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Integrating Solar and Biomass Energy for Sustainable Off-Grid Power Solutions in Adadu Community, Nasarawa State, Nigeria

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Alpha A. Ndah [1] , Adra A. Muhammad [2] , Attah E. Idenyi [3]

1. Department of Mechanical Engineering, Joseph Sarwuan Tarka University, Makurdi, NGA 2. Department of Mechanical Engineering Technology, Federal Polytechnic Nasarawa, Nasarawa, NGA 3. Department of Mechanical Engineering, Federal Polytechnic Idah, Idah, NGA

Corresponding author: Alpha A. Ndah, alphazenga@gmail.com

Abstract

This study examines the viability of integrating photovoltaic and biomass energy in the Adadu community, Nigeria. HOMER Pro v3.14.5 was used to model a hybrid renewable energy system (HRES) capable of consistently supplying power to 280 households with an estimated load of 264,781 kWh, a 5.3785 kWh/m^2/day solar radiation, and an 8 tons/day biomass potential. The HRES includes a 733.23 kW PV module with a 177% penetration rate, an 800-kW biomass generator producing 69,508 kWh annually, a 482.49 kW converter, and two battery types (ABB-P3 and ABB-M1). Five optimal system combinations were simulated based on renewable fraction, initial capital cost, net present cost (NPC), operating cost, and cost of energy (COE). The ABB-M1 storage system emerged as the most viable option, with an NPC of $1.97 million, a COE of $0.0467, 4.72 kg/h of CO_2 emissions, and a 100% renewable fraction.

This approach can be replicated in similar rural areas globally, offering cleaner energy alternatives and leveraging untapped renewable resources. The optimal HRES significantly reduces CO_2 emissions compared to diesel-only systems, making it a sustainable solution for rural electrification. However, the study is limited to techno-economic modeling and does not fully account for environmental life-cycle impacts, socio-political dynamics, or future demand growth. Future research should incorporate these aspects and investigate additional renewable options and smart grid applications to enhance resilience, scalability, and long-term sustainability.

Categories: Renewable Energy Systems, Environmental and Sustainable Engineering
Keywords: hybrid renewable energy system, techno-economic analysis, sustainable energy solutions, biomass energy, homer pro simulation, rural energy access, off-grid power solutions

Introduction

A crucial element in alleviating poverty in rural areas is rural development [1], which substantially influences life expectancy, health outcomes, and living standards. Nevertheless, some rural regions globally continue to lack access to modern amenities, leading to persistently elevated mortality rates and limited opportunities for social and economic progress. The absence of fundamental utilities, such as electricity, exacerbates these problems, hindering the provision of healthcare, education, and agricultural productivity [2,3].

Notwithstanding considerable advancements in global development, rural electrification continues to be a critical challenge, especially in nations like Nigeria that struggle with the disparity between energy demand and availability [4,5]. Inadequate access to power hinders economic advancement and intensifies social disparities, particularly impacting rural communities afflicted by energy poverty. In response to this problem, there is increasing acknowledgement of the significance of decentralized renewable energy systems, which utilize plentiful local resources while fostering environmental sustainability [6-12].

The integration of various renewable energy sources with suitable storage systems and backup mechanisms, formerly referred to as "hybridisation," is an exceptionally successful approach to these issues. During the initial planning phase, establishing the optimal capacity of each component in hybrid renewable energy sources (HRES) is critical [13]. An insufficient arrangement could result in an inadequate energy supply, whilst an excessive one might create surplus electricity and incur greater capital expenditures [14]. Therefore, identifying the appropriate capacity of decentralized HRESs is vital for the sustainable energy transition and general social growth. Nevertheless, resolving the technological, economic, environmental, and socio-political problems and hazards involved with decentralized hybrid energy systems (HES) remains an important concern [15].

Numerous researches have presented strategies for scaling HRES to create a constant power output [16-21]. According to Olatomiwa et al. [22], several configurations of HES were examined in six distinct

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geographical zones of Nigeria using HOMER software. The investigation involved examining economic sustainability under sensitivity scenarios with levelized cost of energy (COE) and net present cost (NPC) ranging from $1.1 to $1.3. In 2015 research, Olatomiwa et al. [23] did a comparison between two ideal system combinations-diesel-PV-battery and wind-PV-diesel-battery-finding that the latter was less economically viable, with COE at $0.409/kWh and NPC at $69,811.
Zhang et al. [24] presented a unique hybrid optimization technique to construct a hybrid autonomous power system. This method incorporates simulated annealing, harmonic search, and chaotic search techniques to measure system dependability. Bajaj and Singh [25] reported considerable economic and environmental implications of off-grid electricity schemes in rural regions. Sharma and Sood [26] created a thorough sensitivity model to analyze how different storage strategies impact hybrid microgrid system performance. According to Choudhury et al. [27], pumped storage is a dependable and cost-effective alternative for storing electrical energy. Khan et al. and Yousaf et al. discussed numerous strategies for estimating electricity expenditures [28,29]. Inci and Aygen [30] studied numerous criteria for modeling a photovoltaic (PV) system in HES, establishing ideal strategies for properly reproducing solar PV arrays. Their recommended technique may provide unique standards for each phase, which is vital for resolving present imbalances efficiently.

Zebarjadi and Askarzadeh [31] employed the harmony search approach to optimize the scale of a solar power system integrated into a grid servicing six houses in Iran, indicating that adding a PV system might become profitable as energy costs climb. Abdelshafya et al. [32] proposed a unique hybrid approach combining Grey Wolf Optimization (GWO) and Particle Swarm Optimization (PSO) designed for an ideal grid-connected wind and PV hybrid system powering a regenerative osmosis desalination unit. Comparing wind/PV/battery and wind/PV/hydrogen systems, the study indicated the former was not only more cost-effective but also more ecologically friendly. Additionally, the hybrid PSO-GWO approach beat PSO and GWO alone. The incorporation of DG was shown to minimize expenses. A sensitivity test indicated that solar radiation had a bigger cost impact than wind speed.

The Sustainable Development Goals (SDGs) of the United Nations underline the crucial need to ensuring that everyone has access to energy that is cheap, dependable, and sustainable [33,34]. In keeping with these aims, the Nigerian government has set ambitious ambitions to boost power availability to 90% by 2030, with 10% of the energy mix coming from renewables by 2025 [35,36]. However, reaching these aims needs new techniques suited to the particular problems encountered by rural populations, where geographical limits and poor infrastructure offer substantial impediments to electrification. Adadu Community, situated in Nigeria's Nassarawa State, symbolizes the problems of many rural places coping with energy poverty. Traditional grid connections are generally impracticable owing to geographical limits, infrastructural constraints, and cost constraints. Consequently, developing dependable, inexpensive, and sustainable energy solutions customized to the individual demands of these communities is vital. One possible solution is mixing biomass and solar energy into off-grid HES, exploiting local resources and environmental circumstances to offer reliable electricity supply. Modern modeling tools, such as the hybrid optimization model for electric renewable (HOMER) Pro, offer crucial help in planning and optimizing HES, assuring their technical feasibility and economic sustainability. By modeling multiple system configurations and doing detailed techno-economic assessments, researchers may discover the most cost-effective and sustainable options for rural electrification.

Beyond technical considerations, it is essential to recognize the broader socio-economic implications of rural electrification initiatives. Access to electricity not only improves living standards and economic opportunities but also enhances social inclusion and resilience. By empowering rural communities with clean and reliable energy sources, governments and stakeholders can foster inclusive and sustainable development, contributing to the achievement of multiple SDGs [33,34].

Battery storage is critical for enhancing system performance and reliability. Recent studies have focused on optimizing single battery systems, emphasizing cost-effectiveness, reliability, durability, and higher energy density [37-41].

Lead-acid batteries are one of the oldest and most widely used battery technologies in HRES due to their reliability and cost-effectiveness. Bortolini et al. [41] analyzed the performance of lead-acid batteries in HRES for off-grid applications, emphasizing their robustness and ability to handle varying load conditions. They are known for their high discharge capability and tolerance to overcharging, making them suitable for rural electrification projects where maintenance might be less frequent [38]. However, lead-acid batteries have a shorter lifespan and lower energy density compared to newer technologies, which limits their long-term viability [42]. Akinyele et al. [43] provided a comprehensive review of the use of lead-acid batteries in renewable energy storage, highlighting their affordability and ease of recycling. Despite these advantages, lead-acid batteries are criticized for their environmental impact due to the use of lead and acid, which pose significant disposal challenges [42]. Furthermore, their efficiency decreases significantly in extreme temperatures, which can be a concern in certain off-grid rural areas [40].

Lithium-ion batteries have gained prominence in HRES due to their high energy density, long lifespan, and efficiency. Ijeoma et al. reviewed the advancements in lithium-ion battery technologies, emphasizing their suitability for hybrid systems because of their superior performance metrics [40]. Lithium-ion batteries offer higher energy storage capacity and longer cycles compared to lead-acid batteries, making them ideal for applications requiring a consistent and reliable power supply [44]. However, the high initial cost and complex battery management systems required for lithium-ion batteries can be a barrier to their adoption in cost-sensitive projects [45]. Moreover, the thermal runaway risk, although mitigated by advanced battery management systems, remains a concern, especially in high-temperature environments [39]. Ghenai and Bettayeb [46] conducted a cost-benefit analysis of lithium-ion batteries in HRES, concluding that while the upfront costs are higher, the longer lifespan and lower maintenance costs can result in significant long-term savings.

