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Design and Analysis of Grid-Connected Photovoltaic-Battery Hybrid Energy System for Remote Area Electrification: A Case Study of Kakuma, Kenya

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A B S T R A C T

This study presents comprehensive research on the potential of photovoltaic systems to improve electricity access in Kakuma, Kenya that houses a United Nations High Commissioner for Refugees camp. The study uses Hybrid Optimization of Multiple Energy Resources (HOMER) to assess viability from economic, environmental and technical standpoints for proposed hybrid resource energy system (HRES). Among the five configurations, configuration 2 that consists of utility grid, photovoltaic system, battery and converter is the most suitable solution due to the limited grid infrastructure with levelized cost of energy (LCOE) of $0.119/kWh, net present cost (NPC) of $8.38 million and annualized savings of $203,027. It can be established from the outcomes of the study that the values of LCEO, NPC, energy purchased from the grid, CO_2 emission and operating cost have reduced by 30.59%, 24.50%, 42.48%, 42.48% and 38.49% when compared to the base system (grid only). The sensitivity analysis revealed that the availability of solar resources is the most significant factor that influences the economic feasibility of the power system. The study provides valuable insights into the potential of solar resources to expand energy access in remote regions while demonstrating that HRES is a feasible solution for the electrification of rural communities.

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1. Introduction

Global industrial development, population growth and high living standards have significantly increased load demand. Conventional power plants, coupled with depleted fossil fuels, cannot meet ever-increasing load demand without detrimental impacts on human activities, harmful gas emissions, soil degradation and high cost of energy. Thus, it is critical to look for reliable, affordable and environmentally friendly ways to produce the necessary amount of electrical energy [1]. The quest to avert the environmental damage occasioned by burning fossil fuels has prompted many countries to shift from conventional plants to renewable energy technologies or a mixture of renewable energy technologies and conventional power plants in a single power system. The concepts of renewable energy resources to improve access to electricity have been globally accepted owing to their availability, clean and affordability, inexhaustible, reduction of carbon footprint, creation of job opportunities, improvement of resilience and security of power supply, delivery of cheap electricity and reduction of economic uncertainty. The most potential forms of environmentally friendly energy production in remote locations are renewable sources such as hydropower, wind and PV systems [2].

Global access to electricity has increased considerably in the past few years, where the number of people who have no access to electricity has reduced from 1.662 billion in 2000 to 746 million in 2023. Despite this significant improvement, the electricity access rate is very low in many Sub-Saharan African countries since about 598.8 million people do not have access to electricity. This shows that Sub-Saharan Africa is the least electrified region in the world, followed by developing Asia countries with a large population without access to electricity. The electricity access rate in SSA countries stands at 80.7% and 30.4% for the urban and rural populations, where many people face frequent power outages and unstable energy supplies. The only feasible solution to reduce the energy deficit, emissions, and global warming is the considerable advancement of renewable energy technologies for power solutions [3]. This would ultimately improve access to electricity in remote or island areas, such as rural and isolated communities.

The rising demand for electricity in Kenya, propelled by demographic and economic growth, necessitates a strategic shift towards renewable energy technologies. In areas like Kakuma, the current dependence on traditional energy sources is not only environmentally unsustainable but also unreliable. Hence, integrating photovoltaic systems is critical [1], [2]. These systems are aligned with Sustainable Development Goal 7, aimed at clean and affordable energy and providing other benefits such as reduced environmental impact, enhanced grid stability and economic efficiency. The power sector is undoubtedly instrumental in driving economic progress, particularly in developing countries like Kenya, where it supports industrial and infrastructural advancement. Hybrid renewable energy systems dynamically respond to both present and future energy requirements, with on-grid systems that use renewable energy coupled with storage solutions to mitigate their intermittent nature. The off-grid systems are especially valuable in remote regions, reducing the need for extensive grid infrastructure and promoting sustainable energy independence [3], [4].

Kenya's equatorial position gifts it with high solar insolation, presenting a significant opportunity for solar energy exploitation. This solar energy potential remains largely untapped, even though hydroelectric power, which constitutes a substantial portion of the current energy mix, is subject to variability due to changing rainfall patterns. The economic and environmental advantages of diversifying the energy mix with solar energy are becoming increasingly apparent, especially considering volatile oil prices and environmental imperatives. With 4–6 $kWh/m^2/day$ of solar radiation on average, Kenya's Northern and North Eastern regions are prime locations for solar energy development, which currently caters to a fraction of the population primarily for basic household uses [5].

Despite these rich solar resources, renewable power sources like PV and concentrated solar power still represent a minimal fraction of Kenya's energy portfolio. However, the landscape is poised for change as the country aims to boost its economy to a middle-income status by 2030, as outlined in the Vision 2030 plan. This ambitious goal necessitates robust energy infrastructure and efficient power production to alleviate the economic losses incurred from frequent power outages, which, in a single month, can estimated to be 6.3 million Kenyan shillings [6], [7]. Hence, this research aims to facilitate Kenya's stride towards achieving SDG 7 and SDG 13 by assessing the performance of PV systems within various African regions, providing empirically backed recommendations for renewable energy deployment to enhance electricity access and reduce the environmental impacts of energy production. By delving into the viability and impact of PV systems, this study not only supports Kenya's vision 2030 by suggesting ways to improve energy resilience and accessibility but also contributes to the global discourse on sustainable energy solutions. Kenya faces a significant problem with insufficient electricity infrastructure and supply deficits, leading to frequent power outages that impact the population's ability to access reliable electricity. Only 70% of the population has access to electricity, with rural areas experiencing significant disparity compared to urban areas. This is due to several factors, such as inadequate infrastructure, insufficient investment in electricity distribution systems and limited access to financing energy projects. These challenges hinder efforts to improve access to electricity in these regions, making it a critical area that policy makers and stakeholders must address urgently.

Hydropower plants are Kenya's primary electricity generation source, but they are highly vulnerable to droughts that impact their generation capacity. These outdated systems have become a critical issue for the nation's energy infrastructure, requiring immediate attention to guarantee a steady and reliable power source. A more thorough and long-lasting strategy is required to solve these issues and enhance Kenya's electrical infrastructure. Moreover, the rapid population growth in Kenya has caused a notable demand for electricity, which has surpassed the additions to generation and grid capacity. This has resulted in a widening supply-demand gap, leading to frequent load shedding. Despite efforts to address the issue through infrastructure development, persistent theft and vandalism of power infrastructure continue to hamper progress in the sector. These problems are pervasive and have further exacerbated the existing supply disruptions, posing significant challenges to the country's energy sector. Small businesses suffer huge losses from frequent blackouts, estimated at 6% of revenue, especially during peak demand hours in the evening when people return home from work.

To address these challenges, solar photovoltaic systems hold significant promise in augmenting grid supply and enabling decentralized, clean energy access to underserved regions such as Kakuma. Deploying PV systems can reduce reliance on conventional fossil fuel-based energy sources, mitigate greenhouse gas emissions and enhance energy security. With the increasing efficiency and decreasing costs of PV technology, it has become a viable alternative and a potential solution to the energy deficit and poverty that are prevalent in many regions of the world. Utilizing PV systems can also have a positive economic impact by fostering the growth of regional industries and creating jobs. Additionally, they can offer dependable and resilient power supplies to isolated areas, enhancing living standards and promoting socio-economic growth because they are decentralized. Implementing solar PV systems can be extremely important for accomplishing sustainable energy targets and encouraging equitable growth.

