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Towards 100% Renewable Energy: Incrementing Solar Electrification in Kenya

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Abstract

Over recent years, the electricity demand in Kenya has grown rapidly due to population increase, increase in prosperity, and industrialization. Electricity supply based on fossil sources however, is unsustainable and detrimental to the environment thus many countries are focusing their attention on renewable energy sources (RES). The Kenyan government has set a target of generating 100% of the country's electricity from RES by 2030, with a specific focus on increasing the share of solar and wind power. Kenya has the geographical potential to generate more electricity from solar photo voltaic (PV) than the total electricity demand, however the technical and economic feasibility of PV is complex and depends – in addition to geographical location and availability of resources – also on the local energy system composition and flexibility options. To address these constraints, this paper aims to undertake techno-economic feasibility evaluation of optimizing grid-connected solar PV in Kenya. To actualize this aim, EnergyPLAN was used to simulate energy demand and generation to analyze the technical, economic, and environmental implications of a transition based on PV. Results obtained show that it is technically and economically feasible to increase electricity generation from PV up to 4,601 MW representing 32% of the total generated power up from 212.5 MW representing 6.8% of the total generated power by the end of 2022. The total annual cost for this investment is 970 MEUR compared with 1246 MEUR for operating the reference scenario. This study adds significantly to the national objective of 100% renewable energy generation by 2030. The results obtained further show that optimizing PV presents great benefits in terms of cost effectiveness, CO_2 emissions reduction, reliability improvements and security of Kenya's power system.

Key words: Solar PV, EnergyPLAN, renewable energy sources, technical simulation, market economic simulation.
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1. Introduction

In recent years, Kenya has been experiencing rapid economic growth, leading to an increase in demand for electricity. However, the country's electricity generation is dominated by thermal and hydroelectric power plants (HEPs). Thermal power plants are expensive to run and have significant negative environmental impact whereas HEPs are susceptible to unreliable precipitation patterns (KNBS, 2023). Kenya also depends on electricity imports, which makes it vulnerable to price fluctuations and frequent power outages. Additionally, a significant proportion of the population lacks access to electricity, particularly in rural areas where access stands at 65% (KNBS, 2023).

To address these challenges, the Kenyan government has set a target of generating 100% of the country's electricity from RES by 2030, with a specific focus on increasing the share of solar and wind power (IRENA & AfDB, 2022). One of the key RES that can help achieve this target is solar power.

The potential for solar power in Africa is substantial, given the continent's abundant solar resources and the need to provide access to electricity to millions of people. Several African countries, including Morocco, South Africa, and Egypt, have made significant progress in increasing their share of solar power generation. Considering the installed capacity in Africa (Figure 1), South Africa, Egypt and Morocco have the largest installed solar generation capacity at 57%, 16% and 7% respectively (IRENA & AfDB, 2022).

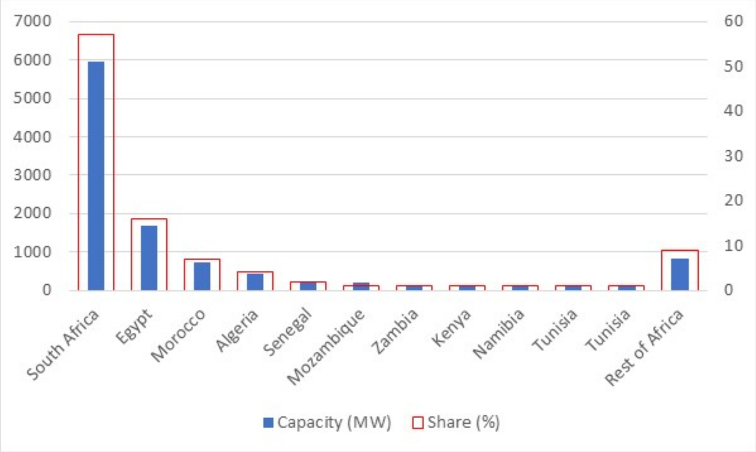

Figure 1: Africa's installed solar capacity in 2020. Based on data from (IRENA & AfDB, 2022)

Despite good solar conditions in Kenya, development has been modest as seen in *Figure 1*. In general, there are challenges regarding integration of solar power into the grid – both in terms of energy system flexibility for accommodating the variability of PV and in terms of supportive policies and regulatory frameworks to promote the technology's adoption. Kenya's limited adoption of PV technology can be attributed to a combination of challenges, including difficulties in integrating solar power into the grid due to inadequate energy system flexibility. The country faces obstacles in accommodating the variability of PV, as well as a lack of supportive policies. Factors such as the cost of solar infrastructure and a potential lack of awareness among consumers and businesses further contribute to the modest development of solar power in Kenya. This applies not only to Kenya, but it appears from the position in *Figure 1* that Kenya is more challenged than e.g. South Africa and most Mediterranean African nations.

Several studies have been conducted on the potential for solar power in Kenya's energy mix. A study by (Oloo, et al., 2016), and (Samoita et al., 2020) assessed the potential of PV systems to provide electricity in rural areas of Kenya. The study found that such systems were a cost-effective and reliable source of electricity for off-grid communities. Another study by (Moner-Girona, et al., 2019) evaluated the technical and economic feasibility of integrating solar power into the grid in Kenya. The study found that with supportive policies and regulatory frameworks in place, PV could be a competitive and reliable source of electricity for the country.

Another study by (Wambui, et al., 2022) presents a socio-techno-economic assessment of electricity development scenarios in Kenya using the Low Emissions Analysis Platform (LEAP) and the Next Energy Modeling System (NEMS). Considering Kenya's Long-Term Electricity and Energy Sector Development Plan (LCPDP) for the period 2017-2037, this study aligned with the national agenda, aiming to guide the energy sector on generation expansion opportunities, transmission infrastructure targets, and resource requirements. The LCPDP serves as an updated roadmap, considering the Feed-in Tariff policy and emphasizing the energy-related aspects of the Big 4 Agenda program. Policy guidelines are set by the Ministry of Energy (MOE), while regulatory requirements are provided by the Energy and Petroleum Regulatory Authority (EPRA). Their study encompasses a comprehensive load forecast, details on committed generation projects, and an expansion program spanning 2025-2037.

The authors explore four different electricity development scenarios for Kenya, including a Business-as-Usual scenario, a Least Cost Scenario, a Sustainable Development Scenario, and a Carbon Mitigation Scenario. The scenarios are assessed based on a range of socio-economic, technical, and environmental indicators, including greenhouse gas emissions, energy security, and affordability. Results of this study indicated that the feasibility of the scenarios depended on a complex interplay of factors. The Least Cost Scenario highlighted the possibility of achieving significant cost savings without compromising environmental sustainability. The Sustainable Development Scenario presented the potential alignment between economic growth and environmental preservation, fostering a harmonious relationship between these aspects. The Carbon Mitigation Scenario demonstrated the potential for substantial reductions in greenhouse gas emissions while maintaining energy security.

Results reveal that a pathway incorporating 98.7% RES and a battery energy system is not only feasible but also offers substantial advantages for Kenya's energy planning. The synergy between REs and Energy Storage Systems (ESSs) emerges as a promising strategy, showcasing benefits in terms of cost effectiveness, reduction in CO_2 emissions, enhanced reliability, and improved security for Kenya's power system in the future. Overall, the study demonstrated Kenya's potential for becoming a progressive and sustainable energy producer.

Both (Samoita et al., 2018) and (Samoita et al., 2020) looked into barriers to PV in Kenya. (Samoita et al., 2020) found that while there are technical barriers, most other barriers can be overcome. (Samoita et al., 2018) focus was on the diffusion of large and small-scale systems, finding that these must be addressed differently.

Outside of Kenya, Ghana has significant solar power potential due to its proximity to the Equator, which provides it with abundant sunlight throughout the year. (Sulley et al., 2022) conducted a study that assessed the feasibility of a grid-connected PV/wind hybrid system for meeting typical commercial loads in Kumasi, Ghana. They used a simulation approach to model the performance of the hybrid system and evaluate its economic viability, considering factors such as capital costs, operating costs, and the levelized cost of electricity (LCOE). However, (Sulley et al., 2022) did not explicitly incorporate energy efficiency analysis in their analysis. The study finds that a hybrid system of PV and wind turbines can provide a stable and reliable source of electricity while also being economically viable.

(Aghahosseini et al., 2020) examine the feasibility of achieving 100% RES in the Middle East and North Africa (MENA) region by 2030, focusing on power, non-energy industrial gas, and seawater desalination sectors. Three scenarios, differing in regional grid interconnection and sector coupling, are explored: Region, Area, and Integrated. PV and wind energy emerge as the most competitive and abundant RES, constituting over 90% of generation capacity in all scenarios. Addressing RES variability, energy storage, surplus generation, and grids are utilized. Battery storage complements solar PV.

The study considers connecting all countries in the region with at least one transmission line, taking into account existing and planned grid connections. The interconnected power system allows for electricity exchange between countries, with regions possessing the highest RES potential acting as net exporters and others as net importers. The grid utilization profile for the MENA region reveals seasonal variations, with higher utilization during the beginning and end of the year and peak usage during morning and evening hours.

The integration of a wide-area transmission network helps balance the variability of solar PV and wind resources across the region. The study emphasizes the importance of storage technologies in managing the variability of REs. The interconnected power system experiences a reduction in the need for energy storage capacities, including large-scale batteries, Compressed Air Energy Storage (CAES), and gas storage. However, Pumped Hydro Energy Storage (PHES) remains relatively unchanged. The study highlights the role of Power-to-Gas (PtG) technology, where water electrolysis capacities increase in the Integrated scenario to meet additional gas demand for the non-energetic industrial gas sector. Battery storage complements solar PV by providing a solution for diurnal electricity supply. Compared to a business-as-usual strategy, a 100% RES-powered system proves 55–69% more cost-effective, considering both economic and environmental factors.