Nickel-cadmium (Ni-Cd) batteries are known for their durability and ability to perform well in a wide range of temperatures. Zhao et al. [47] discussed the application of Ni-Cd batteries in renewable energy systems, highlighting their robustness and reliability. Ni-Cd batteries are less affected by temperature extremes and can tolerate deep discharges better than lead-acid batteries, making them suitable for off-grid installations where environmental conditions can be harsh [37]. Despite these advantages, Ni-Cd batteries have significant drawbacks, including a lower energy density compared to lithium-ion batteries and the environmental hazard posed by cadmium, a toxic heavy metal [48]. Additionally, the memory effect, where the battery loses its maximum energy capacity if repeatedly recharged after being only partially discharged, can affect their performance over time [49]. This makes their maintenance more complex and costly in the long run [50].

Sodium-sulfur (Na-S) batteries are another emerging technology in HRES, known for their high energy density and long cycle life. Spiru and Lizica-Simona [39] reviewed the potential of Na-S batteries in hybrid systems, noting their efficiency and ability to store large amounts of energy. These batteries operate at high temperatures, which can be both an advantage and a disadvantage; while they perform well in hot climates, they require significant insulation and heating systems to maintain operational temperatures [51]. The high operating temperature (around 300-350°C) and the corrosive nature of sulfur are major challenges in the widespread adoption of Na-S batteries [49]. Additionally, the high cost of installation and the need for sophisticated safety systems to manage the high temperatures can limit their use in less developed areas [52].

Flow batteries, including vanadium redox flow batteries, offer a unique advantage in HRES with their ability to decouple energy storage capacity from power capacity. Madziga et al. [53] explored the use of flow batteries in renewable energy systems, highlighting their scalability and long cycle life. Adewuyi et al. highlight the high efficiency and simultaneous charging and discharge of these batteries, which makes them ideal for large-scale energy storage [54]. However, the complexity and cost of flow batteries are significant drawbacks. The need for large, external tanks to store the electrolyte solutions makes them less practical for small-scale or mobile applications [44]. Moreover, the maintenance of these systems can be complex, requiring specialized knowledge and equipment, which might not be readily available in rural off-grid areas [45].

The review of various battery technologies reveals significant limitations that present an opportunity for innovation in HRES. Lead-acid batteries, despite their cost-effectiveness, suffer from shorter lifespans and lower energy density [38,42]. Lithium-ion batteries, while efficient and high in energy density, are costly and require complex management systems [40,45]. Nickel-cadmium (Ni-Cd) batteries offer durability and temperature resilience but pose environmental hazards due to cadmium toxicity and the memory effect [47,48]. Sodium-sulfur (Na-S) batteries, although high in energy density, need high operating temperatures and sophisticated safety systems [39,51]. Flow batteries are scalable and efficient but are complex and costly, requiring significant space and maintenance [53,54].

This study focuses on designing, optimizing, and evaluating a HES tailored to Adadu's needs, integrating biomass and PV solar energy. Simulations were carried out using two different battery types in HRES to exploit their complementary strengths and mitigate individual weaknesses. By combining high-energy-density lithium-ion batteries with cost-effective and robust lead-acid batteries, the system can achieve a balance between performance, cost, and reliability. Leveraging Nassarawa's sunlight and local biomass, this system promises consistent electricity for rural areas while reducing emissions. Advanced software like HOMER Pro aids in system design, component selection, and comparative analysis, aiming to create a blueprint for Adadu's HES. The study also emphasizes the importance of techno-economic analysis, assessing financial feasibility and economic viability to inform decision-makers, investors, and policymakers about the potential of off-grid hybrid energy solutions in combating energy poverty and promoting sustainable development.

Materials And Methods

Materials

The following materials and data were used in the study.

i. Laptop (processor: HP Core i7, 64-bit operating system).

ii. Hybrid Optimization Model for Electric Renewable (HOMER pro v3.14.5) algorithm tool.

iii. Owl meter ADL 400 three phase Din Rall Energy Meter.

iv. Average global horizontal irradiance (GHI) data for one year (Hourly average solar radiation).

v. Monthly Energy Demand of 10 households in Adadu.

Method

The study area is a village called Adadu in Doma Local Government Area of Nasarawa State, Nigeria, located at 8° 51.3´ N, 7° 8.6´ E, with 1485 people living in 280 households.

Adadu Load Profile

The load data is acquired from the village through surveys that include many categories, including home load, school load (nursery, primary, and secondary), community demand, agricultural demand, health center load, and business load. The business load area covers small and medium-sized firms such as supply stores, kiosks, charging booths, Mai Shayi shops, black market fuel stations, mechanic workshops, and pharmacies. The anticipated total daily energy requirement, including a safety load, is 266,430 kWh.

The software's input load profile tool enables users to establish daily load profiles for each month using hourly consumption statistics for weekdays and weekends given by the village's load demand. HOMER adjusts this data for calculating purposes by multiplying baseline values by a common factor, assuring a yearly mean similar to the scaled annual average entered. This scaled average might depart from the baseline for two reasons: sensitivity analysis on load changes or unit conversion. Figure *1* illustrates Adadu's hourly and seasonal load profile over the course of a year, estimated by HOMER utilizing Owl ADL 400-m inputs, with a scaled yearly average of 24,000 kWh/day.

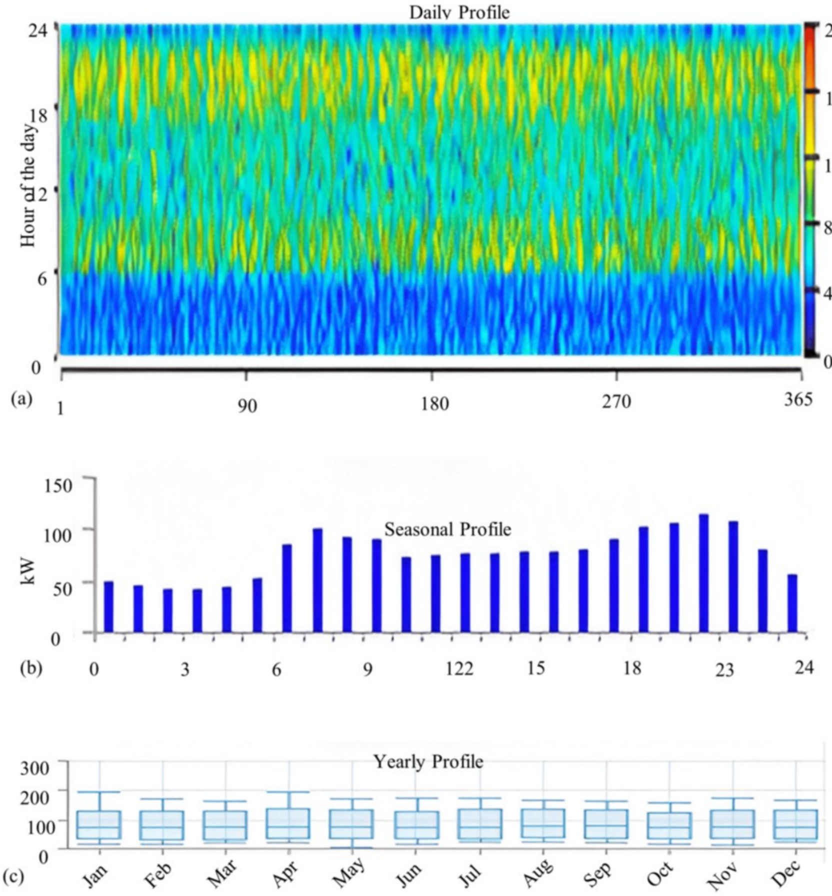

FIGURE 1: Daily (a), seasonal (b), and yearly (c) load profiles for PV/Biomass Gen/Battery

PV, photovoltaic

Renewable Solar and Biomass Assets in the Studied Region

Resources for solar radiation (5.3785 kWh/m²/day) and biomass (10 tons/day) have been identified. The area offers valuable crop waste and a fair amount of sun radiation. The location's mean daily sun irradiance and clarity coefficient are shown in Figure 2. This study has taken into account agricultural residue, as it is a feasible biomass to employ in the manufacture of syngas.

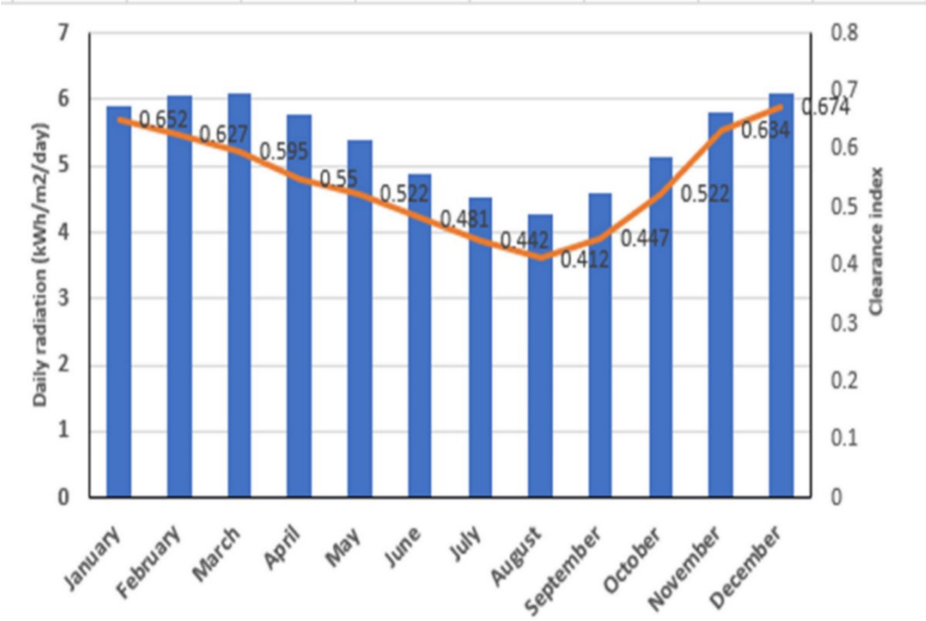

FIGURE 2: Monthly global horizontal irradiance and clearance index data for the specified region

PV System Modeling

Numerous approaches and procedures, including Maximum Power Point Tracking, PV area-based, insolation hierarchy-based, equivalent circuit-based, and PV module output equation-based, with or without temperature effect consideration, are available in the literature for modeling PV systems. Hourly radiation data determines the system's performance, and power production is measured on a stationary surface [55,56].

$$P_{(pv,\text{each})} = \begin{cases} P_{RS}\left(\frac{R^2}{R_{srs}R_{cr}}\right) & 0 \leq R < R_{cr} \\ P_{RS}\left(\frac{R}{R_{srs}}\right) & R_{cr} \leq R < R_{srs} \\ P_{RS} & R_{srs} \leq R \end{cases} \quad (1)$$

where; $P_{pv,each}$ represents the electricity produced by each PV system, P_{RS} denotes the rated power of the PV panel, R stands for the solar radiation factor, R_{cr} indicates a specific radiation level at 150 W/m^2, and R_{srs} denotes the standard solar radiation level at 1000 W/m^2.

