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Techno-Economic Assessment of Solar–Grid–Battery Hybrid Energy Systems for Grid-Connected University Campuses in Kenya

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Abstract: This paper presents the techno-economic feasibility of using grid-connected PV hybrid systems to supply power in large grid-dependent academic institutions. The study was conducted using the administration building of Moi University in Kenya. The power consumption profile of the building was collected using a PCE-360 power analyzer. The peak load demand was found to be 60 kW. Using random variability constants of 4% for day-to-day and 4% time-step load variability, a peak demand of 70.58 kW was obtained, which was used in our simulation. The solar radiation and temperature data for this site were collected from the weather station of the university. The hybrid system was simulated using HOMER Pro software. It was found from the simulation results that the optimal system was the solar PV/grid without battery storage, which had a levelized cost of energy (LCOE) of KSH 8.78/kWh (USD 0.072), net present cost (NPC) of KSH 27,974,492 (USD 230,813), capital expenditure (CAPEX) of KSH 26,300,000 (USD 216,997), and a simple payback period (SPBP) of 5.08 years for a 25-year life span. This system, when compared to the existing grid, showed an 83.94% reduction in the annual electricity bill of the administration building. These results demonstrate a reduction in energy cost by a renewable energy fraction of 67.1%.

Keywords: renewable energy; cost of energy; hybrid systems; green campus; solar PV

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1. Introduction

Electricity demand is rising quickly, putting pressure on increasing the generation of utilities. As a result, researchers are considering power generation methods using renewable energy sources, including solar, wind, and hydro [1]. These energy resources, when used in a hybrid fashion, reduce cost and increase system reliability and efficiency [2–4]. They are chosen for distributed generation because they are readily available, affordable, and clean [5,6]. Also, these systems, when used to supply a load, require appropriate economic dispatch [7]. According to the 2022 Energy Progress Report by the World Bank (WB), the proportion of individuals with access to electricity increased from 83% in 2010 to 91% in 2020. With the percentage increase in the global electricity access rate, 733 million people still lacked access to electricity in 2020, compared to 1.2 billion in 2010. In sub-Saharan Africa, electricity access is still limited to 48%. This means that more than half of the population in this region still has no electricity, which is a basic necessity for economic growth. In addition, over 75% of the global population (568 million people) that lacked access to electricity worldwide in 2020 resided in this African region [8,9].

Sub-Saharan Africa is abundantly blessed with solar energy, which can be used for power generation [10–13]. Kenya is endowed with abundant solar resources, with an annual solar radiation varying between 4 and 6 kWh/m^2/day [14,15]. It has several establishments, such as academic institutions, business enterprises, and large commercial buildings, that solely rely on grid power. The dependence on the grid leads to higher operating expenditure on utility bills, as can be seen in the 2018 photovoltaic (PV) report from Moi University in Kenya, where it was reported that the university spends an average of KSH 633,003 per month on the electricity bill for the administration building [16]. In addition, a high cost of energy was also reported for the University of Nairobi, which spends KSH 552,155.46 per month on the electricity bill for the School of Engineering [15]. Additionally, due to the unreliability of grid electricity, these academic institutions, business enterprises, and large commercial buildings depend on diesel-/gasoline-powered generators as back-up energy systems, which leads to an increase in greenhouse gases emissions and hinders progress in the fight against climate change. This can be mitigated by using hybrid renewable energy and grid systems for power supply.

This work seeks to address the issue of high costs incurred by grid-connected establishments for paying electricity bills in academic institutions and to avoid the use of diesel/gasoline generators as a back-up power supply in Kenya. This is carried out by analyzing the combination of solar PV/grid, solar PV/battery/grid, or battery/grid and proposing the most feasible and cost-effective hybrid option (void of diesel/gasoline generators). The administration building of Moi University in Kenya was used as a case study. In addition, this work contributes to the areas of data-driven design in solar photovoltaic systems, climate change mitigation using renewable energy technologies for power supply, renewable energy system modeling, and the adoption of solar energy conversion systems in academic institutions.

