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An Investigation of Geothermal Energy as a Viable and Sustainable Alternative to Conventional Fossil Fuels

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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. 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*:* Geothermal energy, sustainable energy, sustainable alternative, conventional fossil fuels, geological surveys, geophysical techniques, geochemical analysis, exploratory drilling.

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).
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
The global landscape is facing unprecedented challenges, driven by escalating demand, dwindling fossil fuel reserves, and the pressing need to mitigate climate change (EIA, 2020). Fossil fuels, accounting for approximately 80% of global energy consumption, are major contributors to greenhouse gas emissions and environmental degradation (EIA, 2020). In Nigeria, the reliance on fossil fuels exacerbates energy insecurity, environmental pollution, and health issues (NNPC, 2020). Geothermal energy, a renewable and sustainable alternative, remains underutilized globally, with vast potential in regions like Nigeria (EIA, 2020). This study investigates the viability of geothermal energy as a sustainable alternative to fossil fuels, addressing the challenges, opportunities, and strategies for it adoption, with a focus on Nigeria energy context.

Objectives of the Study
The main aim of this study is to explore geothermal energy as a viable and sustainable alternative to conventional fossil fuels and focuses on how it is discovered and developed. The primary research objectives are:

1. To analyze the source and nature of geothermal energy.
2. To understand temperature classifications of geothermal resources and exploration techniques.

3. To investigate the technological approaches and infrastructure for geothermal development.
4. To explore the environmental and economic benefits of geothermal energy.
5. To examine the challenges and limitations in geothermal exploration and development.
6. To investigate case studies of successful geothermal projects around the world, geothermal potential in Nigeria and other oil-producing nations and future of geothermal energy.

Research Questions

1. What are the sources and nature of geothermal energy?
2. What are the temperature classifications of geothermal resources and the exploration techniques of geothermal energy?
3. What are the technological approaches and infrastructure for geothermal development?
4. What are the environmental and economic benefits of geothermal energy?
5. What are the challenges and limitations in geothermal exploration and development?
6. What are some case studies of successful geothermal projects around the world, geothermal potential in Nigeria and other oil-producing nations and future of geothermal energy?

Significance

This research contributes to the global transition to renewable energy by:

1. Evaluating the potential of geothermal energy in reducing dependence on fossil fuels.
2. Informing policy and investment decisions for sustainable energy development.
3. Enhancing energy security and mitigating climate change impacts (IPCC, 2018).
4. The study contributes to a better understanding of how this energy source can support a more sustainable future.

Scope and Limitations of the Study

Scope

The study focused on geothermal energy as a viable and sustainable alternative to conventional fossil fuels and focuses on how it is discovered and developed. It covers areas such as sources and nature of geothermal energy, temperature classifications of geothermal resources and the exploration techniques of geothermal energy, technological approaches and infrastructure for geothermal development, environmental and economic benefits of geothermal energy, challenges and limitations in geothermal exploration and development, and case studies of successful geothermal projects around the world, geothermal potential in Nigeria and other oil-producing nations and future of geothermal energy.

Limitations

Data availability, site-specific geothermal resource assessment, and technological cost may limit the generalizability of findings.

LITERATURE REVIEW

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).

I. **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).

II. **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).

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).

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:

- 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).
- 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).
- 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:

I. Production wells to extract geothermal fluids
II. Injection wells to return used fluids back to the reservoir
III. Pipelines for fluid transport
IV. Power stations with turbines, condensers, and cooling systems
V. 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 stabilise 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.

Case 1: 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).

Case 2: 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).