(Oyewo et al., 2022) explores the interrelated challenges of climate change and energy crises in Africa, proposing a shift towards sustainable development. A novel and sophisticated techno-economic energy modeling tool is used to describe the scope of the pathways in high geo-spatial and full hourly resolution for Africa covering the entire energy system. This study demonstrates that a RES-based pathway is not only climate-compatible, but also delivers a lower cost system structure than alternative pathways. Their results show that Africa can leapfrog carbonization by using its low-cost renewable electricity and green hydrogen. Furthermore, Africa can become a self-sufficient green economy and an exporter of green fuels. Notably, PV-battery hybrid systems and electrolyzers are instrumental in achieving carbon-neutrality in Africa.

The RES-based pathway, particularly the solar PV-battery hybrid systems and electrolyzers, is considered not only climate-compatible but also more cost-effective than alternative pathways. Solar PV is identified as the most cost-efficient technology, and the solar-driven energy system is described as cost-competitive, climate-compatible, and less dependent on politically unstable countries. Africa is positioned to leapfrog carbonization by leveraging its low-cost renewable electricity and green hydrogen. The RES-based pathway suggests that Africa has both the energy and land resources to pursue clean and cost-competitive energy solutions. The continent could become a self-sufficient green economy and an exporter of green fuels, with a focus on PV-battery hybrid systems and electrolyzers. REs, have lower power density than fossil fuels, requiring only a small percentage of Africa's land for deployment.

(Sterl, 2021) evaluates recent scientific findings on integrating RES into African power grids to expand electricity access, minimize costs, and reduce fossil fuel emissions. This research emphasizes enhanced cross-border transmission and storage solutions, such as batteries and power-to-gas. Model-based studies suggest that leveraging complementarities between RES and interconnections within Africa's power networks, coupled with substantial storage deployment, could effectively fulfill rising power needs with environmentally friendly electricity.

Sterl furthermore emphasizes the value of connecting Grand Ethiopian Renaissance Dam's (GERD) long-term operational plan with the development of solar and wind power infrastructure in Ethiopia and the Eastern Africa Power Pool (EAPP), supported by detailed spatiotemporal modeling. By coupling GERD's operation with solar and wind power, significant advantages can be achieved, including decarbonizing power generation, fulfilling Sudan's environmental flow requirements (which refers to the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems for maintaining their ecological integrity), optimizing infrastructure use, synchronizing GERD's and Egypt's dam schedules, and diversifying Ethiopian power generation for domestic and regional export (Sterl, 2021). This strategy aligns Ethiopia's energy objectives with water needs in the region, benefitting all three nations. The strategy offers improved grid integration of variable renewables, better compliance with environmental flow requirements, and enhanced utilization of GERD's infrastructure, synchronized dam operations, and strategic power mix diversification for Ethiopia.

The feasibility of realizing this coupling strategy hinges on several factors. Foremost, it demands a high degree of political will and cooperation among Ethiopia, Sudan, and Egypt. The technical aspects of integrating GERD's operation with solar and wind power infrastructure require meticulous planning, incorporating detailed spatiotemporal modeling to ensure the compatibility and efficiency of these systems. Adequate investment in the development of renewable energy projects and supportive grid infrastructure in Ethiopia and the Eastern Africa Power Pool. Furthermore, compliance with environmental flow requirements is a critical consideration, emphasizing the need to balance the benefits of power generation with ecological preservation.

(Tsuma & Kibaara, 2022) conducted a review and assessment of the techno-economic tools available for power systems with RES penetration in Kenya. The authors provide an overview of the current state of RES penetration in Kenya and discuss the need for reliable and efficient techno economic tools to support the development and integration of RES into the national grid. The article provides an assessment of the techno economic tools available for RES planning in Kenya such as EnergyPLAN (Lund et al., 2021), energyPRO (Østergaard et al., 2022), H2RES (Gašparović et al., 2014), RetScreen (RETScreen, 2022), Times (Loulou et al., 2021) and Homer (Homer Energy, 2019). The study highlights the importance of reliable and efficient tools for promoting the integration of RES into the national grid and underscores the need for improved data collection and management systems to support effective renewable energy planning.

EnergyPLAN has been used in many countries worldwide to evaluate the potential of RES in the energy mix. This tool is described in (Lund et al., 2021) and a review by (Østergaard, 2009) demonstrates its wide applicability in terms of using different criteria for energy system scenario optimization. A survey from 2022 showed that it had been used in 315 studies published in the journal literature (Østergaard et al., 2022). This large application was seen as an inferred validation of the model, however there rather few studies of studies from Africa.

In Tanzania, (Abdulganiyu, 2017) used EnergyPLAN to examine the potential for RES development. The study modelled and analyzed the feasibility of RES into the existing energy systems. The results obtained showed that Tanzania has significant potential for RES development, particularly in the areas of solar and wind power.

In Egypt, (Salah et al., 2022) conducted a comprehensive review of the potential for RES exploitation, as well as the challenges and opportunities associated with this. The authors used EnergyPLAN to evaluate the feasibility of integrating RES into Egypt's energy system. This tool was used to model the energy demand and supply and to evaluate the potential for RES integration, including wind, solar, and hydropower. The authors also used EnergyPLAN to assess the economic feasibility of different renewable energy scenarios and to identify potential barriers to implementation.

(Chouder et al., 2013) conducted an optimization study for achieving a 75% RES integration by 2050 in Algeria using EnergyPLAN to model and evaluate different scenarios. The study employed a multi-objective cuckoo search algorithm to optimize the energy mix for Algeria and identify the best pathway towards achieving the renewable energy target.

A case study on the potential role of electric vehicles in Nigeria's energy transition was done by (Dioha, et al., 2022) using EnergyPLAN to simulate different scenarios and to assess the impact on the electricity grid.

In Kenya, EnergyPLAN has been used by (Abdulganiyu, 2017) to model and evaluate different RES scenarios , both for the year 2030 and 2050. This study identified regulatory constraints and technological challenges as the main barriers that hinder uptake of RES. however the author did not propose solutions to overcome these barriers. Suggesting actionable recommendations to navigate these barriers and accelerate the RES transition will go a long way in providing useful information for policymakers and stakeholders, towards a more sustainable and resilient energy future, aligned with Kenya's developmental aspirations and global environmental commitments.

From this literature review, it is evident there is lack of comparable scenario research works looking into countries with similar climates and similar potential energy resources – and especially with the high temporal resolution required for adequately analyzing RES-based energy systems. The objective of this paper therefore is to thoroughly analyze the potential of solar power to meet the dynamic electricity demand in Kenya from a technical and economic standpoint. This is a novel study that provides national simulation of large-scale integration of RES into Kenya's electricity mix. The paper also provides an in-depth analysis of Kenya's current energy mix and scaling up of solar power generation and proposes the optimal solar capacity that is technically and economically feasible using EnergyPLAN. For this study, 2022 is chosen as a year of reference.

The paper is structured as follows: Section 2 discusses materials and methods to be employed in this study, section 3 gives an overview of Kenya's installed electricity capacity. Section 4 presents simulation results and discussion and lastly, conclusions are presented in section 5.

2. Materials and Methods

This section outlines EnergyPLAN model's role in examining energy system scenarios and details the approach employed for scenario development. The primary goal of this study is to conduct an analysis that explores the feasibility of large-scale integration of RES into Kenya's electricity mix, with a specific focus on solar power. To achieve this, EnergyPLAN model is utilized as a tool for simulating scenarios. The role played by the EnergyPLAN model is highlighted during scenario development and the resulting analysis provides a comprehensive understanding of the approach employed for scenario development.

An in-depth analysis of Kenya's current energy mix is carried out to provide a foundational understanding of the existing energy infrastructure. Subsequently, scaling up of PV generation is explored as a key element of this study, aiming to identify the optimal solar capacity in Kenya that is technically feasible within the EnergyPLAN framework. The year 2022 is selected as the reference year, providing a glimpse of the current energy landscape.

2.1. Overview of EnergyPLAN

EnergyPLAN provides a comprehensive framework for assessing the potential for solar power generation in the context of Kenya's energy mix and is able to account for a range of factors including economic, and environmental considerations.

EnergyPLAN is designed to model and simulate large-scale integration of RES and radical technological changes of energy systems (Lund, 2015). The general structure of EnergyPLAN is illustrated in *Figure 2*.

EnergyPLAN takes into account the hourly dynamics between electricity, heat, transportation and industrial systems. The electricity market is modeled as an hourly electricity price, a maximum transmission capacity and price elasticity in the electricity exchange. The socioeconomic costs are calculated as the sum of fuel and fuel handling costs, fixed and variable operation and maintenance costs, electricity import and export, annualized investment costs using a discount rate and carbon dioxide emission costs.

The software works on an aggregated level, which means that every energy plant source is not modeled individually, but all plants in the same category are modeled as one. Consequently, it is also a copper-plate model, as there are no internal restriction in, e.g., the electricity grid. The model is able to model the entire energy systems thus including e.g., transportation and district heating systems, but these facilities are not exploited in this work.

EnergyPLAN operates with two general classes of regulation strategies: technical and economic. With the technical, the aim is exclusively to minimize fuel usage while in the economic regulation strategy, power producers will also be optimized against the electricity market. For these analyses, a technical regulation strategy is applied as this can identifying possible pathways. Economic costs may also be calculated with the technical regulation strategy.

Due to the aggregation, all PV systems are aggregated into one. In addition, as with all variable RES, PV is prioritized by EnergyPLAN, thus in general, the technology will be allowed to produce according to availability.

All dammed HEPs are modeled as one, with the same efficiency and drawing on the same reservoir. Data on existing HEPs is a key input in EnergyPLAN's modeling of hydro. This includes information on the capacity, efficiency, and output of HEPs in the region being modeled. Cost data is also a key input in modeling hydro, including the investment costs and operation and maintenance.