2. Literature Review

Some related works have been carried out to study the use of hybrid systems for power supply. Alharthi et al. [17] conducted a techno-economic analysis for a grid-connected solar/wind hybrid system in different locations in Saudi Arabia using HOMER Pro. They obtained an LCOE of USD 0.03655 and concluded that the system was technically and economically feasible in the area. Khisa et al. [18] studied the dynamic behavior of solar and wind on the grid for a school in Naivasha, Kenya. They concluded that 80% of the energy to meet the loads came from solar and that 241.6 kWh battery storage was needed for a two days of autonomy. Barakat et al. [19] simulated a PV/wind/biomass grid-connected hybrid system using HOMER for a location in Egypt and concluded that the system was feasible and could greatly reduce emissions and grid cost. Eze et al. [15] carried out a study on the feasibility of hybrid energy systems for a Kenyan institutional building using HOMER. Their results showed that the PV/grid/diesel hybrid system was the most optimal, with an LCOE of KSH 7.89, an NPC of KSH 69,512,100, an initial capital cost of KSH 30,264,100, a 77% reduction in power purchased from the grid, and an 84% reduction in electricity bills. Kiflom et al. [20] designed a hybrid energy system using HOMER to power a rural village in Ethiopia. Their results yielded an LCOE of USD 0.207/kWh and an NPC of USD 82,734, with a carbon dioxide emissions reduction of 37.3 tons a year. Jameel et al. [21] conducted a study on the techno-economic feasibility of a grid-tied hybrid microgrid system for local inhabitants of Kallar Kahar near Chakwal city in Punjab province in Pakistan using HOMER. They concluded that surplus power was supplied to the national grid during low local demand of the load. The system could generate more than 50 MW. The cost of the hybrid system for a peak load of 73.6 MW was USD 180.2 million and the LCOE was USD 0.05744/KWh. Ali et al. [22] studied the technological, economic, and environmental feasibility of utilizing a PV/diesel/battery hybrid energy system (HES) to power a remote rural village in Iraq. The results indicated that the most feasible and economical combination consisted of 12 kW of PV, a diesel generator with a capacity of 20 kW, 15 batteries, and a 6 kW power converter, at an NPC of USD 162,703. Moreover, sensitivity analysis on ambient temperature showed that the PV and batteries were highly affected by temperature increase, which reduced the lifetime of the batteries from 26.5 months to 23.5 months and the yearly PV production from 18,268 kWh to 17,332 kWh and negatively affected the economic performance of the system. Adaramola et al. [23] examined the feasibility of using a hybrid energy system consisting of PV/biodiesel generators to meet the electricity and domestic water needs of a remote community in Ghana. Their results showed an LCOE of USD 0.76/kWh at a 100% cost (without grant financing). The LCOE decreased to USD 0.20/kWh for the grant-financed upfront cost of the project. They concluded that beneficiaries would pay 200% more under full-grant financing conditions given that the nominal grid cost stood at USD 0.10/kWh. Taghavifar et al. [24] conducted a techno-economic analysis for a PV/wind/grid (case 1) and a PV/wind/grid/gen (case 2) system. For case 1, they obtained an NPC of USD 49,022, a renewable fraction (RF) of 85.5%, and an LCOE of USD 0.0024 at an inflation rate of 10% and a wind speed of 6.8 m/s. On the other hand, for the best feasible design for case 2, they obtained an NPC of USD 224,430, an LCOE of USD 0.0272, and an RF of 63.6%. Oueslati and Mabrouk [25] carried out a techno-economic analysis of an on-grid PV/wind/battery hybrid system to electrify buildings in Borj-Cedria, Tunisia. Their simulation results showed that the NPC and LCOE were USD 44,705 and USD 0.224/kWh, respectively, with a renewable energy penetration of 78%. Alharthi et al. [26] performed a techno-economic analysis of a grid-tied PV/wind energy system using Riyadh city in Saudi Arabia as a case study. Their results yielded an NPC of USD 3,569,094 and an LCOE of USD 0.04449/kWh. Other related works have been performed on hybrid systems, as found in [27–32].

3. Materials and Methods

Moi University is an institution of higher learning in Kenya. Its administration building at the main campus is located between latitude 0.28° N and longitude 35.29° E in the town of Eldoret.

The power consumption data for the administration building (represented as LOAD in Figure 1) for a period of one month was logged using a PCE-360 power analyzer, as shown in Figure 1. The logging was carried out for intervals of 5 s to ensure that detailed information about the power usage was obtained. Temperature and solar radiation data from November 2017 to January 2022 were collected from the weather station of the university, and these values were compared to those provided by National Aeronautics and Space Administration (NASA) in their database. After collecting the necessary data, the simulation of the hybrid system was carried out using HOMER Pro software version 3.10.3, which has the capability of performing technical and economic feasibility studies of hybrid energy systems. The configuration of the HOMER Pro environment is shown in Figure 2.

The input information to the software was solar radiation, temperature, power demand, choice of solar module, choice of battery storage, grid power cost per kWh, and the cost of all the components used in the system. When this information was input into the software, the simulations were completed for different sensitivity cases. The outputs produced after the simulations were the optimization results for the best system to use with the component sizes, the net present cost (NPC) of the system, the levelized cost of energy (LCOE), the initial capital cost, and the simple payback period (PBP).

In Figure 1, L1, L2, L3, and N stand for line 1, line 2, line 3, and neutral, respectively. I1 to I4 are the currents, whereas U1 to U3 are the phase voltages.

The different components that were used in the simulation are specified in the proceeding paragraphs.

