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# THE ROLE OF GEOTHERMAL IN ENERGY MIX: KENYA'S CASE STUDY

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## ABSTRACT

An energy mix is a combination of various primary energy sources used to meet the energy needs of a given country. The energy mix can comprise renewable and fossil fuel energy sources. Efforts to address energy sustainability, reduce greenhouse gas (GHG) emissions and address the climate change challenge have made renewable energy sources (RES) a critical component in the world energy mix. Renewable energy resources are defined as dispatchable or non-dispatchable. Non-dispatchable renewable energy sources, such as wind and solar, are variable and heavily dependent on weather conditions. On the other hand, dispatchable sources, for example, geothermal, hydropower, and biomass, are demand-following. Power systems rely on both dispatchable and non-dispatchable energy sources for electricity supply. The dispatchable renewable sources and fossil fuel power plants provide baseload and peaking services. An increase in the share of non-dispatchable sources in the power generation mix significantly affects the power system's stability and flexibility. Using Kenya's case study, this paper reviews the role of geothermal power generation in the energy mix. The review focuses on the role of geothermal in enhancing grid stability and flexibility while accounting for affordability and reduction in GHG emissions. The deductions indicate that, owing to its high inertia and dispatchability, geothermal generation guarantees more grid stability and flexibility than intermittent renewable sources. Unlike variable renewable sources, geothermal energy is independent of weather changes and has higher capacity factors, thus, can provide baseload power supply, displacing fossil fuel-based baseload generation and reducing GHG emissions. Therefore, in countries where the geothermal resource is proven and the lifetime cost is comparatively cheaper than non-dispatchable renewable sources, for instance, as in Kenya, it is prudent to prioritize geothermal development instead of variable sources for the central grid-supplied power.

## 1. INTRODUCTION

Energy is central to addressing the sustainable development goals (SDGs) challenges, including poverty eradication, gender equality, climate change-related risks, food security, quality health services, quality education, and jobs (United Nations, 2018); thus, the sustainable development goal (SDG) number seven of universal access to affordable, reliable, sustainable, and modern energy services by 2030 (United Nations, 2020). On the other hand, energy-related activities, such as electricity generation from fossil fuels, oil and gas production, and building heating and cooling, account for 25% of the greenhouse gas

(GHG) emissions from anthropogenic activities (IPCC 2014). Still, the global energy demand is projected to grow significantly in the coming decades (IEA, 2021). A large percentage of this growth is projected to be in the Sub-Saharan African (SSA) countries, resulting from the region's forecast rapid population growth (Hoornweg and Pope, 2017), economic development, and accelerated urbanization (Angel et al., 2011).

Various countries rely on a combination of primary energy resources to meet their current and forecast energy consumption needs. Such a combination is referred to as the energy mix. The energy mix can be a combination of both renewable and fossil fuel energy sources (Vidal-Amaro et al., 2015). Renewable energy sources in an energy mix of a country could be made up of solar photovoltaic energy, solar-thermal energy, tidal power, urban solid waste, hydropower, biofuels, and geothermal sources (Edenhofer et al., 2013).

Renewable energy sources can be classified as dispatchable or non-dispatchable. Dispatchable renewable energy sources, for example, hydropower and geothermal, are load-following. Their power generation can be adjusted according to demand. Contrarily, non-dispatchable renewable sources, such as wind and solar, cannot (or have limited ability to) adjust their power output to match electricity demand, as they are weather-dependent (Baroni, 2022). Fossil fuel sources include coal, liquefied petroleum gas (LPG), natural gas, diesel and shale oil, and heavy fuel oil (HFO). To chart low-carbon power development pathways to achieve SDG number seven and thirteen, the global community, mainly developed economies, have aligned their energy policies towards the accelerated development of renewable energy sources (Abdmouleh et al., 2015).

Geothermal energy is one of the renewable resources targeted for deployment to achieve the low-carbon power development pathway. Geothermal energy comes from the heat in the earth's sub-surface, primarily produced by the decay of the naturally radioactive isotopes of uranium, thorium, and potassium (WEC, 2013). The heat is contained in the rocks and fluids beneath the earth's crust and can be found as far down as the earth's hot molten rock, magma (Conserve Energy Future, 2013). The earth's average geothermal gradient is 25-30°C/km (WEC, 2013). Different authors estimate different geothermal electricity potentials. The estimates range from a minimum of 35 GWe to a maximum of 2000 GWe (Sarmiento and Steingrímsson, 2007).

Most geothermal exploration and use occur where the gradient is higher at a shallower depth, thus, shallower drilling and less cost (WEC, 2013). The causes of shallow-depth geothermal resources include high surface heat flow due to a thin crust, high-temperature gradient, and intrusion of molten rock from depth. Such activities result in heating groundwater that has circulated to several kilometers' depth, which then rises to the near-surface (WEC, 2013). Due to the high cost of exploiting geothermal resources, only those at shallow depths are exploited. As such, the feasibility of geothermal resources is site-specific and is controlled by the geological setting of a given area. Therefore, economically feasible geothermal resources are found in limited places on earth, for instance, rift zones.

Geothermal energy has been in existence for billions of years. However, geothermal energy utilization began about 10,000 years ago (Conserve Energy Future, 2013), starting with the Paleo-Indians, who used the hot springs and natural pools for cooking, bathing, and warming. The world's first district heating system was installed at Chaudes-Aigues, France, in the 14th century. The first industrial use of geothermal energy began near Pisa, Italy, in the late 18th century, where geothermal steam was used to extract boric acid in Larderello fields. The first geothermal electric power generation took place in Larderello, Italy, in 1904 by Italian scientist Piero Ginori Conti. By December 2021, geothermal energy had an installed capacity of 16 GW used as a direct heat source and for electricity generation (IRENA, 2022).

So far, geothermal energy is still a marginal player in the energy mix, providing a little over 1% of the worldwide power demand and about 3% of the heat demand (GEO-ExPRO, 2018). On the other hand, there is substantial geothermal potential in the earth's sub-surface, which provides an opportunity to utilize geothermal energy as a cleaner alternative to fossil fuels. With increased reliance on variable renewable sources like wind and solar and rampant grid stability issues relating to their intermittency, the time could now be suitable for the wider-scale adoption of geothermal resources for heat and electricity generation.

Kenya is one of the SSA countries yet to achieve universal access to modern energy services, with an electricity connection rate of 75%. Furthermore, Kenya's energy demand is projected to grow tremendously in the coming years. The growth relates to economic growth, increased rate of urbanization, infrastructural development, and improved living standards for its citizens in the Vision 2030 blueprint (GoK, 2020). Under the Vision 2030 blueprint, energy demand is projected to grow from 13,676 GWh in 2020 to 117,576 GWh in 2045 (Musonye et al., 2021). The government intends to meet the demand using an energy mix comprising renewable and fossil fuel energy sources (EPRA, 2018). The intended energy mix includes coal, natural gas, diesel, geothermal, hydropower, wind, and solar.

