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Economic Analysis of Off-Grid Hybrid Power Solution: A Case Study of Nigerian Maritime University, Okerenkoko, Delta State

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Abstract

This paper presents an economic assessment of a technically feasible off-grid hybrid renewable energy system to address power supply concerns at Nigerian Maritime University, Okerenkoko, Delta State. The HOMER software was used to create, improve, and assess a technically feasible hybrid renewable energy system comprising of battery storage, a converter, solar photovoltaic panels, and compressed natural gas generators. Key economic metrics such as net present cost, levelized cost of electricity, and payback period were assessed and used to determine the most economically feasible design for the university. A sensitivity study was carried out to determine the impact of variable discount rates and electricity prices on system performance. The study found that the ideal hybrid design has a net present cost of ₦417 million, an initial capital expenditure of ₦234 million, an annual operational cost of ₦5.87 million, and a levelized electricity cost of ₦220.96 per kilowatt-hour. This cost is much lower than powering the university with a compressed natural gas generator, which costs ₦1077 per kilowatt-hour. In addition, the system has a 3.8-year payback period and a 25% internal rate of return. The sensitivity analysis revealed that the levelized cost of electricity increased with an increase in discount rates. The study indicated that implementing the planned HRES will save money, increase energy reliability, and promote environmental sustainability at the university. Furthermore, the study emphasized the need to include discount rates in financial assessments of renewable energy projects.

Keywords: *Off-grid hybrid energy systems, Renewable energy, Economic analysis, Electricity demand, Energy audit, System optimization, HOMER software*

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1. Introduction

Electrification of local and remote areas has always been considered as crucial development plan for most emerging economies. Abed et al. (2017) reports that more than 17% of the current global population do not have access to electric-power, majority of which reside in sub–Saharan Africa. Conventional electrification techniques in remote villages comprise of grid extension and hydrocarbon-based generators. In case of grid extension, several issues have been raised like long distance from electric-power grids, difficult terrain and huge initial investment (Aderemi et al., 2018). The use of stand-alone power generation sets like petrol and diesel generators are a common alternative to grid extension in remote areas. However, this alternative presents its own challenges such as environmental pollution and dependence on expensive fuel which is often sourced from nearby towns.

Considering scarcity of hydrocarbon-based fuels, environmental pollution and transportation costs, the adoption of renewable energy resources has attracted massive and widespread attention globally for electrification of rural settlements (Abraham et al, 2014). Efforts targeted on using one energy source based renewable power systems like solar powered arrangement and micro wind-power systems, usually result in issues of over-sizing because of erratic and unpredictable nature of these sources, thereby increasing initial investment cost of the system (Erasmus & Fouzi, 2019). A more effective decentralized off-grid HRES provide means to overturn issues of over-sizing and improve availability and reliability of energy supply in local villages. To resolve the energy deficit in remote areas, it is important that energy is generated and utilized in a sustainable manner in order to achieve dependable and sustainable energy (Babatunde et al., 2020). Renewable energy sources are receiving massive and widespread attention globally in energy generations, mostly due to fear of rapid depletion of the hydrocarbon-based fossil energy, changes in oil price, and rapid increasing awareness on dangers of fossil fuel to the climate (Babalola et al., 2022). It is the aim of this study to conduct an economic analysis of implementation of HRES in the Nigerian Maritime University, Okerenkoko, Delta State.

2. Materials and methods

2.1 Research design

This research was conducted by first reviewing existing literature on the subject matter, next a 9-year weather data (2014-2023) for the study area was obtained from the Nigerian metrological agency (NIMET) to ascertain the solar and wind potential of the study area. Afterwards, the electricity load consumption of NMU was assessed by conducting a walk-through energy audit of the university site. Following the energy audit, the size of the HRES components were determined using appropriate equations and the cost of the components were compiled from online sources and market surveys. These costs were then incorporated into the HOMER simulation software, along with the meteorological data. HOMER was selected for this analysis due to its robust capabilities in modelling complex systems and its ability to optimize system design based on user-defined constraints and objectives. The most effective system configuration of the HRES was determined based on the NPC, LCOE, IRR, and payback period. Finally, a sensitivity analysis was conducted to assess the impact of changes in the nominal discount rate and inflation on the cost of energy.

