

Geothermal Energy in Kenya: A Sustainable Solution for Lowering Carbon Footprints and Addressing Global Climate Challenges

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Keywords

Geothermal energy, Climate change, Carbon emissions, Carbon footprints.

ABSTRACT

The urgent need for sustainable energy sources to mitigate climate change has propelled the exploration of low-carbon alternatives, with geothermal energy emerging as a promising solution. Kenya stands as the world's sixth-largest geothermal energy producer with estimated production of over 985MW in 2023. The role of geothermal energy in lowering carbon footprint in Kenya, as well as the challenges and opportunities in geothermal energy utilization, are evaluated by conducting a comprehensive review of literature on energy production statistics, and government reports. Electricity production data indicates that geothermal energy is capable of displacing fossil fuels and complement other intermittent renewables due to its reliability as a baseload electricity source. Additionally, geothermal energy has low life-cycle emissions hence a great potential to avoided emissions of up to 3.9 million metric tons CO₂ equivalent annually. While the uncertainty nature of the resource and the prevailing competition from fossil fuels pose challenges to the development of the geothermal resources in the country, the ongoing public-private partnerships (PPPs) initiatives and the recent adoption of electric vehicles present significant opportunities for geothermal utilization. The study underlines the critical role of geothermal energy in Kenya's energy sector and its potential to mitigate climate change, while providing policymakers, energy stakeholders, and investors with valuable insights to prioritize geothermal energy development and achieve emissions reduction targets.

1. INTRODUCTION

Climate change has become one of the most pressing challenges facing humanity today and is driven primarily by the accumulation of greenhouse gases (GHGs) in the atmosphere. The burning of fossil fuels for energy production, transportation, and industrial processes is the largest contributor to these emissions. To mitigate climate change and its associated impacts, there has been a global consensus on the urgent need to transition to renewable energy sources. Renewable energy technologies, such as solar, wind, hydroelectric, and geothermal power, offer significant potential for reducing GHG emissions and curbing global warming. These sources of energy are abundant, widely distributed, and can be replenished naturally, making them sustainable alternatives to fossil fuels, Jones and Tait (2023).

Numerous studies and reports have highlighted the role of geothermal energy in combating climate change by providing clean, low-carbon electricity, heating, and transportation options. Unlike fossil fuels, which release harmful GHGs such as carbon dioxide (CO₂) when burned for energy production, geothermal energy emits minimal to no GHGs during operation. This characteristic makes geothermal energy a crucial component of efforts to transition towards a low-carbon economy and reduce dependence on fossil fuels. Globally, geothermal energy is increasingly recognized as a sustainable alternative to traditional energy sources by offering reliable and environmentally friendly electricity generation with minimal environmental impact, Jones and Tait (2023).

In Kenya, geothermal energy represents a largely untapped resource with substantial potential for development and utilization. The country's geothermal potential is estimated to be over 10,000 megawatts (MW), Ministry of Energy and Petroleum (2023). Most of this potential remains untapped, thus it presents a significant opportunity for Kenya to further expand its geothermal capacity and accelerate its transition towards a low-carbon economy. The Olkaria and Menengai geothermal fields are particularly promising, with high-temperature reservoirs capable of supporting large-scale geothermal power generation projects. Kenya's installed geothermal capacity has been steadily increasing over the years, with great support from the government, private sector investment, and international partnerships. As of 2023, the country's installed geothermal capacity was 985 MW, bringing Kenya to the sixth position on the top 10 geothermal energy producers globally Cariaga (2024).

To further boost its geothermal potential and enhance its role in climate change mitigation, the country has put in place various initiatives and ambitions to accelerate geothermal resource utilization. These include government-led efforts to streamline regulatory frameworks, attract investment, and facilitate private sector participation in geothermal development projects. Additionally, partnerships with international organizations and financial institutions have been established to support the financing and implementation of geothermal energy initiatives in Kenya, Ministry of Energy and Petroleum (2023). With ambitious targets set to increase geothermal capacity to 1.6GW by 2030, Kenya is prepared to play a significant role in advancing geothermal energy as a sustainable solution for climate change mitigation and energy security, Burkhardt and Herbling (2021); Krebs (2022).

