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Potential of Accelerated Integration of Solar Electrification in Kenya's Energy System

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Abstract
The global electricity demand is rapidly growing due to population increase and industrialization. However, the reliance on fossil fuels and other non-renewable energy resources has resulted in climate change and other unsustainability-related issues. This study aims to determine the significant penetration levels of solar PV (solar photovoltaic) on system operations and production costs based on the current year (business as usual scenario) and the accelerated solar PV scenario (hypothetical future) in the Kenyan electricity generation system. A one-year dynamic analysis based on an hourly time step energy demand was performed using the energy PLAN simulation tool. The current peak demand for electricity in Kenya was established to be 2,056.67 MW with an installed capacity of 3,074.34 MW with a 2.47% contribution by solar PV, while the curtailed energy was 285.51 GWh. The simulation results showed that large-scale installations of solar PV can decrease CO_2-equivalent emissions from 0.134 Mt to 0.021 Mt. Both scenarios are presented in terms of their ability to avoid excess electricity production regarding system operations and production costs. Increasing the share of solar PV in electricity generation is possible by as much as 39.56% (technical) and 30.54% (market economic) simulation. Additionally, the solar PV electricity produced increased to 19.76 TWh/year from 11.90 TWh/year. Furthermore, the market economic simulation showed that the total investment annual cost for solar PV in the hypothetical future was low at 10 mEUR/Year. Therefore, large-scale installation of solar PV in Kenya's energy system is feasible and economically viable based on technical analysis and economic analysis.

Keywords: *Solar PV, Energy PLAN, Renewable energy sources, Technical simulation, Market economic simulation.*

1. Introduction

The demand for electrical energy has been growing rapidly at an average rate of 6% per annum due to population increase and industrialization [1]. Additionally, a report by EIA (2016) states that the global energy demand is projected to increase by 48% within the next 28 years. Due to the unsustainability of fossil-based fuels, a majority of nations' energy sectors are pushing toward green renewable energy sources (RESs) [3]. Currently, the application of RESs for electricity generation has increased aiming to achieve sustainability, power quality, and reliability due to the growing demand [3].

Kenya's national plan for increasing electricity access rates from below 25% in 2010 to 40% by the year 2030 [2, 4] focuses on expanding public and private investment in coal, large geo-thermal, and gas-power plant projects [5]. However, these projects require large upfront investment costs, and historically they have a low power sector investment throughout the entire Sub-Saharan Africa (SSA) region [6]. Therefore, there is a need to exploit an alternative approach that emphasizes incremental investment in utility-scale solar photovoltaic (Solar PV).

Studies have shown that Kenya can generate more power from solar PV than the total power consumed per year from the national grid [7]. However, solar PV has not been fully exploited compared to other RESs, i.e. geo-thermal and wind [8, 9]. The strategy to increase investment in utility-scale solar PV is attractive in the SSA countries for several reasons. Firstly, solar PV installations have a short construction time, and it is easy to deploy them on a smaller scale and increment investments continuously over time thereby providing an advantage for energy systems planners against load growth uncertainty, thus reducing the investment risk [10, 11]. Secondly, solar PV can be constructed near load centers, thereby eliminating costly investments in transmission infrastructures [11]. Lastly, solar PV plants can substitute the costly diesel power plants, thereby reducing the total production costs so long as other RESs can compensate for solar PV's intermittency [12]. However, the main hindrance to solar PV power generation is the intermittent nature of the RES [13].

More research has been directed toward the impacts of intermittent RES generation on both short-term system operations and long-term capacity expansion planning [14]. In short-term system operations, solar PV output variation and uncertainty present several challenges in solar integration [14]. Osman [15] presented a detailed report on the effects of intermittent RESs on system stability operating reserves, market prices, and cycling of thermal power plants. At low penetration levels, solar PV generation can substitute and complement expensive generators and thus reduce the average production costs [12]. However, with increasing penetration levels, there is an increased cost of cycling conventional thermal plants and storage such as pumped hydro or batteries to smoothen the ramping rates and to improve the response to system disturbances [16]. Additionally, for systems with reservoir hydropower capacity, joint coordination of solar PV and hydrogeneration is necessary to reduce the cycling of thermal generators and net peak loads [17, 18].

The determination of the optimum penetration levels of intermittent RESs has also been an area of interest; most research focuses on developing long-term planning models as a solution such as multistage stochastic optimization and dynamic optimal just to mention a few [19–21]. Baurzhan & Jenkins [22] presented that solar PV penetration is limited due to the ramping limitations of existing generators, hence, there is a need to synchronize the intermittent generation and demand. Thus flexibility as a constraint (level of intermittent renewable energy penetration) has to be factored in during conventional planning processes [23]. Wogrin [24] introduced the concept of system states to load levels to represent outcomes of the market and systems costs in a chronological sequence and accurate manner instead of using the load levels. However, if the system has sufficient flexible generation, a curve for the net load duration is applied to plan the generation mix [25, 26].