2.2 Study area

The Nigerian Maritime University (NMU) is located in Okerenkoko, a town in the Warri area of Delta State, Nigeria. Delta State is located between 5°00 and 6°45'E longitudes and 5°00 and 6°30'N latitudes. The land area is 16,842 square kilometers. Delta State shares its northern boundary with Edo, and its northwest border with Ondo. To the east is Anambra, and to the southeast are Bayelsa and Rivers. The southern side of the bay of Benin has a 160-kilometer-long coastline. The state has a population of over 4 million people, with the majority residing in urban areas such as Warri, Asaba, and Sapele. Delta State is known for its rich oil reserves and agricultural resources, making it a key economic hub in Nigeria. The state is also home to various ethnic groups, including the Urhobo, Itsekiri, and Ijaw. The capital city of Delta State is Asaba, located on the west bank of the Niger River. Delta State presently has a total of twenty-five local government areas; among them is Warri South, Okerenkoko, where the NMU is domiciled. Okerenkoko is located at around 5.4305° N latitude and 5.7336° E longitude in the Gbaramatu Kingdom, in the Warri South-West LGA. Fig. 1 is a base map of NMU indicating the areas where energy audit was conducted using QGIS software.

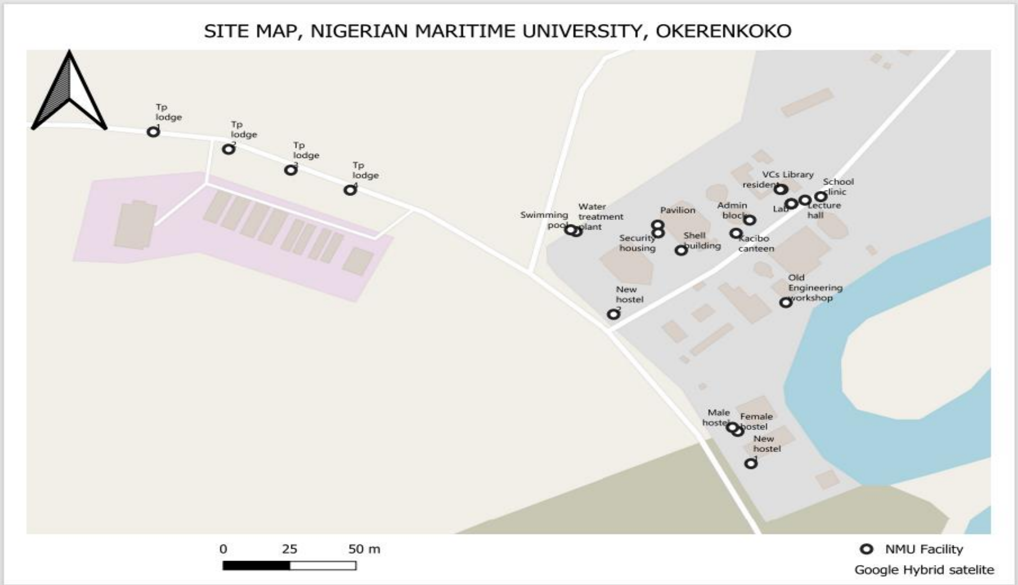


Fig. 1: Google terrain and open street map as base maps of NMU

2.3 Renewable energy potential of study area

The Nigerian Maritime University possesses significant solar energy potential due to its abundant exposure to sunlight year-round. Table 1 displays the mean sun irradiation measurements over nine years, specifically from 2014 to 2023, within the designated study region. The data shows that June has the lowest solar irradiance at 1.7 kWh/m^2/day, while January and February have the maximum solar irradiance at 5.2 kWh/m^2/day each. The data indicates that the average monthly solar radiation was minimal during the main months of the rainy season (June, July, August, and September), moderate during the transitional months between the rainy and dry seasons (May and October), and highest during the main months of the dry season (January, February, March, April, November, and December). The data additionally indicates an obvious pattern of solar radiation variability throughout the year, characterized by prominent peaks and troughs.