Several studies have been conducted to evaluate the performance of renewable energy-based hybrid energy systems in rural and urban areas. Eze *et al.* [8] explored the potential of renewable energy to power a building at the University of Nairobi's School of Engineering in Kenya by considering technical and financial factors. The study assessed whether a renewable hybrid energy system could be implemented. The study recommended this system for the site where access to the utility grid is restricted due to technical constraints and economies of scale. Carralero *et al*. [9] employed a testing platform for hardware-in-the-loop that allowed for thorough system component modeling and ensuring high accuracy in their simulations. The authors considered the system's long-term reliability and safety alongside battery life. Similarly, Chang *et al.* [10] found that single-household systems had lower NPC and LCOE than village microgrids, indicating the potential for scalability and cost-effectiveness in smaller installations. At the same time, Thirunavukkarasu and Sawle [11] minimized NPC and LCOE, highlighting the cost-effectiveness of their PV/wind/diesel/battery HRES by utilizing HOMER Pro software to simulate hybrid renewable energy for their simulation needs. Ge *et al.* [12] utilized another modeling approach through mathematical representations of the various system components. The authors focused on minimizing the LCOE, demonstrating that well-designed HRES can be economically viable and sustainable. Huneke *et al.*[13] applied linear programming for system optimization. These approaches highlight the importance of precise, context-specific modeling in the design and feasibility analysis of HRES. A critical aspect of these studies is the economic evaluation of HRES, often using metrics such as the levelized cost of energy, net present cost and total net present cost.

Silinto *et al.* [14] conducted a thorough analysis of cutting-edge energy systems and spatially explicit modeling techniques with the goal of determining methods appropriate for planning the integration of HRESs in remote communities of developing nations. Silinto *et al.* [15] presented an interactive spatial energy strategy based on an extended tool called the geographic information systems for rural electrification model and to determine the least-cost energy solution. Andrade-Arias *et al.* [16] introduced the Smart PLS software to evaluate public support for solar energy projects in Mexico, pinpoint the elements affecting opinions and suggest legislative changes to improve community involvement. The study made use of survey data from several Mexican cities as well as a conceptual model. Barun *et al.* [17] presented recent cutting-edge research on standalone HRES solutions for supplying freshwater, electric, heating, cooling, hydrogen and electric vehicles with different combinations. This study also offered reasons for choosing configurations appropriate for particular geographic areas. Assouo *et al.* [18] utilized HOMER application to determine the optimal configuration of HRES based on the lowest net present cost while taking the technical and environmental constraints of the proposed system into consideration. Rouzbahani *et al.* [19] conducted techno-economic optimization of HRES with the goal of minimizing energy costs by utilizing solar and bio resource potential. In the study, biomass from the wetlands was used to produce biogas, which supplied energy to neighbouring rural communities. Adefarati *et al.* [20] proposed genetic algorithm and particle swarm optimization to assess the feasibility of PV/wind/battery/diesel hybrid energy system designed for off-grid electrification project. It can be established from the findings of the research that deployment of green energy technologies in the conventional power system significantly reduced the cost of energy and total cost of the system.

Several studies have prioritized the application of renewable energy resources as a potential solution for power supply in urban or semi-urban areas and neglected the unique challenges faced in remote or rural areas, especially refugee-hosting communities like Kakuma. Few studies explored the synergies between diverse renewable sources, such as solar and wind, alongside battery storage systems. Many existing models focus on technical feasibility but lack in-depth economic evaluations, particularly in assessing the levelized cost of energy and long-term financial sustainability. Existing studies often overlook how research findings can influence policy frameworks for renewable energy deployment in refugee camps. While technical and economic aspects are widely studied, there is limited quantification of environmental benefits, such as emissions reduction and ecological footprint. This paper introduced innovative aspects across technical, economic and environmental dimensions. The key novelties are summarized: This study used localized climate and demand data from Kakuma, Kenya, a region with unique socioeconomic challenges and weather patterns. The load profiles are designed for refugee camps and surrounding communities to address variations in daily and seasonal energy consumption. Most HRES studies generalized data, leading to suboptimal designs for specific regions. This work tailored the system to local needs and ensured higher accuracy and sustainability of power supply. Hybrid systems with PV, utility grid and battery systems or more energy sources are rarely used in rural communities and analyzed in detail, especially in remote areas. This approach reduced intermittency and improved power system sustainability. Environmental impact assessments are often overlooked in hybrid energy studies; this research makes it a core component of the analysis. This study provides a holistic assessment, making decision-making more robust and practical.

Numerous studies on the technical and economic analysis of hybrid energy systems have made it clear that inadequate scenario exploration, indecisiveness when choosing key system components and a lack of a thorough grasp of the economic implications of those choices have frequently resulted in an unnecessarily high energy cost and inadequate power system feasibility assessments. Thus, to supply electricity to a typical refugee camp that is located in Kakuma, Kenya, the present study is being conducted to investigate the technical, environmental and financial performance of various configurations of hybrid energy system that comprise PV system, utility grid, battery system, converter and AC load. Within this framework, the study's primary objective aims to conduct an economic analysis using the levelized cost of electricity and net present cost. Several configurations are investigated in this study to find the optimal solution that is well-suited for the selected area. The present study incorporates a sensitivity analysis to examine potential effects on the optimal configuration resulting from varying the values of specific factors such as nominal discount rate, solar radiation and load demand. In this analysis, the HOMER application tool is used in the study to carry out technical, economic and environmental evaluation of the proposed hybrid energy system. The contributions of this paper are stated as follows:

i. Design of a PV/grid/battery hybrid energy system to meet the ever-increasing load demand of the UNHCR camp in Kakuma, Kenya.
ii. Development of the mathematical models for the major components of HRES and ensure that the proposed power system will perform as expected under varying conditions.
iii. The study's output can be used to assess the economic viability and environmental impact of minimizing the LCOE and green gas emissions.
iv. The research aligns with the United Nations' Sustainable Development Goals by explicitly focusing on clean energy and climate action.
v. The research's outputs, through techno-economic analysis and simulations, offer an optimal and sustainable solution for the regions in Kenya.
vi. The research's outputs can benefit policymakers and investors interested in providing affordable and dependable electricity access throughout Kenya and Sub-Saharan Africa.

2. Materials and Methods

2.1. Site selection

The geographic location of Kakuma in East Africa with coordinates of 3°42.5'N and 34°51.7'E is shown in Figure 1 [21]. The pressing need for clean and reliable electricity in the area makes Kakuma an excellent location to explore PV systems, given its unique characteristics and energy demands. It is worth noting that PV systems have substantial power capacity in Kakuma due to the region's abundant solar resources [22]. Kakuma was selected as the study location based on its distinctive socio-economic background and the promising possibilities for solar resource development. The presence of a UNHCR camp established in 1992 adds to the study's significance, as photovoltaic systems can offer a power solution to meet the camp's electricity needs and enhance the residents' standard of living [23]. Addressing the extensive energy shortage in the area requires the implementation of sustainable energy sources, such as PV systems.

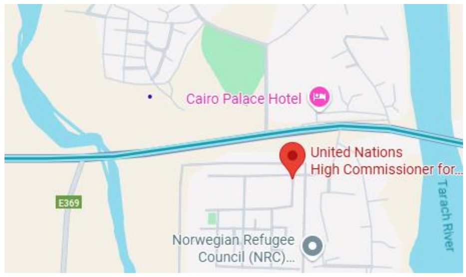

Figure 1. Geographic Location of Kakuma in East Africa

2.2. Electrical load

Electricity consumption refers to the electricity used by individuals, organizations, and public utilities for various purposes, such as lighting, operating appliances and providing energy to nearby facilities [24]. The town's population, local activities, weather conditions and daily routines significantly impact the electrical load, which is synonymous with consumption [25]. This project aims to meet the electricity needs of 1,000 residences. Based on the data, the average load, load factor, peak load and average daily consumption are 354.17 kW, 0.35, 1025.17 kW and 8500 kWh. The graph of daily daily electricity demand per day that was entered into the HOMER application based on the load profile of the selected location is presented in Figure 2. The figure shows the daily electrical load demand, with peak hours between 6:00 PM and 9:00 PM. Figure 3 shows the graph of the load seasonal profile of the selected site on monthly basis. The seasonal profile shown in Figure 3 indicates a decrease in demand during October and an increase in April, which can aid in developing effective energy strategies.