Kenya is a signatory to the global effort to reduce GHG emissions and address climate change. Through its Nationally Determined Contribution (NDC) report submitted to the United Nations Framework Convention on Climate Change (UNFCCC), Kenya has committed to cutting GHG emissions from the electricity sector by 30% by 2030 compared to the 2010 emissions (MoENR, 2017). Therefore, the Kenyan government has to meet the forecast energy demand while limiting GHG. Kenya's power generation mix currently comprises 838 MW of hydropower, 954 MW of geothermal, and 435 MW of wind, while solar power generates 170 MW of the installed capacity. Thermal generation, mainly powered by HFO, gasoil, and kerosene, has a 646 MW capacity. In this paper, we explore the role of geothermal energy in the energy mix regarding SDG number seven and thirteen using Kenya as the case study. The remaining part of this paper will cover a detailed overview of Kenya's energy status in Chapter 2, geothermal development in Kenya in Chapter 3, discussion in chapter 4 and conclusion and recommendation in Chapter 5.

## 2. KENYA'S ENERGY STATUS

Kenya's energy demand is generated from oil-based generators and renewable energy sources. Currently, renewable sources account for 87% of the total energy consumed in Kenya. Kenya still has enormous potential for fossil fuel and renewable energy resources yet to be exploited.

### 2.1 Hydropower

Kenya has considerable hydropower potential estimated to range between 3,000 to 6,000 MW. Only 838 MW has been developed, mainly in large installations owned by KenGen PLC. It is estimated that the undeveloped hydroelectric power potential of economic significance is 2,400 MW. This hydropower potential is drawn from the country's five major drainage basins of Tana River, Lake Victoria, Athi River, Rift Valley, and Ewaso Ng'iro. By December 2021, the developed hydropower capacity accounted for 27% of the national installed grid capacity.

### 2.2 Geothermal

Geothermal power has been identified as a cost-effective power option in Kenya's least cost power development plan (LCPDP). Conservative estimates suggest that the total national geothermal potential along the Kenyan Rift range between 7,000 and 10,000 MW. Currently, geothermal is the single largest generation source for grid-connected electricity in Kenya, providing 954 MW. The rise in installed geothermal capacity follows the commissioning of Olkaria I additional unit 6 in July 2022, injecting an additional 86 MW into the national grid. Geothermal provides nearly 31% of the grid-installed capacity and about 80% of the power consumed in the country as of December 2021.

## 2.3 Wind

Kenya has one of Africa's most promising wind generation potentials, with excellent wind speeds of 6 m/s and above (Kazimierczuk, 2019). The most recent development in wind energy in Kenya is the 310 MW Lake Turkana Wind Power Project in Marsabit County, the single largest wind farm on the continent. There is also the 100 MW Kipeto wind farm and 25 MW Ngong wind farm. It is estimated that the undeveloped technical wind power potential is 4,600 MW. Several other wind projects are in the early planning stages and are expected to see a breakthrough soon. These include Isiolo (100 MW), Meru (60 MW), Ngong (51 MW), and the Baharini Electra Wind Farm project in Lamu (90 MW). The developed wind power contributed about 14.3% of the grid-connected installed capacity as of August 2022.

## 2.4 Solar

The strategic location of Kenya near the equator makes it one of the regions with great potential for the use of solar energy throughout the year. The levels of insolation range between 4-6 kWh/m$^2$/day (EPRA, 2018). The estimated technical potential of solar energy is 70,000 MW. So far, by August 2022, Kenya had a grid-connected solar capacity of 170 MW. The government aims to install an additional 500 MW and 300,000 home solar systems by 2030.

## 2.5 Coal

Coal is one of Kenya's fossil fuel resources for extraction and potential use in power generation. Kenya has an estimated potential of 9.5 GW of coal resources (Musonye et al., 2021). However, coal-based power generation has not been deployed in Kenya to date. Local coal reserves are found in Mui Basin, which runs across Kitui County, approximately 200 kilometers east of Nairobi. The coal basin stretches across an area of 500 km$^2$ and is subdivided into four blocks: Zombe-Kabati, Itiku-Mutitu, Yoonye-Kateiko, and Isekele-Karunga (Kahlen et al., 2019). The coal has been analyzed and ranges from lignite to sub-bituminous coal, with calorific values ranging between 16-27 MJ/kg. The government plans to use coal to meet future energy needs. The planned development of a 981 MW coal plant in Lamu was put on hold after environmental advocates filed an injunction against its development. There are no known quantities of commercial oil and natural gas deposits, although the prospecting process is underway at different stages.

# 3. GEOTHERMAL DEVELOPMENT IN KENYA

Kenya's geothermal resources are mainly located within the Kenyan rift. The latter is part of the eastern branch of the East African Rift System (EARS) that runs from the Red Sea to Beira in Mozambique. Geothermal development in Kenya typically encompasses six key steps: (a) project definition and reconnaissance evaluation; (b) detailed geoscientific exploration; (c) exploration drilling and delineation; (d) resource analysis and assessment of development potential; (e) field development; and (f) steam production and field management. Exploration for geothermal energy resources in Kenya started in the early 1950s. The exploration identified several areas suitable for geothermal prospecting (Figure 1). So far, production drilling has taken place only in Olkaria, Eburru, Menengai, and Paka geothermal fields. The total installed geothermal capacity, mainly in Olkaria and Eburru geothermal fields, in August 2022, was 954 MW.

## 3.1 Olkaria geothermal field

Detailed geological and geophysical exploration began in Olkaria in 1952. The findings of this scientific study resulted in the drilling of two geothermal wells, X1 and X2, in 1956. The two wells had a depth range between 950 m and 1200 m and recorded a maximum downhole temperature of 235°C. However, attempts to discharge the wells were unsuccessful. This failure stopped further geothermal work in March 1959, denting a blow to interest in geothermal development in Kenya.

