

Research Article

Modelling and Optimisation of Integrated Renewable Energy Conversion Technologies with Dual Energy Storage for an Island

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Academic Editor: George Papadakis

Collection: [Optimal Energy Management and Control of Renewable Energy Systems](#)

Journal of Energy and Power Technology
2026, volume 8, issue 1
doi:10.21926/jept.2601005

Received: September 17, 2025
Accepted: January 28, 2026
Published: March 09, 2026

Abstract

The work focused on modelling and optimisation of integrated renewable energy conversion technologies based on sunlight, wind, and biomass, with dual energy storage (battery and hydrogen), for Patani Island, Delta State, Nigeria. The study was aimed at satisfying the energy demand of the Patani Island community (5°13'43" N, 6°11'29" E). A mathematical model was developed to describe the integrated system, and a genetic algorithm was employed to optimize the allocation of energy demand, energy generation, and energy storage. Economic models were also formulated to determine the techno-economic feasibility of the hybrid plant. The mathematical model, optimisation scheme, and analysis were implemented in HOMER® and MATLAB®, while the results were post-processed using MS Excel®. The optimal results indicate that the peak rated power of PV, WT, and Biomass needed to meet the island's energy demand are 0.218 MW, 236 MW, and 0.100 MW, respectively. The energy demand by Patani



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Island is 43662 MWh/year while the total energy generated by the integrated renewable energy system is 43623.845 MWh/year, the minimum storage capacity for both battery and hydrogen was estimated to be 138.38 MWh, the levelized cost of energy (LCOE) was calculated to be \$0.321 per kWh (~~N~~482/kWh), and the loss of load probability (LLP) of the proposed energy system was estimated at 0.11. The present study demonstrates that an integrated renewable energy system can be a practical and applicable approach to electrifying Patani Island.

Keywords

Integrated renewable energy; dual-energy storage; modelling and optimisation; genetic algorithm; techno-economic modelling

1. Introduction

Solar, wind, and biomass power, among others, have become more popular as a result of the rising need for environmentally friendly energy. Sustainable, environmentally friendly, and cost-effective power production relies on renewable energy (RE). The use of renewable energy sources (RES) to meet global energy demand has been increasing, while the use of fossil fuels for power generation has been declining since 2019, according to a formal study by the International Energy Agency (IEA). To further improve Renewable energy (RE) production performance, ongoing research on RE technologies focuses on enhancing energy conversion efficiency [1].

Islands, due to their geographical isolation and limited access to centralized power grids, face unique challenges in ensuring energy security and sustainability. One promising solution is to integrate renewable energy conversion technologies with energy storage systems, which can mitigate the intermittency of renewable energy and ensure a continuous power supply.

Nigeria, like many developing nations, lags behind in integrating renewable energy (RE) into its energy mix. Although large-scale hydro contributes 22% to the country's electricity generation, the contribution of other renewable energy sources remains minimal, despite the nation's abundant renewable resources [2, 3].

Nigeria is highly vulnerable to climate change, experiencing frequent floods and other related challenges. As a signatory to both the Kyoto Protocol and the Paris Climate Accord, Nigeria is committed to addressing climate change. However, the country is grappling with significant electricity shortages, which have led to an increased reliance on fossil fuels for power generation and transportation. The question arises: How can Nigeria balance its international climate commitments with the growing demand for energy? Renewable energy presents a viable solution for Nigeria to achieve both climate change mitigation and energy security. It is important to note that considerable efforts, including numerous policies and projects, have already been initiated in this direction.

Several studies have highlighted the potential to use solar photovoltaics (PVs), wind turbines, and other renewable energy sources (RES) for electricity generation in Nigeria [4]. These RESs are environmentally friendly, producing no pollution or greenhouse gas emissions, and are abundantly available. While many studies focus on the use of a single RES for power generation, others explore

hybrid systems that combine two or more RESs, sometimes incorporating diesel generators as backup for increased efficiency and reliability. Hybrid systems with diesel backup are especially suitable for villages without access to the power grid. The use of hybrid systems is often favoured, as relying on a single energy source can lead to system over-sizing, which in turn may raise capital costs [5]. Additionally, weather conditions, such as fluctuations in wind speed and solar radiation, can affect system performance. [6] present an optimal configuration of hybrid energy systems together with wind and PV, with energy storage and a backup diesel generator, for households in six locations in the South-South geopolitical zone of Nigeria.

A hybrid renewable energy system integrates multiple renewable energy sources to mitigate the intermittency associated with each individual source, ensuring a reliable and continuous power supply. Renewable energy sources (RES) exhibit fluctuating and unstable output due to their reliance on natural conditions [7-10], necessitating additional technological solutions for effective use. This section examines the drawbacks of RES and outlines methods developed to address these challenges, with a focus on the variable power-generation patterns of photovoltaic (PV) panels and wind turbines. Diemuodeke et al. [11] performed a multi-criteria assessment of hybrid renewable energy systems for coastal communities in Nigeria. It also discusses energy storage solutions designed to address these issues of intermittency. The advantages of energy storage systems for both grid operations and end users are highlighted. Additionally, hybrid renewable energy systems are reviewed, along with the benefits and performance improvements that result from combining them with energy storage. The application of energy storage in electric vehicles and uninterruptible power supplies (UPS) is also mentioned.

Solar PV technology has been widely adopted due to its simplicity, scalability, and low operating costs. It works by converting sunlight into electricity through photovoltaic cells. On islands, solar PV can be an excellent source of renewable energy, particularly in regions with high solar insolation. However, its intermittent nature, affected by weather conditions and the day-night cycle, poses challenges for grid integration, making energy storage systems crucial. Bhos & Nasikkar [12] carried out Optimisation-based maximum power extraction from a solar photovoltaic system under non-uniform irradiance. Pavankumar et al. [13] investigated multi-objective optimisation of photovoltaic/wind/biomass/battery-based grid-integrated hybrid renewable energy system. Castro et al. [14] introduce a PV system model that is useful for steady-state power-flow studies of practical electrical networks. This multi-array PV system model features a comprehensive representation of the three main stages taking part in solar energy conversion systems. Pendem & Mikkili [15] modelled, simulated, and analyzed the effect of partial shading conditions (PSCs) on the electrical performance of Series (S), Series-Parallel (S-P), and Honey-Comb (H-C) PV array configurations under various shading patterns, including short and narrow, short and wide, long and narrow, long and wide, and diagonal, using a MATLAB/Simulink simulation model.

Wind energy has seen significant growth due to technological advancements in turbines and their efficiency. Wind energy systems, particularly in coastal areas or regions with high wind potential, complement solar PV systems by generating electricity when solar power is low (e.g., at night or on cloudy days). However, like solar power, wind energy is intermittent and location-dependent, which makes optimization and proper integration essential for reliable operation. According to [16], sustainable and secure energy sources are crucial for the long-term development of society. Wind energy is a promising area in the power generation industry due to its renewable nature and global availability [17, 18].

Biomass energy, derived from organic materials such as wood, agricultural waste, or algae, can provide a consistent and controllable energy source. Unlike solar and wind, biomass generation is not intermittent and can provide baseload power, making it an ideal candidate for hybrid energy systems. In island communities, biomass offers the added advantage of utilizing locally available resources, thereby reducing dependence on imports [19, 20]. As the population is increasing rapidly, we now observe a trend in which cities are using a growing share of renewable energy.

Battery storage technologies have been extensively used to store excess energy produced by renewable sources for later use. Lithium-ion batteries, with their high energy density, fast response times, and decreasing costs, are the most commonly used in hybrid systems. BESS can smooth out the fluctuations in renewable generation, store excess energy during peak production, and discharge it during periods of low generation or high demand. Zhu et al. [21] investigated the technical, economic, and environmental effects of an erratic national grid on four distinct battery technologies in hybrid wind, solar, and diesel energy systems. The study was conducted at Baze University, Abuja, Nigeria, using the Hybrid Optimization Model for Electric Renewables software. The battery types considered are vanadium redox flow battery (VRB), lead-acid battery, nickel-iron battery, and lithium-ion battery (LIB). The VRB-based hybrid energy systems demonstrated superior performances in meeting the electricity demands of the university at the lowest net present cost, levelized cost of energy, and carbon dioxide emissions of \$6,328,003.00, \$0.0722/kWh, and 21,754 kg/year, respectively. This battery technology is characterized by storage depletion, throughput, and losses of 796 kWh/year, 406,570 kWh/year, and 182,757 kWh/year, respectively. Dodo et al. [22] introduce an innovative optimization strategy for hybrid renewable energy systems in microgrids. The approach focuses on multi-objective optimization of a PV-wind-diesel-battery hybrid system to reduce the levelized cost of energy (LCOE) and the loss-of-power-supply probability (LPSP), while maximizing the utilization of renewable energy sources (RES). Han & Vinel [23] assessed a similar approach to address the challenge of limited predictability in wind energy generation. They propose a portfolio optimization model designed to create an efficient wind energy portfolio for a specific harvesting region, with the objective of minimizing prediction errors.

Hydrogen storage has gained attention due to its potential to store large amounts of energy for extended periods. In a hydrogen-based storage system, excess electricity is used to produce hydrogen through electrolysis. The hydrogen can then be stored and converted back into electricity using fuel cells or combustion engines when needed. Hydrogen storage is particularly beneficial in regions with limited grid connectivity, such as islands, where long-term storage is essential. Shari et al. [24] examined the role of green hydrogen inside five Electricity Distribution Companies (DisCos) throughout three geographical zones in Nigeria: North West, North Central, and North East. A bottom-up optimization approach using linear programming and the open energy modeling framework (OEMOF) served as the modeling paradigm. The result indicated that a cohesive distributed strategy will improve the use of green hydrogen in Nigeria, namely in the distribution of energy among the Distribution Companies (DisCos). The research further disclosed the following findings. (1) The levelized cost of electricity may decrease by about 8%, so reducing investment costs; (2) access to electricity has improved relative to the base year; and (3) emissions in the power industry have been reduced. Developed a hydrogen energy storage system (HESS)-based power-to-gas (P2G) and gas-to-power systems using Simulink by collecting and organizing historical data and typical model characteristics. They studied the energy transfer mechanisms and numerical modeling methods of these systems in detail. The integrated HESS model comprises an alkaline electrolyzer

(AE), a high-pressure hydrogen storage tank with a compressor (CM & H₂ tank), and a proton-exchange membrane fuel cell (PEMFC) stack. Chamout et al. [25] highlighted the need for effective storage technologies due to the intermittency of renewable energy sources. They pointed out that hydrogen systems, including electrolyzers, storage tanks, and fuel cells, could serve as alternatives to batteries. However, the literature lacks information on the requirements of the hydrogen purification unit. Their research measured the purification unit's demand for a 4.5 kW PEM electrolyser at 0.8 kW for 10 minutes. Additionally, they presented a simulation of integrating the hydrogen system, including its purification unit, with lithium-ion batteries for energy storage, in which the batteries also support the electrolyser.

The global shift toward renewable-based energy generation has driven the development and application of various optimization models and software to assess the technical, environmental, and economic viability of different hybrid configurations [3]. In Nigeria, several studies have been conducted in different regions of the country using the Hybrid Optimization Model for Electric Renewable (HOMER) software to analyze standalone systems. These studies primarily focused on improving efficiency through hybrid renewable energy systems (RESs) while managing the challenges posed by fluctuations in renewable energy sources. Nyeche & Diemuodeke [10] introduced a clean, reliable, and affordable hybrid energy system that integrates solar and wind power with a hydro-based energy storage solution. The proposed system includes a photovoltaic array, wind turbine, and Pumped Hydro Energy Storage (PHES), with the goal of meeting the energy demands of the coastal community of Patani (Lat. 5.23° N, Long. 6.17° E).

Table 1 shows an overview of the literature reviews. It provides detail on modeling and optimization using various renewable energy sources and technique. Many studies focused on PV, WT, DG with battery energy storage, while a few included Biomass and Hydrogen energy storage. Nyeche & Diemuodeke [10] proposed a hybrid system that comprises PV, WT, and PHES for Patani LGA, in the same location as the current research. The result shows that the LCOE obtained was 0.27 \$/kW, and the LLP was estimated at 0.108, while the minimum storage capacity was 3.9 MWh. Also, no research considered the integration of PV, WT, and BM with battery and hydrogen energy storage at this proposed location. This proposed Hybrid RES therefore fills the gap by integrating the entire components PV-Wind-Biomass system, combined with Battery and Hydrogen (PV-WT-BM-BT & HD) to achieve a more flexible and reliable hybrid system that meets the energy demand of the Patani Island community. The LCOE and LLP obtained were compared with those reported in previous studies.