In terms of prioritization, EnergyPLAN will prioritize hydroelectric to minimize fossil fuel usage of the system. In addition, it will be used to for balancing other RES limited by reservoir capacity and inflow to this.

Fossil fuel plants are least prioritized, and only applied in hours where RES are inadequate in supply. For grid stability reasons, EnergyPLAN can though be instructed to require a certain minimum production from ancillary service providing units such as units based on synchronous generators.

Fuel consumption is calculated based on the fuel mixes of the different plant types and the corresponding operation of these plants.

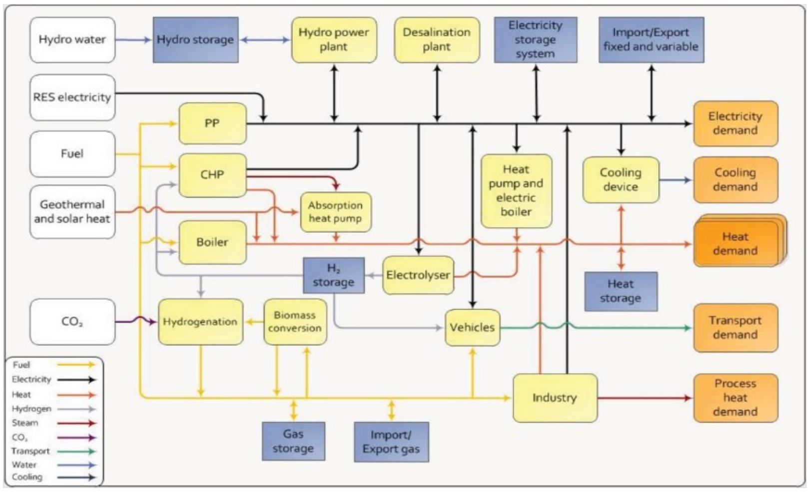

Figure 2: Conceptual Diagram of EnergyPLAN (Lund, 2015)

2.2. Energy System Scenario Analyses

To support the development of scenarios, data is collected from a variety of sources including the Kenya Power and Lighting Company (KPLC) and the International Energy Agency (IEA) using expert interviews. Data required for this process includes: electricity demand, total installed capacity and electricity generation by fuel type.

To gain a comprehensive understanding of Kenya's current energy mix, a thorough analysis of the existing energy landscape is conducted by examining the electricity demand, total installed capacity, and the electricity generation across different production technologies over an extended period of time of twelve years.

The reference scenario for incrementing PV generation is then developed using the year 2022 as the baseline. This in-depth analysis of the current energy situation formed the foundation of subsequent steps.

The simulation, crucial for understanding the potential impact of widespread RES integration at a national level, is conducted using the EnergyPLAN model to ensure precision and reliability in the findings.

Optimal solar power generation capacity is then modeled based on technical and economic scenarios using EnergyPLAN. This is achieved by running a series of calculations for different input solar capacities until an optimal value is realized.

Determination of the optimal PV generation capacity is a pivotal aspect of this study. A series of calculations was conducted by providing EnergyPLAN with a range of input values between 100 and 10,000 MW. The tool, through its calculations, facilitated the exploration of different incremental scenarios to demonstrate scaling up of PV integration. Input values are systematically varied until the optimal PV capacity is identified. The range of input values provided a spectrum of possibilities, and EnergyPLAN helped pinpoint the capacity that is both technically and economically feasible. The model also computes CO_2 emissions based on the inputs.

3. Reference Scenario Development and Availability of RES

This section focuses on Kenya’s existing electricity scenario as at 2022 and the available resources to meet electricity demand. The following aspects of the electricity scenario are considered:

i. Power Generation: This includes existing power plants in Kenya such as thermal, HEP, geothermal, wind, and solar power plants, as well as the potential for new solar power plants. In Kenya, thermal and HEPs have been the dominant sources of electricity generation, but the potential for solar power generation is significant.

ii. Energy Demand: This includes the energy demand in Kenya for the reference year and the projected demand for the year 2030 which is driven by population growth and economic development (Government of Kenya (Ministry of Energy and Petroleum), 2015). The demand for electricity in Kenya has been growing steadily, and solar power has the potential to meet some of this growing demand.

iii. Energy Storage: This includes dammed hydro storage, which is used to balance the intermittency of solar power. In Kenya, energy storage plays a critical role in managing the intermittency of solar power, especially in areas where the transmission and distribution network is weak.

iv. Economic Parameters: This includes the cost of fuel. In Kenya, the cost of energy production from sources such as thermal and HEP is high *(as shown in table 7),* while the cost of solar power production has been decreasing over time.

Parts of the energy system that have not been included in the analysis in the Kenyan context include micro grids. These are small-scale power grids that can operate independently of the main grid. While they may be relevant for specific regions or communities, they are not relevant to the national energy system in Kenya.

The optimal scenario developed in this paper aims to provide a realistic and achievable scenario for optimizing solar power generation in Kenya's electricity generation mix.

3.1. Electricity Demand

The total electricity demand in Kenya in 2022 was 12,985.4 GWh (KNBS, 2023). Demand for each sector is provided in *Table 1*.

Sector	Demand (GWh)	Percentage (%)
Domestic and Small Commercial	4,291.5	33.04
Large & Medium (Commercial and Industrial)	4,958.2	38.18
Street Lighting	94.2	0.73
Rural Electrification	664.5	5.12
Transmission and distribution losses	2,955.7	22.76
Power Exports	21.3	0.17
Total demand	**12,985.4**	**100**

Table 1:2022 Electricity Demand in Kenya per section in 2022, (KNBS, 2022)

Transmission and distribution losses are attributed to resistance losses, and also to an aging and inefficient transmission and distribution network, as well as illegal power connections, poor metering and inefficient reading of power meters. In 2022 losses accounted for 29.5% of the total generated power (KNBS, 2023).

To boost system efficiency, KPLC has implemented various measures to mitigate losses. These include redistribution and balancing of electrical loads to address technical losses, intensified inspections of customer metering installations to ascertain their health and integrity followed by expeditious corrective measures. Other measures are: deployment of smart metering technology, curtailment illegal connections and use of live line technology in network maintenance thus reducing planned and unplanned outages (Kenya Power, 2022).

While losses are significant and alleviating measures are important, we have maintained the same level of losses in both the reference and in the future scenarios.

3.2. Electricity Production

Over the period spanning from 2010 to 2022, Kenya's overall power production profile exhibited a notable trajectory of growth, as depicted in *Table 2.* The recorded values in TWh for each year reveal a consistent upward trend, showcasing an expansion in the country's power generation capacity from 7.22 TWh in 2010 to 12.65 TWh in 2022. This increase of approximately 5.43 TWh over the 12-year span, reflecting a growth of around 75%, suggests a concerted effort to meet the escalating energy demands within the nation. This upward trend implies several noteworthy impacts. Firstly, the consistent growth in power production aligns with the necessity to cater to the rising energy demands driven by factors such as population growth, urbanization, and industrial development.

Year	Production (TWh)
2010	7.22
2011	7.58
2012	8.09
2013	8.69
2014	8.37
2015	9.87
2016	9.69
2017	10.7
2018	11.25
2019	11.49
2020	11.75
2021	11.83
2022	12.65

Table 2: Electricity Production for Kenya 2010 – 2022 (Ritchie & Roser., 2022)

In 2022, geothermal generation was the largest source of electricity, accounting for 43.6% of total electricity generated. This was followed by HEP at 24.0% while solar contributed only 3%.

Production mode	Actual 2022 (GWh)
Hydropower	3,039.9
Wind power	2,143
Solar PV power	383.7
Condensing power diesel and gas-fired and Biomass Cogeneration)	1,585.2
Geothermal	5,517.5
Import	316.0
Export	21.3
Domestic Supply	**12,985.4**

Table 3:2022 Electricity Production in Kenya in 2022 split on technologies (KNBS, 2022)

3.3. Hourly Distribution Profiles

The hourly production and demand profile become an important consideration for development of the reference and the optimal RES scenarios using EnergyPLAN. Hourly distribution profile files for solar, hydro, wind, and the demand for Kenya in the year 2022 were obtained from (KNBS, 2023) and (Abdulganiyu, 2017). The number of values in the annual production and demand distribution profile will depend on the time resolution of the data. In this study data is presented in hourly intervals, hence there are 8,784 values for the entire year for every distribution file as EnergyPLAN models a leap year.

Analyzing the hourly production and demand distribution profiles allows for a better understanding of the energy system's dynamics throughout the year. It provides insights into the variations in electricity generation and consumption patterns, which can be crucial for optimizing the integration of solar power into the overall energy mix.

The distribution profiles help identify periods of high and low energy demand, as well as times when renewable power generation is most abundant. This information can be utilized to optimize the dispatch and scheduling of different energy sources, including solar, hydro, and wind, to meet the fluctuating electricity demand.

Figures 3 and 4 provides a sample two weeks' hourly cumulative demand and production respectively.