2. LITERATURE REVIEW

The sources of Kenya's CO₂ emissions in the energy sector are primarily attributed to the burning of fossil fuels for energy production, industrial activities, and other processes. According to Ritchie (2020), the largest source of CO₂ emissions in energy and industry sector in 2022 was oil, accounting for 70% of the total CO₂ emissions from fuel combustion. This indicates a heavy reliance on oil-based fuels for energy generation and transportation, contributing significantly to the country's carbon footprint.

The Climate Action Tracker (CAT) highlights that Kenya's energy sector plays a crucial role in CO₂ emissions mitigation, CAT (2022). While the country has made strides in incorporating renewable energy sources like wind power, a portion of electricity generation still relies on thermal plants, which accounted for 12.5% of electricity generated in 2022, Economic survey (2023). However, the government of Kenya's goal of entirely transitioning to green energy by 2030 is still achievable.

The need to transition to sustainable energy sources stems from the coupled challenges of environmental degradation, energy security, and global climate change. Fossil fuel combustion, the primary source of energy in most parts of the world, releases GHGs into the atmosphere, leading to global warming and climate change, Kabeyi and Olanrewaju (2022). The negative impacts of climate change, such as more frequent and severe extreme weather events, rising sea levels, and

disruptions to ecosystems and food systems, highlight the critical need to shift towards low-carbon energy alternatives, Lv (2023).

Climate change can be mitigated by reducing GHG emissions, especially from the energy sector, which accounts for 75% of the global emissions, UNDP (2023). Sustainable energy sources, such as renewable energy technologies, offer a pathway to decarbonizing the energy sector while meeting the growing energy demand. Unlike fossil fuels, renewable energy sources like solar, wind, hydroelectric, and geothermal power generate electricity with minimal emissions of GHGs and air pollutants, Moomaw et al (2011).

3. METHODOLOGY

The research adopted a multi-faceted approach to gather and analyze data related to the role of geothermal energy in reducing carbon footprints in Kenya. The primary methods employed involved reading through academic papers, journal articles, books, conference proceedings, and relevant reports from reputable sources. The literature review provided a foundation for understanding the current state of knowledge, key concepts, trends, and challenges in geothermal energy development and its impact on carbon emissions reduction.

Data on energy production, consumption, and associated carbon emissions were obtained from official sources, such as government agencies, energy regulatory bodies (e.g the Kenya National Bureau of Statistics (KNBS)), international organizations such as the United Nations Development Programme (UNDP), Intergovernmental Panel on Climate Change (IPCC) and Our World in Data. Avoided emissions were calculated using The Greenhouse Gas Equivalencies Calculator by the United States Environmental Protection Agency (EPA). Comparative analysis helped in assessing the relative carbon intensity of geothermal energy compared to other sources, such as fossil fuels and renewable energy alternatives.

Qualitative and quantitative data were integrated and synthesized to provide a comprehensive analysis of the role of geothermal energy in lowering carbon footprints in Kenya. The synthesized data are presented through narrative descriptions and graphical representations to facilitate understanding and interpretation. Findings from the literature review, energy production statistics analysis, and government reports review were compiled to validate the conclusions.

4. RESULTS AND DISCUSSION

4.1 Contribution of geothermal energy to lowering carbon footprint

4.1.1 Displacing fossil fuels

Geothermal energy has played a crucial role in displacing fossil fuels (thermal) in electricity generation as illustrated on Figure 1. Prior to the expansion of geothermal capacity, Kenya heavily relied on imported fossil fuels to generate electricity. Oil-fired power plants were often used as backup or peaking plants to meet electricity demand during periods of high consumption or when hydroelectric generation was insufficient. Geothermal energy has recently become a key pillar of Kenya's energy strategy, with a current production of 5.59 TWh of electricity which accounted for 43.6% of the nation's electricity production in 2022, Ritchie and Rosado (2020); Economic survey (2023). Geothermal energy serves as a reliable source of baseload power by operating continuously and independently of weather conditions. This baseload capacity has allowed geothermal power plants to replace fossil fuel-fired plants which were previously relied upon for providing stable electricity supply. This shift has not only reduced CO₂ emissions but has also eliminated pollutants and GHG emissions into the atmosphere.

