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TECHNO-ECONOMIC ANALYSIS AND OPTIMIZATION OF INTEGRATED RENEWABLE ENERGY SYSTEMS FOR RURAL COMMUNITIES

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ABSTRACT

The need to lower carbon emissions and meet the growing demand for sustainable energy sources are driving an increase in the adoption/deployment of hybrid renewable energy systems as a practical alternative for clean power generation. This article assesses the economic and environmental performance, along with its optimum configuration, of a hybrid solar PV/wind//battery energy system intended to supply power to a commercial platform in Maiduguri, Nigeria. Using real-measured data for power demand, solar irradiance, wind speed and biomass availability, the model was created using HOMER software. It was discovered that, as compared to using standalone energy system, the PV/wind/biomass/battery hybrid system is very efficient in terms of cost and carbon savings. A 140-kW converter, 240 kW of PV modules, and a 180 kWh Li-Ion battery park are the outcomes of the energy system's ideal design. An LCOE of 2.80 $/kWh is the outcome of the optimization; also, the suggested system will reduce carbon dioxide (CO_2) emissions by nearly 40% when compared to a biomass system alone. The results of a sensitivity test indicated that the suggested hybrid system is susceptible to changes in discount rates and capital subsidies. This study shows how integrating a hybrid PV/wind/biomass/battery system in Nigeria can be economically viable and have positive environmental effects, making it a desirable option for future sustainable development.

KEYWORDS: PV modules, hybrid renewable energy systems, HOMER, power, standalone, optimization

INTRODUCTION

Energy plays a pivotal role in driving economic and social advancement globally. Currently, fossil fuels are being used to meet the growing energy demand worldwide due to factors such as population growth, increased load requirements, and the depletion of diesel resources. The advancement of climate change is evident in the evolution of electrical energy generation.

According to Al-saleh (2009), the shift towards an economy based on hydrocarbons has significantly impacted the efficient utilization of energy. Natural gas, coal, and oil are the predominant energy sources worldwide, all of which are derived from petroleum. The depletion of non-renewable energy sources during the twentieth century exhausted the natural reserve of these resources. Renewable energy sources can substitute non-renewable resources like fossil fuels, but this transition will necessitate expert

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prediction and forecasting (Roth *et al*., 2009). The integration and use of various renewable energy sources (such as wind turbines, solar photovoltaic systems, hydroelectric power, geothermal energy, biomass, nuclear power, and hydrogen) will be necessary for multi-HRES applications. Figure 1 represents a conventional hybrid renewable energy system model (Ansari, Jalil & Bansal, 2022). The term 'hybrid' is used to describe these energy systems since they incorporate multiple renewable energy sources (RESs) along with the necessary electrical load to power the AC or DC load, or both simultaneously. Energy can be derived from non-renewable, renewable, or energy storage sources (Singh *et al*., 2018). This methodology compensates for the absence of certain energy units by strengthening other units in a regulated or organic manner. It is evident that, despite the presence of other sources like WTG and SPV, they have unpredictable availability and offer additional designs (Tina & Gagliano, 2011). The HRES system can function in both grid-connected and freestanding modes.

These sources will be utilized at both the central power generating level and the consumer level in the restructured renewable energy system (Järventausta *et al.,* 2010). HRES, short for Hybrid Renewable Energy System, refers to a power system that incorporates two or more energy sources. When compared to strategies that use only one energy source, these systems sometimes have the highest reliability and lowest cost. The adoption of HRES in the power market depends on the principal technique used to optimize the design of different types of HERS (Okayim *et al.,* 2024). The process of optimization involves examining the challenges and obstacles in order to select the most optimal set of system components from a given range of possible solutions. The selection consists of one or more optimization problems and their corresponding constraints, along with an Objective Function (OF)

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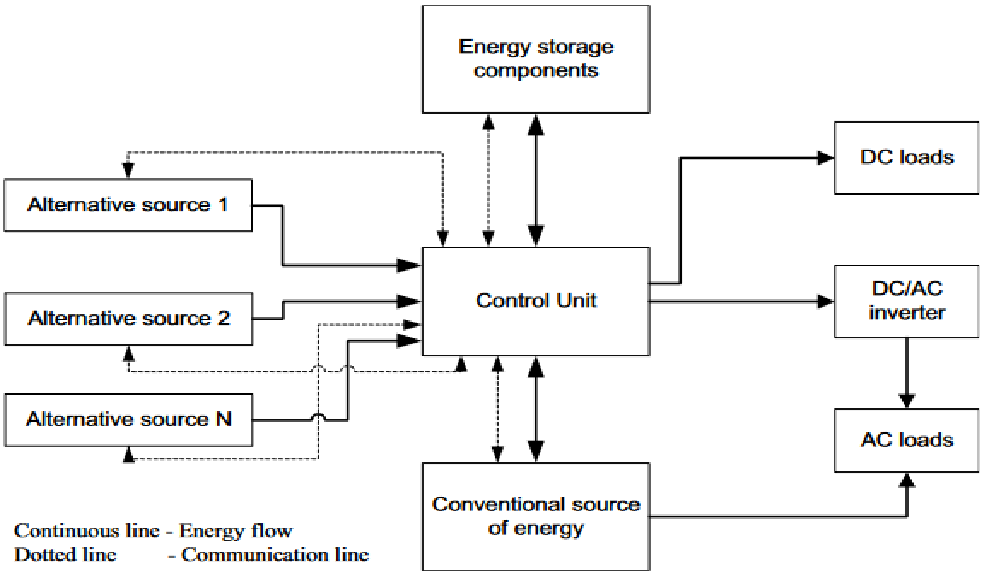


FIG.1: Hybrid energy system (Ansari *et al.* 2022)

The restrictions and the objective function should be driven by one or more optimization variables (Roy *et al*., 2022). The cost-reliability compatibility of the HRES is the most important aspect in the sizing optimization approach. Zhang *et al.* (1999) as cited in Aziz *et al*. (2019) suggest using a Hybrid Renewable Energy System (HRES) to provide electricity for a smart building that is not connected to the electrical grid. The HRES consists of two options: a combination of photovoltaic (PV) panels and battery energy storage (BES), with or without a diesel generator (DG).