Table 1 Overview of the literature review.

Author	Resources	Technique	Conclusion
Suresh et al. (2020) [26]	BG, BM, PV, WT (fuel cell, battery)	HOMER	Compared to HOMER, GA based HRES is found to be the optimal solution supplying energy with 0% unmet load at the least cost of energy, which is at \$0.163 per kWh.
Diemuodeke et al. (2019) [6]	WT, PV, Battery, DG	HOMER and TOPSIS multi-criteria decision-making algorithm	The optimization result of 7.23 kWh/day of the HES is able to meet the energy demand of the household.
Qiu & Entchev (2024) [27]	Solar, Wind, BG, Battery	HOMER	The integrated energy systems are evidenced to be an effective option for electrification in remote communities.
Bakir et al. (2020) [28]	Solar, Wind	STATCOM, MATLAB Simulink	Integration of renewable energy sources can reduce power stability issues in large transmission systems and minimize fluctuations.
Nyeche & Diemuodeke (2020) [10]	Solar, Wind, pump hydro	HOMER, MATLAB	The proposed hybrid system model, connected to a mini-grid, has the potential to meet energy demand and reduce energy costs through efficiency improvements.
Li et al. (2023) [29]	Solar, Wind, Geothermal	Hysteresis band	Utilizing a hysteresis band enhances reliability and minimizes the cost of the system. NSGA-II software is used for system modeling.
Luta et al. (2017) [30]	Solar, Wind	System Modeling Language	The modeling approach focuses on capturing requirements and structural relationships between the different entities.

Patani Island is a coastline community located in Delta state Nigeria (5°13'43" N, 6°11'29" E). In this area, fossil fuel generators are mostly used for power generation, which adversely affects the cost and environmental impact. Therefore, an optimized renewable energy system is required, particularly for the Patani community, which relies on diesel for power generation. The objective of this study is to model and optimize integrated renewable energy conversion technologies for Patani Island to provide an alternative to diesel-based electricity generation. The optimization of this system can significantly minimize net present cost (NPC) and levelized cost of energy (LCOE), thereby making power generation affordable and reliable.

Therefore, this paper presents the modelling and optimization of integrated renewable energy conversion technologies that are based on sunlight, wind, and biomass with dual energy storage (battery and hydrogen) for Patani Island.

2. Materials and Methods

The proposed system integrates renewable energy conversion technologies with dual energy storage for an island application. The system utilizes three primary renewable energy sources: solar, wind, and biomass. It also features dual energy storage systems, including Battery and Hydrogen storage, along with an inverter and a power control system. Evaluating the energy generation potential of a hybrid PV-WT-BM-BT & HD for a sustainable and clean energy supply requires a thorough understanding, which can be achieved through analytical modelling. These models will assist in the techno-economic analysis and optimization of the proposed hybrid system [10, 26-28].

2.1 System Description

The components of the proposed hybrid plant are solar PV, wind turbine, biomass generator, battery, Hydrogen tank, electrolyser, controller, and inverter, as indicated in Figure 1. Wind turbines and biomass generators produce alternating current (AC) while solar PV produces direct current (DC), which is converted to alternating current (AC) with the help of an inverter before being transmitted to the power control system. This regulates the electrical communications among the subsystems. The excess energy generated by the RE system is stored in the battery and the hydrogen energy storage system. After charging the battery, the electrolyzer uses any excess energy from the RES to produce Hydrogen (H₂). In this case, if the power output from the RES is lower than the energy demand and the battery discharge is insufficient to cover the deficiency, the Biomass generator compensates for the deficiency by using the stored H₂ in the tank unit, in accordance with the specified criteria. When the combined output of batteries and H₂ is insufficient to meet the required load, a BMG gasifier is necessary to meet Patani's energy needs.

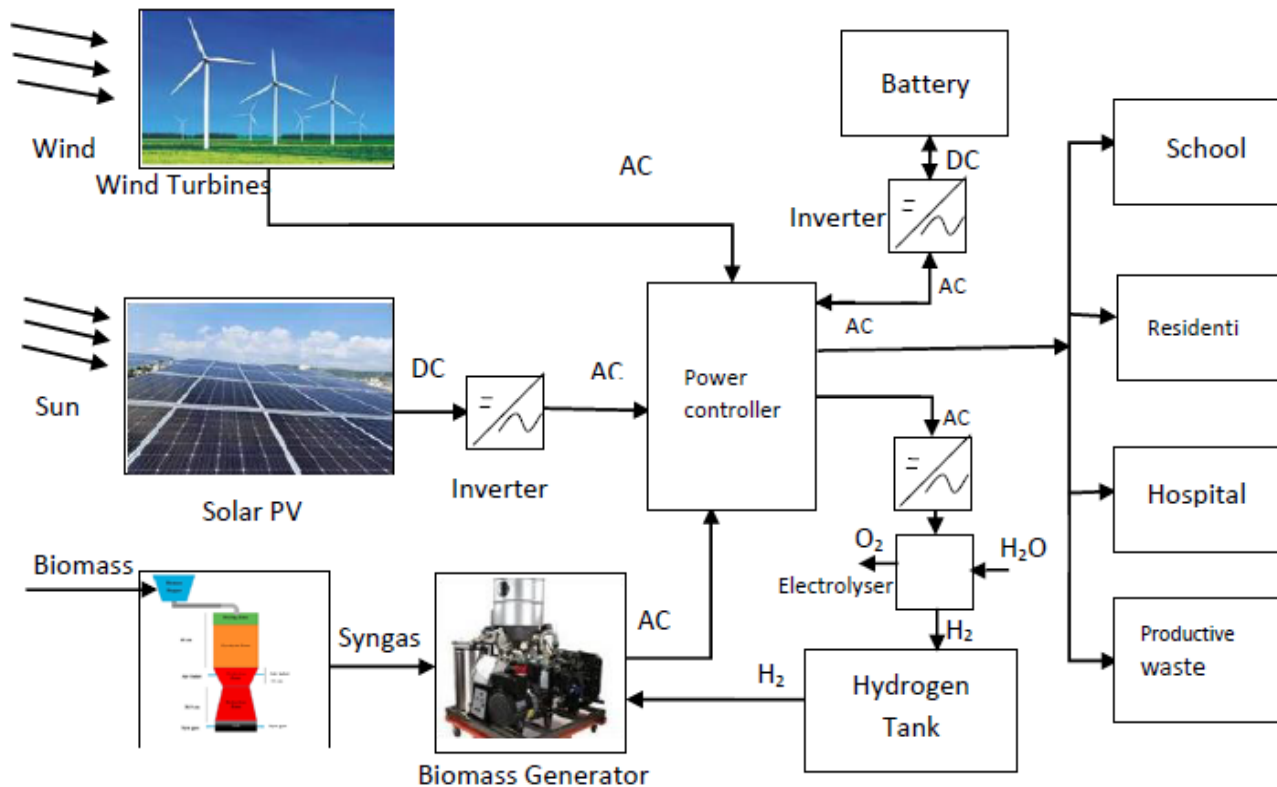


Figure 1 Schematic diagram of the Proposed Hybrid system.

2.1.1 Dispatch Strategy

HOMER Pro uses dispatch strategies to simulate system operation and minimize the economic cost of the system. This dispatch rule focused on meeting the energy demand, managing battery State of charge (SOC), and using excess energy for hydrogen production. Renewable energy (PV and WT) first generates electricity; the Syngass generator then supplies power in response to demand. HOMER is used to simulate the performance of the integrated energy system and optimise its configuration. It developed an algorithm for calculating hourly power balance performance for a predefined integrated RE system, subject to multi-objective criteria and constraints. It uses the load demand profile, energy resources, component specifications, and emission data as inputs to simulate various feasible configurations.

2.2 Energy Resource Assessment

The data profile, including annual solar irradiance, wind speed, and ambient temperature, was retrieved from both the National Aeronautics and Space Administration (NASA) website and the US National Renewable Energy Laboratory (NREL) database, both embedded in the HOMERPro Software®. The availability of solar irradiation and the average wind speed potential particulars of the study location were taken from the latitude and longitudes of the study area, 5.23° North latitude, 6.17° East longitude. The wind data were recorded for over a 10-year period and extrapolated to 50 m above the Earth's surface. HOMER Pro software was used to work out the daily solar irradiation, average wind speed, and optimal sizing of the system. The sources were selected in the hybrid system so that each can compensate for any production shortfall, especially when one source may not be producing enough energy at a given time.

2.3 Energy Demand Assessment

The selected location for the proposed system is Patani Island in Delta State, Nigeria. An hourly energy demand investigation of a given facility is vital for determining the optimal size of a hybrid system [31]. The determination of energy demand focused on the design of appropriate questionnaires, community visits, and brief interviews to assess the existing energy needs of the Patani communities under investigation.

The energy demand profile in this conceptual design study is grouped into four: Residential, Hospital, Schools, and Product waste. A total of 18500 households, 12 primary health centres, 26 public schools, and 6 waste management sites were estimated.

The facility load includes: fluorescent and incandescent lighting, portable stereo, CD player, television, radio, ironing board, air conditioning, refrigerator, ceiling fan, table fan, and other equipment.

The current energy demand estimate includes all electrical appliances in the groups mentioned above.

The average hourly electric load specification of an appliance per household in a day, E_{kj} (Wh/household/day), is known using [6]

$$E_{kj} = \frac{\sum_i^{N_H} P_{ij}^k}{N_H}; \quad j = 1, 2, 3, 4, \dots, 24 \quad (1)$$

where P (kW) is the power consumed by an appliance in a given hour; N_H is the number of households, primary health centres and public schools; k represents individual appliance; i is the current households, primary health centres, public schools and j is the hour of the day.

The average hourly energy demands per household per day, E_{kj} (Wh/household/day), is given as [6]

$$E_j = \sum_k^A E_{kj}; \quad j = 1, 2, \dots, 24 \quad (2)$$

where A is the total number of appliances.

The average daily energy requirement, E_{DER} (Wh/household/day), is given as [6]

$$E_{DER} = \sum_{j=1}^{24} E_j \quad (3)$$

Equations 1-3 are applicable to other groups' i.e., primary health centres and public schools and waste management site.

2.4 Modelling of System Components

Evaluating the energy production of the proposed hybrid PV-WT-BM-BT & HD plant requires comprehension of the interrelated subsystems. The sub-systems are modelled analytically in the following subsections. The models developed in this research were implemented in MATLAB to assess their practicality.

2.4.1 Solar PV Models

Solar photovoltaic technology is widely used to generate electricity from solar radiation. A photovoltaic panel consists of solar cells interconnected in series and parallel configurations to provide the necessary electricity. Each cell primarily functions as a p-n diode [26]. When sunlight impinges on a solar cell, the incoming energy is converted directly into electricity.

Solar radiation on a horizontal surface (G) is given as [32]

$$G = I_b \cos(\theta_z) + I_d \quad (4)$$

where G = Solar radiation on a horizontal surface (W/m^2), I_b = Beam or Direct solar radiation normal to the sun's rays (W/m^2), θ_z = solar zenith angle (angle between the sun's rays and the vertical), and I_d = Diffuse solar radiation on a horizontal surface (W/m^2).

The operating temperature, T_c (K) of a cell is given as [33].

$$T_c = T_{amb} + (0.03 \times G) \quad (5)$$

where T_{amb} (K) is the ambient temperature; G (W/m^2) is the irradiance or solar radiation.