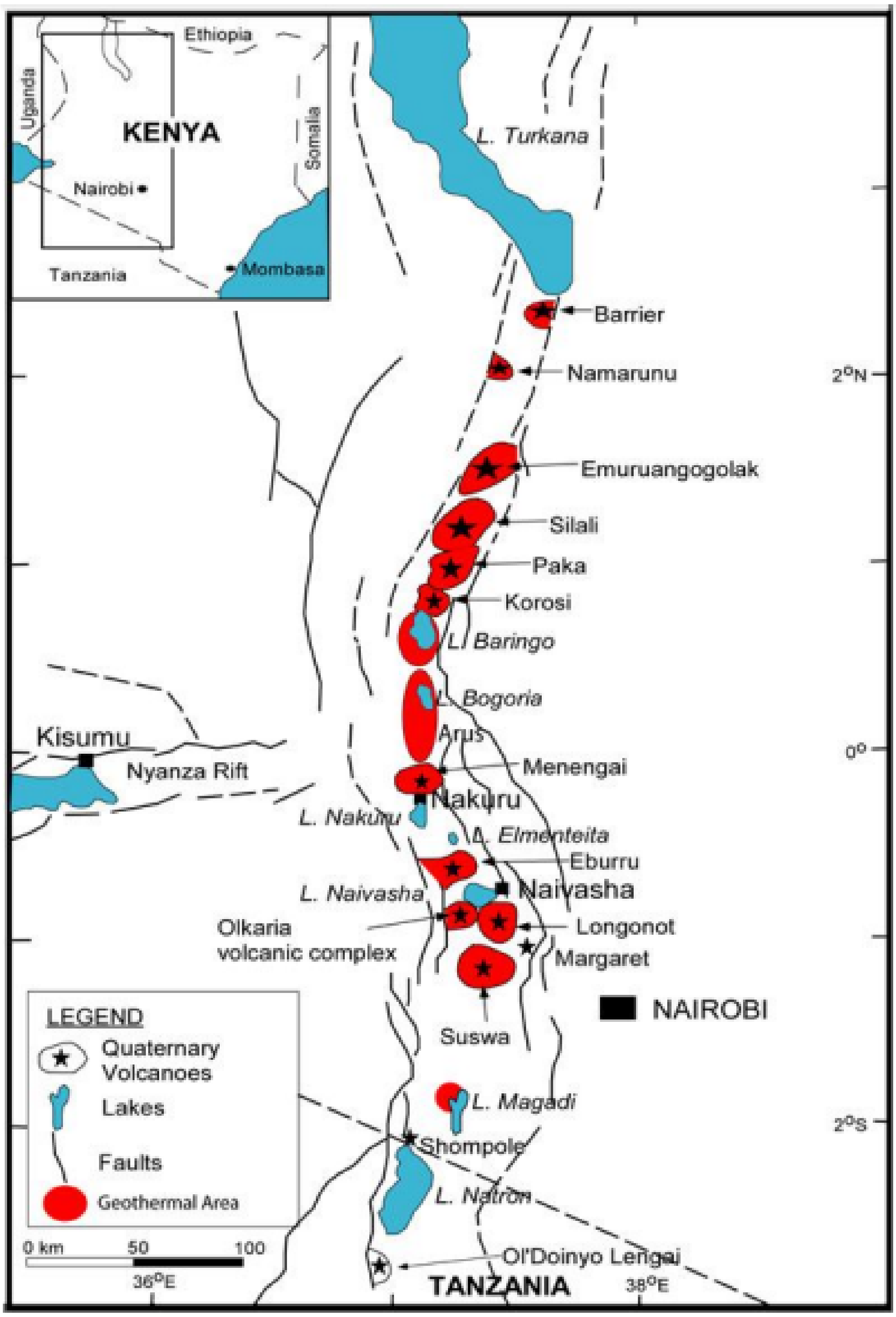

FIGURE 1: Location of geothermal fields and prospects along the axial region of the Kenyan rift (Omenda, 2018)

The oil crisis in the early 1970s led to renewed interest in geothermal development. Consequently, a joint geothermal project by the United Nations Development Program (UNDP) and East African Power and Lighting Company Ltd. (EAPL), representing the Government of Kenya, was initiated in 1970. More geoscientific work was carried out between Olkaria and Lake Bogoria from 1971 to 1972. The geoscientific study results commenced drilling four wells in 1973, with funds from UNDP. By 1976, six wells (OW-1 to OW-6) had been drilled. After drilling, the feasibility study recommended the development of a 2x15 MW power station.

Active drilling commenced, providing enough steam for electricity generation for a 30 MW power plant. In June 1981, the first 15 MW generating Olkaria 1 unit 1 power plant was commissioned. The plant was the first geothermal power plant in Africa. The second 15 MW unit was commissioned in November 1982. By 1985, 33 wells had been drilled in the Olkaria East production field, with the third unit commissioned in March 1985, raising the total to 45 MW. Further exploration work from 1986 led to the drilling of 30 more wells by 1992 in both Olkaria East and North East fields. Financial constraints led to the delay of power plant construction until 2003 when a total of 70 MW power plant comprising two units of 35 MW each was commissioned. The abundant steam led to the construction of an additional 35 MW unit in 2010. The three units were named Olkaria II power plant (Figure 2).

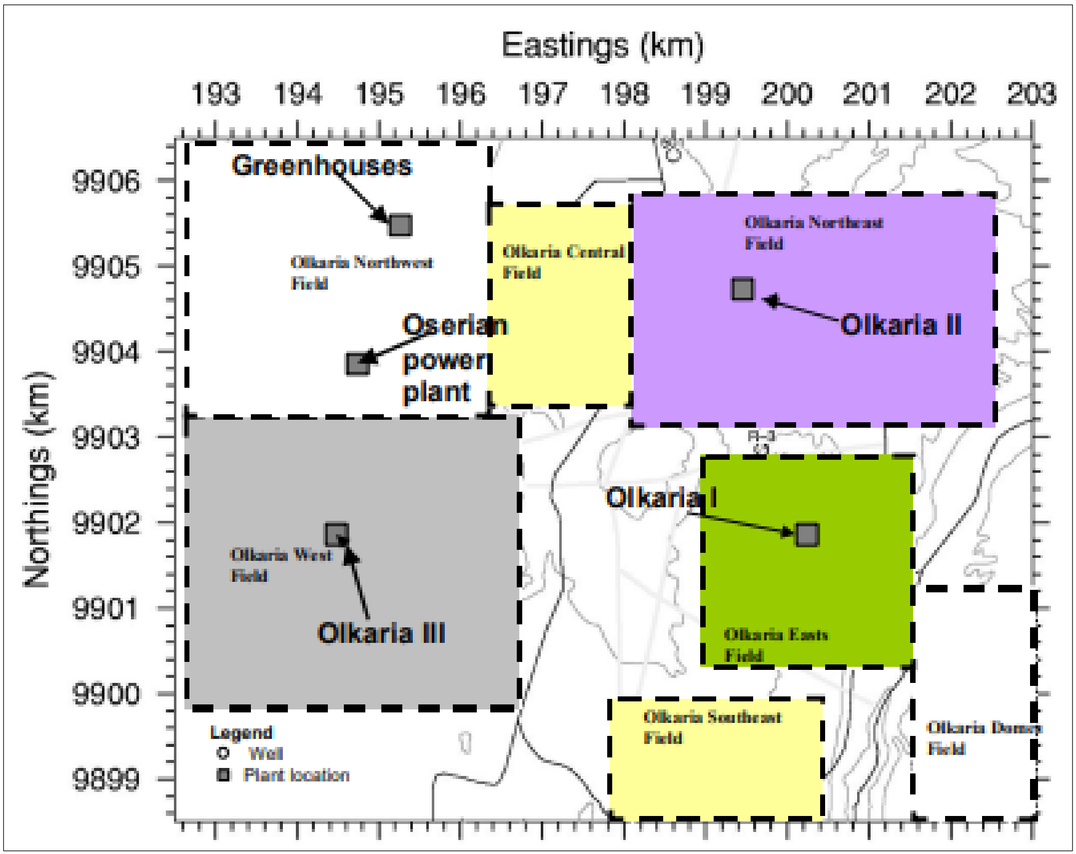

FIGURE 2: Olkaria geothermal field divisions and power plant locations within the Greater Olkaria geothermal field