The primary goal was to determine the optimal configuration that would ensure the highest level of system reliability (ROS) while minimizing the total annual cost (TAC). The multi-objective optimization problem was resolved with a novel meta-heuristic technique known as harmony search (HS). In (Lian *et al.,* 2019), a Hybrid Renewable Energy System (HRES) consisting of a wind turbine (WT), PV panel, and diesel generator, together with a storage system (battery banks or thermal pump), was set up to achieve the lowest annual total cost of the system.

Three demand response (DR) mechanisms are employed to enhance the overall system adaptability. Goddard *et al.* 2009 as cited in Andrews (2023) introduced an optimal method for setting up six distinct Hybrid Renewable Energy Systems (HRESs), taking into account the idea of power-sharing with neighbouring HRESs and socio-demographic parameters. Six separate load profiles were utilized to represent the consuming behaviours associated with HRESs. The researchers in reference (Ouerghi *et al.,* 2024) detailed a reverse osmosis desalination facility that is operated by a hybrid renewable energy system (HRES) consisting of wind turbines (WT), photovoltaic panels (PV), and battery energy storage (BES). In order to minimize the life cycle cost (LCC) of three possible configurations - PV/BES, WT/BES, and WT/PV/BES - a hybrid approach called simulated annealing-chaotic search was employed. From the above discussion, it can be deduced that the most recent research papers primarily employed artificial intelligence approaches. However, only a limited number of research employed conventional methods, such as analytical (Kim & Junghans, 2023), iterative (Islam *et al.,* 2022), and probabilistic (Vaccari *et al.*, 2023) approaches, to determine the magnitude of the HRES. This is because these methods are straightforward and convenient to apply (Ignjatović *et al.*, 2021).

Ifeanyi-nze & Okayim (2022) introduced a model to enhance the efficiency of a hybrid renewable energy and battery storage system, which serves as an energy supply technology (EST) for off-grid farms. The model focusses on optimizing both the economic and environmental implications throughout the life cycle of the system. Micro-hydropower and photovoltaics are the main sources of renewable energy (RE), while batteries and a diesel generator are potential backup options. A revised version of the Non-dominated Sorting Genetic Algorithm II (NSGA-II) was created and utilized to address a specific farm in Southern Spain. The algorithm generated many options for optimizing a design, taking into account economic factors (such as life cycle costing or LCC) and environmental considerations (such as life cycle assessment or LCA). The findings indicated that situations where there is a significant reliance on batteries can lead to reduced prices and less negative effects on climate change and non-renewable energy resources. Conversely, the most efficient approach for reducing the use of material resources (metals/minerals) led to increased fuel consumption, resulting in a cost increase of up to 25%. The most efficient EST solutions utilized 37% of the total energy generated. However, the outcomes were influenced by the distribution of energy production and consumption.

Gbadamosi & Nwulu (2022) conducted a study on a self-sufficient energy system that combines diesel generators, wind turbines, solar PV, and a battery storage system. The purpose of this system is to fulfil the energy needs of healthcare institutions located in a distant community in Nigeria. This study focusses on hybrid energy systems due to the exceptional reliability and availability of solar radiation intensity and wind speeds in Nigeria. An optimization model was created with the objective of minimizing the operational expenses of hybrid energy systems. The suggested model was executed by employing four case studies and resolved utilizing algebraic modelling language. The sensitivity analysis results indicate that the combination of solar PV, wind turbines, a battery storage system, and a diesel generator is the most efficient configuration for meeting the power needs of a rural healthcare centre. This configuration also offers a favourable energy cost and reduces emissions from the diesel generator system.

The study by Saha *et al.* (2023) examined a hybrid system that combines photovoltaic (PV), biomass, and battery technologies to provide electricity for a village in the state of West Bengal, India, that currently lacks access to electricity. An innovative hybrid energy system design has been thoroughly examined considering technical, social, and economic limitations. In addition, two separate resource scenarios have been analyzed and contrasted depending on the cost of the system. In addition, we are considering a total of 12 different combinations of batteries and PV panels that are currently available in the market. The Discrete Grey Wolf Optimization (DGWO) algorithm was employed to examine the optimal dimensions and the net present cost (NPC) of the system. According to the results, Scenario-2, which is a hybrid system based on biomass, solar, and batteries, has the lowest Net Present Cost (NPC) of $159,648.70. Additionally, it has a levelized cost of energy of $0.0712 per kilowatt-hour (kWh).

[18] investigated several combinations of off-grid hybrid renewable energy systems (HRES) to provide electricity to a remote island community. Technical, economic, environmental, and social assessments were conducted on six potential configurations to determine the most optimal design. A sensitivity study was conducted on the system with the highest level of optimisation. In addition, various machine learning models have been utilised to forecast the system's performance. System 6 stands out in economic assessments because to its low levelized unit cost of electricity (LCOE) of $0.31 per kilowatt-hour and strong return on investment (ROI) of 26.4%.

Although System 6 relies partly on a diesel generator for power, the life cycle CO_2 emissions (LCE) of System 6 and System 3 are comparable, with values of 49517.68 kg/year and 46744.45 kg/year, respectively. In the case of system 6, it was noted that a 30% increase in diesel fuel costs resulted in a 4.9% increase in the net present cost (NPC) and a 4.8% increase in the levelized cost of electricity (LCOE). The Matern 5/2 Gaussian Process Regression (GPR) model is determined to be the optimal choice among all the examined machine learning models for forecasting the renewable fraction and levelized unit cost of electricity.