The power output of the PV is expressed as [34]

$$P_{PV} = P_{rated} \times \left(\frac{G}{G_{ref}} \right) \times [1 + K_T(T_c - T_{ref})] \quad (6)$$

The DC power produced by the PV module is given as [35]

$$P_{PV} = \eta_{PV} \times N_{PV} \times A_{PV} \times G \quad (7)$$

Also, the power output from the PV panel is given as [36]

$$P_{PV}(t) = P_{rated} \times Y_{PV} \times \left(\frac{G}{G_{ref}} \right) \times [1 + K_T(T_c - T_{ref})] \quad (8)$$

$$P_{PV}(t) = P_{rated} \times Y_{PV} \times \eta_{PV} \times \eta_{INV} \times \left(\frac{G}{G_{ref}} \right) \quad (9)$$

where P_{PV} (kW) is the power yield of PV cell; P_{rated} (kW) is PV rated power at reference condition; G (W/m^2) is the solar irradiance; G_{ref} (W/m^2) is solar irradiance at standard temperature condition ($G_{ref} = 1000 \text{ W/m}^2$); T_{ref} ($^{\circ}\text{C}$) is cell temperature at reference conditions ($T_{ref} = 25^{\circ}\text{C}$); K_T (—) is the PV panel temperature coefficient. $K_T = (0.4-0.6)\%$ [35]. Y_{PV} (—) is the PV derating factor. In electronics, derating is the action of a device operating at less than its rated maximum capability to prolong its life.

The total number of modules that make up the PV panel can be estimated as:

$$N_{PV} = N_{PV_s} \times N_{PV_p} \quad (10)$$

where N_{PV_s} and N_{PV_p} are number of PV module in series and number of PV module in parallel, respectively, which can be computed by the knowledge of the bus and module voltage and current according to the methodology presented.

The annual energy output of the solar PV panel, E_{PV} (kWh), is determined as

$$E_{PV} = \sum_{t=1}^{8760} P_{PV}(t) \quad (11)$$

2.4.2 Wind Turbine Models

The volume of air entering and leaving a turbine remains constant owing to the conservation of mass in the air stream. Wind energy is transformed into mechanical power using an energy converter known as a wind turbine. The mechanical power is then transformed into electrical power via a generator. Modeling a wind energy conversion system requires knowledge of the mean wind velocity, its dispersion, and the wind power distribution for the specific region under investigation [24].

The average wind velocity at the study site is given in the equation below. The wind velocity discrepancy with height above the ground exhibits a logarithmic relation, known as a power law, given in [6, 37].

$$\frac{v}{v_o} = \left(\frac{h}{h_o}\right)^\alpha \quad (12)$$

where v (ms^{-1}) is the wind velocity at the hub altitude, h (m); v_o (ms^{-1}) is the wind velocity at the original altitude, h_o (m); and α (—) is the surface coarseness coefficient or the wind shear power law exponent, which is taken as 0.143.

The mean wind power density is given [6].

$$P_{Dn} = \frac{P(v)}{A} = \frac{1}{2} \rho v_m^3 \quad (13)$$

where P_{Dn} (MW/m^2) wind power density; $P(v)$ (MW) is the wind power; and A (m^2) is the rotor blades swept area, ρ (kg/m^3) is the air density $\rho = 1.225$ (kg/m^3), v_m^3 (m/s) is the mean wind velocity.

The mean wind speed can be related to the hub height according to [38].

$$v_m(t) = c_h \Gamma(1 + 1/k_h) \quad (14)$$

where c_h (—) and k_h m/s are the hub height dependent shape factor and scale factor, respectively.

The wind turbine power output is given as:

$$P_{wt}(t) = P_D(t) \times C_p \quad (15)$$

where C_p (—) and is the mechanical efficiency of the wind turbine.

The total number of wind turbines required to satisfy the facility load can be estimated as

$$N_{wt} = \frac{P_{wt}}{P_{rated}} \quad (16)$$

where P_{rated} (kW) is the rated power of a selected wind turbine.

The annual energy output of the wind turbine, E_{wt} (kWh), is determined as

$$E_{wt} = \sum_{t=1}^{8760} A_{ts} x P_{wt}(t) \quad (17)$$

where the turbine swept area A_{ts} (m^2) can be estimated as

$$A_{ts} = \frac{\pi}{4} D^2 WTB \quad (18)$$

Mean energy density E_{Dn} is expressed as:

$$E_{Dn} = \frac{1}{2} \rho c^3 \Gamma \left(1 + \frac{3}{k} \right) T \quad (19)$$

The average power output $P_{e, ave}$ (kW), E_{WT} (kWh), and capacity factor C_f (–) of a WT are calculated using:

$$P_{e,ave} = \begin{cases} 0, & v_m(t) < v_c \\ a \cdot v_m^3(t) - b \cdot P_{eR}, & v_c \leq v_m(t) < v_r \\ P_{eR}, & v_r \leq v_m(t) \leq v_f \\ 0, & v_m(t) > v_f \end{cases} \quad (20)$$

But 'a' and 'b' are known using:

$$a = \frac{P_{eR}}{(v_r^3 - v_c^3)}; \quad b = \frac{v_c^3}{(v_r^3 - v_c^3)}; \quad (21)$$

$$E_{WT}(t) = P_{e,ave} \Delta t \quad (22)$$

$$C_f = \frac{P_{e,ave}}{P_{eR}} \quad (23)$$

where ρ (kg/m^3) is the air density ($\rho = 1.225 \text{ kg/m}^3$); A_{WT} (m^2) is the turbine rotor swept area; $v_m(t)$ (m/s) is wind velocity; η_{WT} (–) is the wind turbine efficiency; v_c (m/s) is the cut-in velocity; v_r (m/s) is the rated wind velocity; v_f (m/s) is the furling speed, and Δt is the time interval (i.e., 24×365 hours).

2.4.3 Biomass System Models

The theoretical evaluation examines the maximum potential biomass resources for energy generation, excluding quantities necessary for food or industrial applications, and accounts for the specific region, cultivation area, and net biomass yield, which is determined by factors such as climate conditions, soil characteristics, and biomass properties [39].

The yearly biomass energy obtainable from agricultural and forestry left overs is

$$E_{Th} = \sum_i^n F_j \times LHV: j = (crop, forest) \quad (24)$$

where E_{Th} is the theoretical energy potential, LHV is the low heating value or mean energy content (E_c) [KJ/kg], and F_j is the residue potential or obtainable residue [ktonnes].

$$F_{crop} = \sum_i^n P \times RPR \quad (25)$$

where P is crop production [ktonnes], and RPR is the mean residue-to-product ratio.

The mass forest product volume (m^3) is expressed as above for the forest residue.

$$mF = \rho \times V \quad (26)$$

where mF is the mass of the forest product, ρ is the density of the forest product, and V is the volume of the forest product.

The forest residue can be obtained

$$F_{forest} = mF \times RPR \quad (27)$$

where F_{forest} is the forest residue, and RPR is the residue-to-product ratio, which can be assumed to be 0.72 [40].

2.4.4 Technical Assessment

The proportion of the theoretical energy potential that may be efficiently harnessed for energy use is referred to as the technical assessment. The technical potential is contingent on the theoretical annual residual potential. Consequently, an availability factor (AF) is deemed to represent the quantity of residue that may be used for energy production annually. The AF range is 0–1 and varies according to location and crop residue, as shown by [40, 41]. The technological potential has been calculated.

$$E_{tec} = \sum_i^n E_{Th} \times A_F = (crop, forest) \quad (28)$$

where E_{tec} is the technical potential, and A_F is an availability factor that ranges from 0 to 1.

Availability factors (AF) of 0.4, 0.5-0.75, and 0.8 were estimated for rice residue, wood residue, and oil-palm residues, respectively [39]. According to [41] factor of 0.30 was applied to the other crops, since all agro-crops exhibit a comparable availability factor (AF) range, as reported by [39, 42]. Furthermore, all forest residues in Nigeria were allocated an AF of 0.6, consistent with [39].

2.4.5 Battery Energy Storage Models

In Renewable energy systems, the incorporation of batteries increases system reliability [43]. The batteries serve as an energy storage medium, store surplus renewable energy, and supply energy

during capacity shortages. Then, the energy stored in the battery bank at a specified time can be expressed according to [28, 44]

$$E_{BT}(t) = E_{BT}(t - 1) + E_{EE}(t) \times \eta_{CCE} \times \eta_{CH} \quad (29)$$

where $E_{EE}(t)$ is the extra energy available from all the systems, η_{CCE} is the charging controller efficiency, and η_{CH} is the battery charging efficiency.

The quantity/state of charging the battery is expressed by the given Eq. (30):

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (30)$$

where SOC_{min} is the value of minimum SOC; and SOC_{max} as the maximum value of SOC assumed as 1. Minimum value of SOC is obtained using the following Eq. (31),

$$SOC_{min} = 1 - DOD \quad (31)$$

where DOD is the depth of discharge.

2.4.6 Hydrogen Energy Storage Models

Electrolyser/Hydrogen: An electrolyser operates via electrolysis, wherein an electric current traverses between two electrodes in water, resulting in the decomposition of water into hydrogen and oxygen. After charging the battery, the electrolyzer uses any excess energy from the RES to produce Hydrogen (H_2).

The power transferred from the electrolyser to the hydrogen storage tank has been estimated by [45].

$$P_{ET} = P_{ET} \times \eta_E \quad (32)$$

where, η_E is the electrolyser efficiency assumed as constant.

The output energy stored by the hydrogen tank is expressed by;

$$E_{H2,T}(t) = E_{H2,T}(t - 1) + \left[P_{ET}(t) - \left(\frac{P_{T-SG}(t)}{\eta_{storage}} \right) \times \Delta t \right] \quad (33)$$

where, P_{T-SG} is the output power of a syngas generator, $\eta_{storage}$ is the efficiency of hydrogen storage, approximately 95% for all operating conditions [23].

The mass of hydrogen storage is calculated using

$$M_T(t) = \frac{E_T(t)}{HHV_{H2}} \quad (34)$$

where, HHV_{H2} is the hydrogen storage higher-heating value considered as 38.9 kWh/kg [46].

2.4.7 Power Models of the Hybrid System

To ensure that the proposed hybrid plant functions accurately and efficiently to meet the energy demand, it is designed and controlled to maintain a balanced energy flow. The plant operates such

that at any given time (t), the power generated (PW_G) from the combined renewable energy sources (RES) and the power from the Hybrid Energy Storage (HES) ($PW_{BT\&HD}$) must satisfy the power demand (PW_D) [10].

Mathematically,

$$PW_G(t) = PW_{PV}(t) + PW_{WT}(t) + PW_{BM}(t) \quad (35)$$

$$PW_D(t) = PW_G(t) \pm PW_{BT\&HD}(t) \quad (36)$$

where $PW_{PV}(t)$, $PW_{WT}(t) + PW_{BM}(t)$ and $PW_{BT\&HD}(t)$ (MW) are the power generated by the photovoltaic system, wind turbine, biomass, battery and hydrogen, respectively.

Note:

1. If $PW_D(t) > PW_G(t)$, the supplementary power from the battery and hydrogen, $PW_{BT\&HD}(t) > 0$ (or $PW_{BT\&HD}(t)$ is $+ve$), compensates for the shortfall in the power produced from the RES.
2. If $PW_D(t) = PW_G(t)$, $PW_{BT\&HD}(t) = 0$; that is, the power produced from RES is enough for the power demanded.
3. If $PW_D(t) < PW_G(t)$, the power from the HESS $PW_{BT\&HD}(t) < 0$; (or $PW_{BT\&HD}(t)$ is $-ve$), i.e. the surplus power generated is stored or enthralled by the HESS.

2.5 Optimisation Model of the Hybrid Plant

A genetic algorithm is used to develop the optimization model. The optimization of the hybrid PV-WT-BM-BT & HD system is modelled by minimizing the disparity between produced and needed energy to precisely design the hybrid plant configuration [10].

Excess energy generated by the RE system is given as:

$$E_{excess} = \text{Max}[(E_{RE} - E_D), 0], \text{ if } E_{RE} > E_D \quad (37)$$

where E_D (kWh) is energy demanded (load facility).

Energy shortage from RES is given as:

$$E_{shortage} = \text{Max}[(E_D - E_{RE}), 0], \text{ if } E_{RE} < E_D \quad (38)$$

The difference between the excess energy generated and the energy shortage from the RES for one year is given as:

$$E_{diff} = \sum_{i=1}^{365} (E_{excess,i} - E_{shortage,i}) \quad (39)$$

Storage capacity for BT & HD to be minimised daily.

The loss-of-load probability indicates the plant's availability. It is given as:

$$LLP = \frac{\sum_{i=1}^{365} (E_{shortage})}{\sum_{i=1}^{365} (E_d)} \quad (40)$$

The LLP ranges from 0 to 1.