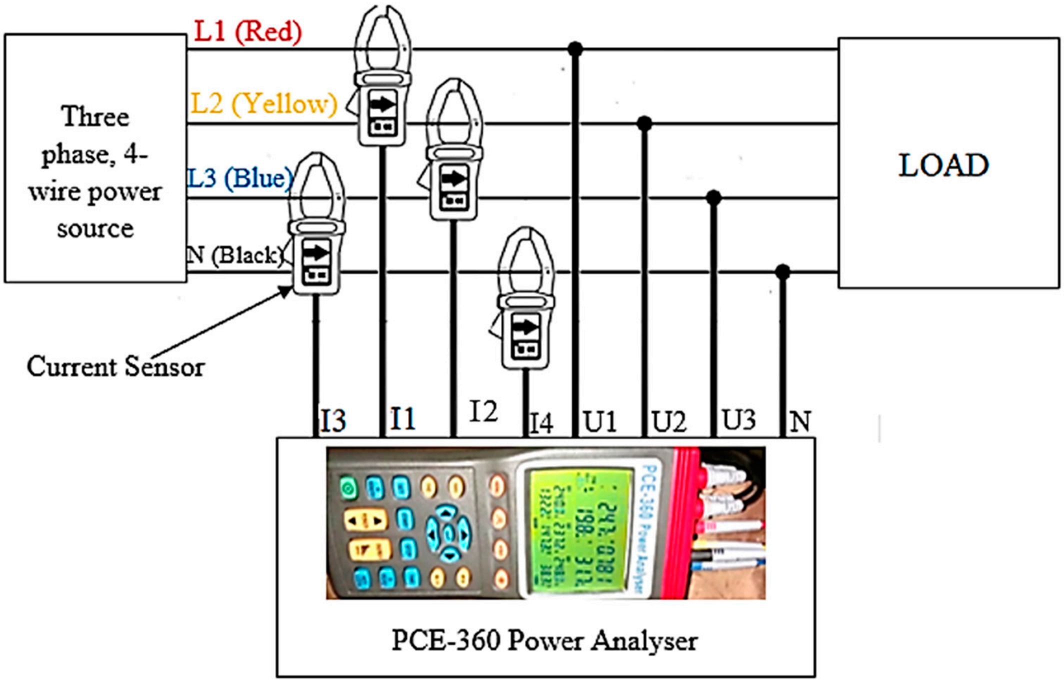

Figure 1. Power consumption data collection using a PCE-360 power analyzer (PCE Instruments UK Ltd, Southampton, UK).

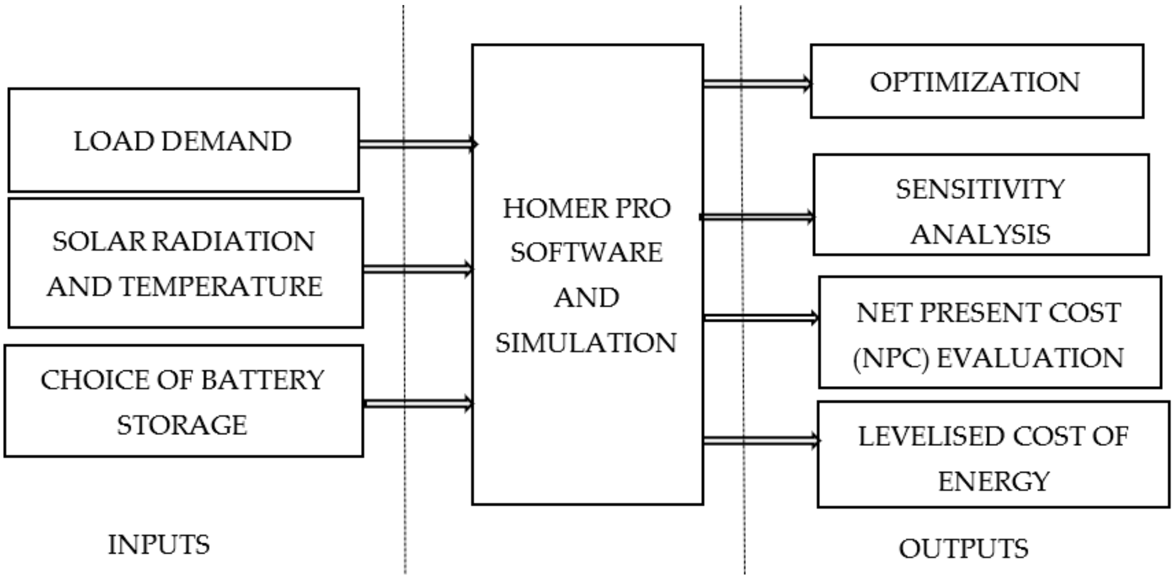

Figure 2. Input and output parameters used in HOMER Pro.

3.1. Grid

The simple rate mode in the HOMER grid window was used. This mode allows for a constant power price and sell-back price to be set. It uses the average electricity cost per kWh, the capacity that can be sold back to the grid, and the sell-back cost. It was selected because the electricity rate in Kenya does not vary on an hourly basis and the grid already existed and did not need an extension. From the one-year utility bill data analyzed, the average cost per kWh for the administration block stood at KSH 21.39. Also, according to the 2019 Energy Act of Kenya, power can be sold back to the grid through net-metering for systems below 1 MW at a maximum fit-in tariff of KSH 12/kWh [33]. The net purchases were calculated monthly in the simulation.

3.2. Solar PV

The SunPower E20-327 monocrystalline solar module with a peak power of 327 W was chosen for the simulation. This module has an efficiency of 20.4%. It was selected because of its high conversion efficiency and its high rated power per module, which limits the installation space to be occupied by the overall system. The characteristics of this module are shown in Table 1. Given that the power output (P_{out}) of a PV module is often affected by aging, temperature, and solar radiation, Equation (1) can be used to calculate P_{out} [34,35].

$$P_{out} = P_{pv} f_{pv} \left(\frac{G_T}{G_{T,STC}} \right) [1 + \propto_p (T_C - T_{C,STC})] \tag{1}$$

Table 1. Choice of components.

Component	Type	Parameters	Values and Units
Solar module	SunPower E20-327	Rated power	327 Wp
		Rated voltage (Vmpp)	54.7 V
		Rated current (Impp)	5.98 A
		Short-circuit current (Isc)	6.46 A
		Open-circuit voltage (Voc)	64.9 V
		Dimension	1.558 × 1.046 m
		Efficiency	20.4%
Battery	Lead acid Trojan SAGM 12 205	Nominal voltage	12 V
		Capacity	219 Ah
		Round-trip efficiency	85%
		Maximum charging current	41 A
		Maximum discharge current	300 A
Inverter	MTP-4110F, 3-phase hybrid	Rated power	120 kW
		AC input frequency	50/60 ± 3 Hz
		AC output frequency	50/60 Hz ± 0.01%
		AC output voltage	380/400/415 V(L-L), 220/230/240 V(L-N)
		Efficiency	96%
Charge controller	SOLARCON SCM-360400	Maximum PV power	124 kWp
		Maximum current	400 A
		Vmp of PV	255–330 Vdc
		Output DC voltage	360 V
		Efficiency	98%

In Equation (1), P_{pv} is the rated power of the PV module under standard test conditions (STC), f_{pv} is the derating factor of the PV module (%), G_T is the solar radiation incident on the PV module (W/m^2), $G_{T,STC}$ is the incident radiation at STC (1000 W/m^2), $\propto_p$ is the power temperature coefficient (%/°C), T_C is the PV cell temperature (°C), and $T_{C,STC}$ is the PV cell temperature at STC (25 °C).