More scientific work resulted in drilling wells in the Olkaria West field. The realized steam led to the construction of the Olkaria III power plant, which is owned by an Independent Power Producer (IPPs), OrPower 4 Inc., a subsidiary of Ormat Technologies. Olkaria III began its operation in 2000, with a generation capacity of 13 MW. An additional 35 MW was commissioned in 2009, 36 MW in 2013, 26 MW in 2014, and a further 29.6 MW and 15.4 MW between 2016 and 2019, bringing the total installed capacity to 155 MW. The wells drilled in the northern portion of Olkaria West field have a steam capacity of 2 MW. These wells have been leased by the Oserian flower farm for in-house generation of 1.8 MW power (OW-306) and for direct use in heating of greenhouses (OW-101).

To increase the share of geothermal energy in the energy mix and reduce reliance on emergency diesel generation, the Kenyan government funded the drilling of three exploration wells in the Domes area of the Olkaria geothermal field in 1999. Further funding for the drilling of appraisal wells was availed in

2006. This led to the production drilling of six wells beginning in 2007. Data from the drilled wells indicated the availability of steam to operate over a 200 MW power plant. At the same time, advanced scientific studies resulted in the drilling of more wells in the Olkaria East and Northeast fields. The gathered steam from the three fields led to the commissioning of a 140 MW Olkaria IV power plant in the Domes area and a 140 MW Olkaria IAU plant in the Olkaria East field in 2014 and 2015, respectively. An additional 172 MW Olkaria IV power plant was commissioned in the Domes area in 2019 and another 86 MW Olkaria 1AU 6 plant was commissioned in July 2022. There has also been the development of wellhead generating units in the Olkaria geothermal field. The wellheads were commissioned between 2012 and 2016 and have a total generation capacity of 81.1 MW. So far, exploration work has continued in the Olkaria geothermal field, which has an estimated area of 204 km$^2$, with 322 wells drilled.

### 3.2 Eburru geothermal field

Eburru volcanic complex is located to the north of Olkaria. KenGen conducted detailed surface studies between 1987-1990 that culminated in the drilling of six exploration wells in Eburru between 1989 and 1991 with a depth range of between 2,222 and 2,791 m below ground level. The results from the exploration wells indicate that the area had experienced temperatures of over 300ºC, possibly due to a localized intrusive. The maximum discharge temperature was 285ºC, and the power output from the one well EW-1 discharged 2.5 MW. Based on the data from the wells, the field's estimated power potential is between 50-60 MW. Further infill MT surveys in 2006 revealed that the Eburru field could support up to 60 MW of power generation. In 2011, KenGen commissioned a 2.5 MW condensing pilot wellhead unit. Currently, KenGen is carrying out further appraisal drilling, with four wells (EW-07, EW-07A, EW-07B and EW-07C) planned for deeper drilling to 3,000 m below ground level.

### 3.3 Menengai geothermal field

Menengai geothermal field is under the management of the Geothermal Development Company (GDC). GDC is a state-owned vehicle formed through an act of parliament in 2008 to enhance geothermal exploration. GDC’s mandate is to explore geothermal resources before handing over the steam to KenGen or other private developers for development. The government is to source the exploration funds.

Detailed surface exploration in Menengai geothermal field was carried out in 2004 and culminated in the drilling of exploration wells in 2011 by GDC. The mapped potential area in Menengai is over 80 km$^2$ translating to 1,200 MW of power generation potential. So far, over 50 wells have been completed, and more than 170 MW of power proved. Production drilling is going on in the field using seven high-capacity rigs. Through international competitive bidding, GDC has engaged three IPPs (Quantam Power East Africa, Orpower 22, and Sosian Energy) to install 35 MWe each at Menengai geothermal field on a build-own-operate arrangement. Power plant construction by the first IPP is in progress. In addition, plans are underway to develop a 400 MW power plant. The development will take place in phases and will be done by the IPPs.

### 3.4 Paka-Silali geothermal field

Detailed surface exploration for Paka-Silali geothermal field began in 2006. Results from this survey indicated the existence of a geothermal system in Paka, with reservoir temperatures of between 180°C and 300°C and an estimated power output of 200 MW. Exploration drilling began in 2018, with appraisal and production drilling commencing in 2021 and 2022, respectively. Ten wells have been drilled in the Paka field with an estimated power output of 33 MW. In Silali geothermal area, surface exploration has led to the siting of three exploration wells, with drilling scheduled to commence in the 2022-2023 financial year. The other geothermal prospects are at different stages of exploration.

## 4. DISCUSSION

In the past two decades, global energy stakeholders and governments have doubled the effort to utilize renewable energy resources. The measures aim to increase renewable energy share in the worldwide energy mix. The objective of accelerating the adoption of renewable energy technologies is to address the climate change and greenhouse gas emission challenges. Further, universal access to affordable, reliable, sustainable, and modern energy by 2030 is critical in achieving the seventeen SDGs (UN DESA, 2017) adopted by the United Nations General Assembly (UNGA) in 2015. So far, the percentage of renewable sources in global electricity generation rose from 8.6% in 2010 to 26% in 2019 (Power Technology, 2018; IEA, 2020b).

Efforts to decarbonize the global energy system have seen geothermal resources receive significant attention. In countries where geothermal resources are easily accessible, geothermal solutions present a clean, reliable, and consistent source of heat and electricity. In December 2021, the total installed geothermal power capacity was 15,854 MWe, operating in 29 countries (IGA, 2020). Furthermore, the direct utilization of geothermal energy, for example, in agricultural applications, crop drying, space heating, and industrial processes, has increasingly gained popularity due to its economic, environmental, and energy efficiency benefits. For instance, efforts by the European Commission to decarbonize the energy used for heating and cooling have increased interest in geothermal resource development. Various energy utilities in European Union countries seek to tap into geothermal energy to meet the heating demand (IGA, 2020).