[19] sort to enhance and evaluate the efficiency of a hybrid energy system in order to fulfil the electrical load demands of a BTS situated in Ogoja, Nigeria, via an off-grid hybrid system. The objective of optimizing the control, sizing, and components of such a system is to efficiently deliver affordable power to these communities. The primary goals are to reduce the energy cost, total net present cost, CO_2 emissions, and unmet load by utilizing the HOMER software. An assessment was conducted on the outcomes of the four distinct energy configurations in order to identify the best optimized combination for the region. The results showed significant variance in the optimal system layout depending on the various potential renewable energy resources. The analysis indicates that the PV/wind/hydro/battery system had a levelized cost of electricity (LCOE) of $2.40. The PV/hydro/battery system had an LCOE of $2.05, while the PV/wind/battery system had an LCOE of $1.64. The hydro/battery system had an LCOE of $2.05, the PV/battery system had an LCOE of $1.38, and the wind/battery system had an LCOE of $5.44. Nevertheless, because of the limited utilization of wind and solar energy in Ogoja, Nigeria, additional storage devices were necessary for setups that did not include hydro power and for large-scale hybrid energy systems that had higher levelized cost of electricity (LCOE). The configuration system that exhibited intermediate hybrid system sizes, resulting in a levelized cost of electricity (LCOE) of $1.38, was the photovoltaic (PV)/battery system with 0% energy unmet.

MATERIALS AND METHOD

The assessment of a hybrid energy system (HES) commences with a precise load demand assessment and meticulous site selection. An HES that incorporates renewable energy sources must take into account environmental and climatic factors. The study addresses the optimization of a hybrid solar photovoltaic and wind system in Maiduguri, Nigeria. The objective is to optimize the hybrid system's economic efficacy and achieve a high level of renewable penetration by determining the optimal configuration of the PV, wind and battery capacities. The primary contributions of this model are the optimization of the economic efficiency of the photovoltaic/wind/battery configuration, the attainment of 100% renewable penetration, and the provision of valuable insights into the system's performance in a hot, semi-arid climate, a context that is rarely considered in existing literature. The model implies that the system parameters remain stable throughout the analysis period and that factors such as solar radiation and windspeed are dynamic variables that affect the system's resilience. The assumed parameters for each energy system are listed in tables 1 to 3. The renewable hybrid energy system (RHES) is extensively examined and simulated using HOMER. The system comprises a wind turbine, a solar PV field, and a battery bank for power generation. Preliminarily, relevant historical data pertaining to sun irradiance, temperature, power demand, and windspeed availability in the specific region of Nigeria has been collected. Subsequently, the data was examined in order to comprehend the fluctuations and trends in energy resources and demand.

TABLE 1: Parameters selected for solar power configuration

Parameter	Specification
Panel Type	Flat
Rated Capacity (kW)	0.325
Temperature Coefficient	-0.41
Operating Temperature (%)	45
Efficiency (%)	16.94%
Lifetime (years)	25
Derating Factor	88
Tracking system	No tracking
Ground Reflectance (%)	20
Panel Slope (0)	11.85
Electrical Bus	DC

TABLE 2: Parameters selected for wind turbine configuration

Parameter	Specification
Capacity	1kW
Hub Height	15.0m
Electrical Bus	AC
Lifetime (years)	20

TABLE 3: Technical & economic features of the battery

Parameter	Specification
Nominal voltage (V) 12	12
Nominal Capacity (kWh) 3.11	3.11
Maximum Capacity (Ah) 260	260
Capacity Ratio 0.563	0.563
Rate Constant (1/hr) 0.176	0.176
Roundtrip Efficiency (%) 80	80
Maximum Current (A) 45	45
Initial State of Charge (%) 100	100
Minimum State of Charge (%) 30	30
Minimum Storage Life (years) 5	5

Study Location

Maiduguri (Borno State) is located at latitude of 11.83^0N and longitude of 13.15° E has solar radiation daily average of 5.90 kWh/m²/d with yearly average windspeed of 5.50m/s. The study area as shown in figure 2 is situated in a region with a hot semi-arid environment, which provides advantageous circumstances for specific categories of renewable energy sources. Climate zones with ample sunlight year-round often result in optimal electricity production from photovoltaic (PV) solar panels. As a result, solar and wind energy are dependable and efficient sources of sustainable power in this area.

The solar and wind data of the location are represented in figures 2 & 3. The global solar radiation shows irradiation data based on the respective months while the wind resource tells us about the windspeed variation.

Electrical Load Demand

An intensive field investigation was conducted to estimate the electricity requirements of base transceiver stations (BTS). This survey entailed examining the unique electrical devices and appliances needed by each mobile network operator for their own BTS. Each BTS comprises a wide array of electronic and non-electronic apparatus, such as telecommunication devices, lighting equipment, and monitoring systems. Based on our research, we have determined that a macro base station site consumes approximately 189 kilowatt-hours of energy each day, with a peak demand of nearly 10.67 kilowatts. Given the continuous operation of the base station, it was presumed that the load profile remains consistent during both weekdays and weekends