3.3. Battery Storage

In this work, lead acid batteries were chosen. This is because it is the battery of choice in solar PV systems, especially in sub-Saharan Africa, due to its low cost compared to other battery technologies such as lithium ion [36]. A summary of the selected battery is shown in Table 1.

3.4. Inverter

Since solar PV systems produce electricity in DC form and not AC form, an inverter is needed to convert DC to AC to enable the AC loads to be powered and also to permit power to be sold to the grid. In this work, a 120 kW MTP-4110F three-phase hybrid inverter was selected, and its characteristics are tabulated in Table 1. This inverter was selected because of its ability to effectively power the load.

3.5. Charge Controller

Because the system was to be simulated with a battery storage system, a SOLARCON SCM-360400 charge controller was chosen. The role of a charge controller in a PV system is to regulate the charge and discharge cycles of the batteries. This protects the batteries from overcharging or under discharging. The electrical parameters can be seen in Table 1. The charge controller was chosen because of its ability to support high current.

The schematic diagram, including all the components that were used for simulation in HOMER Pro, is shown in Figure 3.

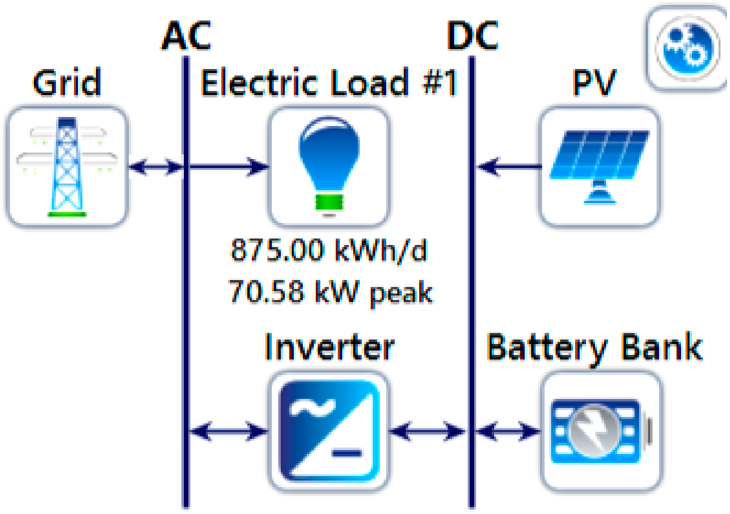

Figure 3. Schematic diagram designed with HOMER Pro for simulation.

3.6. Economic Parameters

According to the Central Bank of Kenya, the discount rate was 7.5% and the inflation rate was estimated to remain at an average of 7.1% in 2022 [37]. In this simulation, 12% was used for both the discount and inflation rates to consider worst-case scenarios.

The main economic matrices used to evaluate the economic feasibility of the project were the net present cost (NPC) and the levelized cost of energy (LCOE). The total NPC is the present value of all costs incurred by the system over its lifetime (which includes capital cost, replacement cost, O&M cost, fuel cost, emissions penalties, and the cost of buying power from the grid) minus the present value of all revenue earned over the lifetime (which includes salvage value and grid sale revenue). HOMER calculates the *LCOE* using Equation (2) [23].

$$LCOE = \frac{C_a - C_b H_s}{E_s} \tag{2}$$

where C_a is the total annualized cost of the system (KSH/year), C_b is the boiler marginal cost (KSH/kWh), H_s is the total thermal load served (kWh/year), and for PV systems that do not serve any thermal loads, H_s is zero. E_s is the total electrical load served (kWh/year). C_a is calculated in HOMER using Equation (3) [15,38].

$$C_a = CRF.C_{NPC} \tag{3}$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{4}$$

where C_{NPC} is the total *NPC*, i is the annual real discount rate (%), n is the number of years (project lifetime), and *CRF* is the capital recovery factor [39]. The real discount rate i is calculated in HOMER using Equation (5).

$$i = \frac{r - f}{1 + f} \tag{5}$$

where r is the nominal discount rate, which is the rate at which money can be borrowed, and f is the inflation rate.

4. Results and Discussion

4.1. Solar Radiation

The average monthly observed solar radiation on the horizontal surface at Moi University's main campus in Eldoret is shown in Figure 4. This data covers a period of 4.3 years, from November 2017 to January 2022. The maximum solar radiation of 5.7 kWh/m^2/day occurred in the month of February, whereas the lowest solar radiation of 4.03 kWh/m^2/day occurred in the month of July, and this is the value that was considered during simulations to account for worst-case scenarios of sunlight. Also, the average annual solar radiation for this site yielded 4.93 kWh/m^2/day, which is approximately 5 h of daily sunshine. This is a good capacity to be exploited for solar PV energy generation. In addition, the site-specific data and the data collected from the National Aeronautics and Space Administration (NASA) database were plotted. Based on these two data sets, it was determined that the month with the highest radiation was February (6.71 kWh/m^2/day, as per NASA data) and the lowest month was July (5.10 kWh/m^2/day, as per NASA data). Furthermore, the annual average solar radiation for this site, according to NASA, was 5.90 kWh/m^2/day. The two annual averages differed from each other by 0.97 kWh/m^2/day. This difference is because the data provided by NASA covered a very large geographical area, as opposed to the data that were measured on site. The clearness index, on the other hand, is a measure of how bright or cloudy the sky is. It varies between zero and one, with zero meaning a completely cloudy sky and one meaning a perfectly sunny day. It should be noted that it is always advantageous to use site-specific data when dealing with solar PV installations.