The Kenyan government energy planning report indicates that it plans to meet the forecast demand from a sustainable mix of fossil fuel- and renewable resource-based generation (EPRA, 2018). The government plans to invest more in non-dispatchable wind and solar resources for the share of renewable-based power generation. However, the variable nature of these renewable energy sources, which depend on seasons and weather, requires support from other technologies, such as advanced batteries, hydrogen, and smart grids, which are yet to mature. Consequently, Kenya needs to plan its demand-supply future energy system to ensure an optimal share of intermittent renewable sources that will provide a stable and reliable power supply and affordable electricity cost.

Kenya is one of the SSA countries with abundant geothermal resources, with an estimated total capacity of between 7,000 MW and 10,000 MW and an installed capacity of 954 MW. Geothermal power plants can improve the power system's stability. Studies indicate geothermal power plants have higher inertia than other power plants, particularly renewable generators (Sutter and Mburu, 2016). Inertia in power systems refers to the energy stored in large rotating generators and some industrial motors, which gives them the tendency to remain rotating. This stored energy can be particularly valuable when a large power plant fails, as it can temporarily compensate for the lost power from the failed generator. This transient response typically available for a few seconds allows the mechanical systems that control most power plants time to detect and respond to the failure (Denholm et al., 2020). High inertia plays a significant role in maintaining the stability of power systems. An increase in the wind and solar capacity connected to the grid leads to the reduction of the power system's inertia constant (Sun et al., 2022). Analysis of the technical parameters of Kenya's power plants indicates that geothermal plants have higher inertia constants among the power plants already developed in Kenya (Figure 3). The Kenyan geothermal generators have inertia constants ranging from 3.1 to 5.1, followed by hydropower, with inertia constants from 2.5 to 3.6. In line with this observation, Kenya's electrical power system is more stable when geothermal plants are used to meet the power demand.

Analysis of energy-generating plants globally indicates that geothermal plants possess the uppermost capacity factor among all other power-generating technologies (IEA, 2020a). The capacity factor of a power conversion technology is the ratio between the actual generated power divided by the maximum potential power output that could have been obtained if the plant operated at full capacity during the same period (Dincer and Ezzat, 2018). The non-existent fuel cycles in geothermal generation eliminate the reliance of geothermal generation on the availability and obtainability of fossil fuels. The obtainability of fossil fuel in non-fuel-producing countries is controlled by global factors, including prices and political stability, affecting the fuel cycles. Thus, geothermal generation's availability and reliability are more guaranteed than fossil fuel generation. Furthermore, the relatively low operating pressure and temperature for geothermal power plants compared to fossil fuel power plants reduce stress on the components of geothermal plants, reducing downtime for maintenance, which permits longer operating hours. Unlike wind and solar, the non-dependence of geothermal heat on weather guarantees constant power output (Dincer and Ezzat, 2018).

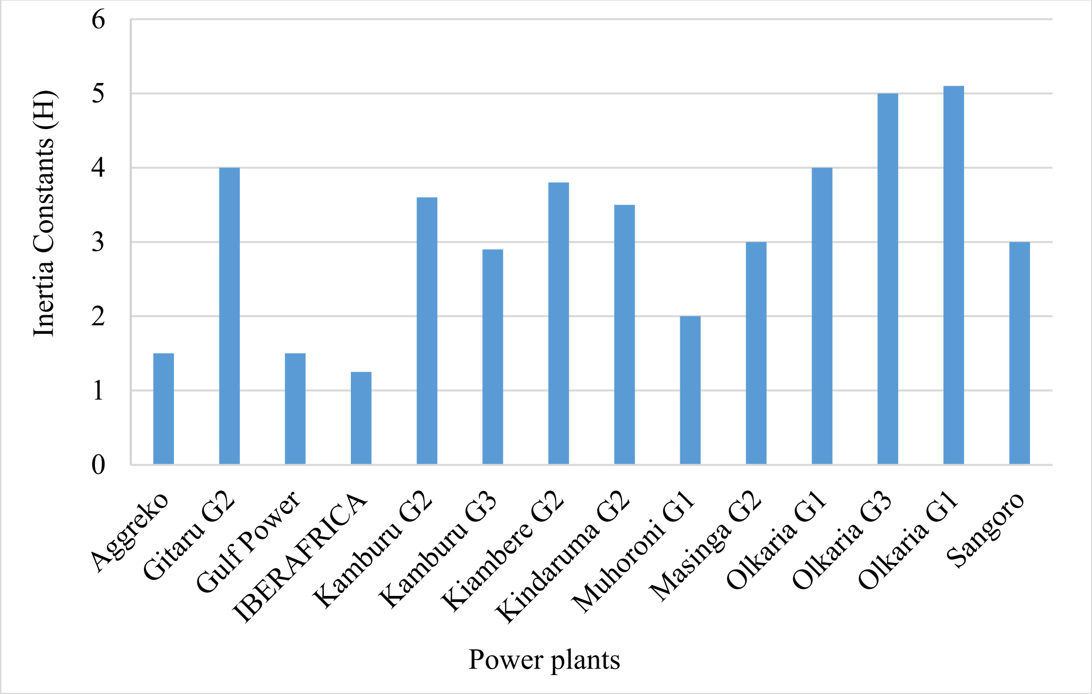

FIGURE 3: Inertia constants of Kenya's power plants.
Data from Sutter and Mburu (2016), analysis by the author.

Geothermal resources have, in the recent past, played a critical role in improving power supply reliability and availability in Kenya. Kenya's geothermal generating units have recorded higher capacity and utilization factors than the other power units (Lahmeyer International, 2016). The units have a capacity factor of 90%, with 100% contribution to the peak, thus supply baseload. The existing hydropower, solar, and wind units have 50%, 36%, and 19% capacity factors, respectively. A simulation model developed to project Kenya's power generation expansion indicates that the planned coal, gas, and nuclear units will have capacity factors of 75%, 85%, and 85%, respectively. These technical parameters present geothermal generation as an alternative source of baseload supply to Kenya's future planned fossil-fuel baseload generation. Geothermal plants have a low life cycle emission compared to their fossil-fuel counterparts. The greenhouse gas emissions coefficients for coal, oil, and gas are 94, 74, and 54 kiloton/GW, respectively (IEA, 2020a), while geothermal has 0.0001 kiloton/GW (Musonye et al., 2021). Figure 4 shows the energy mix for power generation expansion in Kenya from 2020 to 2045, with the associated GHG emissions. With the exhaustion of geothermal resources, adopting coal into the energy mix significantly increases GHG emissions. Therefore, the continued use and accelerated development of geothermal resources for baseload power supply will substantially reduce GHG emissions, thus contributing to Kenya's NDC to global climate change mitigation measures. Key to note is that hydropower generation is also used for baseload supply in Kenya. However, prolonged drought conditions have previously resulted in power rationing, making hydropower an unreliable source of baseload considering the climate change phenomenon and the resultant drought challenges.