HOMER utilizes equations (7) and (8) to determine the power output and efficiency of the PV panel, represented as [57]:

$$P_{\text{pv}} = Y_{\text{pv}} f_{\text{pv}} \left(\frac{G_T}{G_{T,\text{STC}}}\right) [1 + \alpha_p (T_c - T_{c,\text{STC}})] \quad (2)$$

where: P_{pv} (power output in kWh), Y_{pv} (rated capacity in kWh), f_{pv} (de-rating factor), GT (solar radiation in kW/m^2), $G_{T,STC}$ (solar irradiance in standardized testing conditions in kW/m^2), α_p (power temperature coefficient in %), T_c (solar cell temperature in °C), and $T_{c,STC}$ (the temperature of a PV cell in standard test conditions in kWC) [19].

Modeling of Biomass Power

i. Potential gross crop residue

$$\text{GCRP} = \sum i = 1t\text{CA}_{(i)} \times \text{CY}_{(i)} \times \text{PRP}_{(i)} \quad (3)$$

where *GCRP* is the total potential gross crop residue produced from "*t*" different crops in tons (*t*), $CY_{(i)}$ is the yield per hectare of the ith crop, $CA_{(i)}$ is the cultivated area dedicated to the ith crop in hectares (ha), $PRP_{(i)}$ is the residue-to-product ratio of the ith crop.
ii. Recoverable residue biomass potential

$$\mathrm{RCRP} = \sum i = 1t\mathrm{GCRP}_i \times \mathrm{RF}_i \quad (4)$$

where RCRP is the potential of recovered crop residue from "*t*" crops in tons (*t*), and $RF_{(i)}$ is the recoverability factor of the ith crop.
iii. Potential for bioenergy estimation

$$\mathrm{EP}_{(j)} = \sum i = 1t\mathrm{RCRP}_{(i,j)} \times \mathrm{LHV}_{(i,j)} \quad (5)$$

where $EP_{(j)}$ represents the potential bioenergy from crops t at the j region (MJ), $RCRP_{(i,j)}$ represents the recoverable crop residue of the crop i at the region j, and $LHV_{(i,j)}$ represents the lower heating value of crop i at region j (MJ kg^{-1}). The residues that are being examined have reduced heating values.

Modeling of Diesel Generator (DG)

Climate affects the performance and production of HRES. Sometimes data constraints prevent HRES-which includes PV, biomass, hydro, wind, and batteries-from meeting load demand, requiring diesel generator (DG) backup. The kind of load determines the DG application in HRES. Following DG integration, two techniques are employed: load following and cycle charging. Whereas DG just satisfies load demand, load following gives preference to renewable sources for lower-priority jobs. Compared to load following, cycle charging improves efficiency and reliability by using extra power for secondary activities, maximizing DG output. DG serves as a fallback when HRES is insufficient, increasing dependability and efficiency while cutting expenses. The formula developed by [58] is used to analyze the fuel consumption and efficiency of DG.

$$F_{\mathrm{dsl}}(t) = A \cdot P_R + B \cdot P(t) \quad (6)$$

where F(t) represents the consumption of diesel fuel in l/h dsl, P(t) denotes the electrical power generated by a DG, measured in kilowatts (kW). P represents the DG's rated power. Parameters A and B, which are constant values (l/kW), are typically around 0.08145 and 0.246, respectively.

$$\eta_T = \eta_B \times \eta_G \quad (7)$$

where: η_T= total efficiency; η_B = thermal efficiency; η_G = efficiency of the DG

To achieve the lowest cost in determining the optimal size of any HRES, it is critical to operate the DG on 70-90% of the total load [58].

Modeling of Battery System

State of charge (SOC)-based equations and electromotive force-based charging and discharging equations are the two main types of equations used in battery system modeling [59]. When demand is satisfied, excess electricity from HRES charges the battery bank; when demand is not satisfied, the battery bank supplies backup power, increasing efficiency [60]. Battery size is influenced by variables including longevity, heat, and maximum depth of discharge. With input power varying based on charging and draining activities, batteries are essential for power storage and supply and load balancing in HRES [61]. They assess time spent, productivity, and charge state.

$$P_{pv} + P_{bio} = P_{demand} \quad (8)$$

In this battery scenario, the capacity remains stable and unchanged.

$$P_{pv} + P_{bio} > P_{demand} \quad (9)$$

In this case, the system's total hybrid power (PV and biomass) surpasses the required load. The battery is currently in the charging position, and the amount of charge it has at time (t) is indicated as follows:

$$E_{battery}^{T} = E_{battery}^{T-1} \cdot (1-\tau) + \left[\frac{(P_{pv} + P_{bio}) - P_1^T}{\eta_{inverter}} \right] \cdot \eta_{bc} \quad (10)$$

where; $E_{battery}^{T}$ and $E_{battery}^{T-1}$ = charge quantities of the battery, P_{pv} stands for the power generated by a PV panel, P_{bio} indicates the power generated by biomass. P_1^T denotes the energy demand for a specific hour, η_{bc}represents the battery bank charging efficiency, $\eta_{inverter}$ signifies the efficiency of the inverter, and τ symbolizes the hourly self-discharge rate.

$$P_{pv} + P_{bio} < P_{demand} \quad (11)$$

In this case, the hybrid system's (PV + Bio) total power generated is lower than the load requirement. Currently, the battery bank is discharging, and the equation specifies its charge level. Only the nominal capacity of the storage battery bank can be discharged.

$$E_{battery}{}^{T} = E_{battery}{}^{T-1}(1-r) + [(P_{pv} + P_{bio}) - \frac{p_1^T}{\eta_{inverter}}]\eta_{bf} \quad (12)$$

where: η_{bf} = Battery bank discharge efficiency

Converter/Inverter

The electronic converter is necessary to balance the energy flow between the AC and DC components. The converters or inverters convert electrical energy from one form to another at the frequency required for the load (e.g., changing DC to AC with an inverter and AC to DC with a converter) [27]. The following is a representation of the inverter's efficiency:

$$\eta_{inv} = \frac{P}{P + P_0 + KP^2} \quad (13)$$

P, P_0, and K are determined by employing the following equations:

$$P_0 = 1 - 99\left(\frac{10}{\eta_{10}} - \frac{1}{\eta_{10}} - 9\right) \quad (14)$$

$$K = \frac{1}{\eta_{100}} - P_0 - 1 \quad (15)$$

$$P = \frac{P_{out}}{P_n} \quad (16)$$

where η_{10} and η_{10} are the efficiencies of the converter, they are specified by assemblers at 10% and 100%.

Designing, Simulating, and Modeling of HRES

Using HOMER Pro software, the design and simulation procedures for HRES were carried out as follows:

A few limitations were taken into account when conducting the pre-feasibility study. To ascertain resource availability, including solar irradiation and temperature, as well as biomass fluctuation, the location's latitude and longitude were first input as 8° 51.3' N, 7° 8.6' E.

· The add load button was clicked to add the local load information. The load profile page shows a visual representation of the load along with a summary of the statistical data. Calculations employ scaled data. Figure *2* displays the chosen area's yearly load profile.

· The PV module, together with the cost, characteristics, and alignment of a PV array, was included in the HRES. The HRES now includes the solar GHI resource.

Installing a converter and a battery within the HRES. A converter is required for every system that contains both DC and AC components, and the inverter and rectifier's variables are stated.

· By integrating a biogas generator into the HRES, syngas was produced by introducing the biomass feedstock into a gasifier. The information is used to calculate how much biogas the gasifier can provide to the biogas-powered generator.

After the HRES was designed and modeled, a cost analysis was conducted.

· The HRES has been tuned. The optimal answer was found by adjusting the system setup.

Components Inputs into HOMER for the Proposed System

The hybrid system contains biomass generators (CAT 1000), off-grid connections, storage batteries (ABB PS-BatP3 and ABB-M1), a generator converter (CAT 250), and standard flat-plate PV (CS6U-3430M) inputs, as well as the size, capacity, capital and replacement costs, and O&M expenses for each component. HOMER looks for acceptable system designs, evaluating all potential architectures and component combinations. It examines generator emissions based on fuel usage, as well as technical and economic viability. Cycle charging (CC) or load following (LF) strategies control the system, while optimization factors in varied inputs, including two battery technologies and control strategies (cycle charging and load following). Figure 3 displays schematic layouts of the different components based on the inputs provided.