Case 3: 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 decarbonise 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

1. The study with respect to research question one found out that, geothermal energy 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).
2. Furthermore, the study with regards to research question two found out that geothermal resources are classified according to temperature; which include Low Enthalpy (Less than 90°C), Medium Enthalpy (90°C to 150°C), and High Enthalpy (Above 150°C). While the exploration techniques include: Geological Surveys, Geophysical Methods, Geochemical Analysis, and Exploratory Drilling.
3. Conversely, the study in respect of research question three found out that the exploration of geothermal energy require the application of technological tools such as power generation technologies which include: dry steam plants, flash steam plants and binary cycle plants, and ground-source heat pump.
4. The study in reverence to the benefits of geothermal energy highlights that, geothermal energy is beneficial to the environment as it has low greenhouse gas emissions, binary geothermal plants release virtually zero emissions during operation (EPA, 2021), geothermal power requires a relatively small land footprint, and geothermal energy is reliable. While on the economic benefits, the study observed that geothermal energy provides long-term cost savings, it promote energy independence, particularly in countries that rely heavily on imported fossil fuels, and it can also spur job creation.
5. With regards to research question five, the study found out that despite its many benefits, the exploration and development of geothermal resources come with distinct challenges such as: high initial costs and financial risk, geological uncertainty, technological limitations, environmental and social concerns, and limited accessibility and infrastructure.
6. Conclusively, the study found out that geothermal energy has seen successful deployment across various countries, demonstrating its viability and long-term benefits. For instance, the case study of Iceland shows that nearly 90% of homes using geothermal energy are successful due to favourable geology and strong government support. While on geothermal potential in Nigeria, the study highlighted that the country sits on 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). While the future of geothermal energy looks promising, driven by rapid technological advancements and increasing global demand for clean and stable energy sources. The study avered that, one of the most significant innovations is the development of Enhanced Geothermal Systems (EGS).

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.

REFERENCES

Al-Sharif, M., Abdullah, K., & Al-Karaghouli, A. (2020). Geothermal energy resources in the Middle East and North Africa (MENA) region: Current status and future prospects. *Renewable and Sustainable Energy Reviews*, *119*, 109566.

Axelsson, G. (2008). *Management of geothermal resources*. Proceedings of the Workshop for Decision Makers on Direct Heating Use of Geothermal Resources in Asia, United Nations University Geothermal Training Programme.

Bertani, R. (2016). Geothermal power generation in the world 2010–2014 update report. *Geothermics, 60*, 31–43.

DiPippo, R. (2012). *Geothermal power plants: Principles, applications, case studies and environmental impact* (3rd ed.). Butterworth-Heinemann.

DOE Philippines. (2021). *National geothermal energy development roadmap*. Department of Energy, Republic of the Philippines.

EIA (2020). Energy Efficiency Market Report

Gehringer, M., & Loksha, V. (2012). *Geothermal handbook: Planning and financing power generation*. Energy Sector Management Assistance Program (ESMAP), World Bank.

Ghassemi, A. (2012). A review of some rock mechanics issues in geothermal reservoir development. *Geotechnical and Geological Engineering*, *30*, 647–664.

Glassley, W. E. (2014). *Geothermal energy: Renewable energy and the environment* (2nd ed.). CRC Press.

Hochstein, M. P. (1990). Classification and assessment of geothermal resources. In *High enthalpy geothermal systems* (pp. 31–59). UNITAR/UNDP.

International Renewable Energy Agency (IRENA). (2020). *Geothermal power: Technology brief*.

IPCC (2018). Special Report on Global Warming of 1.5°C.

Manzella, A., Allansdottir, A., Pellizzone, A., & Bortolotti, M. (2018). Geothermal energy and the public: A case study on deliberative citizens' engagement in central Italy. *Energy Policy, 116*, 352–365.

Massachusetts Institute of Technology (MIT). (2006). *The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century*.

NNPC (2020). Nigerian National Petroleum Corporation Annual Report.

Onyewuchi, O. I., Okonkwo, V. N., & Iwuagwu, C. J. (2017). Potentials and development of geothermal energy in Nigeria. *Nigerian Journal of Technology, 36*(1), 288–293.

Orkustofnun – National Energy Authority of Iceland. (2022). *Geothermal development in Iceland*.

Ussher, G., Harvey, C., Johnstone, R., & Anderson, E. (2000). Understanding the resistivities observed in geothermal systems. *Proceedings of the World Geothermal Congress 2000*, Kyushu–Tohoku, Japan, 1915–1920.

World Bank. (2014). *Global geothermal development plan: Resource risk mitigation for geothermal projects*.

Zarrouk, S. J., & Moon, H. (2014). Efficiency of geothermal power plants: A worldwide review. *Geothermics, 51*,