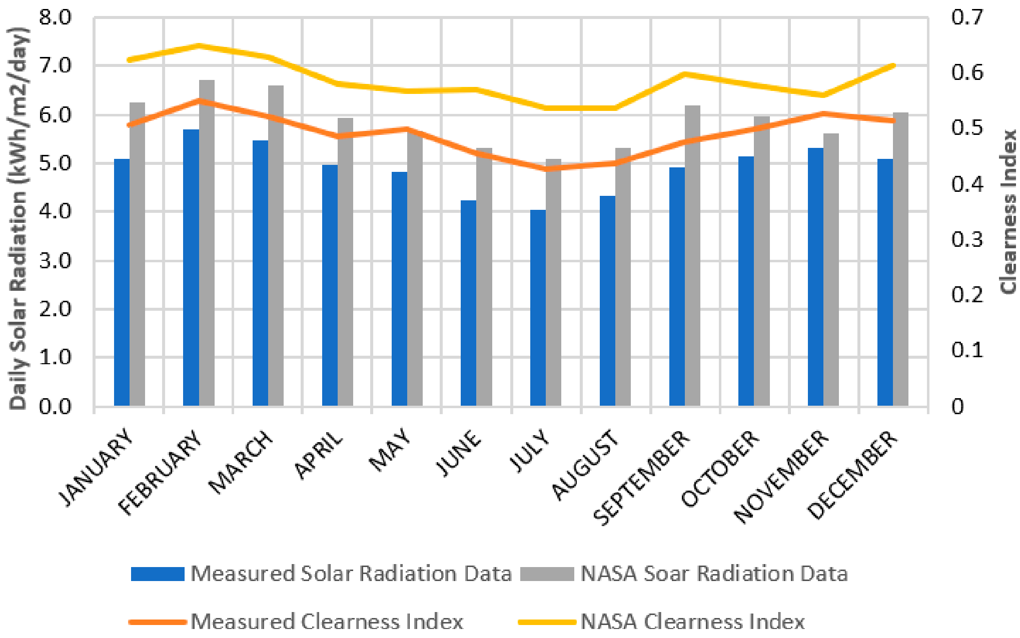

Figure 4. Comparison of NASA and measured solar radiation data for the study site.

4.2. Temperature

The average monthly temperatures were analyzed for a period of 4.3 years (from November 2017 to January 2022), and the results show that the hottest month was February, with an average monthly temperature of 18 °C, whereas the coldest month was July, with an average monthly temperature of 15 °C, as shown in Figure 5. This means that solar panels installed within this site would perform much better, as external cooling systems would not be needed for cooling the solar panels. Cooling of solar panels is often needed because temperature has an effect on the output power of solar modules. Furthermore, the temperature collected on site was compared with the National Aeronautics and Space Administration (NASA) data. The results show that there was a slight variation of about 3 °C. This is because the temperature found in the NASA database for a particular location covered a broader area. This is why it is always important to collect site-specific data when designing solar PV systems.

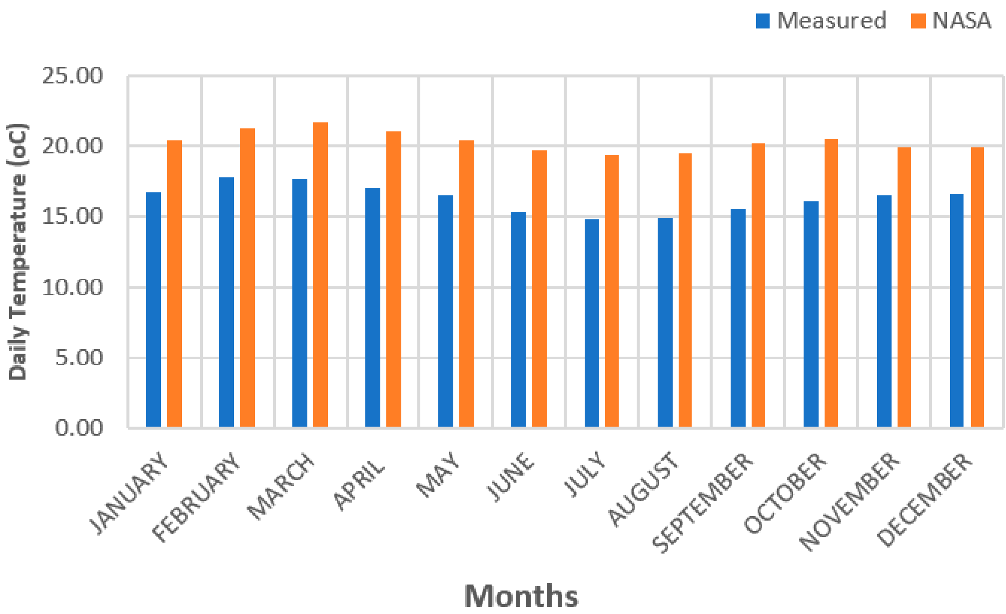

Figure 5. Average monthly temperature variation at the study site.