The main barrier to solar PV deployment as cited by the government of Kenya is high capital costs [27]. Therefore, the government hasn't included it as a contender resource in the recently updated long term power system plan (2011 – 2031 plan) [27]. However, these findings were based on outdated (2005) cost reports from the US and Europe [28]. With the current development in technology, solar module prices have decreased [29, 30] and studies have demonstrated that economic evaluations based on out-of-date data will overestimate the implementation costs of solar PV [31, 32]. Lai & McCulloch [33], and Olson [34] approximated the Levelized Cost Of Electricity (LCOE) for solar PV-based grid connection. Moreover, these studies have also reported that solar PV has having competitive edge in comparison with fossil-based power plants in use currently. Additionally, Rose [11] presented similar outcomes of price comparisons between global markets. LCOE comparisons, however, fail to take into consideration the synergies between solar generation and demand or the effects of adopting new technologies on the existing plants operating modes [33].

Lai & McCulloch [33] introduced the LCOE system that takes the integration and variable costs of intermittent renewables into account. Another option is to forego LCOE comparisons in favor of estimating the avoided costs from greater usage of renewable energy, which would entail utilizing site-specific solar data and current tariff rates to get the avoided energy costs [11, 33, 34]. Furthermore, for various levels of solar PV penetration, time blocks, and load duration curves, it's best to avoid using cost metrics for the various solar PV levels [11].

Additionally, studies on forecasting the time-variant nature of solar irradiation have received much focus due to the significant limits to both short and long-term prediction of solar PV as an energy resource and the effects of climate change [35]. Furthermore, solar PV generation has low conversion efficiency thus unreliable for constant production in addition to low inertia and harmonics problems due to direct current (DC) to alternating current (AC) conversion [36]. Moreover, the limitations associated with RES integration are further complicated by low assess to electricity (less than 50%) and when demand surpasses the supply [37, 38]. Key technology changes are also required to be implemented in RES integration such as energy storage, electric vehicles, and optimal solar power systems [37]. Despite the aforementioned limitations, the researchers have developed policies and plans that would propel different regions to attain their renewable energy goals to improve energy access as well as to achieve the environmental benefits associated with RES e.g. carbon footprint reduction [39].

To the best of the authors' knowledge, currently, no literature has presented an investigation on how Kenya's current energy system can move towards 100% solar PV in any time frame. This study draws an immediate focus on the electricity supply in Kenya. The current industrial and domestic demand is highly dependent on its available energy resources. Hence, there is a need to establish a sustainable solution to decarbonizing the energy system, i.e. reduce carbon emissions associated with industrialization and food production. This introduced study's main objective is to determine the significance of the solar PV penetration levels on production costs and system operations based on the current year (business as usual scenario) and the accelerated PV scenario in the Kenyan electricity generation system. With the specific objectives of the effects of high penetrations of solar PV with the ability to coordinate hydro and solar generation, calculating the value of solar PV in Kenya, and capturing the cost of operational effects that solar PV may have on other power plants. This study will provide more insight into an alternative way to estimate the value of a candidate technology for a future generation mix and assess existing feed-in-tariff (FIT) policies, which will give greater insight into capacity expansion plans with intermittent RESs.

2. Materials and Methods

Kenya is a rapidly developing nation in East Africa, and has been focusing on diversifying its energy sources to meet its growing energy demand, enhance energy security, and reduce greenhouse gas emissions [40]. As of 2021, the country's energy mix consists of various resources, including fossil fuels, renewable energy, and emerging technologies as shown in figure 1 [40, 41]. Currently, there are 53 power stations in Kenya, i.e. hydroelectric (15), fossil fuels (14), geothermal (10), bagasse (8), wind (4), and biogas (2) [40, 42].

This study aims to model and simulate the impact of accelerated solar PV integration into Kenya's electricity mix using the energy PLAN simulation tool. Minimum electric grid stabilization is an important issue that needs attention in any power system that incorporates intermittent RESs. Hence, to ensure grid stability, maintaining a steady frequency and voltage is necessary. In Kenya's energy scenario, grid stability is achieved by non-intermittent electricity sources such as hydroelectric power (HEP), geo-thermal, and thermal electric power sources. This research work is novel in Kenya's context due to the lack of scientific analysis on an hourly resolution that gives the technical and economic impact of accelerated solar PV integration into the country's generation mix while considering grid stability (curtailment). Thus maintaining a steady frequency and voltage is necessary to ensure grid stability.