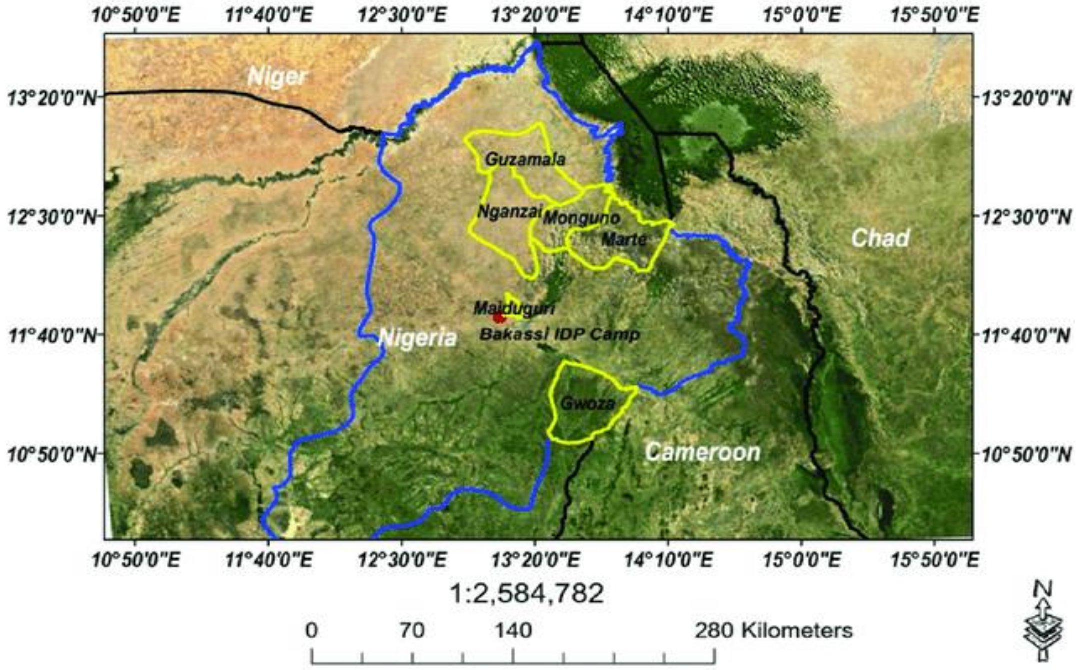


FIG. 2: Climatic map of Maiduguri

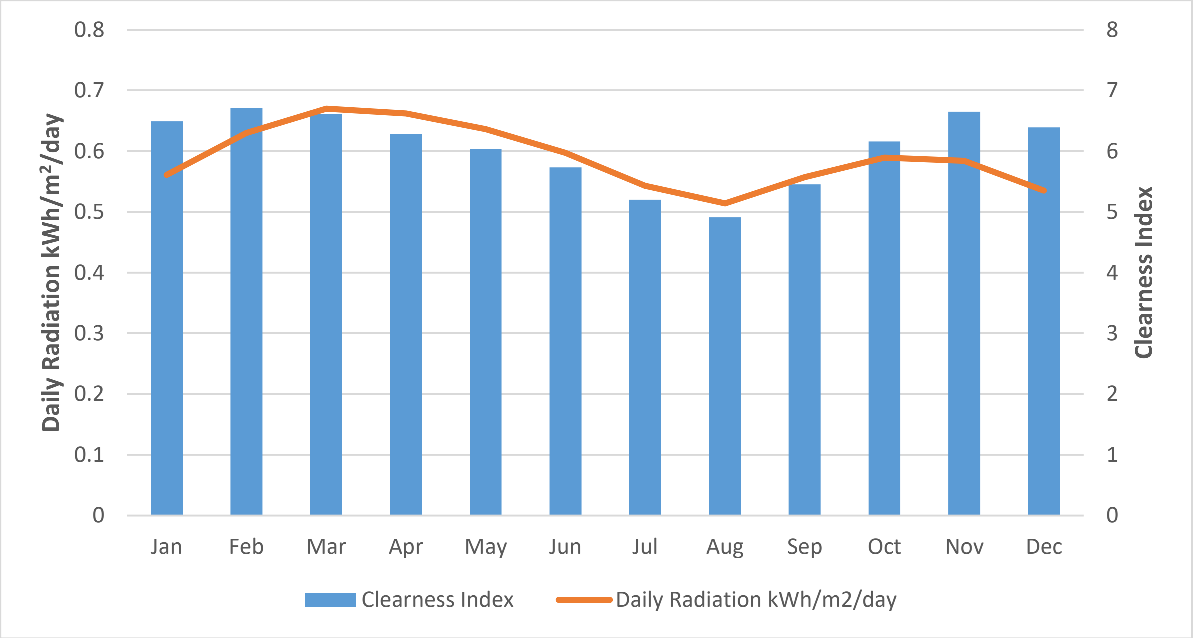


FIG. 3: Global solar radiation resource for Maiduguri

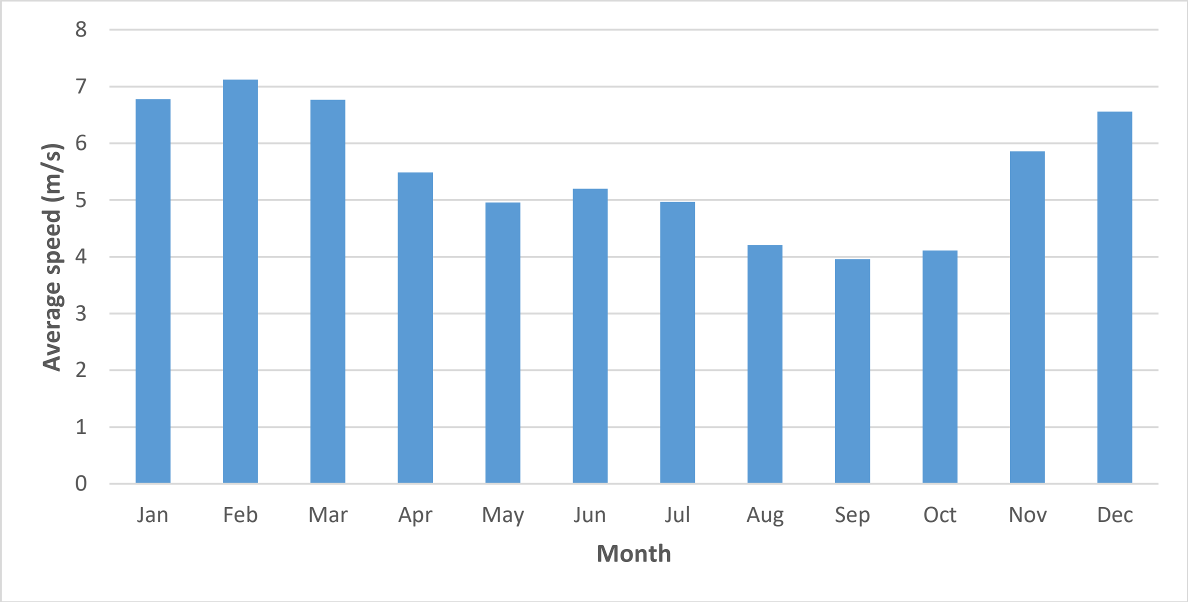


FIG. 4: Global wind resource for Maiduguri

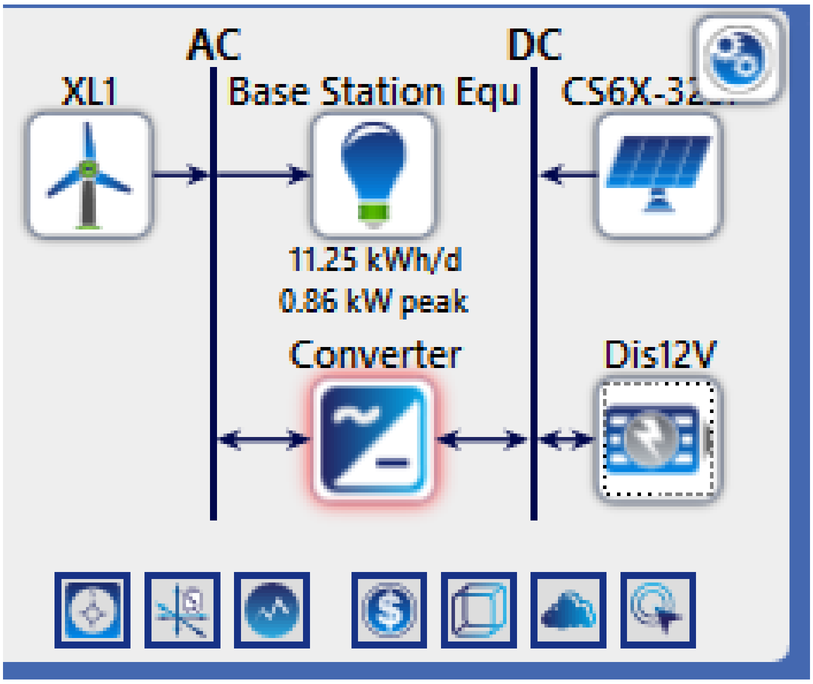


FIG. 5: Schematic diagram of HRES configuration

Hybrid renewable energy system configuration

The schematic design of the proposed hybrid renewable energy system (HRES), as seen in Figure 4, consists of key components such as a photovoltaic (PV) system, a wind turbine, an energy storage system, an energy conversion system, a load, and a control station. The excess electricity produced by the photovoltaic (PV) array, which is a renewable energy source that is not always available, is effectively stored in the battery bank to guarantee its availability for future use. If the battery and PV array do not produce enough power, the wind turbine generator acts as a dependable backup power source to guarantee a continuous supply of electricity. This system design carefully integrates many renewable energy sources to maximize their benefits, resulting in a reliable and consistent power supply that effectively satisfies the energy demands of the load.

Economic parameters

The project's viability is evaluated using two primary economic output measures: net present cost (NPC) and levelized cost of electricity (LCOE). These indicators serve as the objective function to be minimized during the optimization process.

NPC takes into account the complete costs of installing and operating the system throughout its expected lifespan, as well as the net revenues generated during the project. It provides a comprehensive assessment of the project's overall cost. On the other hand, LCOE calculates the average cost of generating electricity over the system's lifetime, considering capital investments, operational expenses, and maintenance costs in relation to the total electricity output. The Levelized Cost of energy (LCOE) is a metric that determines the mean expense of generating energy throughout the lifespan of a system. It takes into account the initial investments, operating costs, and maintenance charges in relation to the total amount of power produced.