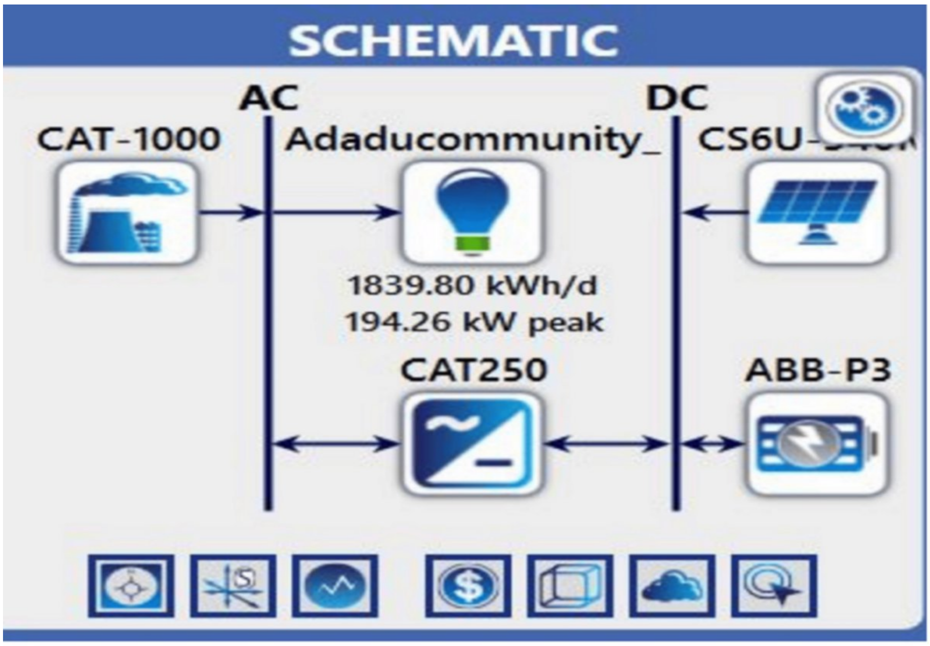

FIGURE 3: Schematic of a PV/BioGen/Battery/Inverter

PV, photovoltaic

Economic analysis

In this study, hybrid system economic analysis relies on NPC. The project with the lowest NPC will be selected. The considered power systems have a 25-year lifespan, chosen due to the PV panel's longest lifespan among components. The equation linking the yearly nominal interest rate and the real interest rate is provided by [62].

$$i = \frac{i' - f}{1 + f} \quad (17)$$

i' denotes the nominal interest rate and f represents the yearly inflation rate.

In the context of this research, the annual real rate is postulated to be 12% of the total cost under consideration (Central Bank of Nigeria, 2015).

The Concept of Present Value

Present worth is the current value of a sum expected to grow with compound interest to a set future amount. For a payment due in years with compound interest at rate i, its present value (PW) is calculated as follows: [62].

$$PW = \frac{C}{(1+i)^N} \quad (18)$$

It is often the case that the annual expenses must be equal. Equations (28) and (29) are then used to determine the present value of a uniform annual sequence of payments p after N years.

$$PW = P\left(\frac{(1+i)^N - 1}{i}\right)\left(\frac{1}{(1+i)^N}\right) \quad (19)$$

$$PW = (\frac{P}{i(1+i)_N})[(1+i)^N - 1] \quad (20)$$

Here, the expression is known as the capital recovery factor or the present worth factor [62].

Net Present Cost (NPC)

The total NPC of a power system is calculated using the following equation [63].

$$NPC = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \quad (21)$$

where $C_{ann,tot}$ denotes the total annualized cost, $\frac{\$}{yr}$ represent the capital recovery factor, and R_{proj} is the project lifetime.

Systems are ranked by NPC count. In their investigation using HOMER software [64], they found that the NPC tends to increase with component size. An annuity's present value is evaluated using the capacity recovery factor ratio. The equation for the capital recovery factor is as follows [65].

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (22)$$

Total Annualized Cost

The overall annual cost equals the aggregate of the annual costs for each individual component of the system.

$$C_{ann,tot} = C_{ann,tot} + C_{ann,bat} + C_{ann,con} + C_{ann,bg} \quad (23)$$

$$C_{ann,comp} = C_{acap} + C_{arep} + C_{ann,o\&m} + C_{ann,fuel} \quad (24)$$

C_{acap} represents the yearly capital cost, C_{arep} stands for the replacement cost, $C_{ann,o\&m}$ signifies the annual operation and maintenance cost, $C_{ann,fuel}$ denotes the annual fuel cost, $C_{ann,bat}$ indicates the yearly battery cost, $C_{ann,con}$ represents the annual converter cost, and $Cann, \ bg$signifies the annual cost of the biomass generator [63].

Annualized Capital Cost (Amortization)

The annualized capital cost for each component is calculated using the following equation:

$$C_{acap} = C_{cap} \times CRF(i, R_{proj}) \quad (25)$$

C_{cap} represents the initial capital expenditure for the component [62].

Depreciation Reserve for Annual Replacement Expenses

The equation provides the annualized replacement expense for a system component (27).

$$C_{arep} = [C_{rep} \times f_{rep} \times SFF(i, R_{comp})] - [S \times SFF(i, R_{proj})] \quad (26)$$

The factor f_{rep} emerges due to the potential variance between the component's lifespan and the project's duration, and it is defined as follows:

$$f_{rep} = \begin{cases} \frac{CRF(i,R_{proj})}{CRF(i,R_{rep})} & \mathrm{R}_{rep} > 0 \\ 0 & ,R_{rep} = 0 \end{cases} \quad (27)$$

R_{rep} represents the duration of replacement costs throughout the entirety of the project's lifespan, as defined by:

$$R_{rep} = R_{comp} \cdot \mathrm{INT}\left(\frac{R_{proj}}{R_{comp}}\right) \quad (28)$$

A mathematical function called INT retrieves the integer part of a real value or expression.

The residual value of the component is presumed to correlate with its remaining duration. Hence, the salvage value (S) can be expressed as:

$$S = C_{rep}\left(\frac{R_{rem}}{R_{comp}}\right) \quad (29)$$

R_{rem} represents the residual lifespan of the component at the conclusion of the project's duration, and it is determined as follows:

$$R_{rem} = R_{comp} - (R_{proj} - R_{rep}) \quad (30)$$

C_{rep} represents the replacement cost of the component, R_{comp} denotes the lifespan of the component, and SFF stands for the sinking fund factor.

The formula representing the SFF is given in [62] as.

$$SFF(i,N) = i/(1+i)^N - 1 \quad (31)$$

Cost of Energy (COE)

The COE equation is presented as follows [62].

$$COE = \frac{C_{ann,tot}}{E_{prim}} \quad (32)$$

where: E_{prim} represents the primary load being served.

Results

CS6U-340M (kW)	CAT-1000 (kW)	ABB-P3	CAT250 (kW)	Dispatch	NPC ($)	COE ($)	Operating Cost ($/yr)	Initial Capital ($)	Ren Frac (%)	Total Fuel (tons/yr)
892.745745	800	1584	379.4177	CC	5890467	0.139481	70730.23	1442347	100	134.4699
	800	3366	698.6078	CC	9776457	0.231498	129601.9	1625982	100	281.488
3158.66667	800		170.3333	CC	1.28E+07	0.303847	166957.5	2332167	100	501.0887
3506.31263		4752	299.2798	CC	1.31E+07	0.310883	137948.9	4445003	100	0
	800			CC	1.68E+07	0.397354	265720.8	70000	100	791.478

TABLE 1: Optimized hybrid system for the simulation using ABB-P3 battery type

COE, cost of energy; NPC, net present cost

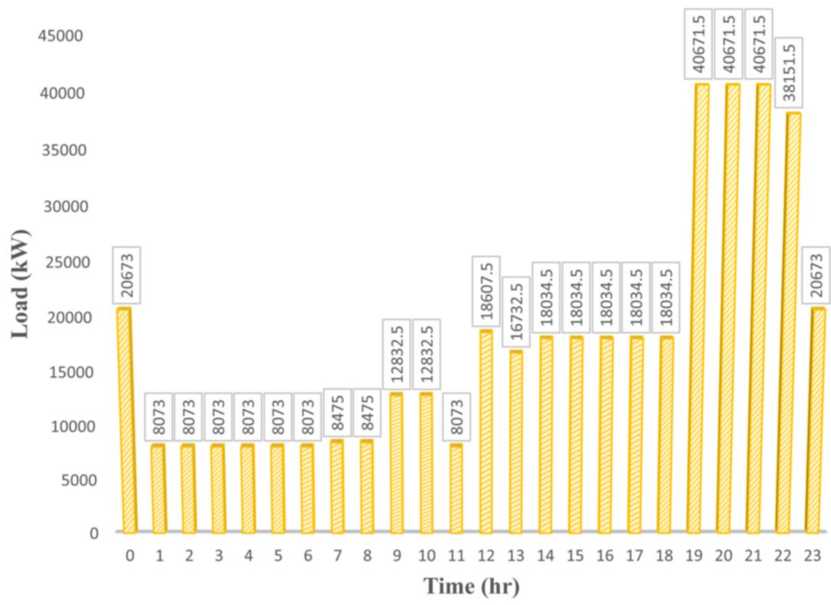

FIGURE 4: Primary load consumption for Adadu

CS6U-340M (kW)	CAT-1000 (kW)	ABB-MI	CAT250 (kW)	Dispatch	NPC ($)	COE ($)	Operating Cost ($/yr)	Initial Capital ($)	Ren Frac (%)	Total Fuel (tons/yr)
733.234344	800	3762	482.4893	CC	1971224	0.046677	10456.68	1313619	100	26.1671
2424.46297		3762	440.4461	CC	3150710	0.074646	11700.77	2414866	100	0
	800	3766	513	CC	3531215	0.083616	44258.47	747865	100	282.012
3496	800		114	CC	1.28E+07	0.304078	163626.4	2551400	100	491.3307
	800			CC	1.68E+07	0.397354	265720.8	70000	100	791.478