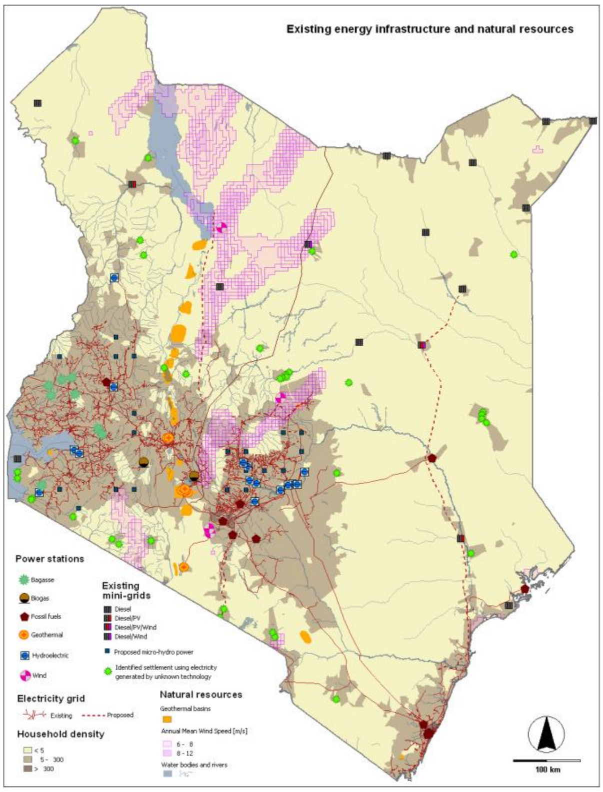


Figure 1. Existing energy infrastructure in Kenya, potential energy sources, and population density [40].

2.1. Energy PLAN simulation

The Energy PLAN simulation tool is a computer (input-output) model that uses a bottom-up approach to energy demand and climate change to identify the optimal system configurations based on hourly calculation within a specified time frame [37, 43], as presented in figure 2 below.

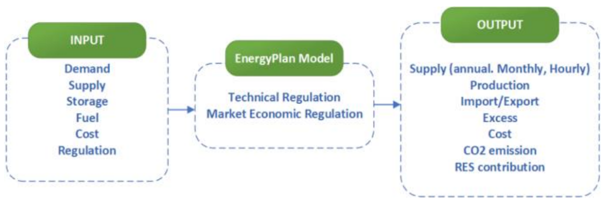


Figure 2. Simulation layout of the energy plan simulation tool.

The annual electricity demand (D_E) is computed as given in (1), where d_E is hourly values of electricity demands.

$$\mathbf{D_E} = \sum_{x=1}^{8784} \mathbf{d_E}(\mathbf{x}) \qquad (1)$$

The main electric power sources in Kenya's energy system are hydro, geo-thermal, and variable renewable energy (solar and wind). The calculation of the annual supply for each source is summarized in table 1 below by (2) to (4) [44].

Table 1. Simulation equations of the main electric energy supply in Kenya's energy system.

Energy source	Simulation equations
Geo-thermal power (E_g)	$E_g = \left(\frac{F_g * C_g * d_g}{\mathrm{Max}(d_g)}\right)$ (2)
where F_g is the correction factor between production and capacity, C_g is the capacity of the geo-thermal power electricity generator (MW), and d_g is the distribution of electricity production between 8784-hour values	
hydropower (E_h)	$E_h = \mathrm{Max}[E_{h(av)}, (W_h - S_h) * \mu_h]$ (3)
where $E_{h(av)}$ is the average hydroelectricity production, W_h is the annual water input, S_h is the water storage capacity, and μ_h is the efficiency of the generator	
Variable renewable energy (E_r')	$E_h' = \left(\frac{E_r}{[1 - F_r * (1 - E_r)]}\right)$ (4)
where E_r is the individual RES capacity, and F_r is the correction factor of RES production	

Additionally, energy PLAN is capable of modeling and simulating large-scale integration of RESs and radical technological changes in energy systems making it an ideal choice for this analysis. The investment and fixed operation and maintenance were simulated based on (5) based on input capacity, per unit price, interest, and lifetime [44].

$$\mathbf{Ai_s} = \left(\frac{\mathbf{I_s} * \mathbf{i}}{\mathbf{1} - (\mathbf{1} + \mathbf{i})^{\mathbf{n}}}\right) \qquad (5)$$

where Ai_s is the annual cost of investment of the energy source s, I_s is the total investment of each production unit s, i is the interest used for socio-economic evaluation, and n is the lifetime of the investment. For economic simulation, specified hourly price distribution (P_{in}) was used to compute the market prices (P_M) based on (6) [44], where F_m is the multiplication factor, and F_a is the addition factor.

$$\mathbf{P_M} = \mathbf{P_{in}}(\mathbf{F_m} + \mathbf{F_a}) \qquad (6)$$

The energy PLAN tool was applied to model and simulate the operation of the current energy and power markets, allowing for the selection of generation sources for the supply of electricity and energy that have the lowest marginal production costs. Energy PLAN tool also takes into consideration the hourly dynamics between electricity and heat systems, for instance, a combined heat and power (CHP) unit can benefit from thermal storage capacity when generating electricity. The price elasticity in the electrical exchange, the maximum transmission capacity, and the hourly electricity price are used to represent the external electricity market. The annualized investment costs using a discount rate are added to the expenses associated with CO_2 emissions, import and export of energy, fixed and variable operation and maintenance costs, and fuel and fuel handling costs to determine the socioeconomic costs.