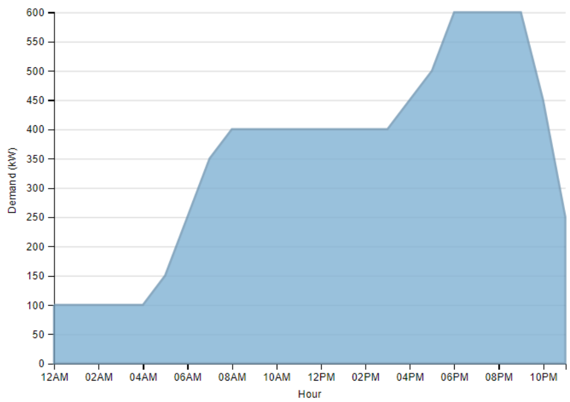

Figure 2. Graph illustrating the daily electricity demand variation in Kakuma

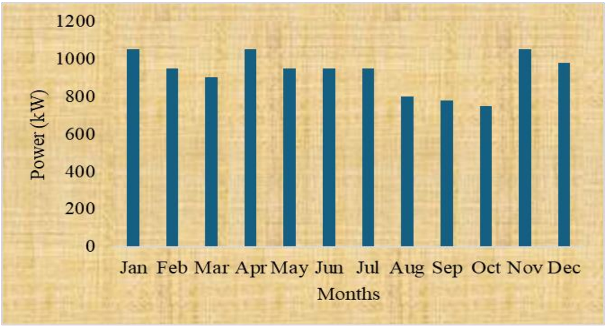

Figure 3. The load seasonal profile showcasing the seasonal fluctuations in electricity demand

2.3. Weather information

It is crucial to analyze the area's meteorological data, including temperature and solar irradiance, when considering implementing HRES in a particular location [26]. This is especially true in regions like Kakuma, where the potential efficacy of PV mainly depends on the amount of solar radiation. By examining detailed solar irradiance data, stakeholders can determine the expected performance and viability of PV installations to ensure that they align with the locality's unique energy demands and sustainability goals [27]. This is particularly important when addressing the energy needs of the UNHCR camp and surrounding communities. Mathematically, the average horizontal radiation for the day can be estimated using Eq. (1) [26].

$$Y_o = \frac{24}{\pi} \times Y_{on}\left[\cos f \cos\delta \sin w_s + \frac{\pi w_s}{180}\sin f \sin d\right] \quad (1)$$

The clearness index is an important metric for evaluating the effectiveness of solar panels. The clearness index of the PV system is expressed in Eq. (2) [26].

$$k = \frac{Y_{o,measured}}{Y_{o,calculated}} \quad (2)$$

The graphical representation of horizontal solar radiation and clearness index by month is presented in Figure 4. The solar irradiance ranges from 5.24 to 6.44 kWh/m^2/day, with an annual mean of 5.78 kWh/m^2/day is shown in Figure 4. This indicates a favourable potential for implementing photovoltaic systems in the region. The NASA database is the source of Kakuma's monthly mean solar irradiance and clearness index of the selected site [28].

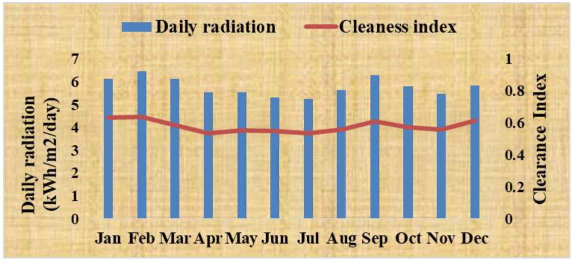

Figure 4. Global Horizontal Irradiance for Kakuma, Kenya

The monthly temperature resources of the selected location are presented in Figure 5. The seasonal temperature fluctuations in Kakuma are depicted in Figure 5, where monthly averages range from 25 °C to 29°C. With an annual mean temperature of 27°C, it is evident how variable it is throughout the year, the region experienced considerable temperature fluctuations across different seasons. Seasonal fluctuations are influenced by changes in solar radiation, prevailing wind patterns and localized climatic factors such as humidity and precipitation. These variations have important implications for energy demand, particularly in relation to cooling needs in buildings and the performance of renewable energy systems such as solar photovoltaic panels.

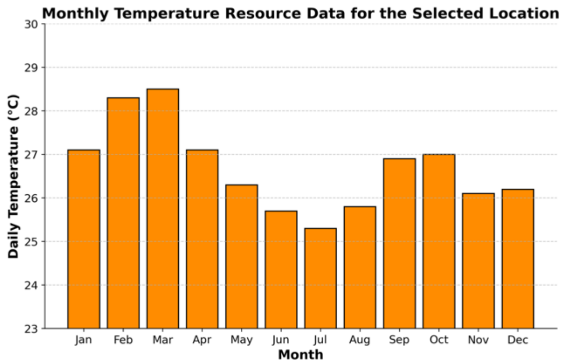

Figure 5. Monthly temperature trends in Kakuma, Kenya

2.4. Hybrid renewable energy system

The PV/grid/converter/battery architecture shown in Figure 6 can be used to illustrate the efficacy of HRES. The HRES as shown in Figure 6 incorporates photovoltaic panels, a bidirectional converter, battery storage and grid connectivity into a single power system for efficient energy management. This architecture combines the generation of renewable energy, grid connectivity and energy storage capabilities into a single energy system. This allows effective energy management that enhances the use of clean energy and manages energy demands and grid outages. The system uses solar panels that convert sunlight into electricity, called photovoltaic panels [29]. These panels generate direct current electricity, which powers the system. Because the system is connected to the electrical grid, it can import electricity when needed and export excess electricity to the grid. The converter is a crucial system component because it transforms the DC electricity from the PV panels into practical AC electricity. It can also charge the battery system by converting AC to DC. The converter ensures the system meets grid standards and maximizes power quality and efficiency.

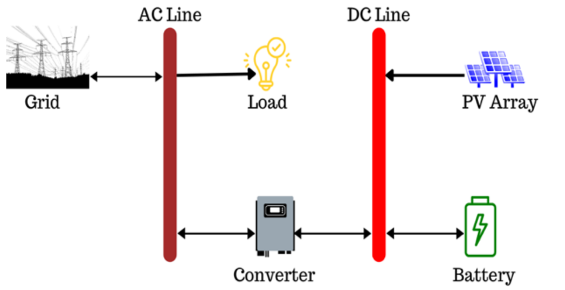

Figure 6. Schematic diagram of the proposed hybrid renewable energy system

2.4.1. Photovoltaic system

The PV panels are strategically placed on structures such as ground frames or rooftops to ensure optimal sunlight absorption and maximum energy yield [26], [30]. These panels are connected to inverters and other system components through electrical connections, allowing for the smooth flow of electricity [29], [31]. To maintain operational safety and efficiency, the balance of system components like circuit breakers, fuses and junction boxes are integrated. The power output of a photovoltaic system at a specific time can be expressed using Eq. (3) [28].

$$P_{pv,out} = A_{pv} \times \eta_{pv} \times Y(t) \times f_{temp} \quad (3)$$

2.4.2. Grid

The electrical grid system functions as a sophisticated network that links power plants, transmission lines, and distribution systems in order to supply electricity to various consumers [32], [33]. The local cost of electricity in Kakuma is \$0.17/kWh, with a \$0.012 buyback rate per kWh. Purchasing electricity from the grid or selling electricity to the grid solely depends on the power of the PV and battery at a given time. At each time, there has to be a power balance, which is presented in Eq. (4) [28].