Mathematically,

$$NPC = \frac{C_{ann,tot}}{CRF(r,N)}$$

Where,

$C_{ann,tot}$= annualized cost of the system

$CRF(r,N)$= CRF is the capital recovery factor

N = project lifetime

r = discount rate

Cann,tot = Cann,cap+Cann,rep +Cann,O&M +Cann,fuel Rann,rev

$$CRF = \frac{r(1+r)^N}{(1+r)^N - 1}$$

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

Where,

i = nominal interest rate

f = annual inflation rate

The LCOE is a parameter which is the average cost per kilowatt-hour (kWh) of electricity generated by the system, taking into account its entire lifecycle. is defined as the ratio of the lifecycle cost of the system to the total energy production over its lifetime.

To evaluate the LCOE, we use the discounting method proposed by [20] which involves applying a discount rate (r) to the future costs (Ct) and outputs (Et) in year t, resulting in the calculation of their present value, denoted as Prval(cost). The present value of costs Prval(cost) is divided by the present value of lifetime outputs Prval(output) todetermine LCOE.

Mathematically,

$$LCOE = \frac{Pr_{cal}(costs)}{Pr_{val}(output)} = \frac{\frac{\sum_{t=0}^{N} Ct}{(1+r)\times t}}{\frac{\sum_{t=0}^{N} Et}{(1+r)\times t}}$$

Where,

Pr_{cal}= present value of costs

Pr_{val}= present value of lifetime output

Ct= steam of real future costs

Et= steam of the electrical output

Table 4 below shows the capital cost, replacement cost and maintenance cost of each of the RES components. The replacement costs of equipment are estimated to be 20% – 30% lower than the initial costs, but because decommissioning and installation costs need to be added, it was assumed that they are the same as the initial costs.