2.5.1 Bound Constraint

The constraints of upper and lower bounds of solar, wind, and battery systems are expressed as [26]

$$0 \leq N_{WTB} \leq N^{max}WT \quad (41)$$

$$0 \leq N_{PV} \leq N^{max}PV \quad (42)$$

$$0 \leq N_{BMG} \leq N^{max}BMG \quad (43)$$

$$0 \leq N_{BT} \leq N^{max}BT \quad (44)$$

$$0 \leq N_{ELE} \leq N^{max}ELE \quad (45)$$

$$0 \leq N_{HT} \leq N^{max}HT \quad (46)$$

where $N^{max}WT$ is the maximum number of wind turbines, $N^{max}PV$ is the maximum number of PV modules and $N^{max}BT$ is the maximum number of batteries. $N^{max}BMG$ is the maximum number of the BMG, and $N^{max}HT$ is the maximum number of Hydrogen tanks.

2.5.2 Battery Storage Constraint

The capacity of a battery bank at any hour “t” lies between the minimum and maximum capacity. Then the constraint is expressed as [46]

$$E_{BT.min} \leq E_{BT}(t) \leq E_{BT.max} \quad (47)$$

2.6 System Optimisation with Genetic Algorithm (GA)

The optimization model is executed using MATLAB’s Genetic Algorithm (GA) tool, which is particularly effective for multi-model and multi-objective optimization challenges, such as power and economic considerations [47]. The Genetic Algorithm (GA) technique, grounded on the theories of genetics and natural selection, has six fundamental stages as shown in Figure 2A [10]. The GA technique starts with the creation of a population (representations of solution vectors) capable of reproduction; the offspring from this population undergo the principle of survival of the fittest. The surviving children are generated via crossover and occasional random mutations, followed by the stopping criteria, encoding, and the fitness function.

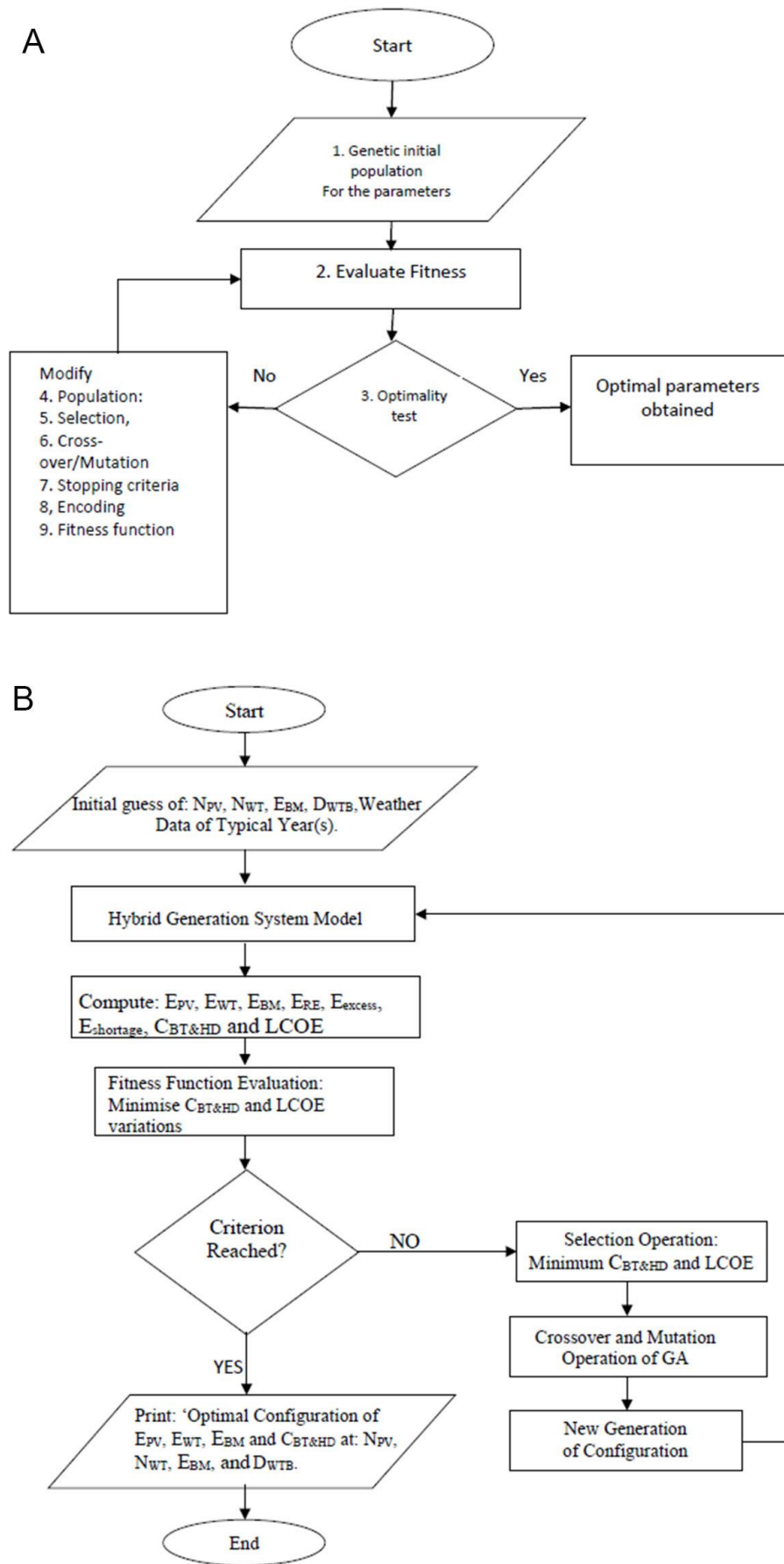


Figure 2 (A) GA Procedure; (B) Flowchart of the GA with optimisation Procedure.

Selection of healthy offspring for the subsequent generation. This procedure is repeated until the optimality requirement is satisfied; interested readers can refer to [10] for more information. Figure 2B illustrates the overarching algorithm (flowchart) of the optimization technique, which integrates the GA methodology.

The decision variables in the optimisation process are: Number of PV panels N_{PV} ; Diameter of wind turbine blade D_{WTB} ; Number of wind turbines N_{WT} ; Biomass generation size (BM) and Battery and hydrogen storage capacity $C_{BT\&HD}$.

2.7 Economic Assessment

The total life cycle costs (LCC) are the addition of all recurring and one-time (non-recurring) costs over the full span or a stated period of goods, services, structures, or systems. The costs of stand-alone hybrid PV-WT-BM-BT & HD system include: construction cost, which includes the installation cost of the individual energy converter, replacement cost, and operation & maintenance cost (O&M). Replacement cost is measured as depreciation cost, which is 10% of the construction cost [10].

The total life cycle costs (LCC_T) for the hybrid PV-WT-BM-BT & HD system is estimated as [48]:

$$LCC_T = \sum_{j=1}^5 LCC_j; \quad j = \{1, 2, 3, 4, 5\} \equiv \{PV, WT, BM, BT \& HD\} \quad (48)$$

$$LCC_j = \sum_{q=1}^3 C_q; \quad q = \{1, 2, 3\} \equiv \{CC, O\&M, RC\} \quad (49)$$

where LCC_j (\$) is the life cycle cost of different parts; C_q (\$) is the present value of different cost components; and the indices PV, WT, BM, BT, HD, INV, PS, CC, O&M and RC refer to PV panel, Wind Turbine farm, Biomass, Battery, Hydrogen, Inverter, Power Station, Construction Cost, Operation & Maintenance and Replacement Cost respectively.

Annual interest rate converts one-time costs into annualised costs [10]

$$j = \frac{j' - f}{1 + f} \quad (50)$$

where j' is nominal interest rate, and f is inflation rate.

The total replacement cost (RC) of main component is given as

$$RC = \sum_j^N [C_{rep_j} \times f_{rep_j} \times SFF_j - S_j \times SFF] \quad (51)$$

where f_{rep_i} is a factor due to components' lifetime and project's lifetime; SFF is the reducing fund factors; S is the selvalue value.

$$f_{rep_j} = \frac{CRF}{CRF_j} \quad (52)$$

$$SFF = \frac{i}{(1+i)^{N-1}} \quad (53)$$

$$S_j = C_{repj} \times \frac{L_{rem}}{L_{comp}} \quad (54)$$

where L_{rem} is the residual life of components; L_{comp} is total life of components and C_{rep} is the RC factor.

The ALCC of hybrid is given as

$$ALCC = LCC_T \times CRF \quad (55)$$

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (56)$$

where CRF is Capital recovery factor; N is lifetime of project.

The unit electrical cost, UEC (\$/kWh) is given as:

$$UEC = \frac{ALCC}{366E_D} \quad (57)$$

The LCOE for a system having energy generated constant over time is expressed as

$$LCOE = \frac{LCC_T}{E_{RE}} \times UCRF \quad (58)$$

$$UCRF = \frac{d(1+d)^N}{(1+d)^N - 1} \quad (59)$$

where E_{RE} (kWh) is the energy generated by RES; $UCRF$ (—) is the unchanging capital recovery factor; $N = 25$ years.

2.8 Analysis of the Proposed Hybrid Plant

The suggested hybrid PV-WT-BM energy system, including BT & HD energy storage, was constructed and analyzed using the created models in Microsoft Excel, MATLAB, and HOMER software. Microsoft Excel was used to assess the energy consumption in Patani. A template was created, and the cells were programmed to perform the necessary function. In the template, the following input variable data are required: load description, quantity in use, power rating and number of hours in use. With all these specified, the template estimates total energy consumed in kWh/day, which shows the estimation of energy demand in Patani.

An energy evaluation and optimization of the hybrid PV-WT-BM energy system, including BT & HD energy storage facilities, was performed using MATLAB. Consequently, a MATLAB-based software tool was developed to perform this task. The application does energy analysis and optimizes the system when provided with the following input data: solar radiation, wind speed, energy demand, wind turbine specifications, photovoltaic module specifications, battery specifications, and hydrogen specifications. The MATLAB optimization tool was used to optimize the storage system's size to minimize the disparity between energy demand and energy produced by

the hybrid plant. Additionally, this is executed by delineating the goal function, the genetic algorithm methodology, and the constraints of the decision variables.

Economic assessment was executed utilising HOMER software. Additional energy storage plants with BT & HD were included in the HOMER model of the hybrid PV-WT-BM system. Data on solar radiation, wind speeds, energy demand, wind turbine specifications, PV module specifications, BT & HD requirements, and economic parameters were entered into the economic analysis.

3. Results and Discussion

The main objective of the study is to model and optimize the size and the economic cost of the integrated renewable energy system for satisfying the energy demand of the Patani community, Delta State, Nigeria. The proposed system configuration is simulated with the help of Homer and the Genetic algorithm (GA).

An hourly duration was adopted for the operational simulation to capture the variability of the renewable energy resources and load demand accurately. This operational performance is simulated for one year, considering the weather and load data (solar irradiance, wind speed, and temperature) to account for seasonal fluctuation. The project lifespan is 25 years, while the economic specification is at 9% inflation rate, 9.5% interest rate, and 10% import tariff. The results obtained based on the modelled systems are displayed and discussed here, from evaluating the power generated from the RES, ESS, the hybrid plant, energy demand assessments, economic assessments, optimal sizing, simulations and finally sensitivity of hybrid PV-Wind-Biomass, Battery and Hydrogen Plant was also conducted.

3.1 Input Data

3.1.1 System Specifications

Table 2 shows the input data (specifications) for wind turbine design, PV module design, Biomass design, Battery and Hydrogen respectively.

Table 2 Input data for RETs components.