4.3. Load Demand

The load demand profile for the administration building is shown in Figure 6. The average peak and base load demands for the building were 64 kW and 30 kW, respectively. The average power demand during weekdays (Mondays to Fridays) was 41 kW, whereas the average power demands on Saturdays and Sundays were 28 kW and 25 kW, respectively. The overall average weekly power demand was 37 kW. Also, because the load varied randomly during the day, random variability constants of 4% for day-to-day and 4% for the time step were used for simulations, because the loads did not vary much each day, as was seen from the data collected for different days. The figure of 4% was selected because it was at this value where the energy requirement for the building was effectively covered. Choosing a value of less than 4% would lead to system under sizing, and choosing a value greater than 4% would lead to an oversized system, which is not needed, as it would increase the cost of the system.

Due to these variability constants, the peak load increased to 70.58 kW, as determined by the HOMER software. Furthermore, during weekends, the power demand for this building was low, with a peak value of 31 kW on Saturday, as shown on Figure 6. This means that most of the energy generated during the day on Saturdays and Sundays would be sold to the grid.

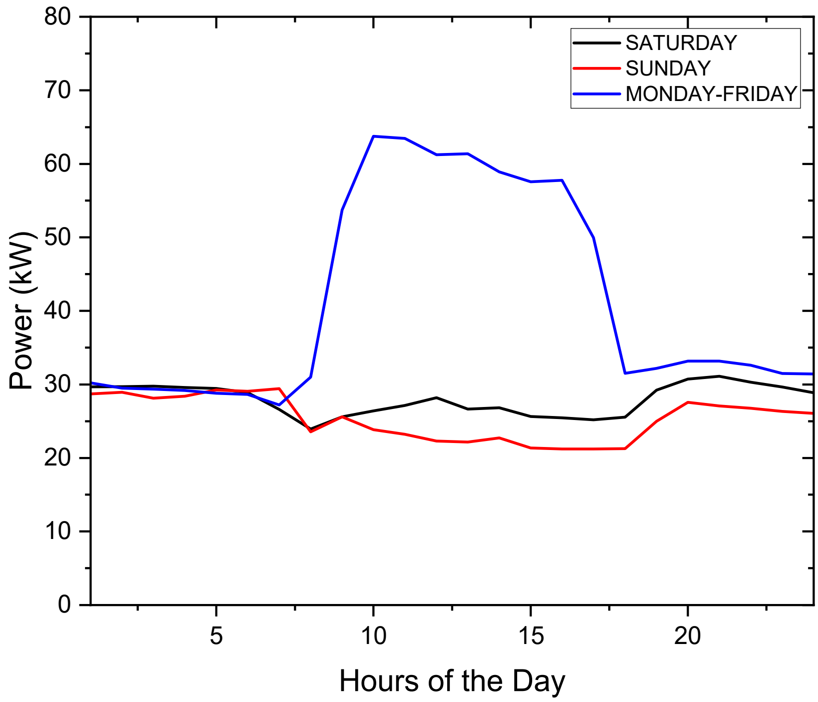

Figure 6. Daily load curve.

4.4. Technical Results from Simulations

After simulating the system, the optimal configuration was selected, which was the system with the lowest LCOE and NPC, as shown in Table 2. The optimal system was the solar PV/grid configuration, and the results presented here are for this optimal configuration. At the time of this study, USD 1 was equivalent to KSH 121.2.

Table 2. Comparison matrix for selecting the optimal system.

System Configurations	LCOE (KSH)	NPC (Million KSH)
Grid	21.39	82.6
Grid/battery	22	84
Grid/solar PV	8.78	43.7
Grid/solar PV/battery	10.49	49.4

The results from the optimal system show that solar PV produced 269,136 kWh/year, meeting 67.9% of the annual electricity consumption of the building, which was 396,092 kWh/year. The PV and grid production to meet the load demand is captured in Figure 7. Based on these results, it was determined that most of the power demanded by the building was covered by the solar PV system, especially during the day during peak sunshine hours.

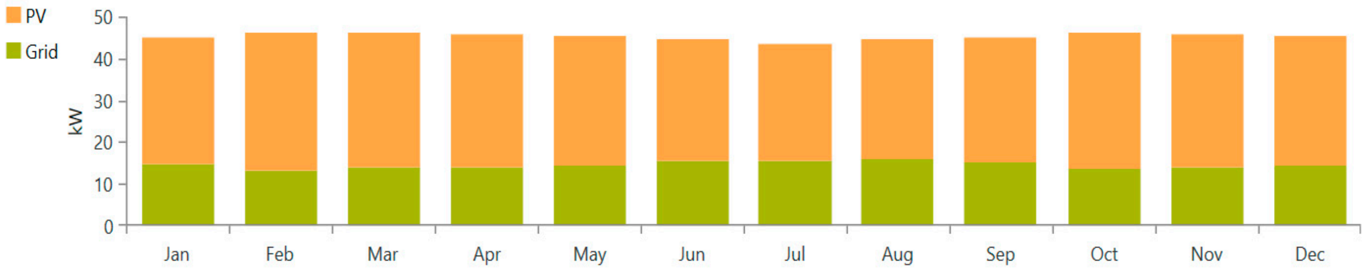

Figure 7. Monthly average electric production.