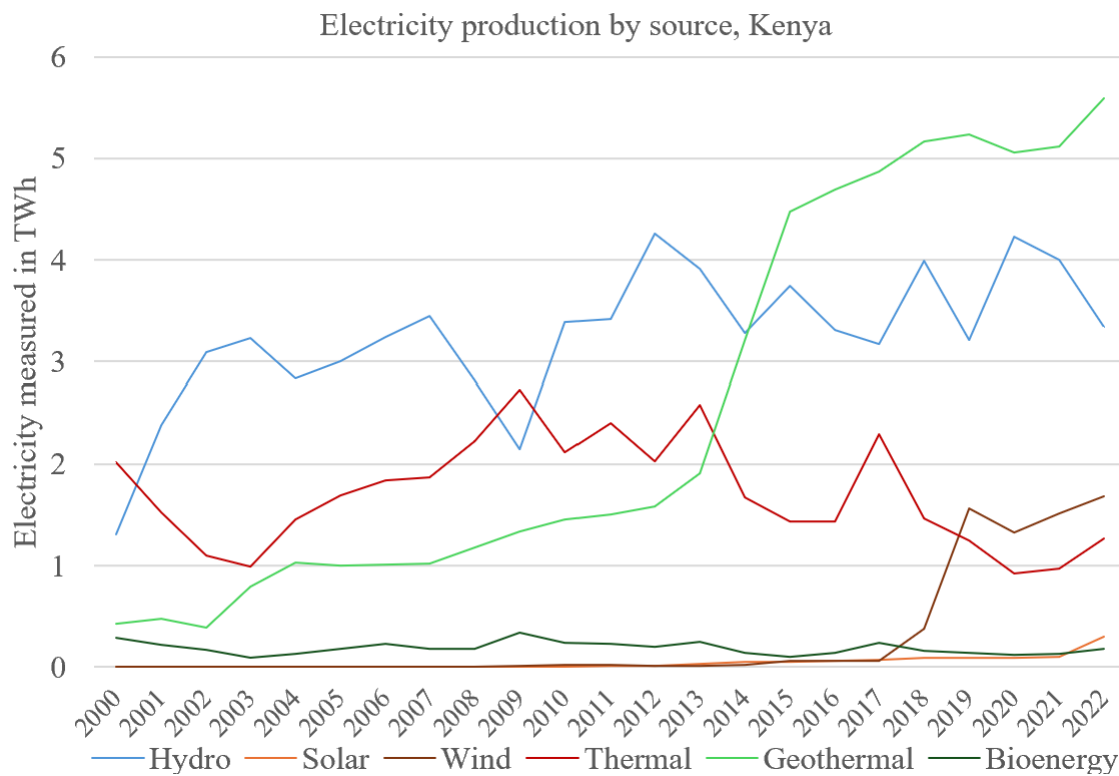


Figure 1: Electricity production by source in Kenya.

Data source: Ritchie and Rosado (2020); Ember - Yearly Electricity Data (2023); Ember - European Electricity Review (2022); Energy Institute -Statistical Review of World Energy (2023)

4.1.2 Complementary role with intermittent renewables

The variability of renewable energy sources like wind and solar can pose challenges for grid stability and management. Geothermal energy, with its stable and predictable output, complements intermittent renewables by providing a reliable source of power that helps stabilize the grid. Geothermal energy can fill the generation gap when renewable sources are not producing electricity due to weather fluctuations. During periods of low wind or solar generation, geothermal power plants can step up production to meet electricity demand, thus ensuring a consistent and reliable power supply. Additionally, hydropower is often subject to seasonal variations in water availability, with higher generation during the wet seasons and lower generation during the dry seasons. Geothermal energy, on the other hand, is not affected by seasonal changes and provides stable generation throughout the year. By reducing the need for backup fossil fuel generators to balance supply and demand fluctuations, geothermal energy indirectly avoids emissions associated with the inefficient operation and curtailment of fossil fuel-based plants, Jefferson et al (2021).

4.1.3 Low life-cycle emissions

Life-cycle emissions, in the context of energy production, refers to the total amount of GHG emissions associated with the entire lifecycle of a particular energy source or energy production process, typically measured in units of carbon dioxide equivalent (CO₂e) per defined function or unit of electricity produced source, NREL (2013). This includes both direct and indirect emissions generated during extraction, processing, transportation, combustion, and disposal of waste. Geothermal energy has relatively low life-cycle emissions compared to other sources of energy like fossil fuels since it does not involve combustion but relies on natural heat from the Earth's interior. While, some emissions may still occur during the drilling process, fluid handling, and power plant

construction, they are significantly lower levels than those associated with fossil fuel-based power generation, Bates (1996); NREL (2013).