Parameter	Unit	Value
Wind turbine input data [10] HOMER pro software		
Hub height	m	82
Rated wind speed	m/s	13
Cut-in speed	m/s	3.5
Furling speed	m/s	32
Total capacity	MW	1.65
Count (No of turbines)		11
Rotor diameter	m	80
PV module data for Peimar SG310MBF Module (flat plate) [10]		
Rated Capacity	kW	1
Panel temperature Coefficient	%	0.5
Derating factor	–	0.85
Inverter efficiency	–	0.95
Module efficiency	–	0.18
Power conditioning efficiency	–	0.95
Biomass System input data [49]; Homer Pro Microgrid Analysis Tool [B]		
Biomass gasifier calorific value	kcal/kg	4015
Rated power	MW	10
System conversion efficiency	–	0.7
Operating hours	Hrs/day	8
Battery storage system (Lithium ion) input data [49]		
Depth of Discharge	–	0.8
Charging controller efficiency	–	0.95
Battery charging efficiency	–	0.95
Single battery capacity	kWh	2600
Hydrogen tank storage input data [49]		
Electrolyser efficiency	–	0.6
Hydrogen storage efficiency	–	0.95
Higher heating value of hydrogen	kWh/kg	38.9

3.1.2 Resource Assessment Data

The annual average meteorological data, including solar irradiance, wind speed and ambient temperature are presented in Table 3, which are in agreement with data presented in [6]. The solar irradiance is highest in the months of January and March due to less rainfall occurring during these months. The highest wind speeds are observed between July and August, likely due to the intense rainy season. The solar resource evaluation was conducted using solar data.” Also, Ambient temperature was highest between March and May.

Table 3 Meteorological data.

Month	Irradiation (kWh/m ² /day)	Wind speed (m/s)	Temperature (°C)
January	4.998	4.425	25.210
February	4.907	4.770	26.410
March	5.023	4.395	26.850
April	4.813	3.870	26.740
May	4.460	3.570	26.380
June	4.236	4.425	25.460
July	3.483	5.100	24.650
August	3.868	5.280	24.580
September	4.274	4.710	24.900
October	4.561	3.855	25.440
November	4.952	3.615	26.020
December	4.899	3.960	25.430

Table 3 shows that the highest annual daily solar irradiation available within the Patani community is 5.023 kWh/m²/day, which occurs in the month of March while the lowest 3.483 kWh/m²/day was found in the month of July.

The highest annual daily wind speed available within the Patani community is 5.280 m/s, which occurs in the month of August while the lowest 3.615 m/s was found in the month of November. The highest ambient temperature is 26.850°C and the lowest is 24.460°C in the months of March and June, respectively.

3.1.3 Energy Demand Assessments

The hourly energy demand profile is obtained using Eqns. 1-3 with the consideration of the appliances and the power rating as shown in Table 4. The selected location for the proposed system is Patani Island, Delta State, Nigeria. The sample community has an average daily energy demand of 121 MWh/day, which is approximately (43623 MWh/year).

Table 4 Power rating of appliances.

Appliances	Power Rating (kW)
Fluorescent Light	0.023
Incandescent Light	0.100
Portable Stereo	0.020
CD Player	0.035
Television	0.150
Radio	0.010
Pressing Iron	1.000
Refrigerator	0.600
Ceiling Fan	0.040
Table Fan	0.020
Air Conditioner	1.000

Source: Ref. [10].

Figure 3 illustrates the hourly energy demand profile in Patani. Table 4 shows the Power rating of appliances. Between 1 and 5 AM, energy consumption was minimal and consistent due to individuals being asleep. Between 6 and 8 AM, energy consumption surged as individuals awakened and prepared for their daily tasks. Energy demand reaches its minimum around 10 AM due to individuals being at their respective workplaces. Approximately 65% of the population of Patani is employed outside the region. Between 12 PM and 6 PM, energy consumption increased consistently as individuals occupied their desks and more appliances were activated. Energy demand peaks around 20:00 hours when individuals return from work, resulting in 95% of appliances in residential households, healthcare facilities, and educational institutions being operational. Subsequently, energy consumption begins to decline as individuals retire for the night.

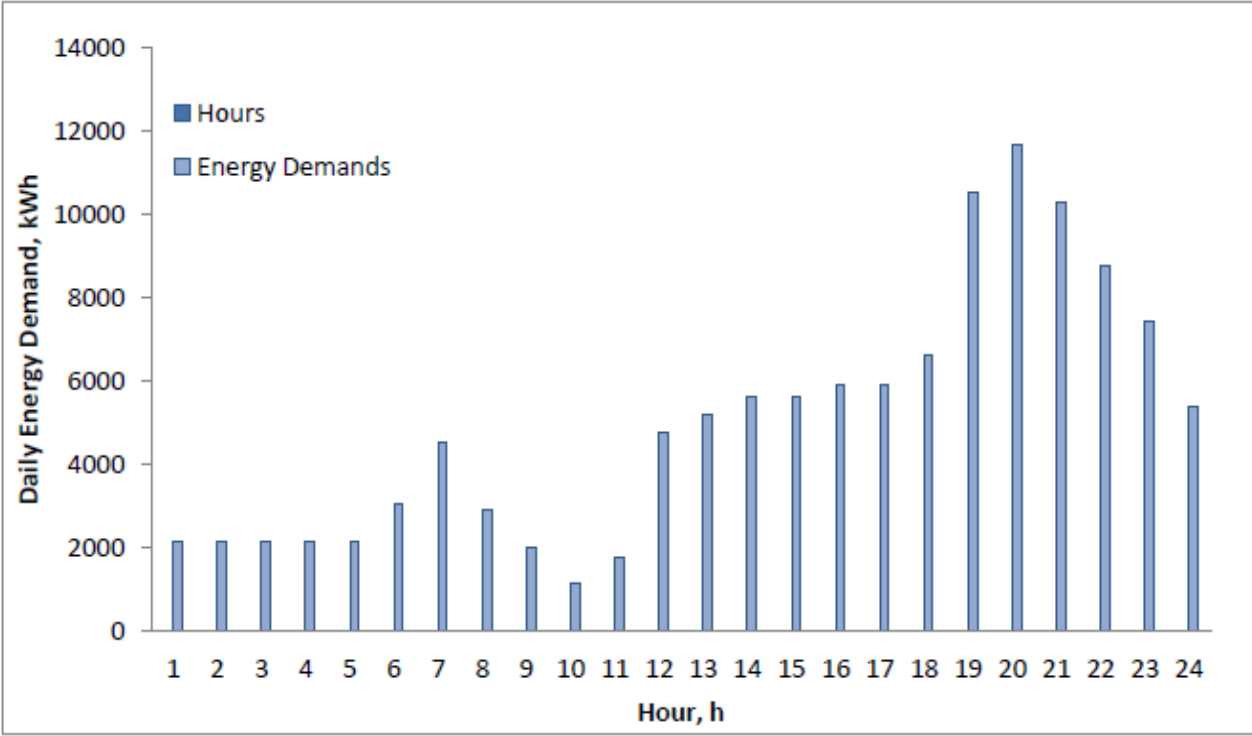


Figure 3 Hourly Energy Demand Profile in Patani.

3.1.4 Economic Specifications and Analysis

Table 5 displays the economic specifications of the system components, including the construction cost of various subsystems (capital cost), the operation and maintenance costs (O&MC) of each subsystem, and the replacement cost (RC) of each subsystem, as shown in Table 5. The project's duration is 25 years. The economic specification indicates a 9% inflation rate and a 9.5% interest rate [6]. A 10% import duty was imposed on the building cost of components not manufactured in Nigeria.

Table 5 Technical and economic specifications.

Description (\$/kW)	Specifications								
	PV module	Wind turbine	Biomass	Inverter	Battery \$/kWh	Hydrogen tank \$/kWh	Power station \$	Fuel cell	Electrolyser
Construction	3518.60	4197.42	2727	301.25	139	13	602.50	216	1500
Operation/Maintenance	70.37	209.87	54.54	100.42	2.78	0.26	12.05	4.32	30
Replacement costs	3518.60	4197.42	2727	301.25	139	13	602.50	216	1500
Lifetime (years)	25	20	25	15	5	20	25	10	10

3.2 Output Data

3.2.1 Optimisation Result of the Hybrid Plant

Table 6 shows the optimal results of the hybrid plant. The results show that to satisfy the energy needs of Patani, 0.218 MW peak rated power of PV, 236 MW rated power of wind turbine, and 0.100 MW rated power of Biomass systems are required. The number of PV modules needed is 15619; the number of wind turbines needed is 11, while the biomass solid waste is 4794240 kg. Furthermore, the minimised storage capacity of the Battery and Hydrogen is 69.19 MWh each.

Table 6 Optimal result of the hybrid plant.

Parameter	Symbol	Unit	Value
PV rated power	P_{rated}	MW _P	0.218
WT rated power	P_{rated}	MW	236.0
BM rated power	BM_{rated}	MW	0.100
Number of PV	N_{PV}	-	15619
Number of WT	N_{WT}	-	11
Diameter of WT	D_{WTB}	m	54.88
Number of Batteries	N_{BT}	m	17.27
Hydrogen tank capacity	C_{HT}	kg	1778.78
Minimum Battery Storage Capacity	C_{BT}	MWh	69.19
Minimised hydrogen tank storage	C_{HD}	MWh	69.19
Annual energy generated by WT	E_{WT}	MWh	5264.02
Annual energy generated by PV	E_{PV}	MWh	22691.52
Annual energy generated by BM	E_{BM}	MWh	15667.69
Total energy generated by RES	E_{RES}	MWh	43623.23
Loss of Load Probability	LLP	-	0.11
Levelized cost of energy	LCOE	\$/kWh	0.321

Figure 4 shows the various energy contributions in the hybrid system, with excess energy generation and energy shortage. The LLP is 0.11 ($LLP < 1$), which agrees with [10]. This implies that approximately 89% of Patani's energy demand can be met, with an 11% chance that the system will not meet demand. Also, the energy shortage in the hybrid plant is minimal. Therefore, the hybrid PV-Wind-and biomass energy system with battery and a hydrogen energy storage plant can satisfy the energy needs in Patani.

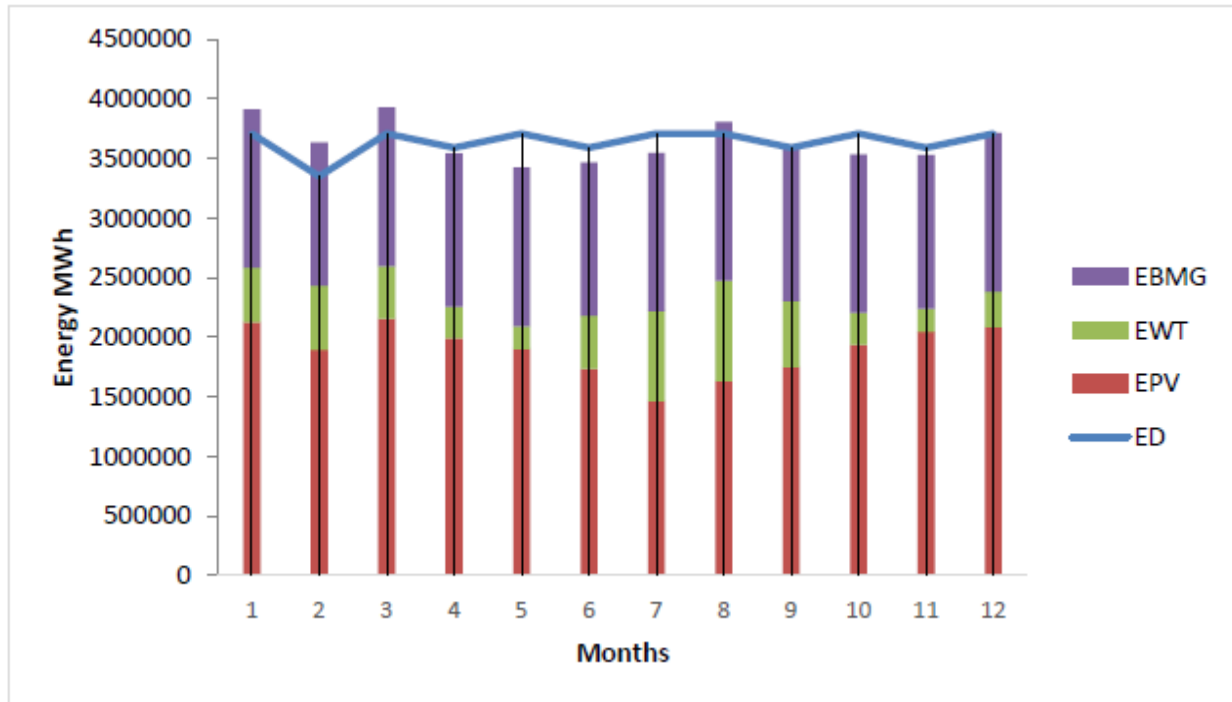


Figure 4 Energy contribution.