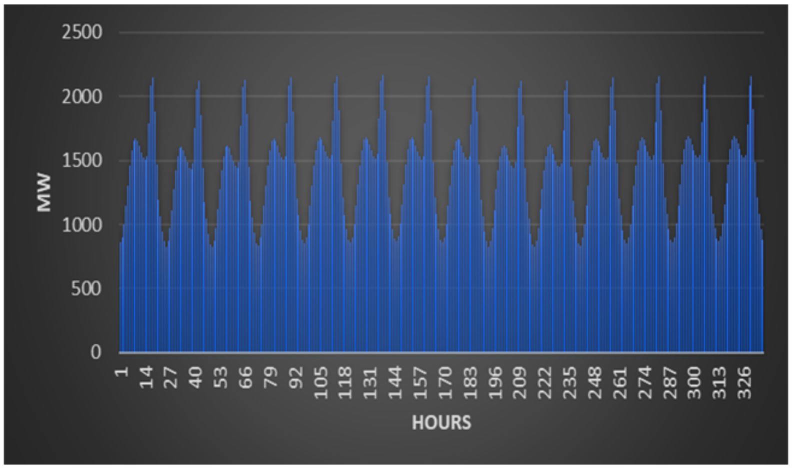

Figure 3: Sample two weeks' of electricity demand for Kenya made using data from (KNBS, 2023)

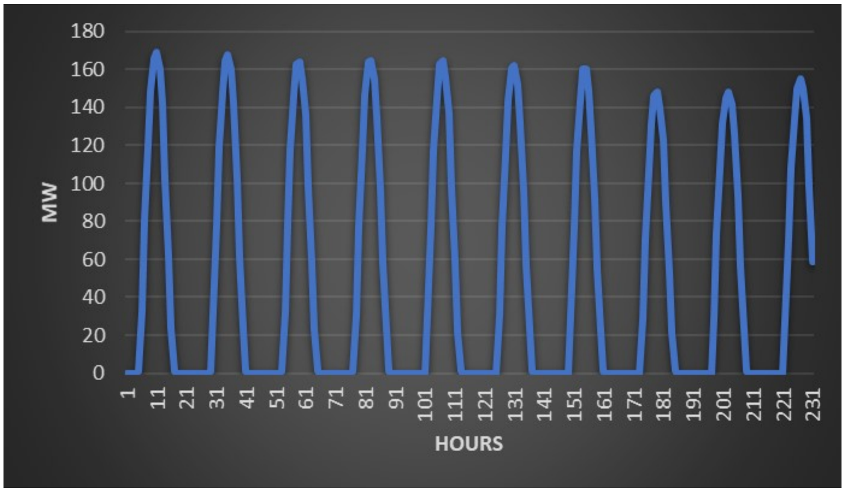

Figure 4: Sample two weeks' of solar electricity production for Kenya made using data from (KNBS, 2023)

Figure 5 gives a sample two weeks' wind power production.

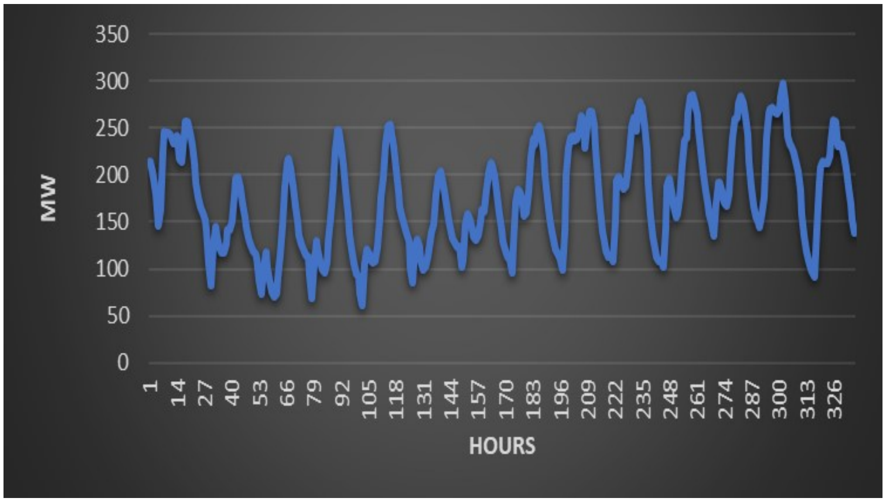

Figure 5: Sample two weeks' wind power production for Kenya made using data from (KNBS, 2023)

The distribution profiles shown in Figures 2-5 show absolute values. The same time series are used as relative weights for other penetration of wind and PV.

3.4. Overall Electricity Capacity Generation and Renewable Resource Availability

The current electricity capacity is given in *Table 4.*

Technology	Total Installed Capacity (MW)
Hydropower	838.9
Geothermal	950.0
Thermal	689.9
Wind	436.1
Solar	212.5
Co-generation	2.0
Imports	200
Total	**3,321.3**

Table 4: Power Capacity as of 31st December 2022 (EPRA, 2022)

3.4.1. Wind Power

Wind power is a growing source of electricity in Kenya; whereas it is still a relatively small part constituting a paltry 13.13% of the country's energy mix, there is significant potential for growth. The country is actively pursuing additional wind power projects to help meet its growing energy needs.

The northern and northeastern parts of Kenya have a significant potential with high wind speeds throughout the year. The country's wind energy potential is estimated at over 3,000 MW, with the potential for more than 5,000 MW of installed capacity by 2030 (IRENA & AfDB, 2022). Kenya has a viable wind energy resource, 73% of the country experiences wind speeds of 6 m/s or higher at a hundred meters above ground level. Of this 28,228 km^2 experiences wind speeds of between 7.5 – 8.5 m/s and 2825 km^2 experiences wind speeds of between 8.5 – 9.5 m/s (EPRA, 2022).

The highest wind can be experienced in the north of the country around the Lake Turkana area with speeds exceeding 8.0 m/s in some areas.

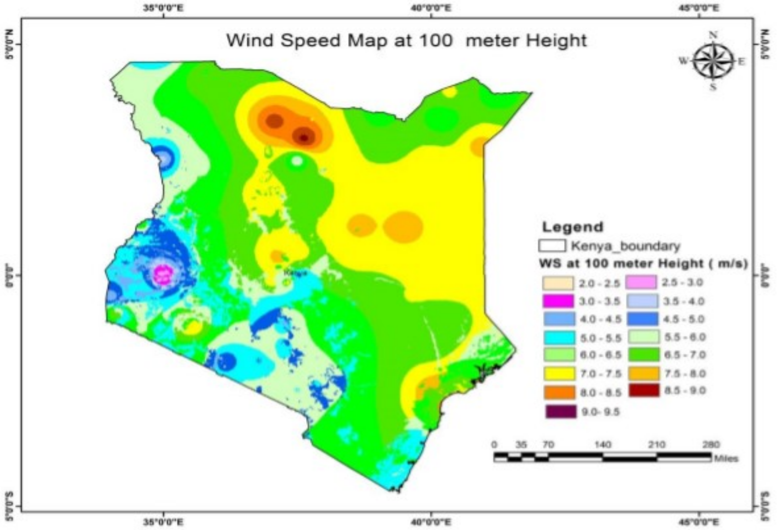

Figure 6: Wind Speed Map (Republic of Kenya, 2014)

There are physical limitations to wind power generation in Kenya, including the cost of wind turbines, the need for grid upgrades and interconnections, and the variable nature of wind resources (Vasquez et al., 2018).

3.4.2. Solar Power

Kenya has the potential of receiving solar radiation of approximately 5 kWh/m^2/day, throughout the year (Opiyo, 2016). The average daily solar energy potential for each month in Kenya is given in *figure 8* and *figure 9*.

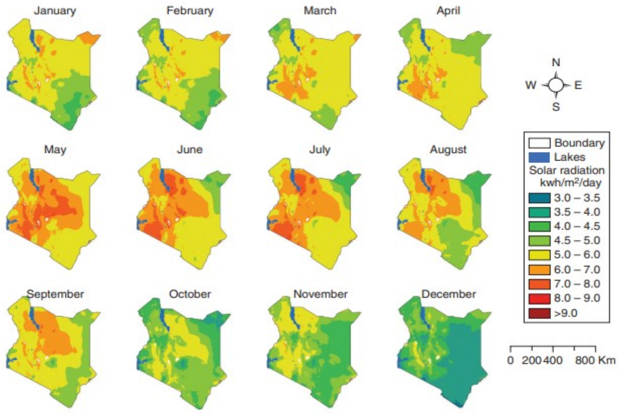

Figure 7: Spatial distribution of Daily Solar Potential in Kenya (kWh/m^2/day (Opiyo, 2016)

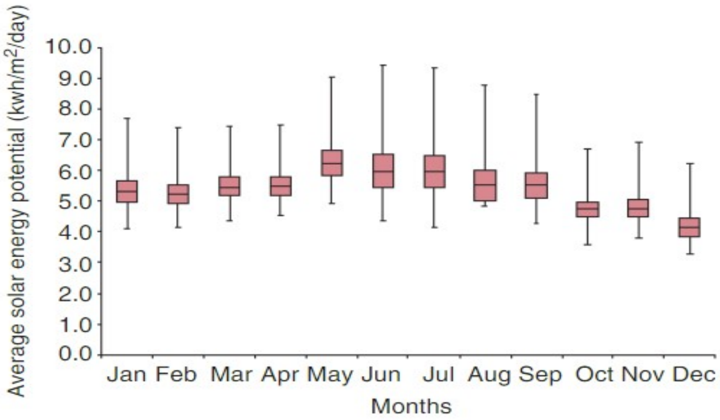

Figure 8: Solar Potential in Kenya averaged per month across the year (Opiyo, 2016).

An area of approximately 188,284 km^2 (32.4%) of the total land in Kenya was predicted to receive between 5.0-5.5 kWh/m^2/day of solar energy, 154,185 km^2 (26.5%) of the land area was estimated to have a potential of receiving between 5.5-6.0 kWh/m^2/day.

An area occupying approximately 58,800 km^2 (10.1%) of the land total land receives a range of between 6.0-6.5 kWh/ m^2/day of solar radiation. In the highest solar energy potential class, approximately 4,230 km^2 (0.7%) of the land area was characterized to receive more than 6.5 kWh/m^2/day of solar radiation. In the lowest solar energy potential category, approximately (176,170 km^2) 30.3% of the land area was estimated to receive less than 5 kWh/m^2/day of solar radiation (Opiyo, 2016).