Table 2. Criterion for the analysis (four possible outcomes or warnings and measures undertaken to correct each warning.

Criteria	Definition	
EG warning (Crit 1)	There is excess electricity produced after the yearly demand is met.	
	Solution:	A gradual decrease in Solar PV supply capacity till an optimum technical solution is achieved
PI warning (Crit 2)	The output from PI is insufficient to meet the yearly demand	
	Solution:	An increase in the generation capacity of the solar PV system until an optimum capacity is achieved
No EG warning and PI warning (Crit 3)	The yearly power supply satisfies the yearly demand	
	Solution:	A slight reduction in the power plant capacity till an optimum economical solution is achieved
Both PI warning and EG warning (Crit 4)	There is both excess electricity supply and unmet demand	
	Solution:	An increase in the supply capacity of power plants while decreasing the solar PV capacity.

This study applied the energy PLAN tool to evaluate Kenya's energy system by analyzing the technical and economic effects of solar PV integration and investments in the county's energy mix. Therefore, two regulation strategies were applied, i.e. Technical Regulation (TR) and

Market Economic Regulation (MER). TR strategy is applied to optimize the generation process (the minimization of excess electricity production and fuel consumption), while the MER is applied to analyze the potential and possibility for electricity exchange in different scenarios, i.e. it aims to meet the energy demands at the lowest marginal costs. In this study, solar PV is initially analyzed independently, after which other combinations are analyzed.

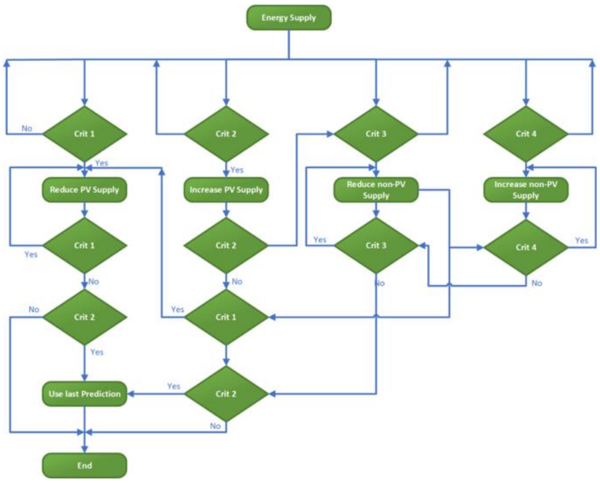


Figure 3. Process simulation (optimization) flowchart.

Additionally, thermal power plants are used as energy sources to ascertain system stability. The optimized results are based on both TR and MER. Four criteria given in table 2 were applied in this analysis based on power plant input (PI) and excess electricity generation (EG) to ensure optimal power generation.

Figure 3 describes the process simulation (optimization) of the above four criteria and measures undertaken to fulfill the criteria. Note that the intermittent RESs are utilized fully before the demand is met by other energy resources.

2.2. Research model and data

This introduced study aims at improving the solar PV input into Kenya's electricity power grid in terms of its effects on system stability and CO_2 reduction based on economic and technical parameters. The solar PV energy source was analyzed on an hourly time stamp to provide a view of the performance of solar PV system integration with other energy sources such as HEP, wind, geo-thermal, and thermal on an annual basis. The data applied in this study were hourly electricity demand for a year, total electricity generated hourly for a year per sector, the unit cost of electricity, efficiency of the respective power plants, and their capacity. The data was obtained from the Energy Regulatory Commission, and the Kenyan Ministry of Energy [45].

In this study, two different case scenarios were evaluated: Scenario 1: represents the current year or business as usual and it is the reference year. Scenario 2: represents the accelerated PV integration, i.e. a hypothetical scenario for the year 2030 with an estimated demand of 25.28 TWh [46]. Its performance regarding technical and economic costs for the current electricity demand is evaluated and compared to the reference year (Scenario 1). Hourly distribution profile for the demand and different energy production technologies was obtained from a Kenyan model. All the setups are designed with Kenya's energy system characteristics. However, the technological solutions deduced can be applied to any country or region with the same potential for wind and Solar PV, HEP, and geo-thermal as Kenya's.

3. Results and discussion

3.1. Kenya power system

The peak demand for electricity in Kenya was observed to be 2,056.67 MW in June 2022, as shown in the demand profile in figure 4. The installed capacity of the country's power plants was at 3,074.34 MW with geo-thermal and HEP as the primary energy sources with a combined contribution of 39.15% and 26.47%, respectively.