Figure 8 shows the renewable energy penetration, which was highest from 8:00 to 18:00. At this same time, energy from the PV system was sold to the grid, as shown in Figure 9. On the other hand, from 18:00 to 8:00, the solar system stopped producing because of the lack of sunshine during this period, warranting energy purchase from the grid. The renewable energy fraction was 67.1%. The amount of energy purchased from the grid was 126,957 kWh/year, whereas the amount of energy sold to the grid was 65,957 kWh/year. This yielded a net energy purchase of 61.005 kWh/year. With this reduced energy purchase from the grid compared to when only grid power was used, the cost incurred on utility bills was reduced.

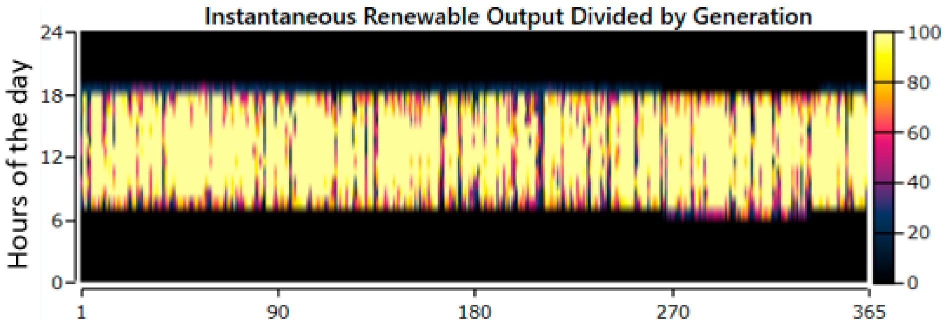

Figure 8. Renewable energy penetration.

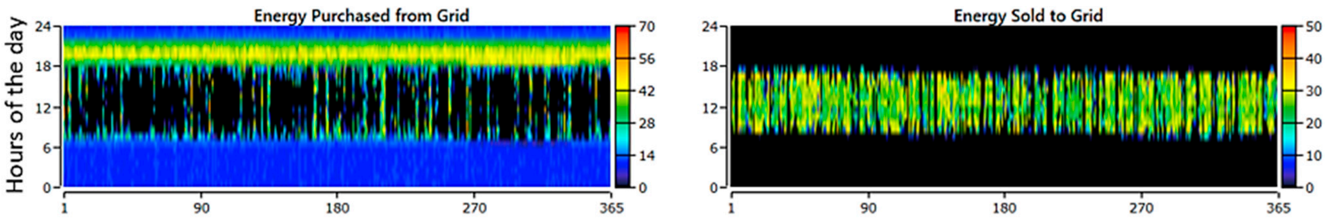

Figure 9. Energy purchased and energy sold to the grid.

4.5. Economic Results from Simulations

The total NPC of the PV/grid system was found to be KSH 43,747,320 and the LCOE yielded KSH 8.78/kWh, which is slightly higher than the value obtained by Eze et al. [15]. This is because this hybrid system does not include diesel generators in the design, which makes it clean and suitable for the environment and especially for promoting the green campus initiative. The distribution of the total NPC per component is shown in Figure 10. The operating cost for the system was KSH 1,353,126.

Also, as seen in Figure 10, the KSH 15,772,828 cost incurred by the grid was the O&M cost, which is not the burden of the renewable energy producer but that of the utility operator. Therefore, subtracting this amount from the NPC of the system yielded a new NPC of KSH 27,974,492. The initial capital expenditure for the system yielded KSH 26,300,000, an internal rate of return (IRR) of 19.1%, an SPBP of 5.08 years, and a discounted payback period (DPBP) of 6.22 years. This system also yielded a current worth of KSH 38,827,200 and a 19.2% return on investment (ROI), which shows that the overall system is profitable and worth investing in. In addition, this system, compared to the grid, reduced the LCOE per kWh by 58.95%.

To better appreciate the contribution this system would bring in saving cost, the monthly cost of energy in 2018 obtained from the utility bills was used as the base year. This year was selected because the years 2019–2021 were characterized by many lockdowns caused by the COVID-19 pandemic. This comparison is shown in Figure 11. With the implementation of this hybrid system, a reduction in monthly electricity charges was witnessed, which would lead to financial gains for the university. Koko [40] also reported a cost reduction in electricity bills when using grid-tied PV systems. Also, by using this system, 83.94% of the annual amount spent on utility bills would be saved, as indicated in Table 3.