Approximately 70% of the land area of Kenya has an annual solar energy potential above 5 kWh/m^2/day. Specifically, 32.4% of the land has an average annual solar potential ranging between 5.0-5.5 kWh/m^2/day, additionally, approximately 26.5% of the country's land area has an average annual solar energy potential in the range of 5.5- 6.0 kWh/m^2/day. Further still, above 10.8% of the land area in Kenya has the potential of receiving more than 6 kWh/m^2/day of solar energy. The very high potential areas, that is, the areas which are estimated to receive solar radiation above 6 kWh/m^2/day are mainly located in the high altitude ridges of the rift valley and also in the regions to the east of Lake Turkana and specifically around Marsabit. The spatial distribution of high-potential areas in the country shows that investments in solar energy generation in the high-potential areas can not only ensure adequate load for solar equipment but also increase the accessibility to electricity and other benefits of solar energy resources to more residents of the country especially those who inhabit far-flung rural areas with little or no access to electricity at the moment (Opiyo, 2016).

3.4.3. Hydro Electric Power

HEP is among the largest source of electricity in Kenya. The country had a total installed hydropower capacity of 838.9 MW in 2022 (KNBS, 2023). Hydropower plants contributed about 30% of the national annual electricity generation. There were eight power stations with a capacity of more than 10 MW and each have reservoirs. At least half of the overall potential originated from smaller rivers that are key for the small-hydro resource. Kenya has significant hydropower potential which is estimated to be 6,000 MW. Of this potential, small hydro potential is projected to be slightly above 3,000 MW. The hydropower potential is distributed across the country's five major drainage basins namely; Mt Kenya, Mau Complex, Aberdare Ranges, Cherangani Hills, and Mt Elgon (Samu et al., 2019). *Figure 9* shows water inflow rates into the dams.

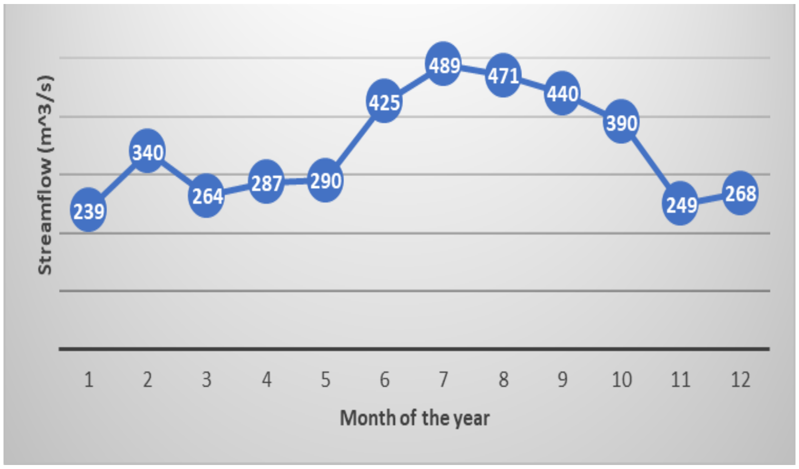

Figure 9: Water inflow to hydro dams in Kenya (Musyoka et al., 2018)

Hydropower generation has a close relationship to precipitation. An increase in precipitation will lead to an increase in power generation vice versa (Samoita.et al, 2019). High power generation is found in a high precipitation period (such as from June to September), while low power generation in low precipitation periods (such as from January to April and December).

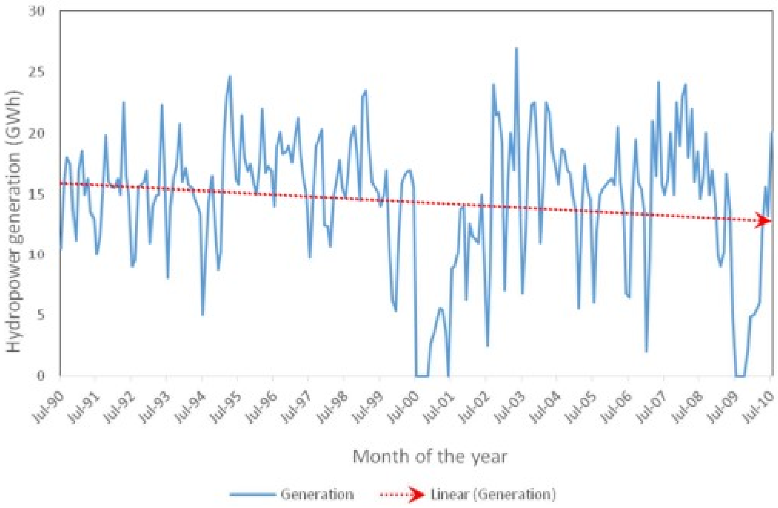

Figure 10: *Evolution of HEP 1990-2010, Kenya* (Musyoka.et *at, 2018)*

Decreasing amounts of precipitation and increasing temperatures have led to declining Masinga dam inflow rates which has led to decreasing HEP generation over the years. Increasing temperatures will also stress the catchments floral biodiversity which may leave the soil bare and therefore susceptible to agents of erosion. Increased erosion rates in the catchment will lead to sediment deposition in the dams thereby reducing the reservoirs storage volume and also reducing overall dam operation efficiency. Extreme climatic events like droughts and floods have also been experienced in the catchment with two major dry periods in 2000/2001 and 2009/2010 (Musyoka et al., 2018).

Despite the significant contribution of HEP to Kenya's electricity mix, there are challenges facing the sector. These challenges include the impact of climate change on water resources, the high cost of developing large-scale hydropower projects, and the impact of hydropower on the environment and local communities.

Power Station	Head (m)	Storage Capacity (GWh)
Wanjii Power Station	115	94.87
Masinga dam	49	33.26
Kamburu	82	72.58
Kindaruma	32	25.57
Kiambere	105.5	139.61
Turkwel	365	561.46
Gitaru	136	126
Tana HEP station		67.7
Gogo	20	18.91
Sondu Miriu	196.9	330
Sangoro		106.2
Total		**1,576.16**

Table 5: 2014 HEP Storage Capacity in Kenya (Lahmeyer, 2020) (Carmen, 2022) (Energypedia, 2015)

3.4.4. Geothermal

Geothermal power remains the most important and growing source of electricity in Kenya, with significant potential for growth and development. Geothermal power has several advantages over other sources of electricity in Kenya, including its reliability, affordability, and low carbon footprint. The development of geothermal power also provided economic benefits to the surrounding communities, including job creation and infrastructure development.

Geothermal power plants in Kenya are operated using a combination of technologies and operational strategies to ensure reliable and efficient power generation. Typically, geothermal plants operate in base-load mode, which means they run at a constant level without any load-following operation.

The operation of geothermal power plants in Kenya involves several key steps. First, steam is extracted from underground reservoirs using wells and fed into a steam turbine generator. The steam drives the turbine, which in turn drives a generator to produce electricity.

To ensure reliable operation, geothermal power plants in Kenya are designed to optimize the flow of steam from the reservoirs to the turbine. This may involve using control systems to regulate the flow and pressure of the steam, as well as monitoring systems to detect any abnormalities or changes in the performance of the plant.

Despite the growth of geothermal power in Kenya, there are also challenges facing the sector. These challenges include the high upfront costs of developing geothermal power projects, the technical challenges of drilling and maintaining geothermal wells, and the impact of geothermal power on local communities and the environment. To mitigate these technical challenges, the Kenyan government has tasked Geothermal Development Corporation to build capacity through manpower training.

3.4.5. Biomass Cogeneration

Biomass cogeneration power is a significant source of electricity in Kenya. The majority of biomass cogeneration power in Kenya is generated by the sugar industry, with several sugar mills in the country producing both sugar and electricity (ERC, 2019). These mills use sugarcane waste, known as bagasse, as fuel to generate electricity, which is then used to power the mills and sold to the national grid.

Biomass cogeneration remains an important source of electricity in Kenya in 2022 and is expected to continue to play a significant role in the country's energy mix in the coming years, particularly as the government continued to promote investment in the sector.

3.4.6. Condensing-mode Power Plants

Condensing-mode power plants fueled by diesel and gas are a potential source of electricity in Kenya. These power plants typically use turbines and generators to produce electricity, with the exhaust heat from the turbine being used to produce steam, which is then used to generate additional electricity in combined cycle operation (Simiyu, et al., 2014).

The condensing power plants fueled by diesel and gas play a role in Kenya's electricity mix in 2022, particularly in providing additional capacity to the grid during times of high demand.

4. Results and Discussion

This section presents and discusses simulation results obtained from EnergyPLAN. These include: validation of the reference scenario, analysis of seasonal operation and optimal PV integration scenario.

4.1. Reference Scenario Validation

To validate the simulation tool and simulation process, simulation results are compared with measured data obtained from Energy and Petroleum Regulatory Authority (EPRA – a government body responsible for technical and economic regulation of energy and petroleum subsectors in Kenya).

Variation between measured data and simulation results is **0.216 %.** This shows that the simulation process closely matches actual data hence validating the software and simulation process.

Production Mode	Actual (TWh)	Simulation (TWh)	Variation (TWh)
HEP	3.04	3.04	0.00
Wind power	2.14	2.14	0.00
Solar PV power	0.383	0.38	0.003
Condensing power	1.58	1.57	0.01
Geothermal	5.52	5.55	-0.003
Import	0.316	0.34	-0.024
Export	-0.021	-0.015	-0.006
Net Supply	12.98	13.005	-0.028
Variation Percent			**0.216**

Table 6: Comparison of Simulation and Measured Data made using data from (EPRA, 2022)

4.2 Analysis of Seasonal Operation

Sample weekly demand and production is given in *Figure 11*. Throughout this week, demand was always higher than production. High electricity demand is experienced during working hours in the morning when industrial operations are busiest. Electricity demand peaks towards evening hours when most of the domestic consumers get to their homes and turn on appliances. During nighttime electricity demand is relatively constant and low since industrial operations, service industry and domestic use are minimal.

From *Table 3,* Solar and wind energy account for just 20% of the total electricity produced in a day, while thermal, geothermal, and hydropower accounted for about 91% of the total electricity produced. Imports accounted for about 5% of the total electricity produced. This demand is met with domestic electricity supply and supplemented with power imports from Uganda's hydroelectric power station at Jinja and Ethiopia.