TABLE 2: Optimized hybrid system for the simulation using ABB-M1 battery type

COE, cost of energy; NPC, net present cost

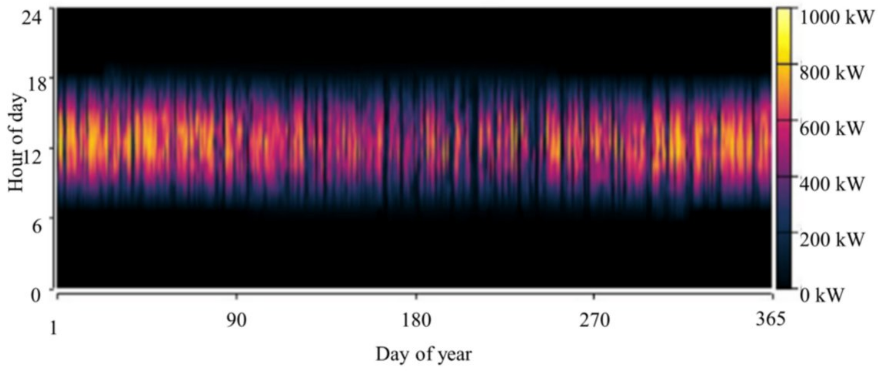

FIGURE 5: PV power output of the ABB-P3 battery type

PV, photovoltaic

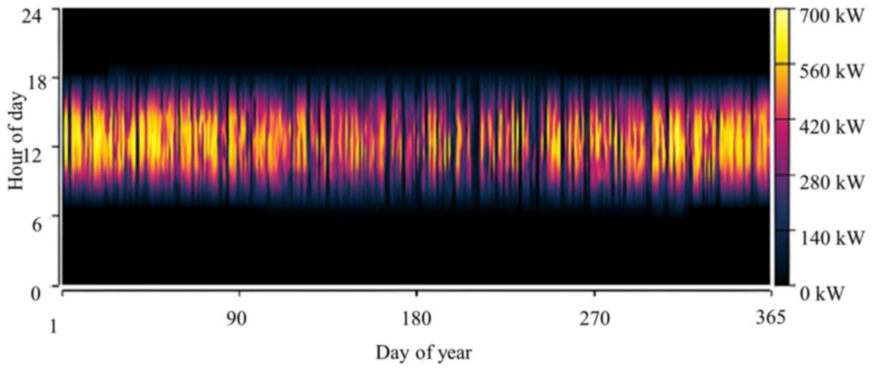

FIGURE 6: PV power output of the ABB-M1 battery type

PV, photovoltaic

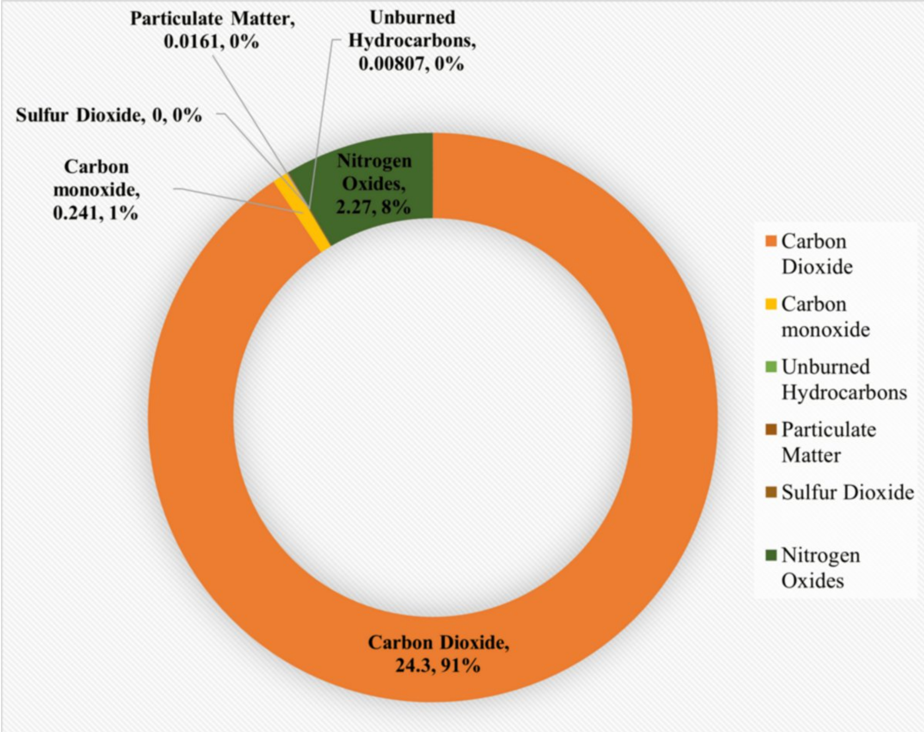

FIGURE 7: Greenhouse Gases (GHG) emissions in kg/h of the HRES

HRES, hybrid renewable energy sources

Economic Metrics	Base Case ($)	Lowest Cost System ($)
Net present cost (NPC)	16.8 M	5.89 M
Initial capital	70,000	1.44 M
Operation and maintenance cost (O & M)	265,720/yr	70,730/yr
Cost of energy (COE)	0.3973/kWh	0.1395/kWh
Internal rate of return (IRR)		13.5%
Return on investment (ROI)		9.6%
Simple payback		6.22 yr

TABLE 3: Economic metrics of the best optimized system as compared to bio generator alone

Economic Metrics	Base Case ($)	Lowest Cost System ($)
Net present cost (NPC)	16.8 M	1.97 M
Initial capital	70,000	1.31 M
Operation and maintenance cost (O & M)	265,721/yr	10,457/yr
Cost of energy (COE)	0.3973/kWh	0.0467/kWh
IRR		20%
ROI		16%
Simple payback		5.0 yr

TABLE 4: Economic metrics of the best optimized system as bio to diesel generator alone

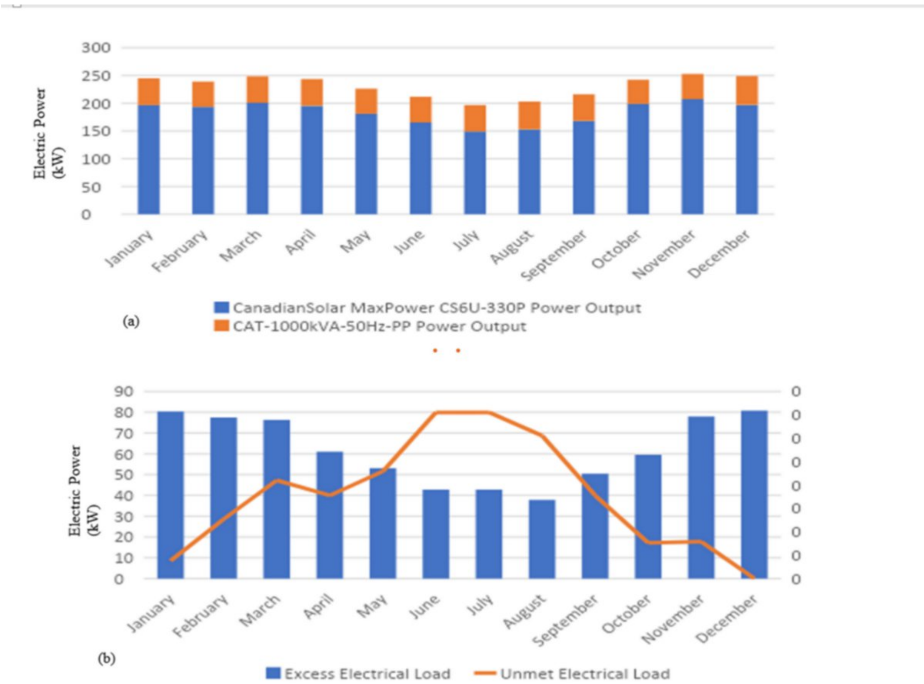

FIGURE 8: (a) Monthly electric production, and (b) excess and unmet electrical production of the ABB-M1 battery type

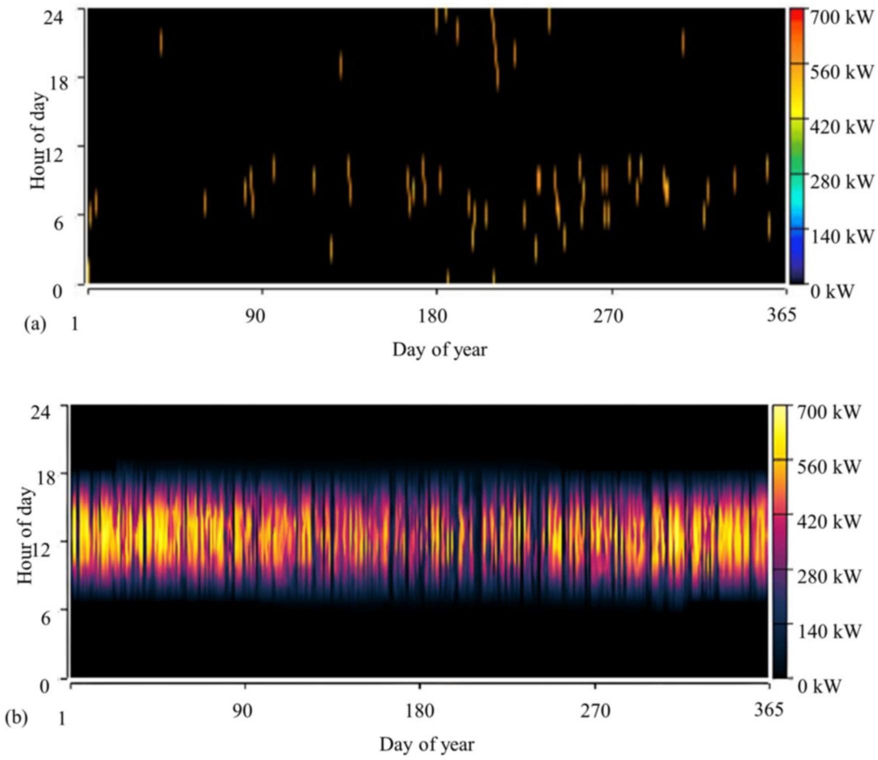

FIGURE 9: (a) ABB-M1 battery type's annual generic power output and (b) PV power output