3.2.2 Energy Analysis of the Hybrid Plant

Table 7 presents the monthly energy generated by the hybrid renewable energy conversion system. The total energy generated is the combination of the energy generated by the PV-Wind and Biomass Renewable energy systems. The excess energy generated is stored in the Battery and the hydrogen energy storage system. The proposed community (Patani Island) has an average daily energy demand of 121 MW/day, approximately 43623.23 MWh/year, while the total energy generated by integrated renewable energy is 43662.84 MWh/year. Energy generated by the wind turbine is 5264.02 MWh/year, energy generated by the PV module is 22691.523 MWh/year, and energy produced by Biomass is 15667.688 MWh/year, which account for 22%, 52%, and 36%, respectively. From the above results, the PV module RES is the primary energy source in the entire energy system. Furthermore, the energy difference between excess and demand is 39.619 MWh/year. Thus, the hybrid PV-WT-BM-BT & HD plant can satisfy the energy needs of Patani.

Table 7 Monthly energy generated by the hybrid plant.

Month	Energy Generated by PV (MWh)	Energy Generated by WT (MWh)	Energy Generated by BM (MWh)	Total Energy Generated (MWh)	Demand (MWh)	State of Charge (SOC)	Mass of Hydrogen (kg)
January	2123.48	457.52	1330.68	3911.69	3708.35	1	1778.8
February	1892.97	540.60	1201.90	3635.48	3349.47	1	1778.8
March	2151.38	446.24	1330.68	3928.31	3708.35	1	1778.8
April	1991.37	263.93	1287.75	3543.06	3588.72	0.65	1161.0
May	1899.47	1924.58	1330.68	3422.61	3708.35	0.2	0.0
June	1735.75	442.76	1287.75	3466.27	3588.72	0.2	0.0
July	1462.22	753.91	1330.68	3546.82	3708.35	0.2	0.0
August	1627.12	847.62	1330.68	3805.43	3708.35	0.83	748.8
September	1746.96	554.00	1287.75	3588.72	3588.72	0.83	748.8
October	1934.85	268.41	1330.68	3533.94	3708.35	0.2	0
November	2043.49	197.11	1287.75	3528.36	3588.72	0.2	0
December	2082.39	299.39	1330.68	3712.47	3708.35	0.23	31.8
				43662.84	43623.23		

3.2.3 Economics Data of the Hybrid Plant

Table 8 presents the economic data of the hybrid plant. The levelized Cost of Energy (LCOE) was obtained as 0.321 \$/kWh, which is within the range of LCOE reported for renewable energy technology by IRENA [50] and is well below 0.95 \$/kWh for a diesel-powered electricity generator [10]. However, the obtained LCOE is well above the national grid electricity cost, averaging 0.19 \$/kWh, without accounting for grid extension costs and an end-to-end grid electricity cost analysis. The implication is that the combined effect of government action and an appropriate finance mechanism will guarantee the general acceptance of the proposed system.

Table 8 Economics data of the hybrid plant.

Description	Symbol	Unit(million)	Value (\$)
Life cycle cost of a photovoltaic module	(LCC _{PV})	\$	108.05
Life cycle cost of a wind turbine	(LCC _{WT})	\$	200488.54
Life Cycle Cost of Biomass	(LCC _{BM})	\$	28767.41
Life cycle cost of Battery storage	(LCC _{BT})	\$	237526.98
Life cycle cost of Hydrogen storage	(LCC _{HD})	\$	2247.72
Life cycle cost of a fuel cell	(LCC _{FC})	\$	59756.96
Life cycle cost of electrolyser	(LCC _{EL})	\$	414978.90
Life cycle cost of the inverter	(LCC _{IN})	\$	47604.49
Life cycle cost of control Station	(LCC _{CT})	\$	1.18
Total life cycle cost	(LCC _T)	\$	1099424.94
Annualise the life cycle cost	(ALCC _A)	(\$/year)	46647.47

According to IRENA [50], the LCOE for RES ranges from (0.1-0.460 \$/kWh). The LCOE for stand-alone PV, WT, and biomass, as reported by IRENA, are \$0.460/kWh, \$0.203/kWh, and \$0.084/kWh, respectively. The LCOE obtained in this dissertation (\$0.321/kWh) is within the range of LCOE for RES reported by IRENA. In light of this, the combination of PV, WT, and Biomass plant is responsible for the low LCOE obtained in this dissertation.

3.2.4 Comparison with Other Studies

From Table 9, the LCOE for the present investigation is \$0.321/kWh while the LCOE for previous studies, Nyeche & Dieduodeke [10], Bade & Tomomewo [51] and Modu et al. [52] are 0.27, 0.48 and 1.076 respectively. The results were compared, and the present study was found to be more cost-effective than previous investigations.

Table 9 LCOE and LLP Comparison with other studies.

Reference	System	LCOE (\$/kWh)	LLP (%)
Nyeche & Diemuodeke [10]	PV, WT, PHES	0.27	0.108
Bade & Tomomewo [51]	PV, WT, BM, Battery, and Hydrogen	0.48	0.8
Modu et al. [52]	PV, WT, BM, Battery, and Hydrogen	1.076	0.08
Present study	PV, WT, BM, Battery, and Hydrogen	0.321	0.11

Secondly, the loss of load probability for the present study was determined to be 0.11, whereas the loss of load probability obtained by Nyeche & Diemuodeke [10], Bade & Tomomewo [51], and Modu et al. [52] are 0.108, 0.08, and 0.08, respectively. In light of this, the current investigation is reliable and capable of meeting Patani's energy requirements.

3.2.5 Parametric Analysis

The hybrid plant was analysed with respect to key parameters influencing its operating conditions and economic outlook.

A simulation of the energy equilibrium of the hybrid plant and energy demand in Patani is depicted in Figure 5. It was observed that the RE system generated excess energy from January to March and from August to September, estimated at 138 MW, which is stored in the Battery and Hydrogen Energy storage systems. This stored energy is released to complement the energy deficit when the RE system cannot meet the energy needs. With the optimised storage capacity of the Battery and Hydrogen Energy storage system, the energy discrepancy between excess energy generated and energy shortages in the hybrid plant, thereby satisfying the energy needs in Patani, is minimised.

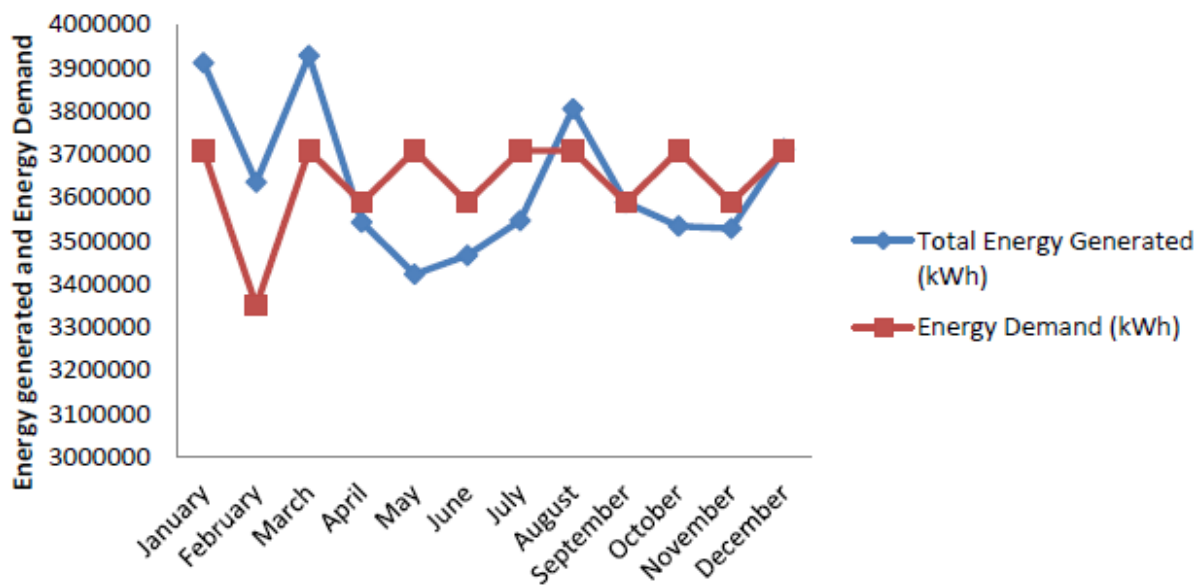


Figure 5 Monthly energy balance of the hybrid plant in Patani.

The effect of the diameter of the turbine blade on the energy generated by the WT is illustrated in Figure 6. A turbine blade of 60 m produces 12000 MW of energy, while an 80 m turbine blade generates 18000 MW of energy. It shows that an increase in turbine blade diameter results in an increase in swept volume, thereby increasing the energy generated by the wind turbine. Consequently, this results in an increase in the hybrid plant's energy output, as it adds energy from renewable resources.

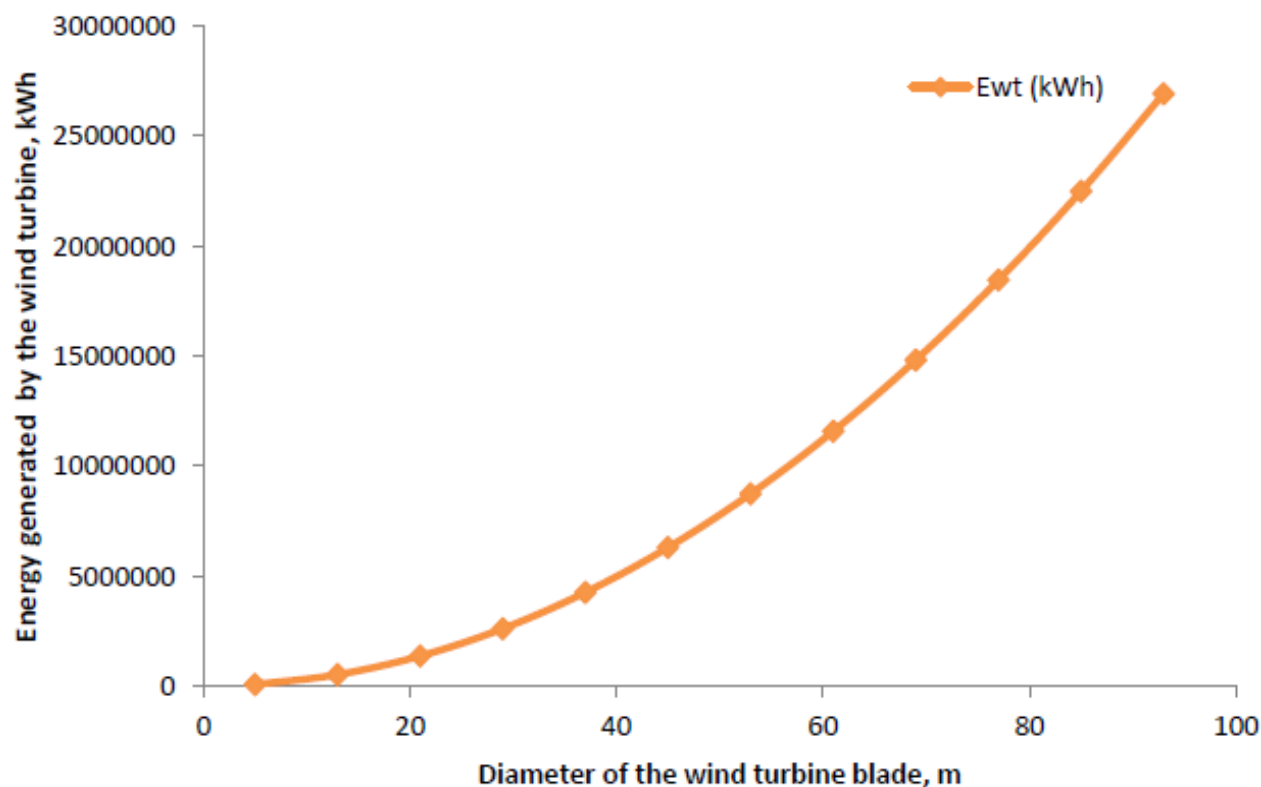


Figure 6 Effect of diameter of the turbine blade on the energy generated by WT.