Globally, geothermal energy is ranked sixth on the World Nuclear Association Average life-cycle CO₂ equivalent emissions (World Nuclear Association, 2022). Geothermal has the third lowest CO₂e in Kenya, after wind and hydro. While hydropower is considered a renewable energy source with low emissions, its environmental impact can vary depending on factors such as reservoir size, land use changes, and ecosystem disruption. Wind energy has relatively low CO₂e but it is intermittent and dependent on weather conditions. This therefore makes geothermal a preferred option for mitigating carbon footprints.

Oil-fired power plants emit the highest CO₂ and other pollutants, with global average CO₂e of 970g/kWh, while the estimated geothermal energy's average life cycle is CO₂e 38g/kWh. By replacing these carbon-intensive fuels with clean and renewable energy, Kenya has significantly reduced GHG emissions which are associated with fossil fuel combustion. Comparative analyses of the CO₂e per electricity source shows that geothermal energy offers a substantial reduction in carbon emissions compared to fossil fuels as shown on Figure 2 (World Nuclear Association, 2022).

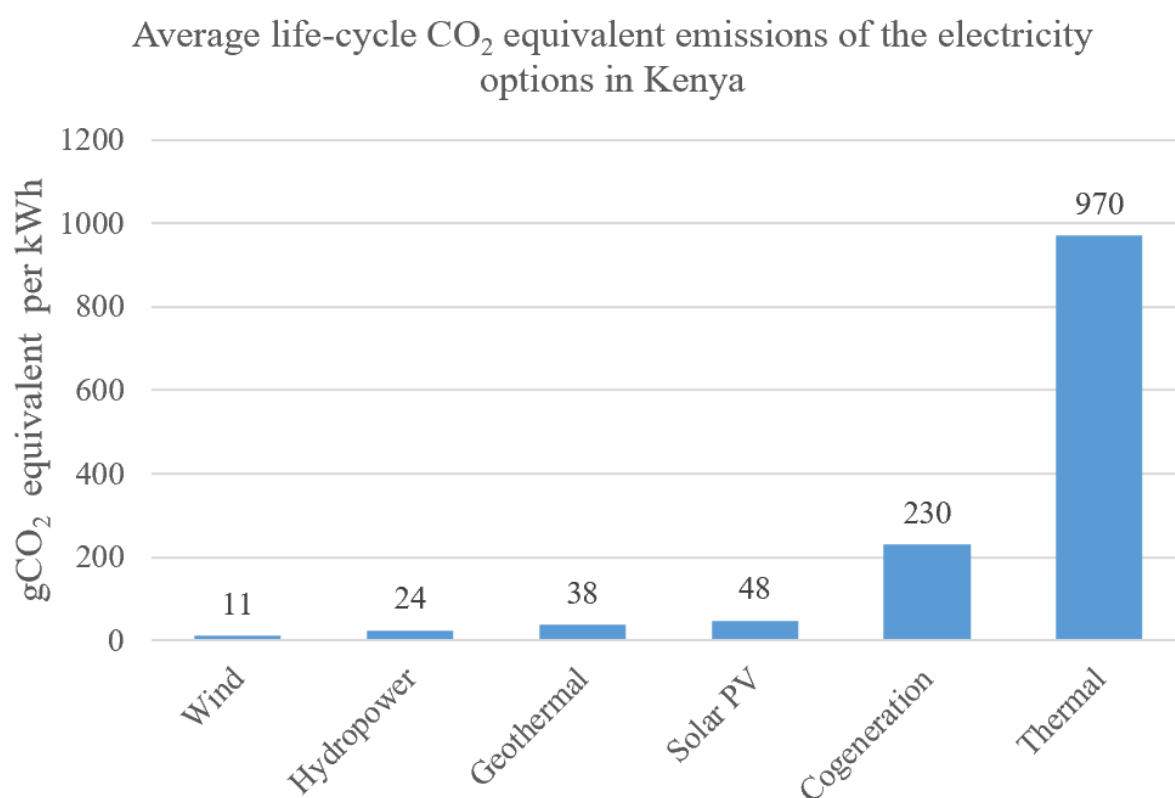


Figure 2: Average life-cycle CO₂ equivalent emissions of the various electricity sources in Kenya.