PV, photovoltaic

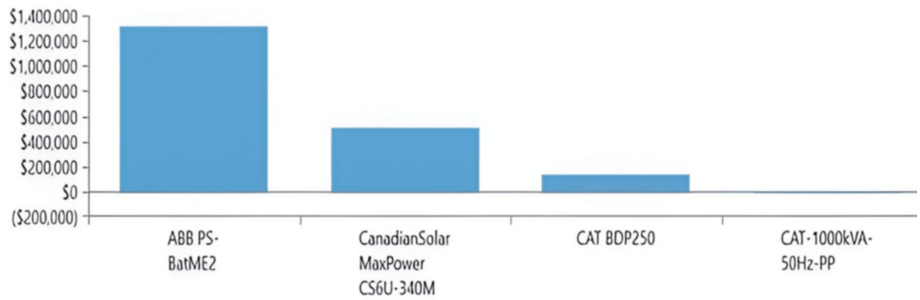

FIGURE 10: Net present cost by component of the ABB-M1 battery type

Discussion

Hourly electricity composition trends for Adadu

The hourly power usage trend for Adadu for a one-month period, as recorded by an Owl ADL400 three-phase DIN rail energy meter, is depicted in Figure *4*. Scaled values of 24,000, 2634, and 38 were employed for the average load (kWh/d), peak load (kW), and load factor (kW), respectively, to accommodate for a spike in periods of increasing load consumption. All three findings utilized this load data.

Investigation of the optimal system

An HRES, including batteries, a biomass generator, a converter, and a PV module, was modeled using PV and biomass resources in the Adadu region. The optimal HRES was identified by optimizing a number of factors, including converter ratings, battery, PV, and biomass generator. For every type of battery, the simulation produced a large number of workable alternatives. Using HOMER simulation, five ideal system combinations were found, with cost-effectiveness being prioritized based on minimized COE and NPC. Of these choices, Configuration-1 turned out to be the most economical. The selected combinations for the

ABB-M1 and ABB-P3 battery types are shown in Tables 1 and 2. CS6U-340M (892.75 kW)/CAT-1000 (800 kW)/ABB-M1 (1584 kW)/CAT250 (379.42 kW) with cycle charging is the optimal dispatch method for ABB-M1. CS6U-340M (733.23 kW)/CAT-1000 (800 kW)/ABB-P3 (3762 kW)/CAT250 (482.49 kW) with cycle charging is the best approach for ABB-P3.

Availability of renewable resources in Adadu

To avoid an unmet primary load in Adadu, Figure 5 shows the necessary electrical load for the hybrid system. In Figure 1b, the major load rises between 7:00 and 22:00. Seasonal and yearly load profiles were derived from daily load profiles and are shown in Figure 1a and c, respectively. With an average annual solar radiation of 5.380 kWh/m²/day, Figure 2 shows the mean monthly solar radiation and clearance index for Adadu. Every day from 7:00 to 18:00, solar insolation peaks in March and troughs in August, with a high of 0.6212 to 0.6322 kW/m². The periods between 0:00 and 6:00 and 18:00 and 24:00 have the lowest insolation, which ranges from 0.0000 to 0.0126 kW/m². This trend is noticeable from 9:00 to 13:00. These conclusions are corroborated by Figures 5 and 6, which demonstrate that PV power generation in Adadu is sustainable. Due to cloud development following rainfall, August has the lowest solar insolation.

PV/Biomass Gen/ABB-P3 optimization configuration (CS6U-340M, CAT-1000kVA-50Hz-PP, ABB PS-BatP3, and CAT250)

Limiting the NPC, capacity shortfall, COE, surplus production, unmet load, fuel consumption, and CO_2 emissions and guaranteeing low capital and maintenance costs while optimizing the renewable energy percentage were some of the criteria used to evaluate the systems. The focus was on NPC and COE. Limitations such as the necessity for at least 40% renewable energy and a maximum permitted yearly capacity shortfall of 10% were also considered. The system lifespan of 25 years and a nominal discount rate of 6.5% were used to explain the economic constraints. Evaluations were carried out using a multicriteria decision-making approach, taking into account several design configurations, to determine which solutions would be best for the location. The most feasible system that consistently satisfies the load and adequately complies with all design constraints and conditions is the CS6U-340 (892.7457 kW), CAT1000 (800 kW), ABB-P3 (1584), and CAT250 (379.4177 kW) scenarios utilizing the HOMER cycle charging controller setup, according to Table 4. The system emits around 24.3 kg/h of CO_2, as seen in Figure 7. The minimal emissions of these system topologies (Table 1) attest to their environmental friendliness. The bio-generator was used as a backup to offset any inconsistencies in renewable resources, such as photovoltaics, rather than as a priority in this study. This system can sufficiently supply the demand without depending on non-renewable energy sources because its renewable energy contribution is 100%. The performance of the other systems examined on this website is just as inspiring and motivating.

ABB-P3 (1584)/CAT250 (379.4177 kW)/CS6U-340 (892.7457 kW)/CAT1000 (800 kW) using the ABB-P3 Battery Type HOMER Cycle charging controller configuration

Based on various component simulations, the ideal system configuration-a CS6U-340/CAT1000/CAT250 arrangement with HOMER cycle charging-is shown in Table 1. NPC and COE, two important cost indicators, help choose the optimal design. Economic characteristics for the basic scenario and the least expensive system are shown in Table 3. At $5.89 million, the CS6U-340/CAT1000/ABB-P3/CAT250 with HOMER cycle charging has the lowest NPC, whereas the CAT1000 alone costs $16.8 million. This system has lower operating, maintenance, and energy costs than the basic scenario, although the former has greater initial capital expenditures. In comparison to the most costly option, the least expensive system has a 9.6% return on investment (ROI) and a 6.22-year payback period.

PV/Biomass Gen/ABB-M1 optimization configuration (CS6U-340M, CAT-1000kVA-50Hz-PP, ABB PS-BatME2, and CAT250)

As previously mentioned, Table 2 displays the outcomes of the simulation utilizing ABB-M1 battery technology. With NPC, COE, CO_2 emissions, and renewable energy fractions of $1.97 million, $0.047, 4.72 kg/h, and 100%, respectively, Table 2 shows that the system configuration with CS6U-340M (733.2343 kW), CAT1000 (800 kW), ABB-M1 (3762), and CAT250 (482.4893 kW) using the HOMER cycle charging dispatch algorithm as its setup is the most feasible of the five categorized systems. The system design for the ABB-M1 simulation has minimal emissions, which validates their environmental friendliness, much like in the ABB-P3 battery type simulation. The system can effectively fulfil the demand without using any non-renewable energy sources, as seen by its 100% renewable energy contribution.

ABB-M1 (3762), CS6U 340 (733.234 kW), CAT1000 (800 kW), and CAT250 (482.4893 kW) using the ABB-M1 Battery Type HOMER cycle charging controller configuration

Table 4, which features the CS6U-340/CAT1000/ABB-M1/CAT250 system employing HOMER cycle charging, summarizes the ideal system configuration. The infeasible alternatives were eliminated after thousands of workable solutions for the various component combinations were simulated. Table 2 shows the presentation of five optimization outcomes based on several criteria. The most crucial cost factors that are used to compare them and help the customer choose the optimal system design are NPC and COE. Table 4 provides specifics on the economic aspects of the basic scenario and the least expensive system. CS6U-340 (733.234 kW), CAT1000 (800 kW), ABB-M1 (3762 kW), and CAT250 (482.489 kW) utilizing the HOMER cycle charging controller setup have the lowest NPC of $1.97 million, while the CAT1000 (800 kW) has the highest NPC of $16.8 million. When comparing the base case (biogen-only system) to the CS6U-340 (733.234 W), CAT1000 (800 kW), ABB-M1 (3762), and CAT250 (482.489 kW) systems, Table 4 shows that while the base case has a lower initial capital expenditure, its operational and maintenance costs and energy costs are higher. When used with a cycle charging dispatch approach, the least expensive system also offers a simple payback period of 5.0 years and a ROI of 16%.

Comparison of the best systems of the two battery types

The cycle charging dispatch algorithm creates the most efficient hybrid system, as shown by the findings in Tables 2 and 3. The ABB-M1 battery, in conjunction with CS6U-340M, CAT1000, and CAT250 components, provides favorable results with minimum NPC, COE, and CO_2 emissions, as well as a 100% renewable percentage, according to Table 2 analysis.

Figures 8 and 9 show that 1,258,807 kWh of power are produced annually utilizing ABB-M1 battery technology, primarily from PV (95%) and Biogen (5%). The system deploys 100% renewable energy with just minor capacity shortages and unfulfilled needs, even if there is a 42% energy surplus. NPC and system dependability are impacted by changes in battery size or generating capacity, with PV size having the most impact on surplus energy.

Cost components for different configurations are shown in Figure 10. The ABB-M1 battery setup shows an NPC of $1,971,224 and a COE of $0.04668/kWh, mostly due to PV and battery expenses. However, this COE is higher than the utility-grid rate because of government subsidies. Emissions are influenced by biomass utilization; Configuration-2 emits less since it uses less biogen.

Because PV contributes significantly to load needs, the ABB-M1 battery design performs better than the ABB-P3 in terms of cost-effectiveness and emissions reduction. Among hybrid systems, its 733 kW PV array size guarantees strong power generation with the lowest COE.

Furthermore, in spite of significant SOC fluctuation and annual losses, the ABB-M1 battery bank in the suggested system performs better and has the maximum energy throughput. It outlasts other battery types, maintaining a 10-year life expectancy.