Figure 7 shows the variation of LCOE in relation to interest rates. Interest rate plays a crucial role in determining the cost-effectiveness of the energy produced. An uptick in interest rates raises the per-unit expense of energy production. This insight necessitates appropriate funding strategies and governmental involvement in the advancement of mini-grids for coastal communities. It was noted that the rate of price increase affects certain aspects of economic value, such as the LCOE. Consequently, a rise in the inflation rate led to a persistent increase in the LCOE [10].

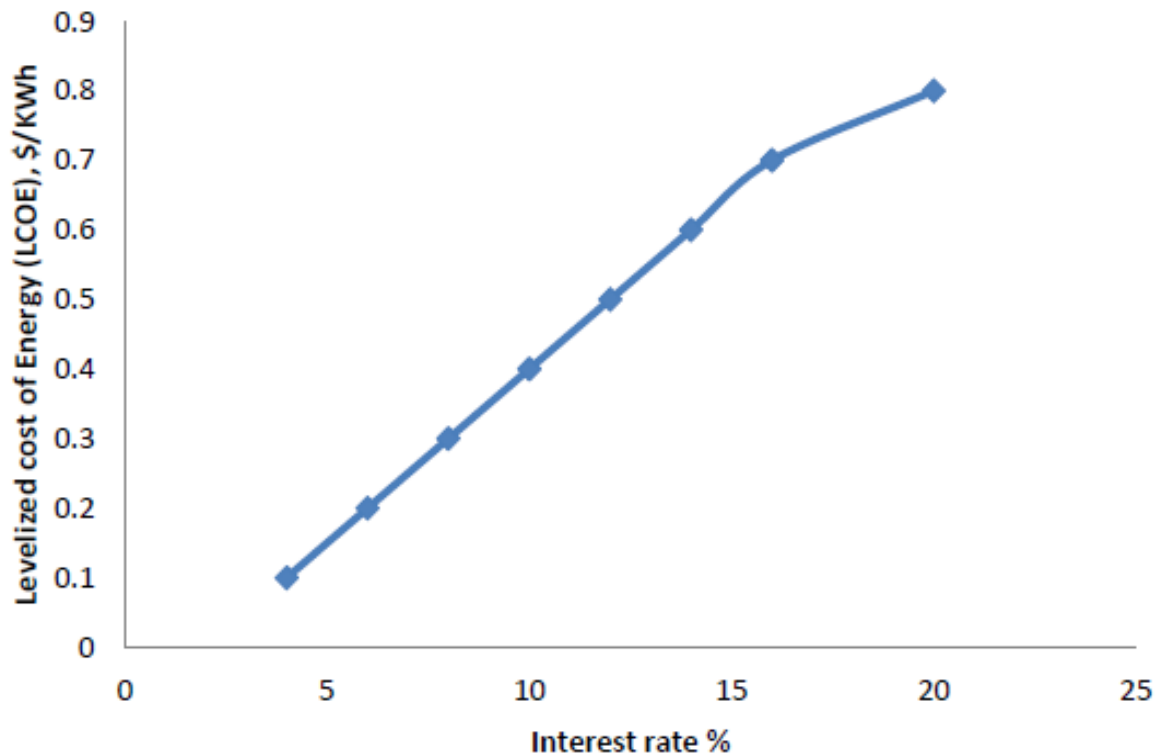


Figure 7 Effect of interest rate on levelised cost of energy (LCOE).

The total energy generated by the renewable energy system is 43662.845 MWh/year. Energy generated by the combined PV, WT, and Biomass system is 22691.52 MWh/year, 5264.02 MWh/year, and 15667.68 MWh/year, which account for 52%, 22%, and 36%, respectively. From the above results, the PV module RES is the primary energy source in the entire energy system. Also, the entire energy demand by Patani Island is 43623.226 MWh/year. Energy shortage in both Battery and Hydrogen is 138.389 MWh/year. Furthermore, the energy difference between excess and demand is 39.619 MWh/year. Thus, the hybrid PV-WT-BM-BT & HD plant can satisfy the energy needs of Patani.

3.2.6 Sensitivity Analysis

Sensitivity Analysis helps to determine how changes in input parameters affect system performance.

Figure 8 illustrates the state-of-charge fluctuation curve of lithium battery energy storage systems. The system on a chip of the energy storage solution for batteries is closely connected to the variations in renewable energy source output. As the power produced by renewable sources increases, the state of charge of battery energy storage systems rises rapidly; conversely, when power output declines, the state of charge decreases correspondingly. This conduct demonstrates the remarkable effectiveness and rapid response time of BESS, rendering them appropriate for uses that demand swift charging and discharging cycles [47]. The batteries exhibited swift variations in state of charge due to alterations in power output, spanning from 22.78 to 81.40%. This conduct demonstrates their remarkable effectiveness and quick reaction times, rendering them ideal for dynamic applications that necessitate regular charging and discharging cycles. These traits make

lithium-ion batteries perfect for scenarios requiring swift modifications to energy provision and consumption.

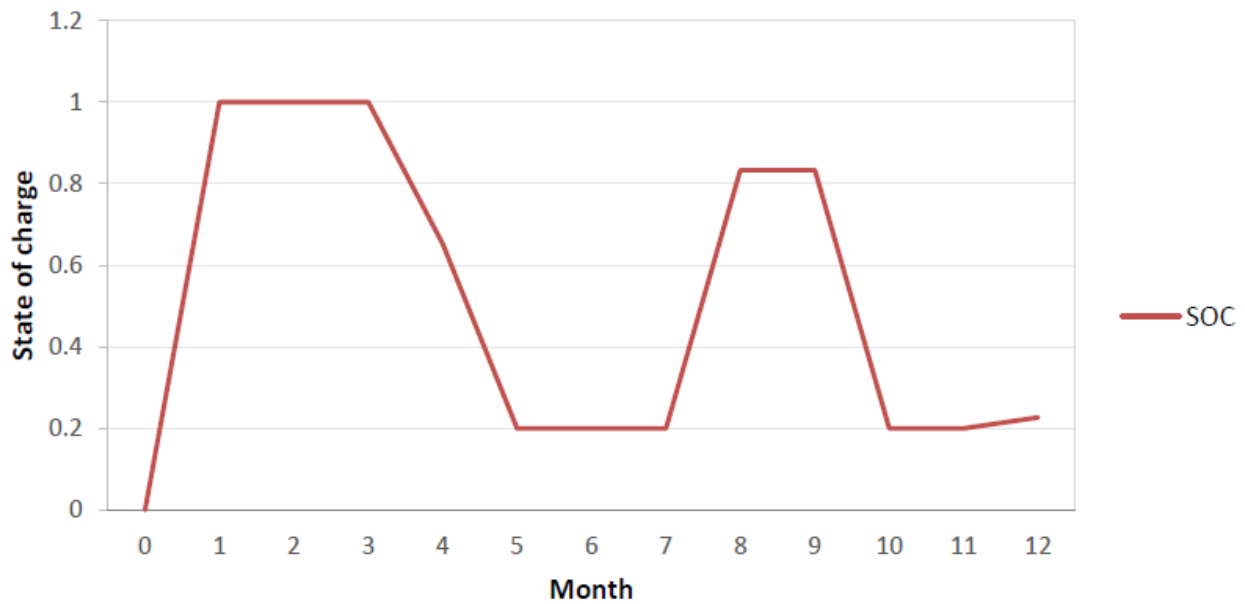


Figure 8 SOC variation curve of lithium BESS.

The starting (SOC) state of charge of the battery energy storage system is established at 50%; when it exceeds 50%, it indicates that there is excess energy provided to the system, which is subsequently utilized to replenish the energy storage system while facilitating hydrogen generation. When the state of charge is under 50%, the energy provision in the system is considered inadequate, and the battery energy storage system's power must be utilized to meet the energy and hydrogen requirements.

The electrolyzer utilizes surplus energy from the renewable energy sources for the process of water electrolysis. From Figure 9, as the hydrogen quantity (mass) increases, the compressor's energy consumption also increases. The tension within the hydrogen storage vessel also increases, consistent with the operation of the real physical system, thereby confirming the accuracy of the proposed model.

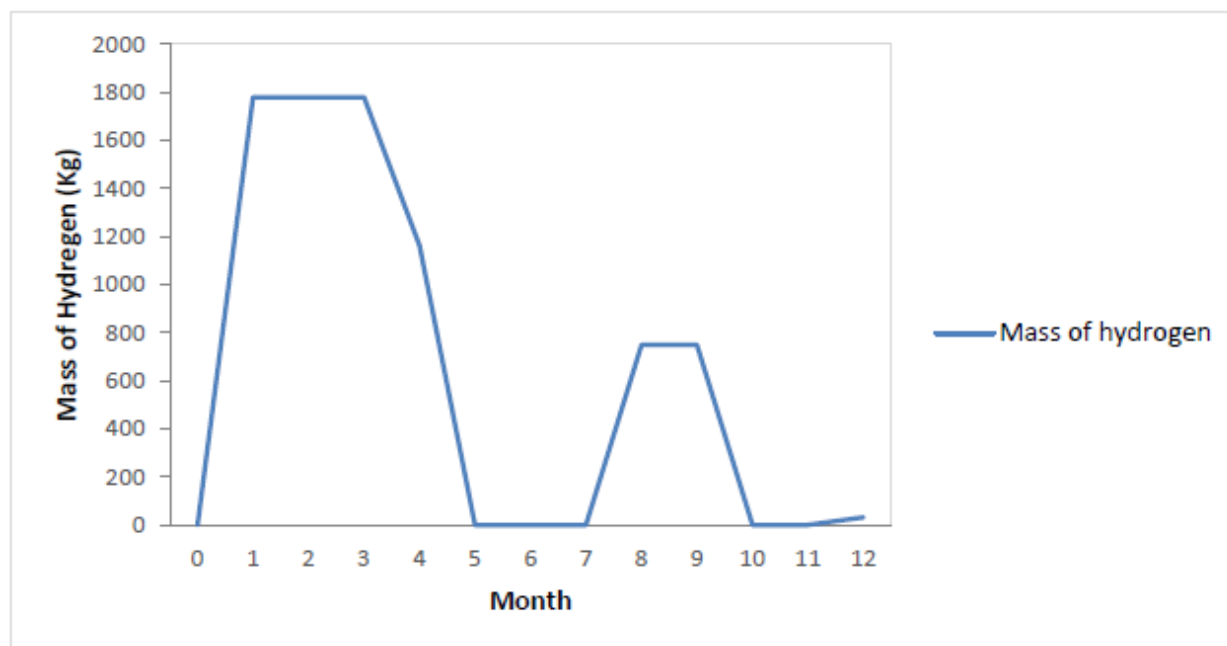


Figure 9 Mass of Hydrogen variation curve of HESS.

4. Conclusions

The paper presents modelling and optimisation of integrated renewable energy conversion technologies for an island in Delta State, Nigeria. The system incorporates battery bank and hydrogen tank energy-storage technologies to ensure a reliable electricity supply that meets the community's energy demand. The model and optimisation scheme were implemented in HOMER, MATLAB, and Microsoft Excel. The following are the highlights of the work.

- i. Modelling and optimisation of hybrid RES offers significant potential for enhancing the energy security of islands.
- ii. Battery and Hydrogen energy Storage system compensates the intermittent nature of RES.
- iii. The modelled hybrid PV-WT-BM-BT & HD system looks promising since the LLP is 0.11 ($LLP < 1$). This implies that about 89% of the energy demand in Patani can be met by the hybrid PV-Wind- Biomass- Battery and Hydrogen plant.
- iv. An optimised hybrid system can meet the energy demand of the community used for the case study.
- v. The Techno-economic analysis of the hybrid plant conducted shows that the Levelised cost of energy (LCOE) is 0.321 \$/kWh in the Nigerian environment.
- vi. The current study is cost-effective and reliable when compared with Nyeche & Dieduodeke [10], Bade & Tomomewo [51], and Modu et al. [52].
- vii. The proposed system addresses some of the Sustainable Development Goals, namely SDGs 4, 7, and 13.