This shows a good prospect and justification to scale up solar power production to replace thermal, hydropower and imported electricity for the reasons earlier highlighted in this paper.

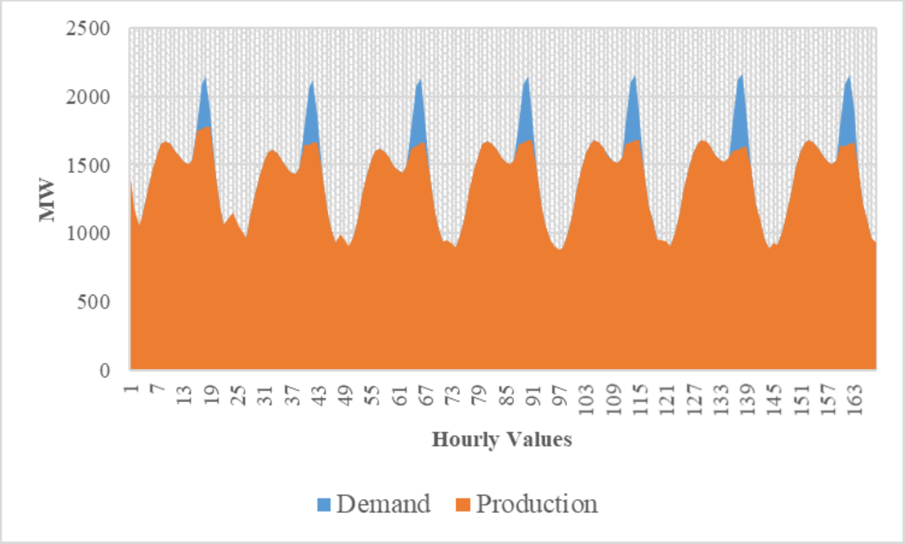

Figure 11: Sample Weekly Electricity Demand & Production for 2022 made using data from (EPRA, 2022) *&* (KNBS, 2023)

Electricity demand and production for a typical month for the reference year are presented in *Figure 12*. For this sampled month, peak demand was witnessed on the 21st day. Throughout the month, the actual consumption of electricity exceed production hence the justification for the need to explore newer sources of electricity supply to plug this demand.

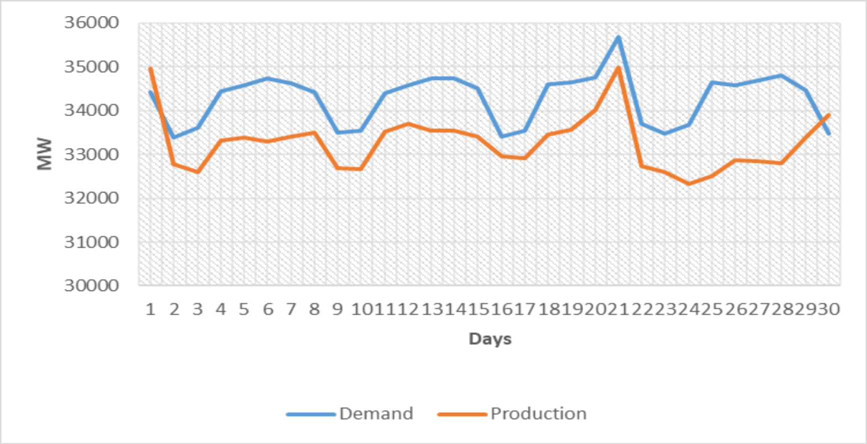

Figure 12: Monthly Electricity Demand and Production for 2022 made using data from (EPRA, 2022) *&* (KNBS, 2023)

4.3. Economy of The Reference Scenario

For the reference scenario, the total annual cost that is incurred in the system for electricity production is 1,246 MEUR as captured in *Table* 7.

In the reference scenario, the annual cost for electricity production in the system amounts to 1,246 MEUR, as outlined in *Table 7*. This cost encompasses various components, including 11 MEUR for natural gas exchange, while other fuel sources such as coal, fuel oil, gasoil/diesel, petrol/JP, biomass, food income, and waste incur no expenses. Natural gas exchange accounts for an additional cost of 243 MEUR, and marginal operation costs stand at 93 MEUR. The electricity exchange component involves a total cost of 20 MEUR, comprising 38 MEUR for imports, -18 MEUR for exports, and zero costs for bottleneck and fixed import/export. CO_2 emission costs contribute 43 MEUR to the total. Variable costs, encompassing diverse factors, amount to 410 MEUR, while fixed operation costs and annual investment costs reach 248 MEUR and 587 MEUR, respectively.

ANNUAL COSTS (M EUR)	**TOTAL:**	**VARIABLE:**	**BREAKDOWN:**
Fuel ex. Ngas exchange		11	
Coal			0
FuelOil			0
Gasoil/Diesel			0
Petrol/JP			0
Gas handling			11
Biomass			0
Food income			0
Waste			0
Ngas Exchange costs		243	
Marginal operation costs		93	
Electricity exchange		20	
Import			38
Export			-18
Bottleneck			0
Fixed imp/exp			0
CO_2 emission costs		43	
Variable costs	410		
Fixed operation costs	248		
Annual Investment costs	587		
TOTAL ANNUAL COSTS	1246		

Table 7: System Energy Costs for the Reference Scenario made using data from (EPRA, 2022)

Table 8 provides data on carbon dioxide gas emissions for the reference scenario measured in metric tons (Mt). The emissions are categorized into two segments: total CO_2 emissions and corrected CO_2 emissions. Total CO_2 emissions for the reference year scenario are recorded at 1.514 Mt, representing the unadjusted carbon dioxide output resulting from our energy operations. To provide a more precise assessment of our environmental impact, the table also presents corrected CO_2 emissions, which stand at 1.647 Mt. These corrected emissions take into account relevant fuel adjustments, offering a more accurate reflection of the carbon footprint associated with energy activities.

ANNUAL CO_2 EMISSIONS (Mt):	
CO_2-emission (total)	1.514
CO_2-emission (corrected)	1.647

Table 8: CO_2 emissions for the reference scenario made using data from (EPRA, 2022)

Table 9 provides RES metrics, illustrating the RES share of primary energy supply (PES), the RES share of electricity production, and the annual RES electricity production, quantified in TWh/year.

The RES share of PES for the reference scenario in 2022 is at 58.4%, indicating a significant portion of primary energy supply is sourced from renewable sources. Simultaneously, the RES share of electricity production stands at 71.3%, underscoring the dominance of RE in our electricity generation portfolio. The annual RES electricity production for the reference year scenario is 9.04 TWh/year.

SHARE OF RES	
RES share of PES	58.4%
RES share of elec. prod.	71.3%
RES electricity prod.	9.04 TWh/year

Table 9: Reference Scenario share of RES made using data from (EPRA, 2022)

4.3. Incremental PV Integration Scenarios

This sub section considers stepwise increase of PV integration into Kenya's electricity mix and analyses its effect on the electricity grid stability, the cost of this increment as well share of carbon dioxide gas emissions.

4.2.1. 20% PV Integration Scenario

With the aim of incrementing solar energy capacity and establishing a sustainable and renewable energy landscape, the first step focuses on achieving 20% increase in PV capacity. To realize this objective, generated solar capacity is increased to 2,879 MW through serial calculations in EnergyPLAN up from the initial 212.5 MW, as indicated in *Table 4*.

As of 2022, solar power contributed only 0.384 TWh, representing approximately 3% of total domestic power supply, as outlined in *Table 3*. Solar power capacity of 2,879 MW yields annual solar energy production of 5.06 TWh which has the potential to provide 20% of total electricity demand. For this output to be realized, the total annual cost incurred is 2,017 MEUR as shown in *table 10.*

ANNUAL COSTS (M EUR)	TOTAL:	VARIABLE:	BREAKDOWN:
Fuel ex. Ngas exchange		18	
Coal			0
Fuel Oil			0
Gasoil/Diesel			0
Petrol/JP			0
Gas handling			18
Biomass			0
Food income			0
Waste			0
Ngas Exchange costs		392	
Marginal operation costs		98	
Electricity exchange		429	
Import			429
Export			-1
Bottleneck			0
Fixed imp/exp			0
CO_2 emission costs		70	
Variable costs	1007		
Fixed operation costs	267		
Annual Investment costs	744		
TOTAL ANNUAL COSTS	2017		

Table 10: System Electricity Costs for 20% PV Increase Scenario made using data from (KNBS, 2023) *&* (EPRA, 2022)

It's important to acknowledge that PV integration of such magnitude impacts on grid stabilization. According to the obtained simulation results in EnergyPLAN for this scenario, grid stabilization measure stands at 100%. This indicates that electrical grid's stability and reliability is maintained, allowing for the seamless integration of the increased solar energy capacity with the existing infrastructure.

To provide a comprehensive overview of the operational dynamics within the 20% PV increase scenario, *Figure*

13 presents a depiction of the demand and supply curves spanning a two-week period. Production exceeds demand for this duration which affirms that this scenario is satisfactory.