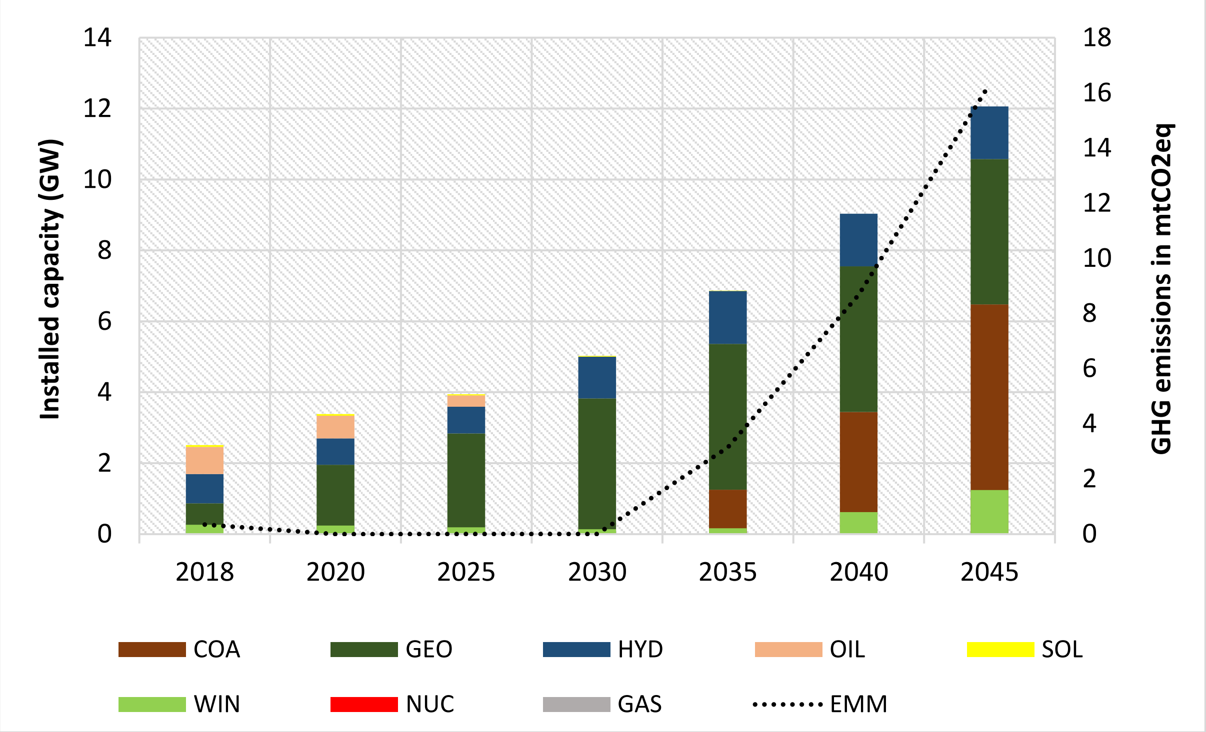

FIGURE 4: Projected optimized generation with the associated GHG emissions (EMM) under the reference demand growth from 2018 to 2045

Generally, geothermal power typically involves high capital expenditure due to high risks during the exploration phase. However, no fuel costs are incurred during operation; hence, low operation and maintenance costs. For Kenya, the capital cost of geothermal development is low compared to the average global capital cost of coal development (EPRA, 2018). The low cost of geothermal results from derisking the exploration phase by the Kenyan government and its development partners over the last 50 years. Furthermore, the establishment of royalty schemes in the Energy Act 2019 makes the legal and regulatory costs more predictable for geothermal, unlike coal (EPRA, 2020). The projected capacity factor of a power plant plays a critical role in the Levelised Cost of Electricity (LCOE). The twenty-year least cost power development plan (LCPDP) done by the government of Kenya using an econometric model indicates that the LCOE for geothermal is lower compared to fossil fuel, wind, and solar sources, for the Kenyan case (EPRA, 2018) (Figure 5).

The screening curve shows the LCOE for all the generation resources, representing site-specific power plant with the lowest LCOE for each resource, including transmission link cost at different discounting rates. For example, a power plant in Suswa geothermal field presents the least LCOE amongst the fields targeted for geothermal development, while Magwagwa represents the LCOE among hydropower sites. The LCPDP report further indicates that geothermal power generation has a higher priority for dispatch due to its lower marginal cost than fossil fuels. Furthermore, two optimization-based power generation-expansion modelling studies done for Kenya prioritize the development of the geothermal resource, with or without GHG emission reduction restrictions (Musonye et al., 2021; Carvallo et al., 2017) (Table 1). Table 1 indicates installed capacities for Kenya's power generation expansion under an optimized energy system expansion for the LCPDP and the two studies in 2035.