Data source: World Nuclear Association (2022); Smoot (2024)

4.1.4 Emissions avoidance potential

The use of geothermal energy in Kenya has resulted in significant emissions avoidance, primarily by displacing the need for fossil fuel-based power generation. Based on the EPA-Greenhouse Gas Equivalencies Calculator, it is estimated that every kilowatt-hour (kWh) of energy produced from energy efficiency or renewable energy programs can avoid emitting 0.007 metric tons of CO₂

equivalent into the atmosphere, EPA (2023). Figure 3 shows that the utilization of geothermal resource between 2000 and 2022 has avoided a total of 40.8 million metric tons of CO₂ emissions. In 2022 alone, 3.9 million metric tons of CO₂ emissions were avoided. This is equivalent to CO₂ emissions avoided from consuming 308,000 gallons of petrol or burning 300,000 pounds of coal. Oil and coal are still by far the biggest emission emitters in the energy and production sectors in Kenya. By generating electricity from geothermal resources, Kenya can avoid the release of large quantities of CO₂ into the atmosphere, thereby mitigating climate change impacts and contributing to global efforts to reduce GHG emissions.

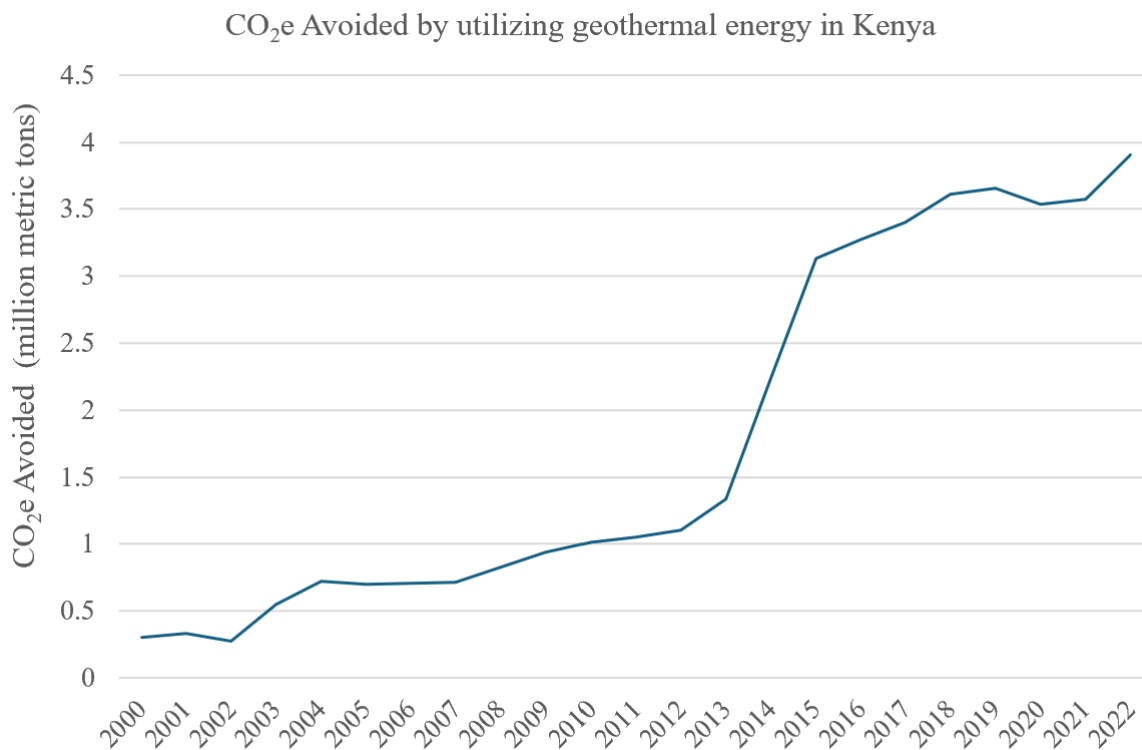


Figure 3: Annual avoided CO₂e from the utilization of geothermal energy

4.1.5 Direct use applications

Direct use applications of geothermal energy in Kenya include various sectors such as agriculture, aquaculture, and industrial processes. For instance, farmers have been utilizing geothermal heat to dry pyrethrum flowers at Eburru. The Oserian Development Company in Naivasha uses geothermal energy to heat greenhouses for cut roses export. Additionally, the Olkaria geothermal spa and a tourist hotel at Lake Bogoria utilize geothermal waters for spa pools. Recent additions in direct use applications are the milk pasteuriser and grain dryer in Menengai which use geothermally heated water for industrial processes, (Mburu, 2022). These applications demonstrate the diverse uses of geothermal energy beyond electricity generation. The shift towards utilizing geothermal energy directly not only reduces the dependence on imported fuels but also eliminates pollutants and GHG emissions into the atmosphere. This therefore contributes to economic development and environmental sustainability, Kanna (2024).

4.1.6 Low land use impacts

Geothermal energy production primarily involves drilling wells to access hot underground reservoirs and installing surface infrastructure such as power plants, pipelines, and transmission lines. After the cessation of geothermal operations, sites are rehabilitated and restored to their natural state relatively easily. For example, wells can be plugged, and surface infrastructure such as pipes can be removed to allow the land to recover and regenerate naturally. While this may result in some

surface disturbance, the overall impact on land is minimal compared to activities such as mining or the extensive deforestation associated with fossil fuel extraction and infrastructure. Extensive deforestation is a significant contributor to carbon emissions, primarily through the release CO₂ stored in trees and soil. In addition, fossil fuel extraction has long-term environmental impacts which may result in permanent habitat destruction and landscape alteration. Moreover, geothermal power plants typically have a relatively small land footprint compared to other renewable energy sources such as solar and wind. Solar farms and wind turbines require clearance of large expanses of land for installation. Such land use changes result to loss of carbon sinks due to deforestation which in turn reduce the Earth's capacity to remove CO₂ from the atmosphere, Richter (2021).