With yearly average outputs for the rectifier and inverter guaranteeing seamless operation, the converter system efficiently controls the transmission of electricity. When taking into account NPC, COE, dependability, emissions reduction, and location, the ABB-M1 battery design turns out to be the most sensible and ideal option for providing sustainable energy in isolated rural locations.

Conclusions

This study has demonstrated the technical and economic feasibility of integrating PV and biomass resources into a HRES for sustainable off-grid power generation in the Adadu community, Nasarawa State, Nigeria. By employing HOMER Pro to design, simulate, and optimize various system configurations, the analysis identified solutions that can provide reliable, cost-effective, and environmentally friendly electricity access to rural households. The results revealed that among the different configurations tested, the PV/Biomass/ABB-M1 system exhibited superior performance, achieving the lowest NPC of $1.97 million, the lowest COE at $0.0467/kWh, and a 100% renewable fraction with minimal carbon dioxide emissions (4.72 kg/h). This outcome highlights the significant potential of combining locally available renewable resources with advanced storage technologies to meet rural energy demands sustainably.

The findings further emphasize that adopting hybrid energy solutions can substantially reduce reliance on diesel generators, thereby lowering greenhouse gas emissions, operational costs, and fuel dependency while ensuring long-term system reliability. Such systems not only contribute to climate change mitigation but also foster socio-economic development by improving healthcare, education, small businesses, and overall quality of life in rural areas. Additionally, the HOMER Pro optimization framework proved effective in guiding decision-making, enabling the identification of the most viable configurations that balance technical performance, environmental sustainability, and economic viability.

More broadly, this research contributes to the growing body of knowledge supporting decentralized renewable energy systems as a pathway for achieving Nigeria's electrification targets and the United Nations SDGs, particularly Goal 7, which advocates for affordable, reliable, sustainable, and modern energy for all. Importantly, the approach presented in this study is replicable and adaptable to other rural regions with similar socio-economic and environmental conditions, thereby serving as a blueprint for scaling renewable energy adoption in underserved communities.

Future research should extend beyond the techno-economic analysis presented here to incorporate detailed environmental life-cycle assessments, socio-political considerations, and policy frameworks that can enhance system adoption and sustainability. Moreover, investigating the integration of additional renewable sources such as wind and small hydropower, coupled with smart grid technologies, could provide further resilience and flexibility to rural energy systems.

In conclusion, the optimized PV-biomass hybrid system with advanced storage offers a practical, clean, and sustainable solution to rural energy poverty, ensuring energy security while contributing to a net-zero energy future.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Alpha A. Ndah, Adra A. Muhammad, Attah E. Idenyi

Acquisition, analysis, or interpretation of data: Alpha A. Ndah, Adra A. Muhammad

Drafting of the manuscript: Alpha A. Ndah, Adra A. Muhammad

Critical review of the manuscript for important intellectual content: Alpha A. Ndah, Attah E. Idenyi

Supervision: Alpha A. Ndah

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

References

1. Mihai FC, Iatu C: Sustainable rural development under Agenda 2030. Sustainability Assessment at the 21st Century. Bastante-Ceca MJ, Fuentes-Bargues JL, Hufnagel L, Mihai FC (ed): IntechOpen, 2020. 9-18. 10.5772/intechopen.90161
2. Zhang C, Zhou K, Yang S, Shao Z: On electricity consumption and economic growth in China. Renewable and Sustainable Energy Reviews. 2017, 76:353-68. 10.1016/j.rser.2017.03.071
3. Kaygusuz K: Energy services and energy poverty for sustainable rural development. Renewable and Sustainable Energy Reviews. 2011, 15:936-47. 10.1016/j.rser.2010.11.003
4. Akuru UB, Onukwube IE, Okoro OI, Obe ES: Towards 100% renewable energy in Nigeria. Renewable and Sustainable Energy Reviews. 2017, 71:943-53. 10.1016/j.rser.2016.12.123
5. Babajide A, Brito MC: Solar PV systems to eliminate or reduce the use of diesel generators at no additional cost: A case study of Lagos, Nigeria. Renewable Energy. 2021, 172:209-18. 10.1016/j.renene.2021.02.088
6. Malik P, Awasthi M, Upadhyay S, et al.: Planning and optimization of sustainable grid integrated hybrid energy system in India. Sustainable Energy Technologies and Assessments. 2023, 56:103115. 10.1016/j.seta.2023.103115
7. Rabea K, Michailos S, Udeh GT, et al.: A comprehensive technoeconomic and environmental evaluation of a hybrid renewable energy system for a smart farm in South Korea. International Journal of Energy Research. 2023, 2023:1-18. 10.1155/2023/4951589
8. Zhang S, Hu W, Du J, Bai C, Liu W, Chen Z: Low-carbon optimal operation of distributed energy systems in the context of electricity supply restriction and carbon tax policy: a fully decentralized energy dispatch strategy. Journal of Cleaner Production. 2023, 396:136511. 10.1016/j.jclepro.2023.136511
9. Dong H, Shan Z, Zhou J, Xu C, Chen W: Refined modeling and co-optimization of electric-hydrogen-thermal-gas integrated energy system with hybrid energy storage. Applied Energy. 2023, 351:121834. 10.1016/j.apenergy.2023.121834
10. Batool K, Zhao ZY, Atif F, Dilanchiev A: Nexus between energy poverty and technological innovations: a pathway for addressing energy sustainability. Frontiers in Environmental Science. 2022, 10:10.3389/fenvs.2022.888080
11. Saulat H, Khan MM, Aslam M, et al.: Wind speed pattern data and wind energy potential in Pakistan: current status, challenging platforms and innovative prospects. Environmental Science and Pollution Research. 2021,

28:34051-4073. 10.1007/s11356-020-10869-y
12. Giwa A, Alabi A, Yusuf A, Olukan T: A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria. Renewable and Sustainable Energy Reviews. 2017, 69:620-41. 10.1016/j.rser.2016.11.160
13. He Y, Guo S, Zhou J, Song G, Kurban A, Wang H: The multi-stage framework for optimal sizing and operation of hybrid electrical-thermal energy storage system. Energy. 2022, 245:123248. 10.1016/j.energy.2022.123248
14. He Y, Guo S, Zhou J, Ye J, Huang J, Zheng K, Du X: Multi-objective planning-operation co-optimization of renewable energy system with hybrid energy storages. Renewable Energy. 2022, 184:776-90. 10.1016/j.renene.2021.11.116
15. Das S, De S: MCDM for simultaneous optimum economy, investment risk and environmental impact for distributed renewable power: Demonstration with an Indian village data. Energy Conversion and Management. 2023, 277:116631. 10.1016/j.enconman.2022.116631
16. Muhammad AA, Ibrahim JS, Alpha NA: Optimising solar-biomass hybrid energy systems for sustainable rural electrification. Journal of Engineering Research and Reports. 2025, 27:267-84. 10.9734/jerr/2025/v27i51506
17. Dahunsi FM, Abdul-Lateef OA, Melodi AO, Ponnle AA, Sarumi OA, Adedeji KA: Smart grid systems in Nigeria: prospects, issues, challenges and way forward. FUOYE Journal of Engineering and Technology. 2022, 7:183-92. 10.46792/fuoyejet.v7i2.781
18. Xu J, Wang J, Wang F, Wang J, Li G: SOC balancing control based on predictive power model amongst supercapacitor packs in MMC with embedded energy storage system. IEEE Transactions on Power Delivery. 2023, 38:2641-649. 10.1109/tpwrd.2023.3250469
19. Uzedhe GO, Febaide IC, Azubogu ACO: Optimal configuration and energy scheduling algorithm for an off-grid hybrid microgrid. FUOYE Journal of Engineering and Technology. 2022, 7:10.46792/fuoyejet.v7i3.913
20. Ganjei N, Zishan F, Alayi R, Samadi H, Jahangiri M, Kumar R, Mohammadian A: Designing and sensitivity analysis of an off-grid HybridWind-solar power plant with diesel generator and battery backup for the rural area in Iran. Journal of Engineering. 2022, 2022:1-14. 10.1155/2022/4966761
21. Achirgbenda VT, Kuhe A, Okoli K: Techno-economic feasibility assessment of a solar-biomass diesel energy system for a remote rural health facility in Nigeria. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2020, 46:15755-5772. 10.1080/15567036.2020.1813848
22. Olatomiwa L, Blanchard R, Mekhilef S, Akinyele D: Hybrid renewable energy supply for rural healthcare facilities: An approach to quality healthcare delivery. Sustainable Energy Technologies and Assessments. 2018, 30:121-38. 10.1016/j.seta.2018.09.007
23. Olatomiwa L, Mekhilef S, Huda ASN, Sanusi K: Techno-economic analysis of hybrid PV-diesel-battery and PV-wind-diesel-battery power systems for mobile BTS: the way forward for rural development. Energy Science & Engineering. 2015, 3:271-85. 10.1002/ese3.71
24. Zhang W, Maleki A, Rosen MA, Liu J: Sizing a stand-alone solar-wind-hydrogen energy system using weather forecasting and a hybrid search optimization algorithm. Energy Conversion and Management. 2019, 180:609-21.
25. Bajaj M, Singh AK: Design and analysis of optimal passive filters for increasing the harmonic-constrained hosting capacity of inverter-based DG systems in non-sinusoidal grids. Electrical Engineering. 2021, 104:1883-907. 10.1007/s00202-021-01415-1
26. Sharma S, Sood YR: Optimal planning and sensitivity analysis of green microgrid using various types of storage systems. Wind Engineering. 2020, 45:939-52. 10.1177/0309524x20941475
27. Choudhury S, Acharya SK, Khadanga RK, et al.: Harmonic profile enhancement of grid connected fuel cell through cascaded H-bridge multi-level inverter and improved squirrel search optimization technique. Energies. 2021, 14:7947. 10.3390/en14237947
28. Khan A, Jaffery MH, Javed Y, et al.: Hardware-in-the-Loop implementation and performance evaluation of three phase hybrid shunt active power filter for power quality improvement. Mathematical Problems in Engineering. 2021, 2021:1-23. 10.1155/2021/8032793
29. Yousaf A, Asif RM, Shakir M, Rehman AU, Adrees MS: An improved residential electricity load forecasting using a machine-learning-based feature selection approach and a proposed integration strategy. Sustainability. 2021, 13:6199. 10.3390/su13116199
30. İnci M, Aygen MS: A modified energy management scheme to support phase balancing in grid interfaced photovoltaic/fuel cell system. Ain Shams Engineering Journal. 2021, 12:2809-822. 10.1016/j.asej.2020.12.018
31. Zebarjadi M, Askarzadeh A: Optimization of a reliable grid-connected PV-based power plant with/without energy storage system by a heuristic approach. Solar Energy. 2016, 125:12-21. 10.1016/j.solener.2015.11.045
32. Abdelshafy AM, Hassan H, Jurasz J: Optimal design of a grid-connected desalination plant powered by renewable energy resources using a hybrid PSO-GWO approach. Energy Conversion and Management. 2018, 173:331-47. 10.1016/j.enconman.2018.07.083
33. Mehmood U: Contribution of renewable energy towards environmental quality: The role of education to achieve sustainable development goals in G11 countries. Renewable Energy. 2021, 178:600-7. 10.1016/j.renene.2021.06.118
34. Obaideen K, Shehata N, Sayed ET, Abdelkareem MA, Mahmoud MS, Olabi AG: The role of wastewater treatment in achieving sustainable development goals (SDGs) and sustainability guideline. Energy Nexus. 2022, 7:100112. 10.1016/j.nexus.2022.100112
35. Oyedepo SO, Babalola OP, Nwanya SC, et al.: Towards a sustainable electricity supply in Nigeria: the role of decentralized renewable energy system. European Journal of Sustainable Development Research. 2018, 2:40. 10.20897/ejosdr/3908
36. Nwozor A, Oshewolo S, Owoeye G, Okidu O: Nigeria's quest for alternative clean energy development: A cobweb of opportunities, pitfalls and multiple dilemmas. Energy Policy. 2021, 149:112070. 10.1016/j.enpol.2020.112070
37. Usman M, Khan MT, Rana AS, Ali S: Techno-economic analysis of hybrid solar-diesel-grid connected power generation system. Journal of Electrical Systems and Information Technology. 2018, 5:653-62. 10.1016/j.jesit.2017.06.002
38. Setiawan AA, Ramadhan SA, Wahyuni NS, Hidayah AN, Rouf Arifin MLN, Suyatna H: Economic analysis comparison between solar photovoltaic and diesel generator for water pumping system in an Indonesia rural