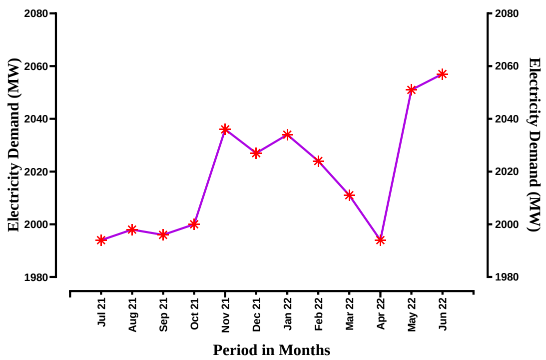


Figure 4. Annual Electricity demand profile in Kenya (2021 – 2022).

Wind and solar had a combined contribution of 16.22% and 2.47%, as presented in table 3. The electrical energy generated (electrical energy delivered to the national grid) during peak demand (June 2022) was 12,652.74 GWh.

A total of 285.51 GWh of electrical energy was curtailed in Kenya's energy system for the period 2021 – 2022, with the maximum curtailed energy at 24,457 MWh from wind sources in November

2021 and 46,604 MWh from geo-thermal sources in June 2022, as presented in figure 5.

Table 3. Contribution to energy generation by Source in Kenya (2021 – 2022).

Energy Source	Installed capacity (MW)	Generation capacity (GWh)	Contribution (%)
Hydro	837.58	3,348.71	26.47%
Thermal	646.32	1,647.75	13.02%
Wind	435.5	2,052.26	16.22%
Geo-thermal	949.13	4,953.15	39.15%
Bagasse/Biogas	2	0.38	0.00%
Imports	-	337.50	2.67%
Solar	170	312.99	2.47%
Off-grid	33.81	-	-

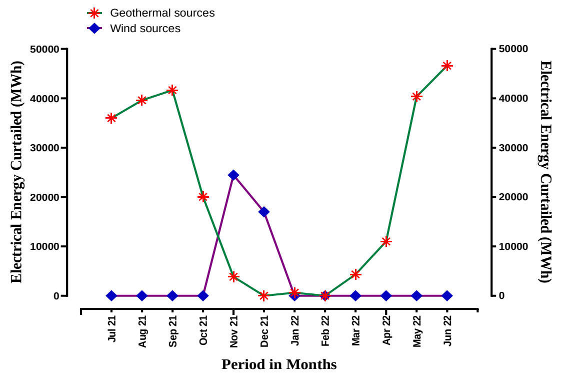


Figure 5. Annual electricity curtailment in Kenya (2021 – 2022).

3.2. Scenario 1: business-as-usual

From the business-as-usual Scenario 1 (Reference case), all the electrical energy within Kenya is generated from geo-thermal, HEP, wind, solar, thermal, and imports, as presented in table 3. The reference model was created using technological inputs after which fuel, investment, and O&M costs were incorporated to perform the energy system's socio-economic analysis. Table 4 presents the cost assumptions for energy system components in TR-based analysis.

Table 4. Cost assumptions for energy system components.

Production type	Parameters	Unit	Value
Large power plant	Capex	€/kWh	990
	Lifetime	Years	20
	Opex fixed	% of investment	3.05
Wind	Capex	€/kWe	2400
	Lifetime	Years	20
	Opex fixed	% of investment	2.09 %
Solar PV - ground-mounted	Capex	€/kWe	1150
	Lifetime	Years	30
	Opex fixed	% of investment	0.6 %
Solar PV - Rooftop	Capex	€/kWe	1200
	Lifetime	Years	30
	Opex fixed	% of investment	1 %
Hydropower - Run of the river	Capex	€/kWe	2750
	Lifetime	Years	50
	Opex fixed	% of investment	1.5 %
Geo-thermal electricity	Capex	€/kWe	4550
	Lifetime	Years	20
	Opex fixed	% of investment	3.48%

From the reference model (Table 5), river hydro had the highest estimated production of 4.07 TWh/Year followed by wind at 1.09 TWh/Year and lastly, solar at 0.3 TWh/Year for the variable renewable electricity generation systems, while geothermal was the central power plant.

Table 5. Reference model for Scenario 1: business-as-usual.