Additionally, geothermal exploration activities can often coexist with other land uses, such as forestry and conservation areas. For example, the Olkaria geothermal field co-exists with the Hell's gate national park. This has allowed for the simultaneous use of land for energy production and other purposes consequently minimizing conflicts over land use. Such simultaneous use of land aligns very well with Kenya's commitment to sustainable development and environmental conservation through the adoption of clean energy solutions like geothermal power.

4.2 Challenges of geothermal exploitation

4.2.1 Localized nature of geothermal resources

Geothermal energy extraction relies on the presence of high-temperature reservoirs of steam or hot water beneath the Earth's surface. These reservoirs are often localized and confined to specific geological characteristics, such as tectonic plate boundaries, volcanic activity, or geothermal gradients, Uzelli et al (2024). In Kenya for example, the geothermal resource is confined along the Kenyan Rift System, with only three (Olkaria, Menengai and Eburru) of the 23 prospects being under active exploitation. As a result, there is uneven distribution of direct use applications of geothermal in the country since not all regions have suitable geological conditions for harnessing geothermal energy. This presents a significant barrier to the widespread adoption of geothermal energy in the country.

4.2.2 Geological uncertainty and exploration risks

Unlike some other renewable energy sources such as wind or solar, geothermal resources are not readily visible on the Earth's surface. Geothermal exploration involves probing deep beneath the Earth's surface to identify and characterize underground reservoirs of hot water or steam. The subsurface geology is often complex and heterogeneous, with variations in rock type, structure, and permeability that can influence the distribution and behaviour of geothermal fluids. Understanding these subsurface conditions involves siting suitable exploration drilling targets and making accurate predictions about reservoir properties (e.g., temperature, depth, permeability). Careful interpretation of geological data and models is also very crucial. However, the success of exploration efforts is not guaranteed, and there is always a degree of uncertainty regarding the presence, size, and productivity of geothermal resources. Additionally, exploration drilling is costly and carries the risk of encountering dry or unproductive wells, leading to financial losses for developers, International Geothermal Association (2014).

4.2.3 Competition with fossil fuels

Competition with fossil fuels presents a significant challenge to the widespread adoption and commercial viability of geothermal energy. Fossil fuel industries for example, often benefit from government subsidies, tax breaks, and incentives that artificially lower their production costs and make them more competitive in the energy market, Black et al (2023). Additionally, the low cost of fossil fuels is partly attributed to their abundance and accessibility, as well as existing infrastructure for extraction, transportation, and storage. In contrast, geothermal energy does not receive the same level of support or preferential treatment, thus limiting its ability to compete on price. Besides, the

higher upfront costs for geothermal development can make it less attractive to investors and utilities seeking immediate returns on investment. Without adequate policy support and financial incentives, geothermal projects struggle to attract investment and achieve economies of scale.