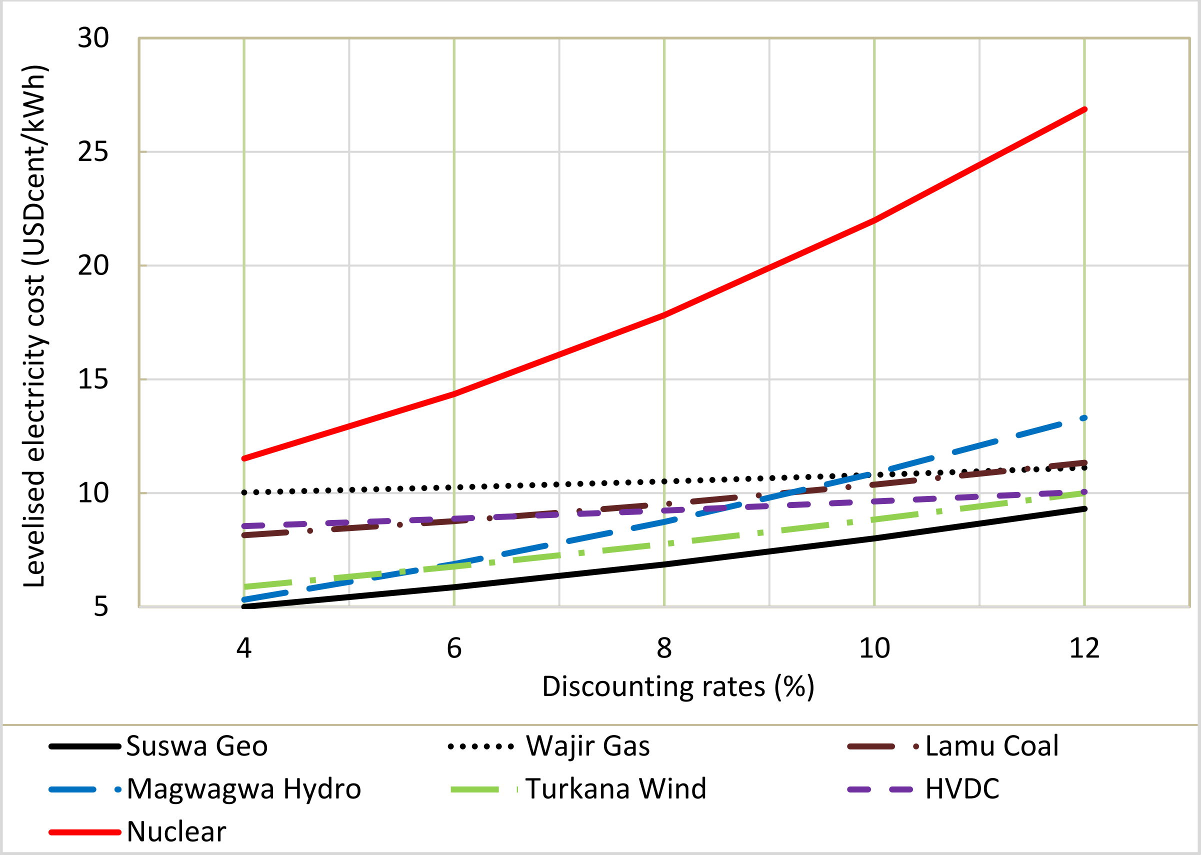

FIGURE 5: Screening curve indicating the LCOE for the different generation sources for Kenya. Data from Lahmeyer International (2016), analysis by the author.

TABLE 1: Power generation mix in 2035 under different optimization studies done for Kenya. From Musonye et al. (2021).

| **Technology** | **Capacity (MW)** | | | **Energy (GWh)** | | |
|---|---|---|---|---|---|---|
| | LIPS-OP&LIP-XP(2035) | SWITCH-Kenya (2035) | Kenya-TIMES (2035) | LIPS-OP&LIPS-XP(2035) | SWITCH-Kenya (2035) | Kenya-TIMES (2035) |
| Coal | 981 | 0 | 1,250 | 1,533 | 0 | 9,291 |
| Geothermal | 3,082 | 7,953 | 4,100 | 23,194 | 65,387 | 32,278 |
| Hydro | 1,759 | 792 | 1,490 | 5,688 | 3,457 | 6,500 |
| Oil | 0 | 4,087 | 0 | 0 | 1,067 | 0 |
| Wind | 1,140 | 6,071 | 210 | 4,337 | 29,132 | 575 |
| Solar | 250 | 0 | 10 | 430 | 0 | 12 |
| Natural Gas | 0 | 5,860 | 0 | 0 | 12,108 | 0 |
| Nuclear | 0 | n/a | 0 | 0 | n/a | 0 |
| Imports | 400 | n/a | n/a | 2,678 | n/a | n/a |

The analysis in this paper indicates that a higher share of geothermal power in the energy mix significantly improves the power system's stability and availability. Furthermore, the displacement of fossil-fuel-based baseload generation by geothermal significantly cuts down GHG emissions, thus helping to mitigate climate change. For the Kenyan case, geothermal power has comparatively low capital cost compared to coal generation and low marginal cost compared to wind, solar, and fossil fuel-based generation. Resultantly, the Kenyan government should prioritize the development of the available geothermal resources to exhaustion before embarking on accelerated wind and solar development in short to medium term. With its ability to operate consistently at a high availability rate, geothermal power can provide a low-carbon and sustainable power supply without compromising reliability and at a comparatively low cost. The development of the geothermal resource for power generation could also present an opportunity for the direct utilization of drilled geothermal resources in the planned projects within Kenyan geothermal areas, for instance, in geothermal industrial parks. Moreover, the global policy disincentives for fossil fuels and numerous ongoing research programs in geothermal have the potential to make deep-seated geothermal energy resources more accessible.

Critical to note is that the development of geothermal resources has its challenges. These challenges include environmental and social, policy and legislative, technological and financial (Malafeh and Sharp, 2014). Exploration, appraisal, and production drilling in geothermal development require significant up-front financial investment and long-term investment returns. The high risk associated with the uncertainty of geothermal resource drilling makes financiers shy away from financing this early phase of geothermal development. This challenge is being addressed through grants, mobilization of resources through carbon credits from already developed green generation technologies, and using fossil fuel taxes to fund geothermal exploration.

Socioeconomic and environmental challenges arise from the location of most geothermal resources. Most geothermal resources are located in remote scenic, wild, and protected areas. The critical socioeconomic impact of developing these resources includes opening up these areas, losing wildlife habitat, and visual intrusion in scenic tourist areas. These challenges are addressed through Environmental Impact Assessment (EIA) regulations and policies, local and international legislation concerning biodiversity conservation, and national and international policy on resettlement/relocation and compensation.

## 5. CONCLUSIONS

Energy is central to addressing the seventeen SDGs; thus, SDG number seven calls for universal access to sustainable, reliable, affordable, and secure energy services. The global energy demand is projected even further in the coming years, particularly in developing economies. On the other hand, energy use for cooling and heating contributes significantly to anthropogenic GHG emissions. Governments worldwide have adopted policies and strategies to increase the share of renewable energy in their energy mix. However, there are challenges associated with variable renewable energy sources, such as solar and wind, including availability and reliability. As such, geothermal is one of the renewable energy resources that can be used to meet the growing demand sustainably while cutting emissions and ensuring reliability and availability. The geological setting of a given area controls the availability of geothermal resources.

Kenya is a developing economy whose power demand is projected to grow tremendously. Kenya plans to meet its future demand with a mixture of fossil fuel-based power generation and renewable energy. Kenya is one of the countries with abundant geothermal resources. Geothermal resources have been used in Kenya to reduce power generation costs and ensure stability and reliability. Studies have also indicated that geothermal power is the most competitive in Kenya, with or without emission cut constraints. Its adoption for future power generation could assist in offsetting the planned fossil-fuel-based baseload generation, such as coal. Adopting a larger share of geothermal in Kenya’s energy mix could allow the country to tap into geothermal resources for direct utilization. Therefore, energy stakeholders in Kenya and worldwide should align strategies to exploit geothermal resources and invest in research and development for geothermal.

## REFERENCES

Abdmouleh, Z., Alammari, R.A.M., and Gastli, A., 2015: Review of policies encouraging renewable energy integration and best practices. *Renewable and Sustainable Energy Reviews*, *45*, 249-262.