TABLE 4: Cost of individual components

System component	Capital Cost ($)	Replacement Cost ($)	Maintenance Cost ($)
Canadian Solar Max Power CS6X	360.0	200.0	100.0/yr
Power converter	300.0	300.0	100.0
Begey BWC XL wind turbine	10,785.50	8,000.0	500.0
12VRE-3000TF battery	588.31	588.31	100.00
Labour	35,000.0	-	-

TABLE 5: Cost analysis of system components

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Bergey BWC XL.1	$8,500.00	$1,912.84	$1,292.75	$0.00	($1,078.01)	$10,627.59
CanadianSolar MaxPower CS6X-325P	$8,513.31	$0.00	$9,171.33	$0.00	$0.00	$17,684.64
Discover 12VRE-3000TF	$8,400.00	$2,677.98	$0.00	$0.00	($1,509.21)	$9,568.77
System Converter	$848.94	$360.18	$0.00	$0.00	($67.79)	$1,141.34
System	$26,262.26	$4,951.01	$10,464.08	$0.00	($2,655.02)	$39,022.33

TABLE 6: Electricity production by HRES

	PV/wind/battery (kWh/yr)	PV/battery	Wind/battery
CanadianSolar MaxPower CS6X-325P	4,086	6,075	0
Bergey BWC XL.1	2,684	0	13,418

TABLE 7: Summary of the technical and economic performances of the HRES

	PV/wind/battery	PV/battery	Wind/battery
NPC	$39,022.34	$39,775.53	$73,607.02
LCOE	$0.74	$0.75	$1.39
Operating cost	$987.05	$1,194.42	$1,030.10
Excess Electricity	2,165	1,172	8,862
Unmet Electric Load	1.42	2.95	2.33
Capacity Shortage	2.85	3.95	3.65

RESULTS AND DISCUSSION

The model performs an optimization procedure to identify the most efficient system architecture by investigating all potential component combinations in order to meet the highest peak load requirement of 10.67kW. To compare the performance of the ideal system architecture to the base case system, the levelized cost of energy and the net present cost are evaluated. The practical HRES designs (technical and economic performance) are presented in table 7. The 2.31 kW CanadianSolar MaxPower CS6X-325P, the 1.00 kW Bergey BWC XL1 wind turbine, the Discover 12VRE-3000TF (14 units) storage system, and a charging cycle dispatch method make up the optimized power system configuration known as PV/wind/Battery in table 5. 6,770 kWh of power are produced by the system annually. The system has an annual operating and maintenance cost of $987.05. Its Net Present Cost (NPC) is $39,022.34, and its Levelized Cost of Energy (LCOE) is $0.7355 per kWh as shown in figure 6. The findings show that the ideal hybrid system achieves an annual capacity shortage of 0.07% while successfully meeting the full load demand, leaving an unmet load of 0.03%.