4.2.4 Specialized knowledge and skills

Geothermal development requires a diverse range of specialized knowledge and skills across multiple disciplines, including geology, geophysics, reservoir engineering, drilling engineering, and power plant operations. Acquiring and maintaining expertise in these specialized areas can be challenging due to the complexity and interdisciplinary nature of geothermal projects. Developing technical skills requires comprehensive training programs, educational resources, and hands-on experience opportunities. However, many educational institutions and training facilities lack specialized geothermal programs or curricula, limiting the availability of formal training opportunities for aspiring geothermal professionals.

4.3. Opportunities for geothermal exploitation/utilization

4.3.1 Increasing electricity demand

Kenya's electricity demand has been steadily increasing due to population growth, urbanization, and economic development. As the demand for electricity continues to rise, there is a need to diversify the country's energy sources to ensure energy security and meet growing demand, Takase (2021). This provides an opportunity for the country to utilize its energy resources for electricity generation and meet the growing demand, since only 985 MW of the estimated 10,000 MW geothermal resource has so far been exploited.

4.3.2 Local economic development

The development of geothermal energy in Kenya has the potential to drive local economic development by creating jobs, stimulating investment, and encouraging the growth of supplementary industries and services. Geothermal projects require a range of skilled and semi-skilled workers, from geologists and engineers to drillers and technicians, hence providing employment opportunities for local communities, Krebs (2022). Additionally, the development of geothermal infrastructure, such as roads, transmission lines, and power plants, can spur economic activity and support local businesses.

4.3.3 Public-private partnerships (PPPs)

The government has actively promoted public-private partnerships (PPPs) to accelerate geothermal development and influence private sector expertise and resources. Through PPPs models, the government can collaborate with private companies, international organizations, and multilateral institutions to finance, develop, and operate geothermal projects. PPPs enable the sharing of risks and responsibilities between public and private entities to control public funds and attract private investment and expertise, and to facilitate the transfer of technology and best practices, Ministry of Energy and Petroleum (2023).

4.3.4 Adoption of electric vehicles (EVs)

As the world is transitioning towards a new era of electric vehicles (EVs), the government of Kenya is also making strides to be counted among the many. A range of policies have been put in place to promote the adoption of EVs. As of 2023, there were several public transport busses, private vehicles, and motorcycles on the Kenyan roads, Njanja, (2023). Additionally, EVs are increasingly being adopted by businesses and organizations in Kenya. The government's main goal is to expand the ownership of EVs to 5% of all registered vehicles in Kenya by 2025, Wachira (2022). This widespread adoption of EVs will lead to an increase in electricity demand as these vehicles need to

be charged. This increased demand for electricity presents an opportunity for Kenya to expand its power generation capacity, including tapping into its abundant geothermal resources.

5. CONCLUSION

In conclusion, Kenya's ambitious targets for increasing renewable energy capacity align with its commitment to climate change mitigation and sustainable development. Geothermal energy emerges as a pivotal solution in Kenya's quest for sustainable energy sources to combat climate change. With its significant role in electricity production and low carbon footprint, geothermal energy showcases immense potential in reducing GHG emissions and promoting environmental sustainability. Besides electricity production, geothermal energy can be used for direct industrial applications, such as industrial process heat to displace fossil fuel-based heat sources and contribute to industrial decarbonization.

Despite challenges related to the uncertainty nature of the resource, competition from fossil fuels, and specialized knowledge concerns, the ongoing PPPs initiatives and the increasing adoption of electric vehicles present promising opportunities for the further utilization of geothermal resources in Kenya.

The findings of this study emphasize the critical importance of geothermal energy in Kenya's energy landscape and its role in mitigating climate change. By evaluating the challenges and opportunities associated with geothermal energy utilization, this research provides valuable insights for policymakers, energy stakeholders, and investors to strategize and prioritize efforts towards the development of this sustainable energy. Furthermore, the identification of geothermal energy as a key contributor to emissions reduction highlights its significance in achieving Kenya's climate goals and fostering a transition to a low-carbon economy.

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