Karsts area. KnE Energy. 2015, 2:8-15. 10.18502/ken.v2i2.351
39. Spiru P, Lizica-Simona P: Technical and economical analysis of a PV/wind/diesel hybrid power system for a remote area. Energy Procedia. 2018, 147:343-50. 10.1016/j.egypro.2018.07.102
40. Ijeoma MW, Lewis CG, Chen H, Chukwu BN, Carbajales-Dale M: Technical, economic, and environmental feasibility assessment of solar-battery-generator hybrid energy systems: a case study in Nigeria. Frontiers in Energy Research. 2024, 12:1397037. 10.3389/fenrg.2024.1397037
41. Bortolini M, Gamberi M, Graziani A, Pilati F: Economic and environmental bi-objective design of an off-grid photovoltaic-battery-diesel generator hybrid energy system. Energy Conversion and Management. 2015, 106:1024-38. 10.1016/j.enconman.2015.10.051
42. Dei T, Batjargal N: Technical and economical evaluation of micro-solar PV/diesel hybrid generation system for small demand. International Journal of Renewable Energy Development. 2022, 11:1101-112. 10.14710/ijred.2022.46747
43. Akinsipe OC, Moya D, Kaparaju P: Design and economic analysis of off-grid solar PV system in Jos-Nigeria. Journal of Cleaner Production. 2021, 287:125055. 10.1016/j.jclepro.2020.125055
44. Ibrik IH: Techno-economic feasibility of energy supply of water pumping in Palestine by photovoltaic-systems, diesel generators and electric grid. International Journal of Energy Economics and Policy. 2020, 10:69-75. 10.32479/ijeep.8816
45. Al Garni HZ, Mas'ud AA, Baseer MA, Ramli MAM: Techno-economic optimization and sensitivity analysis of a PV/Wind/diesel/battery system in Saudi Arabia using a combined dispatch strategy. Sustainable Energy Technologies and Assessments. 2022, 53:102730. 10.1016/j.seta.2022.102730
46. Ghenai C, Bettayeb M: Modelling and performance analysis of a stand-alone hybrid solar PV/Fuel Cell/Diesel Generator power system for university building. Energy. 2019, 171:180-89. 10.1016/j.energy.2019.01.019
47. Zhao N, Wang L, Ding C: Modeling and optimization of a hybrid solar-battery-diesel power system for remote consumers. Environmental Science and Pollution Research. 2024, 31:38542-8552. 10.1007/s11356-023-29048-w
48. Ji L, Liu Z, Wu Y, Huang G: Techno-economic feasibility analysis of optimally sized a biomass/PV/DG hybrid system under different operation modes in the remote area. Sustainable Energy Technologies and Assessments. 2022, 52:102117. 10.1016/j.seta.2022.102117
49. Yunus MY, Lewi L, Rijal AS, Huda N, Ikram A: Planning study of hybrid power plant solar PV-diesel generator on kodingare island, sinjai regency. International Journal of Innovation in Mechanical Engineering and Advanced Materials. 2023, 5:69-76. 10.22441/ijimeam.v5i2.23245
50. Salisu S, Mustafa MW, Olatomiwa L, Mohammed OO: Assessment of technical and economic feasibility for a hybrid PV-wind-diesel-battery energy system in a remote community of north central Nigeria. Alexandria Engineering Journal. 2019, 58:1103-118. 10.1016/j.aej.2019.09.013
51. Khan MJ, Yadav AK, Mathew L: Techno economic feasibility analysis of different combinations of PV-Wind-Diesel-Battery hybrid system for telecommunication applications in different cities of Punjab, India. Renewable and Sustainable Energy Reviews. 2017, 76:577-607. 10.1016/j.rser.2017.03.076
52. Amole AO, Owosibo RA, Adewuyi OB, Oladipo S, Imarhiagbe NO: Comparative analysis of control strategies for solar photovoltaic/diesel power system for stand-alone applications. Renewable Energy. 2024, 226:119717. 10.1016/j.renene.2023.119717
53. Madziga M, Rahil A, Mansoor R: Comparison between three off-grid hybrid systems (solar photovoltaic, diesel generator and battery storage system) for electrification for Gwakwani village, South Africa. Environments. 2018, 5:57. 10.3390/environments5050057
54. Adefarati T, Bansal RC, John JJ: Techno-economic analysis of a PV-wind-battery-diesel standalone power system in a remote area. The Journal of Engineering. 2017, 2017:740-44. 10.1049/joe.2017.0429
55. Kumar P, Pal N, Sharma H: Optimization and techno-economic analysis of a solar photo-voltaic/biomass/diesel/battery hybrid off-grid power generation system for rural remote electrification in eastern India. Energy. 2022, 247:123560. 10.1016/j.energy.2022.123560
56. Nsafon BEK, Owolabi AB, Butu HM, Roh JW, Suh D, Huh JS: Optimization and sustainability analysis of PV/wind/diesel hybrid energy system for decentralized energy generation. Energy Strategy Reviews. 2020, 32:100570. 10.1016/j.esr.2020.100570
57. Rahaman MH: Design, analysis and control of solar heating system with seasonal thermal energy storage (Doctoral dissertation. Memorial University of Newfoundland, 2020. 10.48336/f49b-4279
58. Bouchekara HREH, Sha'aban YA, Shahriar MS, Abdullah SM, Ramli MA: Sizing of hybrid PV/Battery/Wind/Diesel microgrid system using an improved evolutionary algorithm considering uncertainties and battery degradation. Sustainability. 2023, 15:11073. 10.3390/su151411073
59. Khan AA, Minai AF, Pachauri RK, Malik H: Optimal Sizing, Control, and Management Strategies for Hybrid Renewable Energy Systems: A Comprehensive Review. Energies. 2022, 15:6249. 10.3390/en15176249
60. Muleta N, Badar AQH: Designing of an optimal standalone hybrid renewable energy micro-grid model through different algorithms. Journal of Engineering Research. 2023, 11:100011. 10.1016/j.jer.2023.100011
61. Chauhan A, Saini RP: Size optimization and demand response of a stand-alone integrated renewable energy system. Energy. 2017, 124:59-73. 10.1016/j.energy.2017.02.049
62. Masaud TM, El-Saadany EF: Correlating optimal size, cycle life estimation, and technology selection of batteries: a two-stage approach for microgrid applications. IEEE Transactions on Sustainable Energy. 2020, 11:1257-267. 10.1109/tste.2019.2921804
63. Malik P, Awasthi M, Sinha S: Techno-economic and environmental analysis of biomass-based hybrid energy systems: a case study of a Western Himalayan state in India. Sustainable Energy Technologies and Assessments. 2021, 45:101189. 10.1016/j.seta.2021.101189
64. Vendoti S, Muralidhar M, Kiranmayi R: Optimization of hybrid renewable energy systems for sustainable and economical power supply at SVCET Chittoor. i-manager's Journal on Power Systems Engineering. 2017, 1:26-34. 10.26634/jps.5.1.13534
65. Kumar R, Channi HK: A PV-Biomass off-grid hybrid renewable energy system (HRES) for rural electrification: design, optimization and techno-economic-environmental analysis. Journal of Cleaner Production. 2022, 349:131347. 10.1016/j.jclepro.2022.131347