Variable renewable electricity			
Energy source	**Estimated production (TWh/Year)**	**Estimated post-correction production (TWh/Year)**	**Estimated capacity factor**
Wind	1.90	1.90	0.50
Solar	0.30	0.30	0.20
River hydro	4.07	4.07	0.55
Central power plants			
Power plant	**Annual production (TWh/Year)**		
Geo-thermal	1.97		

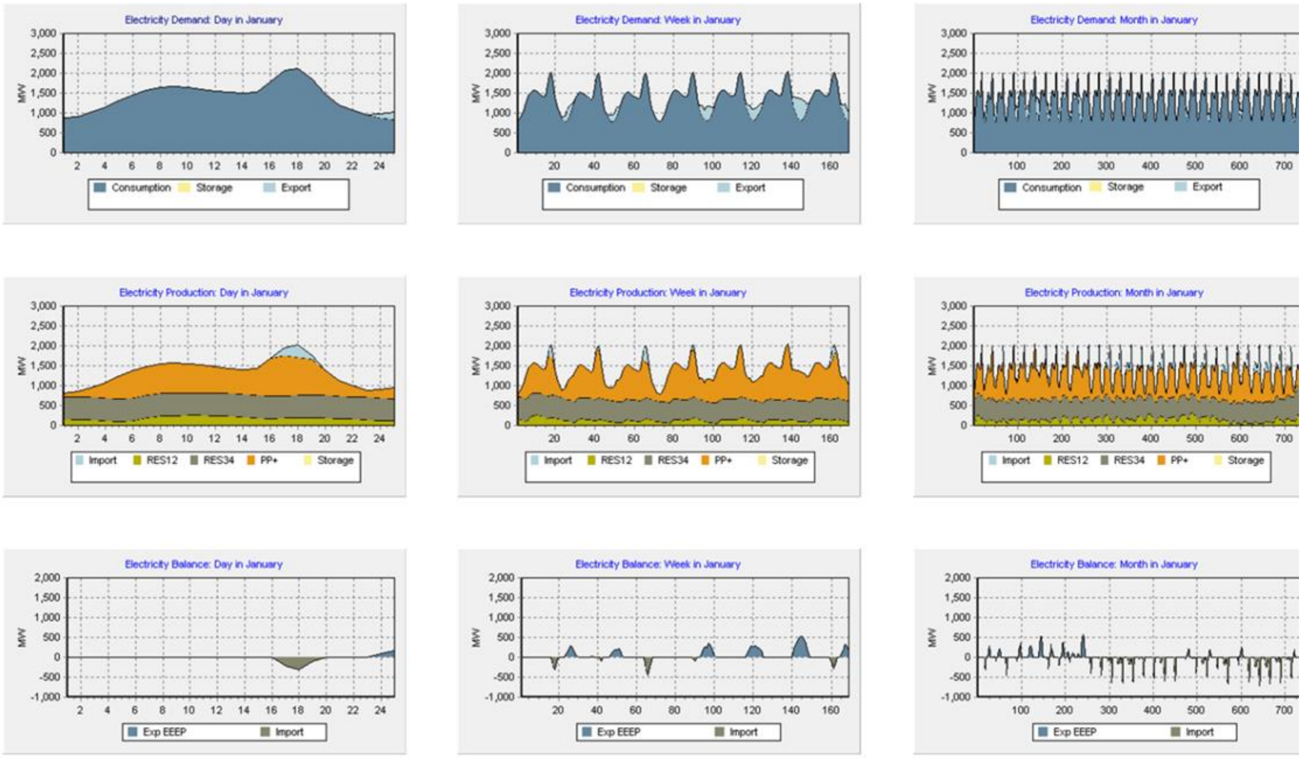
A large proportion of the total power produced is from hydroelectric and geothermal power plants. A smaller portion of the overall amount of power generated comes from solar and wind energy sources. Additionally, power is imported to meet the daily energy needs, as shown in figure 6. The monthly average demand per energy source is given in table 6.

Table 6. Monthly average demand values.

Energy source	Annual average (MW)	Annual max (MW)	Total for one Year (TWh)
Wind	217	408	1.9
River hydro	464	828	4.07
PV	34	137	0.3
Thermal	424	648	3.73
Geo-thermal	224	940	1.97
Off-grid	11	34	0.1
Import	84	1053	0.74

It was established that electrical energy is imported when demand is greater than supply to balance monthly electricity needs. However, during off-peak hours, there is less demand for electricity than supply, as shown in figure 6. In this analysis, balancing and storage systems were not taken into account.

The main objective of the socio-economic analysis based on MER was to reduce the expenses to society, or the cost for the nation to deliver the required energy. The purpose of this socio-economic analysis is to determine the costs related to the technical simulation. The results of the socio-economic analysis are presented in table 7. It was established that the overall cost for running and maintaining the energy system, even while some power units are not operating was 265 mEUR/Year (Fixed O&M sum annual costs) and investment sum annual costs as 612 mEUR/Year.



(a) (b) (c)

RES12 – Wind and Solar PV Renewable Energy Source
RES34 – River Hydro
PP+ – Geothermal and Hydro Power
Exp-EEEP – Exportable Excess Electricity Production
Exp-CEEP – Critical Excess Electricity Production

Figure 6. Electricity energy profile in Kenya in Scenario 1, (a) A day in January 2022, (b) A week in January 2022, and (c) Month of January 2022.

Table 7. Socio-economic analysis results based on annual costs of investment and annual costs of fixed O&M.