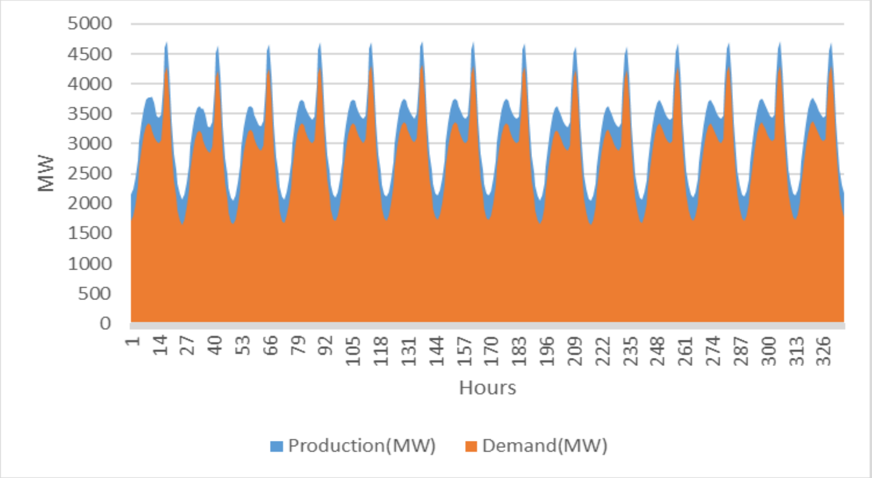

Figure 13: Two Weeks' Demand & Production for 20% PV Increase Scenario made using data from (EPRA, 2022) & (KNBS, 2023)

Table 11 presents an overview of the annual CO_2 emissions, both total and corrected, expressed in metric tons (Mt) obtained from the EnergyPLAN simulation for this scenario. It incorporates import/export adjustments to accurately determine the carbon footprint associated with energy production.

Annual CO_2 emissions (Mt):	
CO_2-emission (total)	2.446
CO_2-emission (corrected)	5.223

Table 11: Annual CO_2 Emissions for 20% PV Increase Scenario made using data from (EPRA, 2022) & (KNBS, 2023)

Table 12 presents RES metrics, including the RES share of primary energy supply (PES), the RES share of electricity production, and the annual RES electricity production measured in TWh/year.

Share of RES	
RES share of PES	55.8%
RES share of elec. prod.	54.4%
RES electricity prod.	13.76 TWh/year

Table 12: Share of RES for 20% PV increase scenario (KNBS, 2023) & (EPRA, 2022)

4.3.2. Optimal PV Integration Scenario

This sub section gives simulation results for the optimal PV generation scenario. Technical simulation is based on the technical abilities of the components within the energy system. The difference between demand and supply is met as long as the power-producing units are capable of completing the task.

Solar power can be boosted to 4,601 MW in this scenario to supply **31.96%** of the total electricity generated. This was achieved by running a series of serial simulations, where the input is defined as a series of different Solar PV units, and defining the output as the total cost for the referenced Energy system, under the Technical Simulation option.

For this scenario, the total annual cost incurred to optimize solar power production is 970 MEUR as shown in *Table 13*. Compared with the reference scenario whose cost is 1246 MEUR, the optimal scenario is economical besides supplying additional electricity from RES that will replace thermal sources.

Recognizing the significance of incorporating such a substantial PV energy capacity, it is crucial to consider and ensure that grid stability is maintained. As indicated by the output data from EnergyPLAN for this scenario, the grid stabilization measure remains at an optimal 100%. This outcome underscores the fact that the stability and dependability of the electrical grid are upheld, facilitating the smooth assimilation of the augmented solar energy capacity into the existing infrastructure which forms the basis for the upper limit of PV penetration in the system.

ANNUAL COSTS (M EUR)	**TOTAL:**	**VARIABLE:**	**BREAKDOWN:**
Fuel ex. Ngas exchange		5	
Coal			0
FuelOil			0
Gasoil/Diesel			0
Petrol/JP			0
Gas handling			5
Biomass			0
Food income			0
Waste			0
Ngas Exchange costs		113	
Marginal operation costs		88	
Electricity exchange		-377	
Import			29
Export			-428
Bottleneck			21
Fixed imp/exp			0
CO_2 emission costs		20	
Variable costs	-152		
Fixed operation costs	279		
Annual Investment costs	845		
TOTAL ANNUAL COSTS	**970**		

Table 13: System Electricity Costs for Optimal Scenario made using data from (KNBS, 2023)

Table 14 presents the annual CO_2 emissions data, measured in metric tons (Mt). These emissions are classified into two categories: total CO_2 emissions and corrected CO_2 emissions. The total CO_2 emissions stand at 1.934 Mt, reflecting the raw output of carbon dioxide generated as a result of energy operations. The table also includes corrected CO_2 emissions, which account for import/export adjustments.

Annual CO_2 emissions (Mt):	
CO_2-emission (total)	1.934
CO_2-emission (corrected)	3.839

Table 14: Annual CO_2 Emissions for Optimal Scenario (KNBS, 2023)

Table 15 presents RES metrics within the optimal scenario for PV integration, including the RES share of primary energy supply (PES), the RES share of electricity production, and the annual RES electricity production measured in TWh/year.

Share of RES	
RES share of PES	65.8 %
RES share of elec. prod.	66.5 %
RES electricity prod.	16.82 TWh/year

Table 15: Share of RES for the optimal scenario (KNBS, 2023)

Two weeks' operation of the optimal scenario gives results shown in *Figure 14 and 15.* Production exceeds demand for this scenario throughout the two weeks and the electricity system is stable.

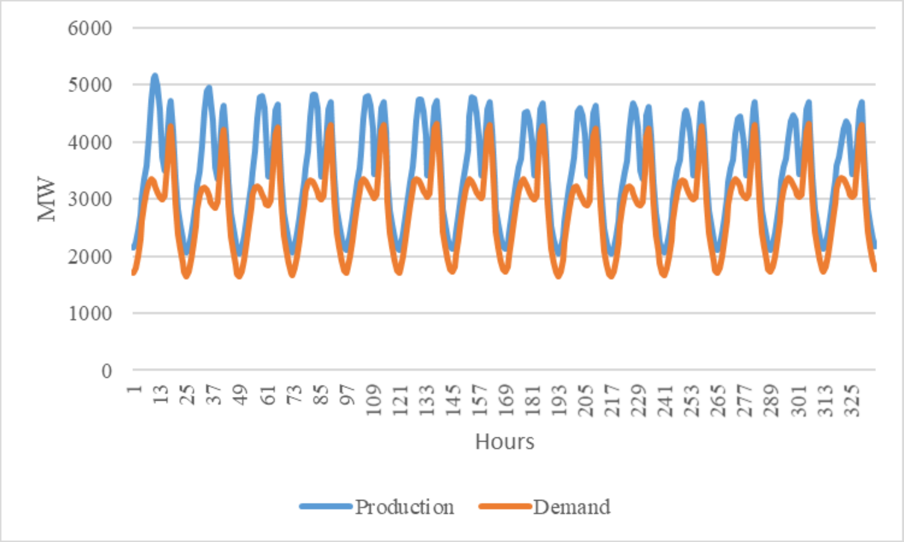

Figure 14: Two Weeks' Demand & Production for Optimal Scenario made using data from (KNBS, 2023)

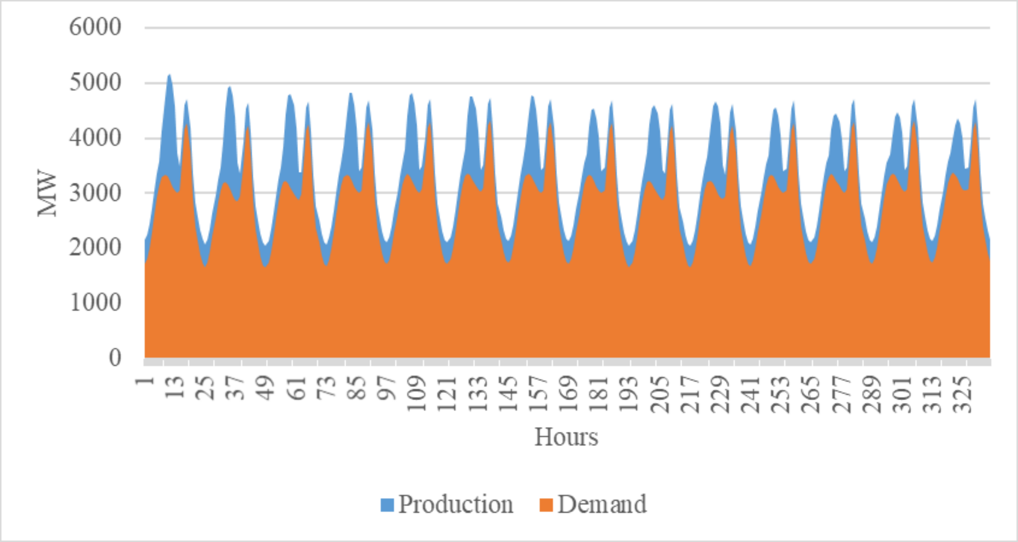

Figure 15: Two Weeks' Demand & Production for Optimal Scenario made using data from (KNBS, 2023)

5. Conclusion

In spite of the demonstrated large potential of solar power, current exploitation is still limited, and projections show a modest growth that may not even match the increase in electricity and general energy consumption. Also, a predominant focus in the existing studies on Kenya is on the potential of PV as a source of RES from a technical perspective and with a particular focus on stand-alone applications. While other countries especially more economically developed already target an increased PV exploitation even with poorer solar insulation conditions than Kenya, the country is still lagging behind in this respect.

Increasing electricity demand has prompted the need to seek clean, cost effective and sustainable alternatives to traditional fossil-based electricity sources. Renewables help to modernize power system operations particularly where renewable energy resources are abundant. As a result, the current study investigated the economic and technical viability of scaling up solar electricity generation to meet the national electricity demand for Kenya. The reference scenario is based on Kenya's electricity demand and production for 2022. The optimal solar power scenario is based on Kenyan government's vision 2030 economic development master plan and other existing policies. The study is conducted using EnergyPLAN.

The results obtained show that it is technically and economically feasible to increase solar power capacity production to 4,601 MW. This will represent 31.96% of the total generated power. The total annual cost for this investment is 970 MEUR. In comparison, by the end of 2022, the total solar power capacity was 212.5 MW representing 6.8% of the total installed capacity; the total annual cost for operating the reference scenario is 1246 MEUR. These results show that optimizing solar electrification presents great benefits in terms of cost effectiveness, CO_2 emissions reduction, reliability improvements in the future and security of Kenya's power system.

