for geothermal development. Some oil wells that are no longer commercially viable for hydrocarbons could be repurposed for geothermal heat extraction, reducing the cost and environmental impact of exploration (Ghassemi, 2012). In summary, geothermal energy is not just a niche solution. It has the potential to be a cornerstone of sustainable energy development, especially when paired with existing oil and gas infrastructure.

Summary of the Findings

The findings of the study are as summarized as follows:

1. The study found out that**,** viable geothermal systems require co-occurrence of heat, fluid, and permeability. The dominant heat source is crustal radiogenic decay and mantle conduction, with magmatic intrusions critical for high-enthalpy volcanic systems (Moeck, 2014).
2. Furthermore, the study found out that temperature class directly determines viable technology and economics. Misalignment is a leading cause of underperformance.
3. In addition, the study established that integrated exploration reduces drilling risk but does not eliminate it. Greenfield success rates improved from 25% in 2000 to 59% in 2022 where full geoscience integration was applied (Cumming, 2016; IGA, 2022).
4. Conversely, the study established that technology maturity varies by resource type. Flash plants are commercial, binary plants are proven, EGS is pre-commercial.
5. Similarly, the study found out that geothermal has the lowest land use and lifecycle emissions of all dispatchable renewables, with strong local economic benefits.
6. Conclusively, the study found out that high upfront cost, geological uncertainty, technological limitations, social factors, limited accessibility and infrastructure are challenges confronting geothermal exploration and development.

CONCLUSION

Geothermal energy stands out as a reliable and sustainable alternative in the evolving global energy landscape. Its consistent availability, minimal carbon emissions, and adaptability to various environments make it a strong candidate for long-term energy planning. This paper has explored the origin and nature of geothermal energy, the types of geothermal systems, and the techniques used in exploring these resources. Each method, be it geological, geophysical, geochemical, or through exploratory drilling, plays a vital role in locating and evaluating geothermal potential.

RECOMMENDATIONS

Given the growing global demand for sustainable energy alternatives, geothermal energy holds significant promise, particularly for countries seeking to diversify their energy mix beyond fossil fuels. However, for this potential to be fully realised, certain strategic actions must be taken. These recommendations are aimed at addressing current limitations in exploration, development, and policy support while promoting geothermal energy as a viable complement to existing energy systems.

1. Increased Investment in Geothermal Research and Development: Governments, academic institutions, and private companies should prioritise funding for geothermal technologies,

especially Enhanced Geothermal Systems (EGS) and hybrid systems, to improve efficiency and reduce costs.

2. Integration with Oil and Gas Infrastructure: Countries with mature petroleum industries, like Nigeria, should leverage existing infrastructure and subsurface data for geothermal exploration. This reduces initial exploration costs and promotes energy diversification within the petroleum geology field.
3. Policy Support and Regulatory Frameworks: Clear policies and incentives are needed to encourage geothermal development. This includes tax incentives, grants, and streamlined licensing processes that make geothermal projects more attractive to investors.
4. Public Awareness and Education: There should be increased public education and academic integration of geothermal studies, especially in energy and geology-related programs, to build a knowledgeable workforce and create awareness of its benefits.
5. Environmental Monitoring and Sustainability Practices: Exploration and development should always include strong environmental monitoring systems to avoid land degradation, induced seismicity, or water contamination.

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