Production type	Total investment cost (mEUR)	Annual costs (mEUR/Year)	Annual Costs (mEUR/Year)
		Investment	Fixed O&M
Large power plants	675	45	21
Interconnection	3346	145	33
Renewable energy			
Wind	479	32	14
Solar PV	175	10	1
Hydro river	2303	90	46
Geo-thermal	4319	290	150
Total		**612**	**265**

3.3. Scenario 2: Accelerated solar-PV integration

Scenario 2 presents the grid performance with accelerated PV integration using the process simulation (optimization) in figure 2. Figure 7 presents the applied energy flow by energy PLAN for Scenario 2. The Technical Simulation (TR) was based on the technical capabilities of the components within the energy system. The optimal capacity of the solar power based on technical simulation was established to be 5703 MW. The equatorial location of Kenya has ensured a rich solar resource within the country hence making solar PV an available energy option. Figure 7 presents the simulated optimal energy generation in Scenario 2.

The electrical energy generated from the solar PV under Scenario 2 was 10.01 TWh, which is approximately 39.56% of the total energy generated.

Additionally, it was established that accelerated solar PV can reduce emission levels, as shown in table 8, the CO_2-equivalent emissions were reduced to 0.021 Mt (Scenario 2) from 0.134 Mt (Scenario 1) and the RES electricity produced increased to 19.76 TWh/year (Scenario 2) from 11.90 TWh/year (Scenario 1). Furthermore, based on technical simulation the total annual cost that will be incurred in the energy system that increments solar power up to an optimal level was established to be 895 mEUR.

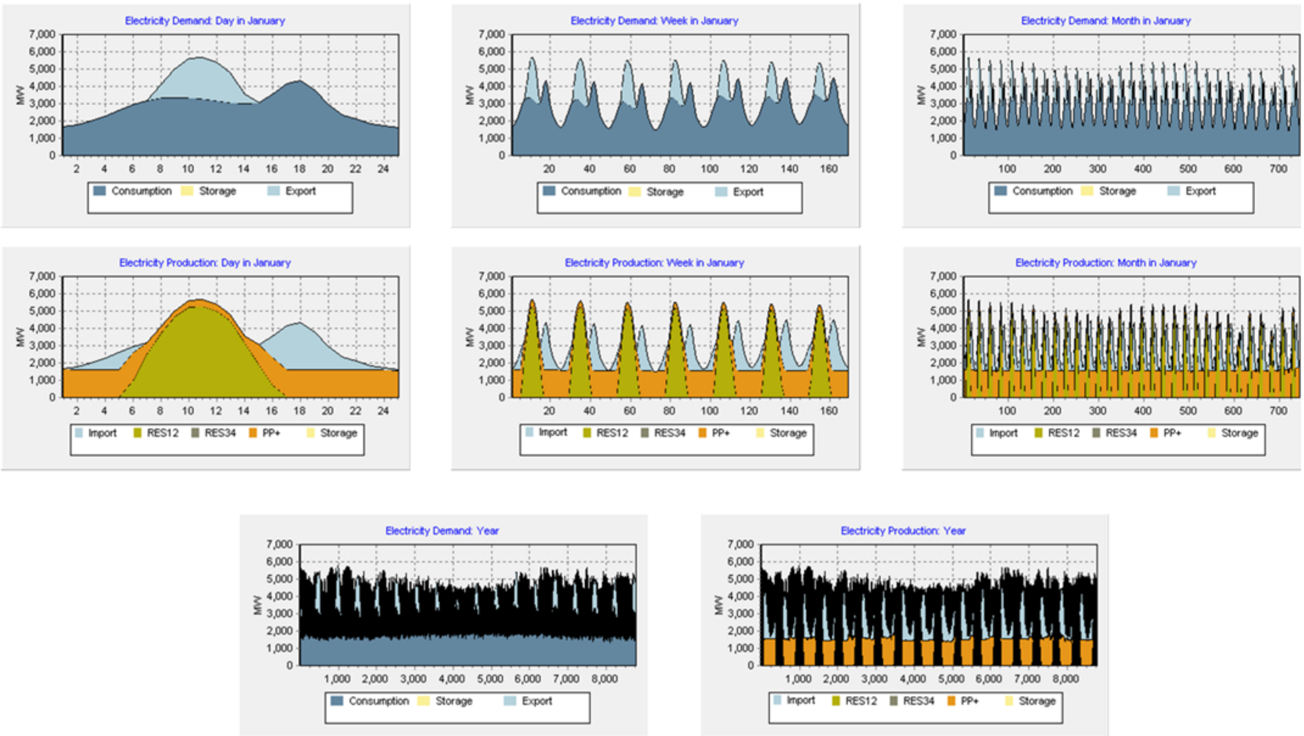


Figure 7. Simulated electricity energy profile in Kenya in Scenario 2.