$$P_{grid}(t) = \left\{ \begin{array}{l} P_{demand}(t) - P_{pv}(t) + P_{battery}^{+}(t) B_{c/d} \\ - P_{battery}^{-}(1 - B_{c/d}) \end{array} \right\} \quad (4)$$

The total cost of power consumed is then given as [28]:

$$TC = \sum_{t=1}^{T} \left\{ \begin{array}{l} \left(C_{buy}(t) \times \max(P_{grid}(t), 0)\right) \\ -\left(C_{sell}(t) \times \max\left(-P_{grid}(t), 0\right)\right) \end{array} \right\} \quad (5)$$

2.4.3. Converter

The bi-directional converter is an essential part of this system that enables effective energy flow management between solar panels, the grid and electrical loads [29], [34], [35]. It performs the vital functions of converting DC-AC and AC-DC and controlling frequency and voltage to ensure system stability and power quality [36], [37]. Efficient management and power transfer between a bidirectional converter's input and output sides is guaranteed by Eq. (6) [35].

$$\eta_c = \frac{P_{out}}{P_{in}} \quad (6)$$

2.4.4. Battery system

The application of a reliable and efficient battery system is a critical aspect of HRES projects, with energy storage playing a pivotal role [29], [38-41]. In the proposed HRES, the LG Chem RESU 10H has been deemed an optimal choice due to its robust performance, long-lasting lifespan, impressive 9.8 kWh capacity and advanced lithium-ion technology. The required battery system capacity can be estimated using Eq. (7) [42].

$$B_{cap} = \frac{E_L \times D_A}{DOD_{\max} \times \eta_c \times \eta_{bs}} \quad (7)$$

2.5. Techno-economic indicators

Techno-economic metrics are essential for evaluating renewable energy projects' viability and financial yields, mainly solar energy-related ones [43-45]. These metrics provide a thorough analysis that considers technical and financial factors, such as system longevity and efficiency, cost and revenue [46]. Using this integrated approach, stakeholders can evaluate the project's financial feasibility and long-term sustainability.

2.5.1. Levelized cost of energy

The levelized cost of electricity is a crucial metric for determining the actual costs related to generating electricity from the power systems [47]. The LCEO is expressed in Eq. (8) as [35]:

$$LCEO = \frac{c_{ann,tot}}{H_{served}} \tag{8}$$

2.5.2. Total annualized cost

A financial measure known as total annualized cost is used to express a system's or project's lifetime cost [48]. It comprises the initial capital expenditure and continuing costs for maintenance and operations, which are distributed over the system's anticipated operational life. The total annualized cost is expressed in Eq. (9) as [35]:

$$C_{ann,tot} = CRF(i, R_{proj}) \times C_{NPC,tot} \tag{9}$$

2.5.3. Capital recovery factor

A financial metric called the capital recovery factor determines the annual cost or payment needed to recover the initial capital outlay over a period. It can be used to determine the investment's annual cost by accounting for the time value of money [49]. The CRF can be computed using Eq. (10) [50].

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{10}$$

2.5.4. Return on investment

Return on investment measures the financial returns in relation to the initial capital outlay to determine whether HRES is economically feasible [51], [52]. This is accomplished by calculating the ratio between the system's net profit and the investment's total cost [53]. ROI is a crucial metric that investors and financiers use to assess economic feasibility and projected returns of photovoltaic projects. It can be inferred from the following equation [35].

$$ROI = \frac{\sum_{i=0}^{R_{proj}} (C_{i,ref} - C_i)}{R_{proj}(C_{cap} - C_{cap,ref})} \tag{11}$$

2.5.5. Payback period

One of the most important metrics for evaluating the financial sustainability of HRES is the payback period, which indicates how long the initial investment will be recovered through energy savings or production [54], [55]. In essence, it denotes the point at which the system achieves positive cash flow or breakeven. Generally speaking, shorter payback times are better since they signify a faster return on investment, which improves financial viability [56]. Therefore, carefully considering the payback period is necessary when determining whether HRES is suitable for a given application [57]. The payback period is presented in Eq. (12) as [35]:

$$PP = \frac{ICC}{ACF} \tag{12}$$

2.5.6. Internal rate of return

Internal rate of return is one of the key financial metrics used to assess an investment's profitability. It is computed by determining the discount rate at which the net present value of the cash flows is equal to zero [58]. The IRR, as it relates to HRES, represents the average yearly return that will be generated by the project during its lifetime. Eq. (13) makes the calculation of IRR easier [28].

$$0 = \sum_{n=1}^{N} \left(\frac{NCF_n}{(1+IRR)^n} \right) \tag{13}$$

2.5.7. Net present value

Net present value is a necessary financial metric for evaluating the economic feasibility of renewable energy projects. This measure takes the time value of money into account. It calculates the difference between the present value of projected earnings (profits and savings) and outlays (outgoing cash) by discounting future cash flows to their present value. [59]. A positive net present value hints at a project's financial viability, while a negative NPV indicates possible losses. The net present cost is expressed in Eq. (15) as [28]:

$$NPV = \sum_{n=1}^{N} \left(\frac{NCF_n}{(1+IRR)^n} \right) \tag{14}$$

2.5.8. Operating cost

Operating costs are determined by several factors, including how a plant operates. The system's output of electricity may also impact the plant's efficiency. When determining the total costs, it is also necessary to factor in the cost of system maintenance and any prospective repairs or upgrades. Operating cost is expressed in Eq. (15) as [35]:

$$C_{operating} = C_{ann,tot} - C_{ann,cap} \tag{15}$$

2.6. Technical and economic inputs of the proposed hybrid renewable energy system

It is critical to consider economic factors that affect a system's overall cost over its operational lifespan when analyzing a cost-dependent system. Important variables include the project lifespan, which indicates the length of operation; the expected inflation rate, which reflects projected price increases; and the nominal discount rate, which determines the future benefits and costs' present value [60]. These factors provide a more accurate understanding of costs. The selected location is expected to see the project completed in 25 years, with location-specific NDR and EIR values of 9.5% and 8.0%, respectively. The technical and economic details of the proposed HRES are presented in Table 1.

Table 1. Technical and economic details of the proposed hybrid energy system [28], [61-63]

Description	Capital cost ($)	Replacement cost ($)	Maintenance cost ($/yr)	Lifetime (yr)
Solar PV	370	370	3.7	20
Battery system	5800	5800	50	5
Converter	2520	2520	25.20	15
Grid	-	-	-	-

3. Results and Discussion

Photovoltaic systems have gained popularity as a feasible solution for customers in various sectors, including domestic, industrial, commercial and institutional, across different regions in Africa. In order to determine if a proposed HRES is feasible, a thorough assessment that considers the system's benefits is performed in this study in terms of the environment, technical and economy at the location. Overall, the goal is to provide a comprehensive and detailed analysis that will help inform decision-making processes regarding the implementation of HRES. The five different configurations are looked upon for the location, and the configurations are shown in Table 2. The analysis of the five configurations is conducted at this location by maintaining the input that was described in Section 2. The optimal configuration of the proposed HRES is obtained based on the minimum NPC.