Author Contributions

Ogheneruona Endurance Diemuodeke conceptualized the problem; Ogheneruona Endurance Diemuodeke & Mohammed Moore Ojapah formulated the research questions, designed the methodology, supervised its implementation, and finalized the manuscript; Brendan Ifeanyi

Ekwueme executed the methodology, performed data analysis, implemented the work and prepared the initial draft of the manuscript; and Chidozie Ezekwen was involved in methodology, curated the data, interpreted the results, and participated in the initial and final drafts of the manuscript.

Competing Interests

The authors declare that there are no known conflicts of interest related to this publication.

AI-Assisted Technologies Statement

Artificial intelligence (AI) tools were used solely for basic grammar correction and language refinement in the preparation of this manuscript. Specifically, OpenAI's ChatGPT was employed to improve the readability and linguistic clarity of the English text. All scientific content, data interpretation, and conclusions were developed independently by the author. The authors have thoroughly reviewed and edited the AI-assisted text to ensure its accuracy and accept full responsibility for the content of the manuscript.

References

1. Ang TZ, Salem M, Kamarol M, Das HS, Nazari MA, Prabakaran N. A comprehensive study of renewable energy sources: Classifications, challenges and suggestions. *Energy Strategy Rev.* 2022; 43: 100939.
2. Obada DO, Muhammad M, Tajiri SB, Kekung MO, Abolade SA, Akinpelu SB, et al. A review of renewable energy resources in Nigeria for climate change mitigation. *Case Stud Chem Environ Eng.* 2024; 9: 100669.
3. 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. *Alex Eng J.* 2019; 58: 1103-1118.
4. Babatunde MO, Akinbulire TO, Oluseyi PO, Emezirinwune MU. Techno-economic viability of off-grid standalone PV-powered LED street lighting system in Lagos, Nigeria. *Afr J Sci Technol Innov Dev.* 2019; 11: 807-819.
5. Ohunakin OS, Matthew OJ, Adaramola MS, Atiba OE, Adelekan DS, Aluko OO, et al. Techno-economic assessment of offshore wind energy potential at selected sites in the Gulf of Guinea. *Energy Convers Manag.* 2023; 288: 117110.
6. Diemuodeke EO, Addo A, Oko CO, Mulugetta Y, Ojapah MM. Optimal mapping of hybrid renewable energy systems for locations using multi-criteria decision-making algorithm. *Renew Energy.* 2019; 134: 461-477.
7. Aktaş A, Kirçiçek Y. Hybrid renewable generation systems. In: *Solar Hybrid Systems: Design and Application.* Academic Press; 2021. pp. 69-86.
8. Anoune K, Ghazi M, Bouya M, Laknizi A, Ghazouani M, Abdellah AB, et al. Optimization and techno-economic analysis of photovoltaic-wind-battery based hybrid system. *J Energy Storage.* 2020; 32: 101878.

9. Datta U, Kalam A, Shi J. Hybrid PV–wind renewable energy sources for microgrid application: An overview. In: Hybrid-renewable energy systems in microgrids. Woodhead Publishing; 2018. pp. 1-22.
10. Nyeche EN, Diemuodeke EO. Modelling and optimisation of a hybrid PV-wind turbine-pumped hydro storage energy system for mini-grid application in coastline communities. *J Clean Prod.* 2020; 250: 119578.
11. Diemuodeke EO, Hamilton S, Addo A. Multi-criteria assessment of hybrid renewable energy systems for Nigeria’s coastline communities. *Energy Sustain Soc.* 2016; 6: 26.
12. Bhos CD, Nasikkar PS. Optimization-based maximum power extraction from solar photovoltaic system under non-uniform irradiance. *Int J Ambient Energy.* 2022; 43: 6629-6642.
13. Pavankumar Y, Kollu R, Debnath S. Multi-objective optimization of photovoltaic/wind/biomass/battery-based grid-integrated hybrid renewable energy system. *IET Renew Power Gener.* 2021; 15: 1528-1541.
14. Castro LM, Rodríguez-Rodríguez JR, Martín-del-Campo C. Modelling of PV systems as distributed energy resources for steady-state power flow studies. *Int J Electr Power Energy Syst.* 2020; 115: 105505.
15. Pendem SR, Mikkili S. Modeling, simulation and performance analysis of solar PV array configurations (Series, Series–Parallel and Honey-Comb) to extract maximum power under Partial Shading Conditions. *Energy Rep.* 2018; 4: 274-287.
16. Olabi AG, Obaideen K, Abdelkareem MA, AlMallahi MN, Shehata N, Alami AH, et al. Wind energy contribution to the sustainable development goals: Case study on London array. *Sustainability.* 2023; 15: 4641.
17. Hasan WS, Hassan AS, Shukri MA. Assessment of wind power potential and economic viability at Al-Hodeidah in Yemen: Supplying local communities with electricity using wind energy. *Energy Rep.* 2024; 12: 2981-2996.
18. Attabo AA, Ajayi OO, Oyedepo SO, Afolalu SA. Assessment of the wind energy potential and economic viability of selected sites along Nigeria’s coastal and offshore locations. *Front Energy Res.* 2023; 11: 1186095.
19. Amjith LR, Bavanish B. A review on biomass and wind as renewable energy for sustainable environment. *Chemosphere.* 2022; 293: 133579.
20. Benti NE, Gurmesa GS, Argaw T, Aneseyee AB, Gunta S, Kassahun GB, et al. The current status, challenges and prospects of using biomass energy in Ethiopia. *Biotechnol Biofuels.* 2021; 14: 209.
21. Zhu J, Lin H, Yang X, Yang X, Jiang P, Marin Del Valle T. Social network relationships between biomass industry stakeholders in the agricultural waste power generation industry-A case of Northern Jiangsu, China. *Sustainability.* 2022; 14: 571.
22. Dodo UA, Salami BA, Bashir FM, Hamdoun HY, Alsadun IS, Dodo YA, et al. Investigating the influence of erratic grid on stationary battery energy storage technologies in hybrid power systems: Techno-environ-economic perspectives. *Energy.* 2024; 304: 132140.
23. Han C, Vinel A. Reducing forecasting error by optimally pooling wind energy generation sources through portfolio optimization. *Energy.* 2022; 239: 122099.
24. Shari BE, Moumouni Y, Ohunakin OS, Blechinger P, Madougou S, Rabani A. Exploring the role of green hydrogen for distributed energy access planning towards net-zero emissions in Nigeria. *Sustain Energy Res.* 2024; 11: 16.

25. Chamout MW, Perl A, Hengeveld EJ, Aué JJ. Simulation and analysis of hybrid hydrogen-battery renewable energy storage for off-electric-grid Dutch household system. *Int J Hydrog Energy*. 2024; 70: 170-182.
26. Suresh V, Muralidhar M, Kiranmayi R. Modelling and optimization of an off-grid hybrid renewable energy system for electrification in a rural areas. *Energy Rep*. 2020; 6: 594-604.
27. Qiu K, Entchev E. Modeling, design and optimization of integrated renewable energy systems for electrification in remote communities. *Sustain Energy Res*. 2024; 11: 10.
28. Bakir H, Kulaksiz AA. Modelling and voltage control of the solar-wind hybrid micro-grid with optimized STATCOM using GA and BFA. *Eng Sci Technol*. 2020; 23: 576-584.
29. Li Z, Liu Y, Du M, Cheng Y, Shi L. Modeling and multi-objective optimization of a stand-alone photovoltaic-wind turbine-hydrogen-battery hybrid energy system based on hysteresis band. *Int J Hydrog Energy*. 2023; 48: 7959-7974.
30. Luta D, Raji A. A system modelling language based hybrid photovoltaic-wind power system model. *J Energy Technol Res*. 2017; 1: 2.
31. Malik P, Awasthi M, Sinha S. A techno-economic investigation of grid-integrated hybrid renewable energy systems. *Sustain Energy Technol Assess*. 2022; 51: 101976.
32. Duffie JA, Beckman WA. Solar engineering of thermal processes. 4th ed. John Wiley & Sons, Inc.; 2013.
33. Engin M. Sizing and simulation of PV-wind hybrid power system. *Int J Photoenergy*. 2013; 2013: 217526.
34. Olatomiwa L. Optimal configuration assessments of hybrid renewable power supply for rural healthcare facilities. *Energy Rep*. 2016; 2: 141-146.
35. Bawazir RO, Cetin NS. Comprehensive overview of optimizing PV-DG allocation in power system and solar energy resource potential assessments. *Energy Rep*. 2020; 6: 173-208.
36. Kumar A, Biswas A. Techno-economic optimization of a stand-alone photovoltaic-battery renewable energy system for low load factor situation-a comparison between optimization algorithms. *Int J Eng Trans A Basics*. 2017; 30: 1555-1564.
37. Lopez-Villalobos CA, Martinez-Alvarado O, Rodriguez-Hernandez O, Romero-Centeno R. Analysis of the influence of the wind speed profile on wind power production. *Energy Rep*. 2022; 8: 8079-8092.
38. Ahmad J, Imran M, Ali SF, Adnan M, Ashraf SR, Hussain Z, et al. Wind-to-hydrogen production potential for selected sites in Pakistan. *IEEE Access*. 2021; 9: 134874-134898.
39. Okedu KE, Oyinna BC, Diemuodeke EO, Colak I, Kalam A. Multicriteria GIS-based assessment of biomass energy and hydropower potentials in Nigeria. *Meas Sens*. 2024; 33: 101243.
40. Ukoba MO, Diemuodeke EO, Briggs TA, Okedu KE, Owebor K, Imran M, et al. Assessment of biomass energy potentials and appropriate sites in Nigeria using GIS computing strategy [Internet]. ICICT Conference; 2023. Available from: <https://ictjournal.icict.org.zm/index.php/icict/article/view/289>.
41. de Souza LL, Hamedani SR, Lora EE, Palacio JC, Comodi G, Villarini M, et al. Theoretical and technical assessment of agroforestry residue potential for electricity generation in Brazil towards 2050. *Energy Rep*. 2021; 7: 2574-2587.
42. Kaniapan S, Hassan S, Ya H, Patma Nesan K, Azeem M. The utilisation of palm oil and oil palm residues and the related challenges as a sustainable alternative in biofuel, bioenergy, and transportation sector: A review. *Sustainability*. 2021; 13: 3110.

43. Liu Y, Yu S, Feng R, Bernard A, Liu Y, Zhang Y, et al. A bioinspired, reusable, paper-based system for high-performance large-scale evaporation. *Adv Mater*. 2015; 27: 2768-2774.
44. Qiu K, Entchev E. Analysis and optimization of hybrid renewable energy systems for remote community applications. *Int J Green Energy*. 2025; 22: 2767-2780.
45. Vendoti S, Muralidhar M, Kiranmayi R. Techno-economic analysis of off-grid solar/wind/biogas/biomass/fuel cell/battery system for electrification in a cluster of villages by HOMER software. *Environ Dev Sustain*. 2021; 23: 351-372.
46. Ghanjati C, Tnani S. Optimal sizing and energy management of a stand-alone photovoltaic/pumped storage hydropower/battery hybrid system using Genetic Algorithm for reducing cost and increasing reliability. *Energy Environ*. 2023; 34: 2186-2203.
47. Khan FA, Pal N, Saeed SH, Yadav A. Modelling and techno-economic analysis of standalone SPV/Wind hybrid renewable energy system with lead-acid battery technology for rural applications. *J Energy Storage*. 2022; 55: 105742.
48. Mohtasim MS, Das BK, Paul UK, Kibria MG, Hossain MS. Hybrid renewable multi-generation system optimization: Attaining sustainable development goals. *Renew Sustain Energy Rev*. 2025; 212: 115415.
49. Razak NA, Abdulrazik A. Modelling and optimization of biomass-based cogeneration plant. *IOP Conf Ser Earth Environ Sci*. 2019; 257: 012027.
50. IRENA. Renewable Power Generation Costs in 2023 [Internet]. Abu Dhabi, United Arab Emirates: IRENA; 2023. Available from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf.
51. Bade SO, Tomomewo OS. Optimizing a hybrid wind-solar-biomass system with battery and hydrogen storage using generic algorithm-particle swarm optimization for performance assessment. *Clean Energy Syst*. 2024; 9: 100157.
52. Modu B, Abdullah MP, Bukar AL, Hamza MF, Adewolu MS. Energy management and capacity planning of photovoltaic-wind-biomass energy system considering hydrogen-battery storage. *J Energy Storage*. 2023; 73: 109294.