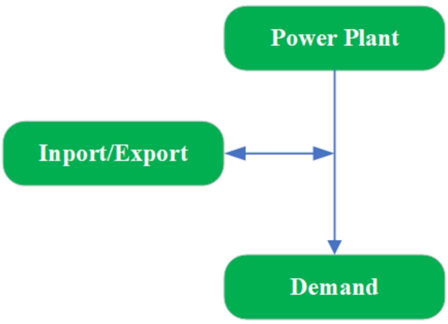


Figure 6. Schematic representation of energy flow by energy PLAN.

Instead of focusing on the least amount of fuel used, the Market Economic Simulation (MER) was created to match supply and demand. For this simulation two primary steps were completed, i.e. the short-term marginal cost of producing electricity is calculated for each power-producing unit, and the least-cost combination of production units is chosen to supply the demand. Based on this market economic simulation, the optimal capacity of solar power obtained was 4394 MW, which will supply 30.54% of the total electricity generated at 7.72 TWh. Additionally, the total annual cost that will be incurred in the energy system that increments solar power up to an optimal level at 919 mEUR. To increase solar PV contribution, solar PV mini-grids can be interconnected into one common grid for better technical performance [47]. Additionally, a system-level model of Kenya's power system by Rose [11] based on various generation mixes for 2012 showed that accelerated solar PV integration will exceed the FIT payments. From the dimensions of rural electrification in Kenya, studies have expressed that RESs have the potential to meet energy demand, i.e. solar PV mini-grids can serve up to 17% of the country's population [48].

Both market economic simulation and technical simulation for the accelerated solar PV integration resulted in the supply exceeding the demand at some times of the year, thus excess electricity is exported, as shown in figure 6. The emission associated with Scenario 2 decreased as the percentage of RES increased. The current electricity cost is € 0.17 per kWh when compared to Scenario 2. This encourages investment into renewable energy sources as viable alternatives. Additionally, the total investment cost annual cost for solar PV in Scenario 2 is the lowest at 10 mEUR/Year this is due to the large-scale investment and research in PV technologies that have increased its market competitiveness and thus lowers the overall cost of the system. Additionally, studies have reported that the cost of solar PV systems has been declining at an average of 16% per annum from 5000 EUR per kWp in 2006 to 1640 EUR per kWp in 2017 [49,50]. Lastly, the accelerated integration and increased uptake of solar PV also depend on the performance of solar PV technology such as generation efficiency [51], improved solar tracking systems [52, 53], solar concentrators [54], efficient energy storage [55], and energy management systems [56, 57].

Table 8. Carbon emissions and share of renewable energy.

	Scenario 1	Scenario 2
CO_2-equivalent emissions	0.134 Mt	0.021 Mt
RES electricity produced	11.90 TWh/year	19.76 TWh/year

4. Conclusions

The screening curves and other independent metric systems such as levelized cost of electricity are frequently used by energy planners for guidance in investment decisions, and might lead to inaccurate conclusions due to the intermittent nature of the RESs, whose value may be substantially influenced by the system's features such as the system's total generation mix and consumption patterns. The potential and limitations of integrating large-scale solar PV power systems into the power sector in Kenya have been analyzed in this study. The use of solar PV was considered in this study as an available alternative to mitigate climate change from the power sector.

This study aimed to determine the significance of the penetration levels of solar PV on system operations and production costs based on the current year (business as usual scenario) and the accelerated solar PV scenario (hypothetical future) in the Kenyan electricity generation system. The current peak demand for electricity in Kenya was established to be 2,056.67 MW with an installed capacity of 3,074.34 MW with a 2.47% contribution by solar PV, while the curtailed energy was 285.51 GWh. Based on Scenario 2, the optimal capacity of the solar power based on technical simulation was established to be 5703 MW which is approximately 39.56% of the total energy generated at 10.01 TWh. The optimal capacity of solar PV power based on market economic simulation was 4394 MW which will supply 30.54% of the total electricity generated at 7.72 TWh. The emission associated with Scenario 2 decreased as the percentage of solar PV increased, i.e. CO_2-equivalent emissions reduced from 0.134 Mt (Scenario 1) to 0.021 Mt (Scenario 2). Additionally, the total investment cost annual cost for Solar PV in Scenario 2 is the lowest at 10 mEUR/Year. Despite the study not considering distribution and transmission losses, increased penetration of solar PV is feasible in Kenya at 39.56% to meet energy demand without compromising electricity access and grid stability. Significant changes must occur in the Kenyan energy system mainly an element of flexibility to balance the intermittent nature of solar PV. This is important in accelerated solar PV integration into the national grid. Additionally, storage challenges can be addressed by hydro solar PV hybrid systems. Furthermore, economic, technical, political, and institutional barriers have hindered the uptake of solar PV technology. Therefore, robust policy regulation, research and development, training, and coordination between key stakeholders are necessary to overcome these barriers.

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