The following recommendations are aimed at future research: the viability of including RES; further analysis can be undertaken on the issue of voltage and frequency stability of grid connected RES too

RES are not available around the clock, which creates intermittency. RES generation does not always align with peak demand hours, causing grid stress due to fluctuations and power peaks. Unpredictable weather events can disrupt these technologies. The current infrastructure as currently designed does not support energy storage. RES, such as solar and wind power, can be unpredictable and generate surplus energy. Efficient storage systems are needed to store excess energy during low demand and release it when demand is high.

The stochastic nature of solar and wind makes the frequency and voltage produced unstable. Renewable energy affects power quality by increasing voltage fluctuations i.e. when there's an overabundance of renewable energy at some points, voltage may spike or dip more than normal. This could lead to fluctuating frequency hence the need to further investigate stability of grid connected renewable energy technologies.

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Conflicts of Interest: The authors declare no conflict of interest.

References

Abdulganiyu, I. O. (2017). *POSSIBILITIES AND BARRIERS FOR INCREASING RENEWABLE Lappeenranta University of Technology* (Lappeenranta University of Technology). Retrieved from https://lutpub.lut.fi/handle/10024/135170

Aghahosseini, A., Bogdanov, D., & Breyer, C. (2020). Towards sustainable development in the MENA region: Analysing the feasibility of a 100% renewable electricity system in 2030. *Energy Strategy Reviews*, *28*(January), 100466. https://doi.org/10.1016/j.esr.2020.100466

Chouder, A., Silvestre, S., Taghezouit, B., & Karatepe, E. (2013). Monitoring, modelling and simulation of PV systems using LabVIEW. *Solar Energy*. https://doi.org/10.1016/j.solener.2012.09.016

Dioha, M. O., Duan, L., Ruggles, T. H., Bellocchi, S., & Caldeira, K. (2022). Exploring the role of electric vehicles in Africa's energy transition: A Nigerian case study. *IScience*, *25*(3), 103926. https://doi.org/10.1016/j.isci.2022.103926

Elmer, U., Gregersen, C., Lema, R., Samoita, D., & Wandera, F. (2018). *Energy Research & Social Science Technological shape and size : A disaggregated perspective on sectoral innovation systems in renewable electri fi cation pathways*. (July 2017).

EPRA. (2022). Petroleum Statistics. In *ENERGY & PETROLEUM STATISTICS REPORT*. https://doi.org/10.1021/ie50147a014

ERC. (2019). Energy Regulatory Commission - Biomass. Retrieved April 1, 2020, from http://erc.go.ke/index.php?option=com_fsf&view=faq&catid=2&faqid=14

Goran Gašparović a, Goran Krajačić a, Neven Duić a, M. B. b. (2014). New Energy Planning Software for Analysis of Island Energy Systems and Microgrid Operations – H2RES Software as a Tool to 100% Renewable Energy System. *Computer Aided Chemical Engineering*. Retrieved from https://doi.org/10.1016/B978-0-444-63455-9.50144-6

Government of Kenya (Ministry of Energy and Petroleum). (2015). *Draft National Energy and Petroleum Policy*. 1–130.

Hansen, U. E., Gregersen, C., Lema, R., Samoita, D., & Wandera, F. (2018). Technological shape and size: A disaggregated perspective on sectoral innovation systems in renewable electrification pathways. *Energy Research and Social Science*, *42*, 13–22. https://doi.org/10.1016/j.erss.2018.02.012

Homer Energy. (2019). Homer Pro. Retrieved September 4, 2023, from Manual Homer Energy website: https://www.homerenergy.com/pdf/HOMER2_2.8_HelpManual.pdf

IRENA and AfDB. (2022). Renewable Energy Market Analysis : Africa and Its Regions, International Renewable Energy Agency and African Development Bank, Abu Dhabi and Abidjan. In *Energy Market*.

KNBS. (2023). *Providing, Managing and Promoting Quality Statistics*.

Loulou, R., Goldstein, G., Kanudia, A., Lettila, A., & Remme, U. (2021). Documentation for the TIMES Model - Part 1. *IEA Energy Technology Systems Analysis Programme*, (April), 1–78.

Lund, H. (2015). *EnergyPLAN*. (January).

Lund, H., Thellufsen, J. Z., Østergaard, P. A., Sorknæs, P., Skov, I. R., & Mathiesen, B. V. (2021). EnergyPLAN – Advanced analysis of smart energy systems. *Smart Energy*, *1*, 100007. https://doi.org/10.1016/j.segy.2021.100007

Moner-Girona, M., Bódis, K., Morrissey, J., Kougias, I., Hankins, M., Huld, T., & Szabó, S. (2019). Decentralized rural electrification in Kenya: Speeding up universal energy access. *Energy for Sustainable Development*, *52*, 128–146. https://doi.org/10.1016/j.esd.2019.07.009

Musyoka, F. K., Wambua, R. M., & Mutua, B. M. (2018). *Effect of Streamflow on Hydro-Power Generation in the Upper Tana River Basin, Kenya*. (April).

Oloo, F., Olang, L., & Strobl, J. (2016). Spatial Modelling of Solar Energy Potential in Kenya. *International Journal of Sustainable Energy Planning and Management*, *06*, 17–30. https://doi.org/10.5278/ijsepm.2015.6.3

Opiyo, N. (2016). A survey informed PV-based cost-effective electrification options for rural sub-Saharan Africa. *Energy Policy*, *91*, 1–11. https://doi.org/10.1016/j.enpol.2015.12.044

Østergaard, P. A., Lund, H., Thellufsen, J. Z., Sorknæs, P., & Mathiesen, B. V. (2022). Review and validation of EnergyPLAN. *Renewable and Sustainable Energy Reviews*, *168*(June). https://doi.org/10.1016/j.rser.2022.112724

Østergaard, Poul Alberg. (2009). Reviewing optimisation criteria for energy systems analyses of renewable energy integration. *Energy*, *34*(9), 1236–1245. https://doi.org/10.1016/j.energy.2009.05.004

Østergaard, Poul Alberg, Andersen, A. N., & Sorknæs, P. (2022). The business-economic energy system modelling tool energyPRO. *Energy*, *257*, 124792. https://doi.org/10.1016/j.energy.2022.124792

Oyewo, A. S., Bogdanov, D., Aghahosseini, A., Mensah, T. N. O., & Breyer, C. (2022). Contextualizing the scope, scale, and speed of energy pathways toward sustainable development in Africa. *IScience*, *25*(9), 104965. https://doi.org/10.1016/j.isci.2022.104965

Power, K. (2022). *& Financial Statements Powering a Sustainable Future*. (June).

RETScreenExpert. (2022). Clean Energy Management Software. Retrieved September 4, 2023, from Ottawa, Canada website: https://doi.org/10.1016/B978-0-444-63455-9.50144-6

Ritchie, H., Roser, M., & R. (2022). *kenya @ ourworldindata.org*. Retrieved from https://ourworldindata.org/energy/country/kenya

Salah, S. I., Eltaweel, M., & Abeykoon, C. (2022). Towards a sustainable energy future for Egypt: A systematic review of renewable energy sources, technologies, challenges, and recommendations. *Cleaner Engineering and Technology*, *8*(December 2021), 100497. https://doi.org/10.1016/j.clet.2022.100497

Samoita, D., Nzila, C., Østergaard, P. A., & Remmen, A. (2020). Barriers and solutions for increasing the integration of solar photovoltaic in kenya's electricity mix. *Energies*, *13*(20). https://doi.org/10.3390/en13205502

Samoita, Dominic, Remmen, A., Nzila, C., & Østergaard, P. A. (2019). *Renewable Electrification in Kenya: Potentials and Barriers*. Copenhagen/Nairobi/Eldoret.

Samu, R., Poyrazoglu, G., & Fahrioglu, M. (2019). The Potential and Economic Analysis of Grid-connected Solar PV Power in Kenya. *Proceedings - 2019 IEEE 1st Global Power, Energy and Communication Conference, GPECOM 2019*, (July), 298–301. https://doi.org/10.1109/GPECOM.2019.8778467

Simiyu, J., Waita, S., Musembi, R., Ogacho, A., & Aduda, B. (2014). Promotion of PV uptake and sector growth in kenya through value added training in PV sizing, installation and maintenance. *Energy Procedia*, *57*, 817–825. https://doi.org/10.1016/j.egypro.2014.10.290

Sterl, S. (2021). A Grid for all Seasons: Enhancing the Integration of Variable Solar and Wind Power in Electricity Systems Across Africa. *Current Sustainable/Renewable Energy Reports*, *8*(4), 274–281. https://doi.org/10.1007/s40518-021-00192-6

Sulley, M., Acakpovi, A., Adjei, P., Sackey, D. M., Offei, F., Afonope, M., … Tay, G. (2022). Techno-Economic Assessment of Grid Connected Solar PV/Wind hybrid System. *IOP Conference Series: Earth and Environmental Science*, *1042*(1), 0–15. https://doi.org/10.1088/1755-1315/1042/1/012016

Tsuma, M., & Kibaara, S. (2022). Review and Assessment of the Technoeconomic Tools for Power Systems with Renewable Energy Penetration in Kenya. *Proceedings of the Sustainable Research and …*, 45–49. Retrieved from https://sri.jkuat.ac.ke/jkuatsri/index.php/sri/article/view/345%0Ahttps://sri.jkuat.ac.ke/jkuatsri/index.php/sri/article/download/345/312

Vasquez, L. O. P., Meneses, C. A. C., Martínez, A. P., Redondo, J. L., García, M. P., & Hervás, J. D. Á. (2018). Optimal energy management within a microgrid: A comparative study. *Energies*, *11*(8), 1–22. https://doi.org/10.3390/en11082167

Wambui, V., Njoka, F., Muguthu, J., & Ndwali, P. (2022). Socio-Techno-Economic Assessment of Electricity Development Scenarios in Kenya Using Low Emissions Analysis Platform and the Next Energy Modeling System for Optimization. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4078697