Table 2. Configuration with equivalent component selection

Configuration	PV	Battery	Grid	Converter
1	✓	×	✓	✓
2	✓	✓	✓	✓
3	×	×	✓	×
4	×	✓	✓	✓
5	✓	✓	×	✓

3.1. Configuration 1

The load demand is satisfied in configuration 1 by utility grid, PV system of 1294 kW and converter of 519 kW. The electrical production of the grid and PV system is designed to meet load demand. The electrical production of utility grid and PV system on monthly basis is presented in Figure 7. This system supplied daily electricity of 9278 kWh/day and a peak power of 1026 kW. The renewable fraction of 46.5% obtained in configuration 1 shows that CO_2, SO_2, and NO_x values are 1,139,067 kg/yr, 4,938 kg/yr and 2415 kg/yr. These emissions' values are attributed to fossil fuel combustion at the respective power plants. In this analysis, it is observed that configuration 1 has a moderate value of emission owing to a renewable fraction of 46.5%. The energy purchased from the grid and energy sold to the grid in this configuration are 1,802,231 kWh and 268,386 kWh, as shown in Table 3. The NPC and COE of the PV and grid configuration are estimated to be $8.38 million and 0.118 $/kWh while the operating costs, CAPEX, simple payback period, ROI, IRR, NPV annualized savings are $326,620/yr, $1.52 million, 7.29 yrs, 9.21%, 2.7%, $2.7 million and $201,165. It can be seen from Table 4 that PV/BSS hybrid energy system is one of the best configurations in terms of low LCOE, NPC, energy purchased from the grid, emissions and high renewable fraction.

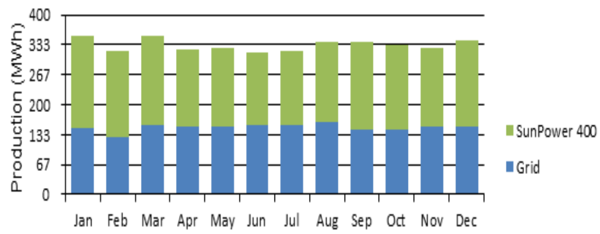

Figure 7. Monthly electrical production of configuration 1 by each component

Table 3. Components, economic indicators and emissions for configuration 1

Components	Capacity (KW)	Unit Price ($/Unit)	Unit Rating (kW/Unit)
PV	1294	370	0.4
Grid	Infinite		
Converter	519	2520	4

Economic Indicator	Value	Units
NPC	8.38 Million	$
LCOE	0.118	$/kWh
Operating Cost	326,620	$/yr
CAPEX	1.52 million	$
Renewable Fraction	46.5	%
Energy Purchased (grid)	1,802,231	kWh
Energy Sold (grid)	268,386	kWh
Simple Payback	7.29	Yrs
ROI	9.21	%
IRR	12.7	%
NPV	2.7 million	$
Annualized Savings	201,165	$

Emission	Value	Units
CO_2	1,139,067	Kg/yr
SO_2	4,938	Kg/yr
NO_x	2,415	Kg/yr

3.2. Configuration 2

It can be observed from the analysis of the results obtained in configuration 2 that the utility grid, PV system of 1335 kW, converter of 505 kW and three units of battery system are utilized to meet the dynamic load demand of UNHCR camp, Kenya. The electrical production of each component of configuration 2 such as utility grid and PV system on monthly basis is presented in Figure 8. The proposed grid-connected HRES supplied a peak load of 1026 kW and required daily electricity of 9278 kWh/day. The hybridization of multiple resources in configuration 2 is the optimal solution with an LCOE of 0.119 $/kWh and an NPC of $8.38 million. The values of payback period, ROI, IRR, NPV and annualized savings obtained in this configuration are 9.32 yr, 7.44%, 8.94%, $2.69 million and $203,027, as shown in Table 4. The annual energy purchased from the grid and energy sold to the grid have been estimated to be 1,784,604 kWh/yr and 246 873 kWh/yr. The values of CO_2, SO_2 and NO_x have been reduced to 1,127,870 kg/yr, 4,890 kg/yr and 2,391 kg/yr with the application of PV, battery system and utility grid. This configuration produced minimum emission compared to other configurations discussed in the paper owing to renewable fraction of 46.7. After thoroughly considering the various factors, configuration 2 is the most suitable choice. This setup met the power needs while using low energy from the utility grid. It also allowed energy storage in the battery and the option to send any extra energy back to the grid. While configuration 1 has similar results in terms of NPC and operating cost, it lacks a battery system to provide energy during blackouts when the PV is not generating power. This shows that configuration 2 is the most environmentally friendly HRES with the lowest emissions and is technically and economically accepted owing to the lowest value of NPC ($8.38 million), LCEO ($0.118/kWh), and the highest renewable fraction (46.7%).

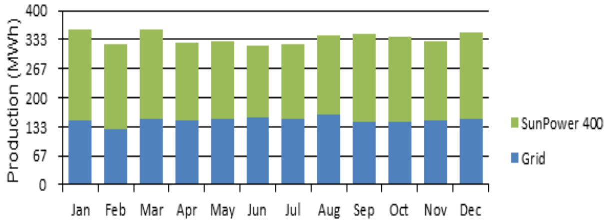

Figure 8. Monthly electrical production of configuration 2 by each component

Table 4. Components, economic indicators, and emissions for configuration 2

Components	Capacity (KW)	Unit Price ($/Unit)	Unit Rating (kW/Unit)
PV	1,335	370	0.4
Grid	Infinite		
Converter	505	2520	4
Battery	Number	Unit Price ($/Unit)	Rating(kWh/ Unit)
	3	5800	9.8
Economic Indicator		Value	Units
NPC		8.38 million	$
LCOE		0.119	$/kWh
Operating Cost		324,398	$/yr
CAPEX		1.57 million	$
Renewable Fraction		46.7	%
Energy Purchased (grid)		1,784,604	kWh
Energy Sold (grid)		246,873	kWh

Battery Autonomy	0.0691	Hr
Nominal Capacity (Battery)	27.2	kWh
Accessible Capacity (Battery)	24.4	kWh
Simple Payback	9.32	Yrs
ROI	7.44	%
IRR	8.94	%
NPV	2.69 million	$
Annualized Savings	203,027	$
Emission	Value	Units
CO_2	1,127,870	Kg/yr
SO_2	4,890	Kg/yr
NO_x	2,391	Kg/yr

3.3. Configuration 3

The monthly electrical energy obtained from the utility grid as can be seen in Figure 9 shows that the utility grid only served the electrical load demand of configuration 3. Most of the costs associated with the operation of the system are related to maintaining the electricity purchased. However, this system produced many emissions compared to other systems discussed earlier. Table 6 presents comprehensive details of the corresponding economic indicators and the emissions generated by the system. The CO_2, SO_2 and NOx emissions produced by this configuration are 1,960,780 kg/yr, 8,501 kg/yr and 4,157 kg/yr. This configuration produced more emissions than other systems discussed earlier since the renewable fraction is zero. The harmful emissions released into the atmosphere are attributed to fossil fuel consumption by respective power plants tied to the utility grid. In this scenario, the energy purchased from the utility grid is 3,102,500 kWh; this shows that all the required electricity is obtained from the grid. Configuration 3 presented NPC, LCEO and operating costs with the following values: $11.1 million, $0.170/kWh and $527,425, as shown in Table 5. This configuration is not economically, technically and environmentally friendly owing to high values of LCOE, NPC, emissions and energy obtained from the grid and 0% of the renewable fraction.