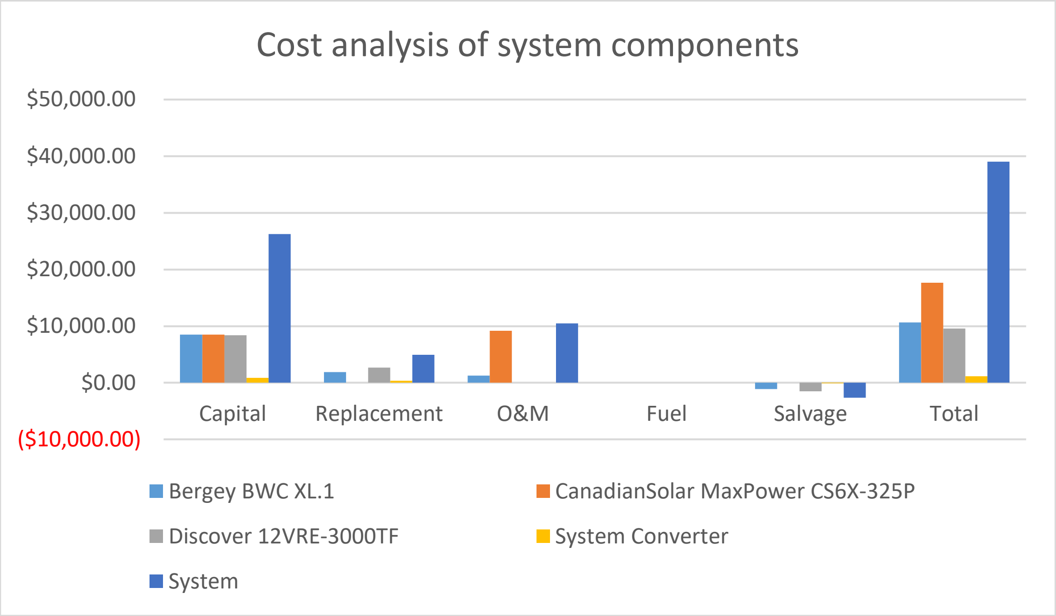


FIG. 6: Cost analysis of system components

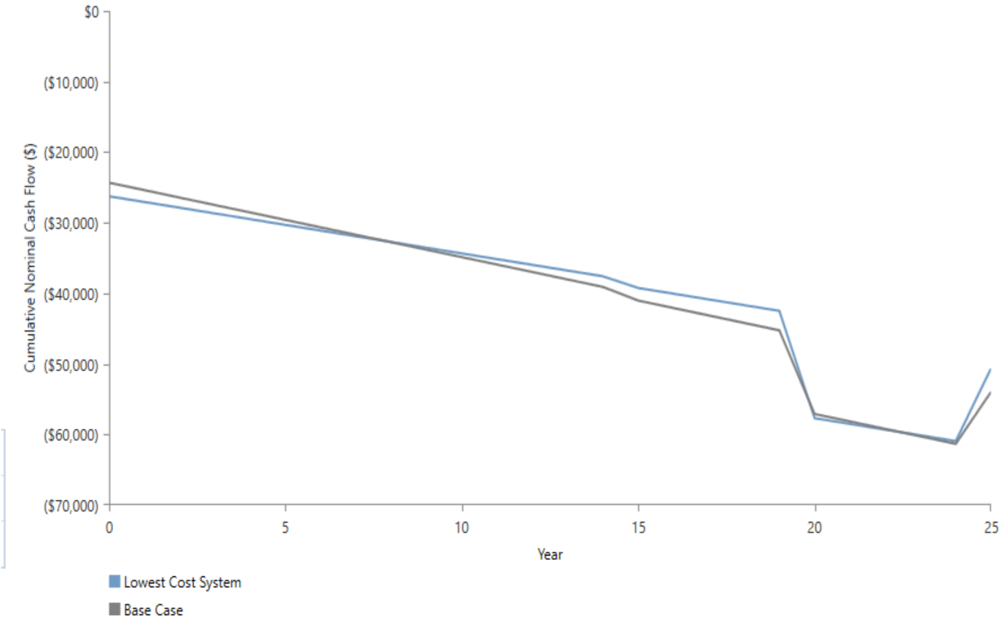
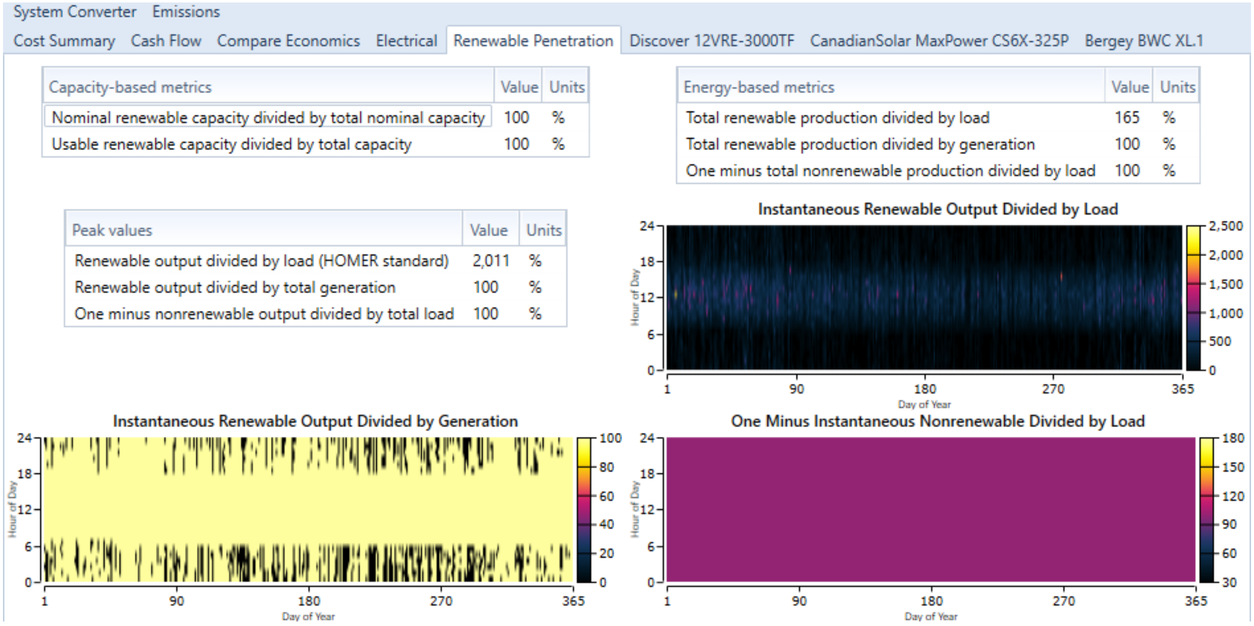


FIG. 7: How the hybrid system saves money over the lifecycle



Capacity-based metrics	Value	Units
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%

Energy-based metrics	Value	Units
Total renewable production divided by load	165	%
Total renewable production divided by generation	100	%
One minus total nonrenewable production divided by load	100	%

Peak values	Value	Units
Renewable output divided by load (HOMER standard)	2,011	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