Angel, S., Parent, J., Civco, D.L., Blei, A., and Potere, D., 2011: The dimensions of global urban expansion: Estimates and projections for all countries, 2000–2050. *Progress in Planning*, *75*(2), 53-107.

Baroni, M., 2022: The integration of non-dispatchable renewables. In: Hafner, M. and Luciani, G. (eds.), *The Palgrave handbook of international energy economics*. Springer International Publishing, 269-299.

Carvallo, J.P., Shaw, B.J., Avila, N.I., and Kammen, D.M., 2017: Sustainable low-carbon expansion for the power sector of an emerging economy: The case of Kenya. *Environmental Science & Technology*, *51*(17), 10232–10242.

Conserve Energy Future, 2013: *History of geothermal energy (and emergence over the years)*. Conserve Energy Future, website: https://www.conserve-energy-future.com/geothermalenergyhistory.php

Denholm, P., Mai, T., Keynon, W.R., Kroposki, B., and O'Malley, M., 2020: *Inertia and the power grid: A guide without the spin*. National Renewable Energy Laboratory, report NREL/TP-6120-73856, 48 pp.

Dincer, I. and Ezzat, M.F., 2018: 3.6 Geothermal Energy Production. In: Dincer, I. (ed.), *Comprehensive Energy Systems*. Elsevier, 252-303.

Edenhofer, O., Hirth, L., Knopf, B., Pahle, M., Schlömer, S., Schmid, E., and Ueckerdt, F., 2013: On the economics of renewable energy sources. *Energy Economics*, *40*(S1), S12–S23.

EPRA, 2018: *Least cost power development plan for Kenya, 2018.* Energy and Petroleum Regulatory Authority, Nairobi, Kenya, 358 pp.

EPRA, 2020: *Energy and Petroleum Regulatory Authority: The Energy Act, 2019*. Energy and Petroleum Regulatory Authority, Nairobi, Kenya.

GEO-ExPRO, 2018: *GEO ExPro Geoscience-Expo-Petroleum*. GEO-ExPRO, 72 pp.

GoK, 2020: *About Vision 2030*. Government of Kenya, website: https://vision2030.go.ke/about-vision-2030/

Hoornweg, D. and Pope, K., 2017: Population predictions for the world's largest cities in the 21st century. *Environment and Urbanization*, *29*(1), 195-216.

IEA, 2020a: *IEA-ETSAP | Energy Supply Technologies' Data*. International Energy Agency, Paris, France, website: https://iea-etsap.org/Latest_ETSAP_VT-Starter.zip

IEA, 2020b: *Renewables – Global Energy Review 2020*. International Energy Agency, Paris, France, website: https://www.iea.org/reports/global-energy-review-2020/renewables

IEA, 2021: *World Energy Outlook 2021*. International Energy Agency, Paris, France, 386 pp.

IGA, 2020: *2020 to become a milestone year for the global geothermal energy sector.* International Geothermal Association, Hague, Netherlands, website: https://www.geothermal-energy.org/2020-to-become-a-milestone-year-for-the-global-geothermal-energy-sector/

IPCC, 2014: *Summary for policymakers*. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., and Minx, J.C. (eds.), Mitigation of Climate Change - Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change – Summary for policymakers. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 32 pp.

IRENA, 2022: Renewable capacity highlights. International Renewable Energy Agency, Masdar City, United Arab Emirates, 3 pp.

Kahlen, L., Kurdziel, M.J., Day, T., and Tessa, S., 2019: The role of geothermal and coal in Kenya's electricity sector and implications for sustainable development. New Climate Institute, Cologne / Berlin, Germany, 55 pp.

Kazimierczuk, A.H., 2019: Wind energy in Kenya: A status and policy framework review. *Renewable and Sustainable Energy Reviews*, *107*, 434–445.

Lahmeyer International, 2016: *Development of a power generation and transmission master plan, Kenya. Medium term plan, 2015-2035.* Lahmeyer International, report for the Kenyan Ministry of Energy and Petroleum, 266 pp.

Malafeh, S. and Sharp, B., 2014: Geothermal development: Challenges in a multiple access scenario. *Thirty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, USA,* 11 pp.

MoENR, 2017: *Kenya's nationally determined contribution (NDC); Update of Kenya's emission baseline projections and impact on NDC target.* Ministry of Environment and Natural Resources, Nairobi, Kenya, 12 pp.

Musonye, X.S., Davídsdóttir, B., Kristjánsson, R., Ásgeirsson, E.I., and Stefánsson, H., 2021: Environmental and techno-economic assessment of power system expansion for projected demand levels in Kenya using TIMES modeling framework. *Energy for Sustainable Development*, *63*, 51–66.

Omenda, P., 2018: *Update on the status of geothermal development in Africa*. GRC Annual Meeting.

Power Technology, 2018: *Renewable energy to reach 22.5% share in global power mix in 2020.* Power Technology, website: https://www.power-technology.com/comment/renewable-energy-reach-22-5-share-global-power-mix-2020/?cf-view

Sarmiento, Z. and Steingrímsson, B., 2007: *Review on estimated power potential and realistic development of geothermal resources in leading geothermal countries.* Presented at "Short Course on Geothermal Development in Central America – Resource Assessment and Environmental Management", organized by UNU-GTP and LaGeo, San Salvador, El Salvador, 21 pp.

Sun, F., Sun, J., Zhang, X., Yang, H., Qian, X., and Ye, P., 2022: Measurement method of inertia constant of power system based on large-scale wind power grid connection. *Energy Reports*, *8*, 200–209.

Sutter, J. and Mburu, P., 2016: Power system stability improvement with geothermal as a major source of power in Kenya. *Proceedings 6th African Rift Geothermal Conference, Addis Ababa, Ethiopia*, 11 pp.

UN DESA, 2017: *Ensure access to affordable, reliable, sustainable and modern energy for all*. United Nations Department of Economic and Social Affairs, website: https://sdgs.un.org/goals/goal7

United Nations, 2018: *Achieving targets on energy helps meet other Global Goals, UN forum told*. United Nations, website: https://www.un.org/sustainabledevelopment/blog/2018/07/achieving-targets-on-energy-helps-meet-other-global-goals-un-forum-told-2/

United Nations, 2020: *Ensure access to affordable, reliable, sustainable and modern energy*. United Nations, website: https://www.un.org/sustainabledevelopment/energy/

Vidal-Amaro, J.J., Østergaard, P.A., and Sheinbaum-Pardo, C., 2015: Optimal energy mix for transitioning from fossil fuels to renewable energy sources – The case of the Mexican electricity system. *Applied Energy*, *150*, 80–96.

WEC, 2013: World energy resources – 2013 survey. World Energy Council, London, United Kindgdom, 468 pp.