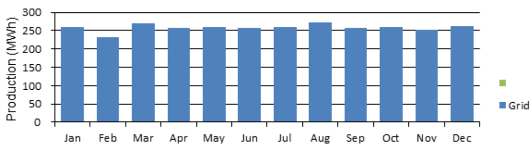

Figure 9. Monthly electrical production of configuration 3 by each component

Table 5. Economic indicators and emissions for configuration 3

Economic Indicator	Value	Units
NPC	11.1 million	$
LCOE	0.170	$/kWh
Operating Cost	527,425	$/yr
Energy Purchased (grid)	3,102,500	kWh
Energy Sold (grid)	0	kWh
Emission	Value	Units
CO_2	1,960,780	Kg/yr
SO_2	8,501	Kg/yr
NO_x	4,157	Kg/yr

3.4. Configuration 4

This configuration is designed to operate with a utility grid, a converter of 8.02 kW and five units of battery systems to meet the required energy demand at the load points. The electrical production of utility grid and PV system on monthly for configuration 4 is presented in Figure 10. It is shown in Figure 10 that the grid served the electrical load but also charged the battery system through the converter. This configuration allows for bidirectional power flow, enabling the grid to serve the electrical load effectively. The environmental results obtained from this analysis show that configuration 4 produced high values of CO_2, SO_2 and NO_x emissions with 1,960,757 kg/yr, 8,501 kg/yr and 4,157 kg/yr as shown in Table 6. The values of CO_2, SO_2 and NO_x emissions obtained in this scenario are 832887 kg/yr, 3611 kg/yr and 1766 kg/yr higher than optimal configuration. The value of energy purchased from the grid is 3,102,463 kWh; this shows that energy purchased from the grid has been reduced by 37 kWh when compared to configuration 3, owing to the inclusion of a battery system in this configuration. This configuration has high values NPC of $11.1 million, LCOE of $0.171/kWh, the operating cost of $528,895/yr and CAPEX of $34,050 and can satisfy the load demand by using a utility grid and battery system. This configuration is considered not environmentally friendly and not technically and economically accepted from the perspective of the above-mentioned key performance indicators when compared to configuration 2. This configuration is not sustainable owing to the high values of energy purchased from the grid and the hazards associated with carbon footprint emissions from conventional power plants.

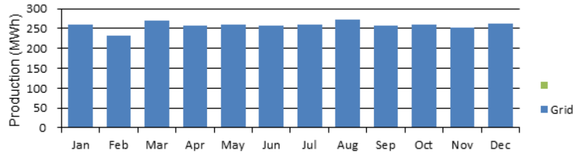

Figure 10. Monthly electrical production of configuration 4 by each component

Table 6. Components, economic indicators, and emissions for configuration 4

Components	Capacity (KW)	Unit Price ($/Unit)	Unit Rating (kW/Unit)
Grid	Infinite		
Converter	8.02	2520	4
Battery	Number	Unit Price ($/Unit)	Rating (kWh/Unit)
	5	5800	9.8
Economic Indicator	Value	Units	
NPC	11.1 million	$	
LCOE	0.171	$/kW.h	
Operating Cost	528,895	$/yr	
CAPEX	34,050	$	
Energy Purchased (grid)	3,102,463	kW.h	
Battery Autonomy	0.115	Hr	
Nominal Capacity	45.4	kW.h	
Accessible Capacity	40.7	kW.h	
ROI	-8.27	%	
IRR	-	%	
NPV	-64,921	$	
Annualized Savings	-1,470	$	
Emission	Value	Units	
CO_2	1,960,757	Kg/yr	
SO_2	8,501	Kg/yr	
NO_x	4,157	Kg/yr	

3.5. Configuration 5

This configuration required 966 units of battery, 1,209 kW of converter and 6,403 kW of PV to meet the community's energy needs. This configuration operates exclusively on photovoltaic panels and battery storage. The electrical production of PV system for configuration 5 is presented in Figure 11.

The electrical production of the PV system to meet electricity needs at the load points is depicted in Figure 11. The NPC, LCOE, operating cost and CAPEX of configuration five are $19.4 million, $ 0.297/kWh, $337,169/yr, and $ 12.3 million as shown in Table 7. This configuration has the highest value of the renewable fraction of 100% and is able to meet the load demand without obtaining any energy from the utility grid. It is not technically accepted from the reliability point of view since solar resources are intermittent in nature.

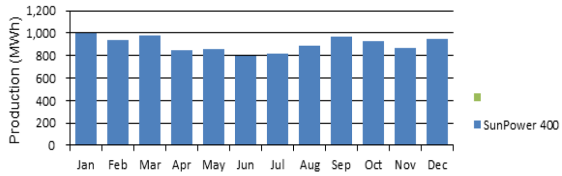

Figure 11. Monthly electrical production of configuration 5 by each component

Table 7. Components and economic indicators for configuration 5

Components	Capacity (KW)	Unit Price ($/Unit)	Unit Rating (kW/Unit)
PV	6,403	370	0.4
Converter	1,209	2520	4
Battery	Number	Unit Price ($/Unit)	Rating(kWh/Unit)
	966	5800	9.8
Economic Indicator		Value	Units
NPC		19.4 million	$
LCOE		0.297	$/kWh
Operating Cost		337,169	$/yr
CAPEX		12.3 million	$
Renewable Fraction		100	%
Battery Autonomy		22.2	Hr
Annual Throughput		1,563,799	kWh/yr
Nominal Capacity		8,764	kWh
Accessible Capacity		67,870	kWh

3.6. Comparison of the five configurations based on some key performance indicators

The optimal configuration is selected based on the location's specific needs at any given time to ensure that all electrical loads in Kakuma are supplied with electricity. Unfortunately, Kakuma is a remote area with limited access to Kenya's national power grid. The most important parameter to determine the optimal configuration of hybrid energy system is the minimum NPC. The most viable option for this location is configuration 2, which is based on multiple power sources and battery system that acts as a backup. Moreover, there is a marginal difference between the values of NPC and LCEO obtained in configuration 1 and 2 as presented in Table 8. The accepted configuration has been the better choice since the utility grid in Kakuma is unreliable and not powered by clean energy sources. The power supplied by the power utility is not reliable in rural and even some urban areas. Battery system is utilized in configuration 2 to bridge the gap during outages or low-voltage scenarios and improving overall energy reliability. It also allows storage of excess solar energy for use during peak tariff hours or at night, this significantly reduces monthly costs significantly. The optimal configuration has a renewable factor of 46.7% and NPC of $ 8.38 million and the lowest energy obtained from the grid is 1,784,604 kWh. The optimal configuration offers a 46.7% renewable fraction; it has a lower LCOE of $0.119/ kWh in contrast to the average price of grid-supplied electricity, which is $0.17/kWh. These results show that configuration 2 is the best long-term energy solution for Kenyan residential buildings, farms, businesses and institutions, especially under persistent load shedding conditions.

Table 8. Comparison of the five configurations

Configurations	NPC ($)	LCEO ($/kWh)	RF (%)	CO_2 (kg)
1	8.38	0.118	46.9	1,139,067
2	8.39	0.119	46.7	1,127,870
3	11.1	0.171	0	1,960,780
4	11.1	0.171	0	1,960,757
5	19.4	0.297	100	0

3.7. Sensitivity analysis

One of the valuable methods to assess the performance of HRES is by conducting a sensitivity analysis. By assessing how the system responds to changes in its operational and economic parameters, this analysis helps identify which variables have the most significant impact on the performance of HRES. Such variables may include average solar radiation, average temperature, inflation rate and discount rate. Within this study, configuration 2 emerged as the optimal choice, given limited access to the electric grid and the reliance on a diesel generator to serve a significant portion of the area. This analysis makes a thorough understanding of the system's performance in various scenarios and the crucial factors affecting its operation of configuration 2 possible.