FIG. 8: Renewable energy penetration

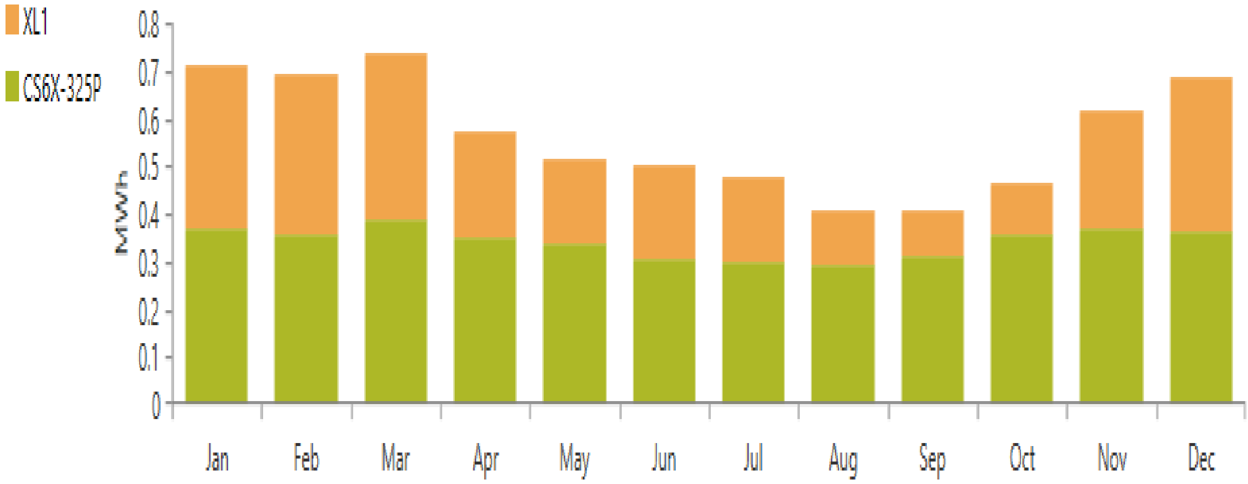


FIG. 9. Monthly electricity production

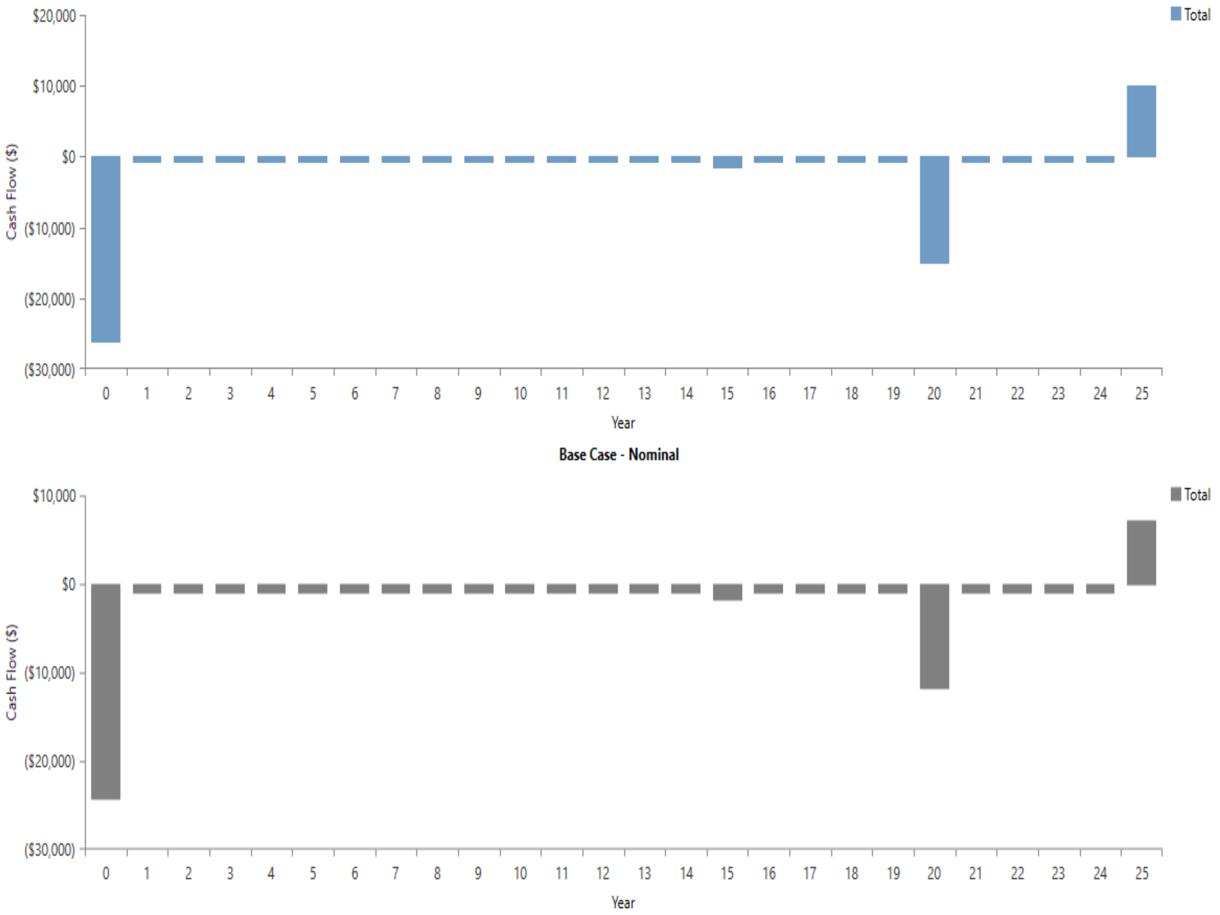


FIG. 10: Base system versus proposed system

Figure 7 illustrates the optimal configuration of the hybrid renewable energy system, which includes solar PV panels, wind turbines, and battery storage. The design is pivotal as it demonstrates how integrating multiple renewable sources can enhance reliability and efficiency. The configuration optimally balances energy generation and storage, ensuring that the energy demands of the base transceiver stations (BTS) are met consistently. This figure underscores the importance of multi-source systems in regions with variable resource availability, such as Maiduguri, where both solar and wind resources are abundant but intermittent. The inclusion of battery storage is crucial for managing supply during low production periods, thus providing a stable energy supply. Figure 8 presents key economic performance metrics, including Levelized Cost of Electricity (LCOE) and Net Present Cost (NPC). The LCOE of $2.80/kWh indicates a competitive pricing structure for renewable energy in comparison to traditional fossil fuel systems. This figure emphasizes the cost-effectiveness of hybrid systems in reducing reliance on diesel generators, which are often more expensive and environmentally detrimental.

Furthermore, the NPC analysis shows that initial investments in HRES can lead to significant long-term savings due to lower operational costs and reduced carbon emissions. The economic viability highlighted in this figure is essential for encouraging investment in renewable technologies, particularly in developing regions like Nigeria. Figure 9 depicts the environmental impact assessment results, showcasing a nearly 40% reduction in CO_2 emissions compared to conventional energy systems. This finding is significant as it aligns with global efforts to mitigate climate change by transitioning to cleaner energy sources. The figure illustrates how adopting hybrid renewable energy systems can not only fulfill energy needs but also contribute positively to environmental sustainability. By demonstrating substantial reductions in greenhouse gas emissions, this figure supports policy initiatives aimed at promoting renewable energy adoption as a means to combat climate change while meeting local energy demands.

CONCLUSION

The study highlights the critical role of hybrid renewable energy systems (HRES) in addressing the energy needs of rural communities, specifically in Maiduguri, Nigeria. The findings demonstrate that integrating solar photovoltaic (PV), wind, and battery storage systems can significantly enhance energy reliability while reducing costs and carbon emissions. The optimal configuration identified—consisting of a 140-kW converter, 240 kW of PV modules, and a 180 kWh Li-Ion battery park—achieves a Levelized Cost of Electricity (LCOE) of $2.80/kWh. This cost is competitive compared to traditional energy sources, underscoring the economic viability of HRES in regions with abundant renewable resources. Furthermore, the system is projected to lower CO2 emissions by nearly 40% compared to standalone biomass systems, contributing positively to environmental sustainability. Sensitivity analyses reveal that the system's performance is influenced by variations in discount rates and capital subsidies, indicating that financial mechanisms play a crucial role in the adoption of renewable technologies. Overall, this study illustrates that HRES not only meets the growing energy demands but also aligns with global efforts to transition towards cleaner energy solutions. The findings advocate for policy support and investment in hybrid systems as a pathway to sustainable development in Nigeria and similar contexts.

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