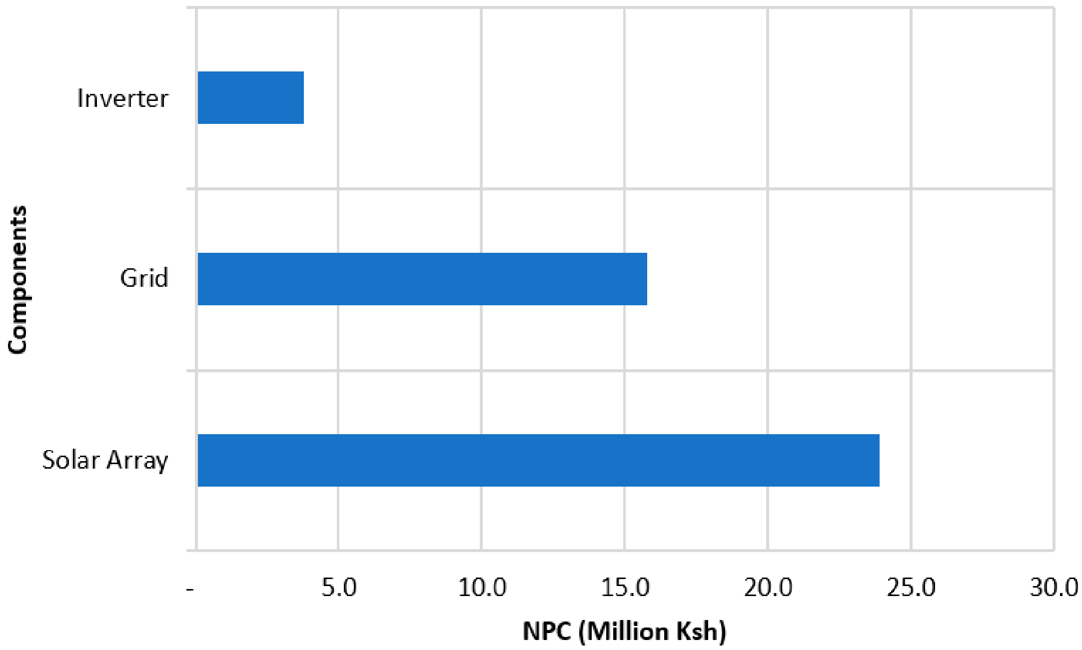

Figure 10. Net present cost (NPC) for different components.

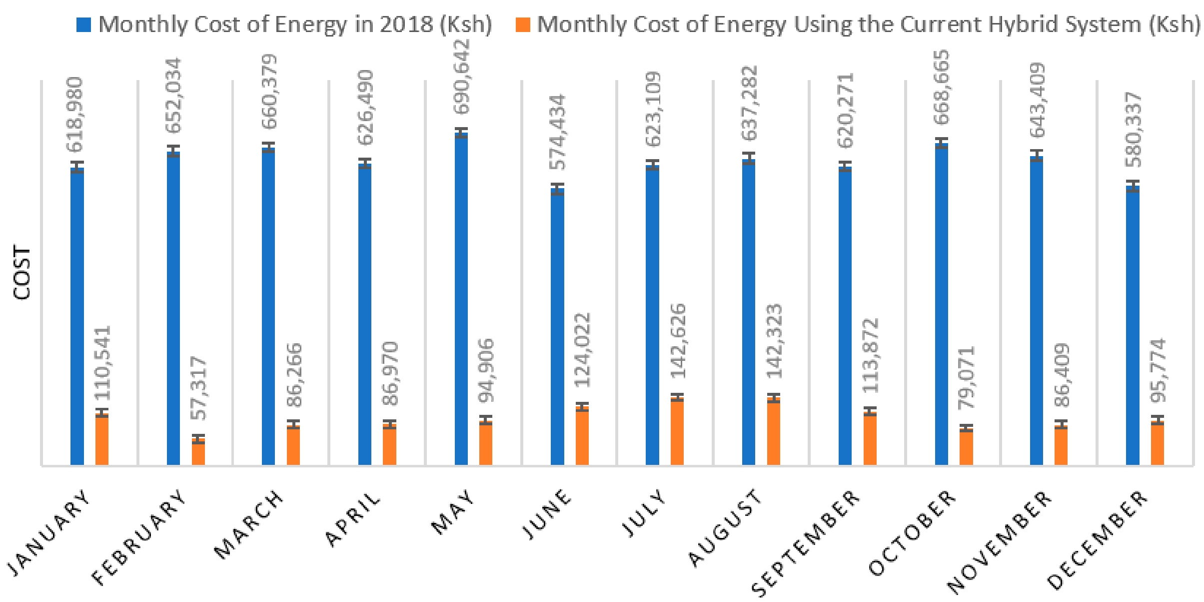

Figure 11. Monthly cost of energy in 2018 and current hybrid system.

Table 3. Techno-economic comparison of existing system and current system using 2018 as base year.

Parameter Considered	Base Year System	Current System
Annual energy consumed	356,333 kWh	61,005 kWh
Annual cost of energy	KSH 7,596,032	KSH 1,220,098
Annual cost to be saved	-	KSH 6,375,934
Percentage saved on energy cost	-	83.94%

Compared to similar work carried out in the literature to solve the problem of electrification in academic institutions [15], this work did not make use of diesel generators, which are not considered to be environmentally friendly, though they are reported to contribute to cost reduction in hybrid systems. This design approach is therefore an eco-friendly approach and should be implemented practically, as it contributes to the fight against climate change.

5. Conclusions

A solar PV/battery/grid hybrid system was simulated in this study. The simulation results show that the solar PV/grid hybrid system without battery storage is the most optimal system that can be implemented to power the administration building of Moi University. This is because the grid already exists and is solely being used to power the building. Using batteries would only increase the overall cost of running the system, which would no longer be cost effective. Based on the results obtained with this optimal system, the LCOE was reduced from KSH 21.39/kWh to KSH 8.78/kWh, yielding a percentage reduction of 58.95%. In addition, the results show that implementing this system would reduce the annual electricity bill for the administration block by 83.94%. Finally, when compared to other hybrid systems that have been proposed in the literature, this system does not make use of diesel generators, which makes it advantageous, as diesel generators cause pollution to the environment. Also, this study contributes to the area of solar energy adoption in academic institutions, which is a good pathway towards developing green campuses. In addition, the work contributes to the area of data-driven design by using site-specific data for the design of solar PV systems. Moreover, this work, through its advocacy for renewable energy adoption, aligns with sustainability goals and contributes to the reduction of greenhouse gas emissions and, hence, the fight against climate change and a more environmentally friendly energy landscape. The research also contributes to the area of renewable energy system modeling through the use of software and simulations. The system is therefore strongly recommended to be implemented, especially in large establishment where the grid is the sole source of power supply. This is also favored by the energy policy in Kenya, which allows for net-metering for systems of less than one megawatt.

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