3.7.1. Effects of varying the expected inflation rate

The projected inflation rate is a crucial economic element that impacts the anticipated price increase. HOMER leverages this factor to determine its influence on input expenses, equipment, and operational costs over the project's lifespan. Through a sensitivity analysis, developers can assess how shifts in the inflation rate affect the project's NPC and COE. Armed with this knowledge, they are better equipped to make cost projections and effectively manage risks. As the projected inflation rate is not always a precise science, conducting a sensitivity analysis based on future inflation values is necessary for informed decision-making. The EIR-based sensitivity result for configuration 2 in Kakuma shows a strong relationship between the inflation rate and the NPC and COE, as shown in Figure 12. The figure suggests that as inflation increased from 0% to 10%, the NPC increased exponentially from $15.2 million to $20.8 million in accordance with the line of best fit. At the same time, the COE decreased exponentially from $0.58/kWh to $0.25/kWh along the same line. This reveals that financing a project becomes more costly with rising inflation while the cost of equity decreases. These valuable insights can aid in making wise investment decisions, project planning and budgeting in the context of inflation.

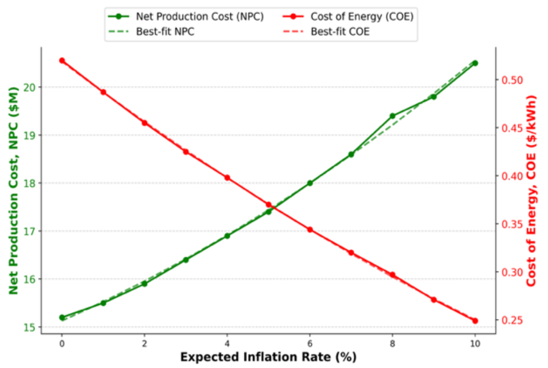

Figure 12. Impact of varying expected inflation rate on the net present cost and cost of energy

3.7.2. Effects of varying the nominal discount rate

The sensitivity analysis based on the impact of NDR on the CEO and NPC is conducted in this subsection. This analysis is essential for planning projects and making long-term financial decisions. The sensitivity result based on NDR for configuration 2 in Kakuma is shown in Figure 13. It can be established from Figure 13 that as the nominal discount rate increased from 0% to 16%, the value of NPC increased from \$16 million to \$32 million. Conversely, the value of COE reduced from \$0.46/kWh to \$0.075/kWh when NDR changed from 0% to 16%. This shows that NDR plays a prominent role in evaluating the economic viability of a project. Renewable energy investors can investigate the project's financial performance under various economic conditions by changing the discount rate, enabling them to understand its profitability and financial risks.

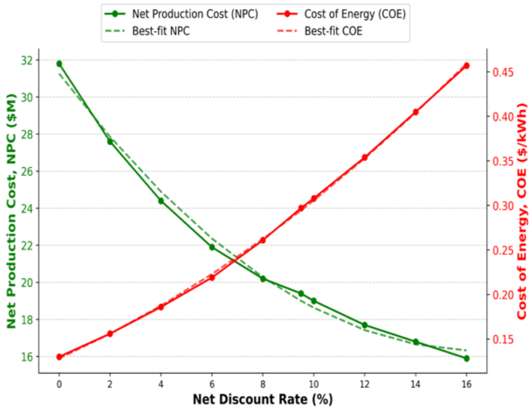

Figure 13. Impact of varying nominal discount rate on the net present cost and cost of energy

3.7.3. Effects of varying the solar annual average radiation

The effect of varying solar annual average radiation on the performance of HRES is carried out in this subsection. The value of NPC was reduced from \$21.38 million to \$18.50 million, and the value of COE was reduced from \$0.32/kWh to \$0.28/kWh when solar radiation increased from 5 to 6 kWh/m^2/day. This shows that there is a linear relationship between solar radiation and economic metrics (COE and NPC) as illustrated in Figure 14. According to the study, the system's economic performance is notably affected by alterations in solar radiation. The results show that the solar annual average radiation and the NPC have a negative linear relationship, with the NPC falling as the SAA radiation increases. The COE also experiences a decrease, albeit not a significant one. This underscores the significance of the SAA radiation in the photovoltaic process and how the recommended configuration's economic criteria are subject to the value of the SAA radiation.

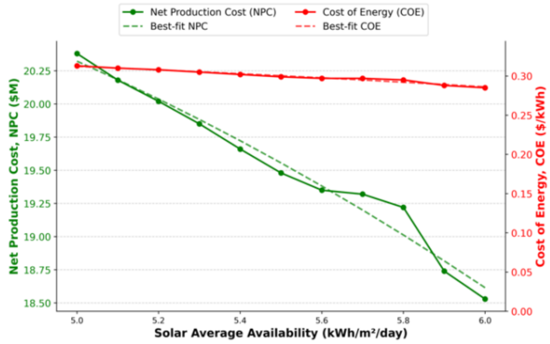

Figure 14. Impact of varying solar annual average radiation on the net present cost and cost of energy

3.7.4. Effects of varying the demand

A system's performance and sizing are determined mainly by its load-scale average. This provides an estimated approximation of the electrical load at a particular location. Therefore, conducting a sensitivity analysis based on different load scenarios is crucial in understanding the system's performance under varying conditions. The NPC of configuration 2 has increased from \$14.3 million to \$23.8 million as the load demand increased from 6500 to 10500 kWh/day, as shown in Figure 15. The PV penetration has been constant despite variations in the load demand, resulting in a shift in the COE value from \$0.286/kWh to \$0.284/kWh. Thus, rather than the cost of the PV system, the cost of the local utility grid affects the COE. According to a study, solar radiation variations significantly affect a system's financial performance. The study indicates that as the load scaled average increases, the NPC also increases, suggesting a positive linear relationship. While the COE also increases, the change is insignificant. So, the greater the load, the higher the NPC and, potentially, the COE.

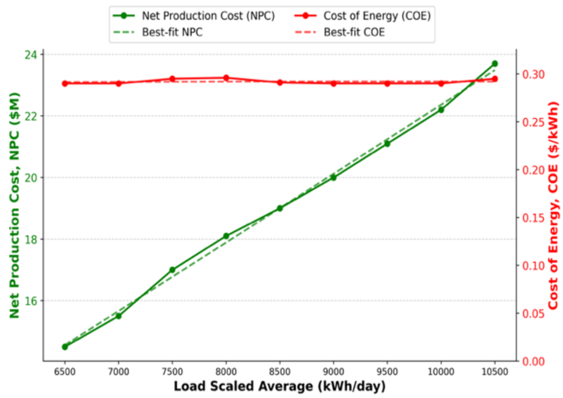

Figure 15. Impact of varying joad demand on the net present cost and cost of energy

3.8. Comparison of the obtained results with the relevant studies

The validation of the proposed hybrid renewable energy system located in Kakuma, Kenya, against both regional and global studies, would provide robust evidence for the system's effectiveness in addressing the energy challenges in remote areas. The comparison of the results obtained from the optimal configuration of the present study with existing literature or studies is carried out. The comparison with existing literature confirmed the relevance and potential of hybrid energy systems in reducing the dependence on fossil fuels and energy costs. The performance of the proposed HRES is compared with the standalone and grid-connected HRESs. The results obtained from the optimization and analysis of optimal configuration of the proposed HRES can be validated using LCEO, which is one of the key performance indicators for hybrid renewable energy systems. It represents the per-unit cost of electricity the system generates over its lifetime. It can be established from Table 9 that the value of LCEO ($0.119/kWh) obtained in this present study is within the range of $0.023 to $1.87 per kWh obtained in other studies. This makes the proposed HRES highly competitive and more affordable for remote area electrification.

Table 9. Comparison of the present study with other techniques

Techniques	Configuration	LCEO ($/kWh)
DGWO [64]	PV/biomass HES	0.071
IGWO [65]	PV/WT/DG HES	0.216
WOA [66]	Grid-connected PV HES	1.87
iHOGA [67]	Grid-connected WT/ PV/BS HES	0.215
PSO [68]	Grid-connected PV HES	0.159
HAIGA [69]	WT/ PV/BS HES	0.215
SSA [65]	WT/ PV/BS/DG HES	0.216
WOA [68]	Grid-connected PV HES	0.151
IGWO [65]	WT/ PV/BS/DG HES	0.216
HBO [70]	PV/BS/WT/biomass HES	0.121
GA [71]	WT/ PV/BS/DG HES	0.250
GSA [72]	WT/ PV/BS/DG HES	0.067
ACO [73]	WT/ PV/biogas/BS/DG HES	0.198
HOMER [74]	Grid-connected PV HES	0.073
HOMER [75]	WT/ PV/BS/DG HES	0.270
Fmincon [76]	Grid-connected PV WT/FC HES	0.012
HOMER [77]	Grid-connected DG, water turbine, and biomass generator HES	0.023
MOIAOA [78]	PV/WT/BS HES	0.027
ABO [79]	PV/WT/FC HES	0.413
GA [80]	PV/WT/BG/BM/FC/BT	0.163
SA [81]	PV/FC/HT/BT	0.117
SA [82]	PV/WT/BG/PHS	0.256
SA [83]	PV/WT/BG/SB	0.20
SA [84]	PV/WT/FC/SB	0.54
SA [85]	PV/WT/HYDRO/DG/SB	0.207
Present study (HOMER)	Grid-connected PV/BS HES	0.119

4. Conclusions

This research has demonstrated the potential of hybrid renewable energy systems to address the energy access challenges in Kakuma, Kenya. This study has provided a cost-effective, reliable and environmentally sustainable solution for electrifying remote communities by integrating PV and battery storage. The optimization of the HRES using HOMER, alongside its technical, economic and environmental evaluation, highlights the feasibility of transitioning from conventional power systems to renewable energy. This study offered a comprehensive design and analysis of the HRES for Kakuma. The study evaluated five configurations of HRES that included grid, PV, battery and converter components to determine their technical, economic and environmental feasibility of powering 1,000 households. After extensive analysis, it was determined that configuration 2, a grid-connected

PV-battery hybrid energy system with 1,335 kW of PV capacity and 29.4 kWh of battery storage is the most suitable option for Kakuma due to its multiple sources. This system has NPC of $8.38 million, LCOE of $0.119/kWh, annualized savings of $203,027, energy purchased from the grid of 1,784,604 kWh and operating cost of $324,398. The grid-connected PV-battery hybrid energy system is environmentally and technically friendly due to a renewable fraction of 46.7% that led to a reduction of CO_2, SO_2, and NO_x emissions to 1,127,879 kg/yr, 4,890 kg/yr and 2391 kg/yr. This significantly reduced the GHG emissions that should have been released into the atmosphere. It can be established from the results obtained in configuration 2 that the values of LCEO, NPC, energy purchased from the grid, CO_2 emission and operating cost have reduced by 30.59%, 24.50%, 42.48%, 42.48% and 38.49% when compared to the base system (grid only). The deployment of a large-scale HRES presents a technically and economically feasible solution for providing electricity to Kakuma while also significantly reducing greenhouse gas emissions from conventional sources. The sensitivity analysis was carried out in the study to investigate the effects of varying the values of EIR, NDR, SAA, and LSA on the performance of HRES. It can be established from the results obtained from the analysis that the values of CEO and NPC changed in proportion to the change in the values of the above-mentioned parameters.

The research outputs provide a robust, scalable and sustainable solution to electrification challenges in Kakuma, Kenya, and showcase the potential of HRESs to transform remote communities. The study's findings align with the UN's SDGs by focusing on clean energy and climate action and offering an optimal and sustainable solution for the region in Kenya. The research can guide policymakers and investors in implementing HRES throughout Kenya and Sub-Saharan Africa by providing clean, affordable and reliable electricity access. The research also emphasized how integrating solar photovoltaics with other renewable energy sources, such as wind, biomass, small hydro and geothermal can improve the electricity system's affordability and sustainability. These insights are crucial for expanding renewable energy deployment, enhancing electricity access and fostering sustainable development on a global note. The following directions are suggested for further exploration and improvement of the present study in the nearest future: Integration of more renewable resources, smart grid, and demand response systems, community-based energy management, long-term performance monitoring and evaluation, dynamic pricing and tariff modeling and climate change resilience and system adaptation. The research is expected to be expanded to develop a more resilient, scalable and inclusive solution for other regions facing similar challenges.

Acknowledgements

The authors thank NASA for providing helpful data utilized in this study.

Nomenclature

ABO	Artificial bee swarm optimization
A_{PV}	PV module or panel area (m²)
AC	Alternating current
ACF	Annual cash flows
ACO	Ant colony optimization
$B_{c/d}$	$\{0,1\}$ when charging; 0 when discharging
BT	Battery technologies
BG	Bio gas
BM	Biomass
C_{cap}	Current system capital cost ($)
$C_{cap\ ref}$	Base system capital cost ($)
$C_{ann\,cap}$	Total annualized capital cost ($/yr)
$C_{ann\,tot}$	Total annualized cost ($/yr)
C_{buy}	Local electricity cost bought from the grid at time *t*
C_i	Nominal annual cash flow for the current system
$C_{i\,ref}$	Nominal annual cash flow for the base system
$C_{NPC\ tot}$	Net present cost [$]
CRF	Capital Recovery Factor (%)
C_{sell}	Buyback electricity cost ($/kWh)
D_A	Battery autonomy
DC	Direct current
DGWO	Discrete grew wolf optimization algorithm
d	Angle of declination

DOD_{max}	Maximum battery depth of discharge
E_L	Load consumption (Ah)
EIR	Expected inflation rate
f	Latitude
f_{temp}	Temperature coefficient or factor
GA	Genetic algorithm
GHG	Greenhouse gas emission
GWO	Grey Wolf optimization
HAIGA	Hybrid iteration adaptive genetic algorithm
HES	Hybrid energy system
HBO	Heap based optimizer
$H_{e\ served}$	Total electric load served (kWh/yr)
HOMER	Hybrid optimization of multiple energy resources
HRES	Hybrid renewable energy system
HT	Hydrogen tank
i	Annual real discount rate (%)
IBAT	Improved bat algorithm
ICC	Initial capital cost ($)
iHOGA	Improved hybrid optimization using genetic algorithm
IRR	Internal rate of return (%)
LCEO	Levelized cost of energy ($/kWh)
MOIAOA	Multi-objective improved arithmetic optimization algorithm
n	Number of days in the year
N	Total number of years
NCF_n	Net cash flow
NDR	Nominal discount rate
PHS	Pump hydro system
NPC	Net present cost ($)
NPV	Net present value ($)
$P^{+}_{battery}(t)$	Power charged to the battery at time *t*
$P^{-}_{battery}(t)$	Power discharged to the battery at time *t*
$P_{grid}(t)$	Net power extracted from the grid at time t
P_{in}	Input power to the converter (kW)
P_{out}	Output power from the converter (kW)
PSO	Particle swarm optimization
PV	Photovoltaic
P_{pv} (t)	PV system's power output at time t
R_{proj}	Duration of the project (yr)
ROI	Return on investment (%)
SA	Simulated Annealing
SAA	Solar annual average
SB	Storage battery
SDG	Sustainable Development
TC	Total cost ($)
UNHCR	United nations high commissioner for refugees
WAO	Whale optimization algorithm
w_s	Sunset hour angle
Y_{on}	Solar radiation intensity near the summit of the earth
$Y_{o,calculated}$	Calculated solar radiation
$Y_{o,measured}$	Measured solar radiation
Y(t)	Solar irradiance at the time of measurement (W/m²)
$CE\sum_{pv}$	System efficiency (%)
η_{bs}	Efficiency of the battery system (%)
η_c	Efficiency of the converter (%)
$CE\sum_{temp}$	Battery temperature correction factor

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