Table 1: Monthly solar irradiation (kWh / m^2 / day)

Month	Warri South-West (LGA)		Warri North (LGA)		Burutu, (LGA)	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
January	3.8	4.9	3.9	5.2	3.8	5.2
February	3.6	4.9	3.8	5.2	3.7	5.2
March	2.9	4.5	3.2	4.9	3.1	4.9
April	3.0	4.6	3.3	4.9	3.3	5.0
May	2.4	4.0	2.7	4.3	2.7	4.4
June	1.7	3.3	1.9	3.6	1.9	3.6
July	1.8	3.4	2.0	3.6	2.0	3.7
Aug	2.1	3.7	2.3	4.0	2.5	4.2
Sept	1.9	3.6	2.1	3.8	2.2	4.0
Oct	2.2	3.8	2.4	4.1	2.4	4.2
Nov	2.9	4.3	3.1	4.5	3.0	4.6
Dec	3.6	4.7	3.7	5.0	3.7	5.0

Source: Nigerian Meteorological Agency (NIMET) (2023)

The mean monthly minimum and maximum wind velocities (in m/s^2) for Warri South-West, Warri North, and Burutu in Delta State, collected along the Escravos, Benin Forcados river over a period of nine years is displayed in Table 2. The minimum wind speeds vary between 1.03 and 2.57 m/s^2 across all three locations. Typically, the wind velocities are at their minimum levels throughout the months of January, November, and December. The maximum wind speeds vary between 2.57 and 5.66 m/s^2, with the highest values usually observed during the months of June, July, and August. The data further indicates that the region encounters wind speeds of a moderate nature. While the minimum speeds are very modest, the highest speeds experienced during specific months (reaching up to 5.66 m/s^2) are adequate for harnessing wind energy through the use of wind turbines. Wind speeds exhibit seasonal fluctuation, with elevated speeds occurring in the months around the middle of the year. Consequently, wind energy production may be more substantial over these time intervals.

2.4 Electricity demand of NMU

The electricity demand in NMU was obtained via a walk-through energy audit which indicated that the university has a total daily demand of 525.8 KW. This load comes from 24 load canters consisting of academic buildings, dormitories, administrative offices, and recreational facilities spread across the campus. Table 3 shows the utilization of electrical power across these load canters.

2.5 Components of proposed HRES

The first major component of the hybrid power system proposed for the NMU consists of an array of solar panels. The second main component is the battery bank. The energy stored in the battery bank is used to power the system at night or during periods of cloud cover when there is no solar radiation. The third main component of the hybrid power system is the compressed natural gas generator. The CNG generator serves as a standby backup power in the system to operate when there is a prolonged cloud cover or sometimes at night. The control system, DC/DC converters, and DC/AC inverters are power conditioning circuits in the system. Fig. 2 displays the schematic block diagram of the proposed off-grid hybrid electric power system.

Table 2: Monthly wind speed (m/s^2)

Month	Warri South-West		Warri North		Burutu, LGA	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
January	1.03	3.09	1.54	4.12	1.54	4.63
February	1.54	3.60	2.06	4.63	2.06	5.14
March	1.54	3.60	2.06	4.63	2.06	5.14
April	1.54	3.09	2.06	4.63	2.06	4.63
May	1.03	3.09	1.54	4.12	2.06	4.21
June	1.54	3.60	1.54	4.63	2.06	5.66
July	1.54	3.60	2.06	5.14	2.06	5.66
Aug	1.54	4.12	2.06	5.66	2.57	6.17
Sept	1.54	3.60	2.06	4.63	2.06	5.14
Oct	1.03	2.57	1.54	3.60	1.54	4.12
Nov	1.03	2.57	1.54	3.60	1.54	3.60
Dec	1.03	3.09	1.54	4.12	1.53	4.12

Source: Nigerian Meteorological Agency (NIMET) (2023)

Table 3: Load distribution in the study area

S/N	Load Centres	Wattage (W)	Volt-Ampere (VA)
1	New hostel 1	13140	15324
2	New hostel 2	15250	17237
3	Female hostel	56952	66417
4	Male hostel	44072	52840
5	Old engineering workshop/Kacibo canteen/ Ex-hostel	44224	52028
6	Lab	2418	2748
7	Lecture hall	54764	61898
8	School clinic	15922	17996
9	Staff resident 1	37748	42895
10	VC’s resident	10428	11850
11	Water treatment plant	6700	8233
12	Staff residency	23334	26517
13	Library	21034	25936
14	Admin block	60755.6	69040
15	Pavilion	1045	1306
16	Swimming pool/ security housing	8400	9796
17	Shell building	49528	57759
18	Picnic L1	13740	14691
19	Picnic L2	9931	11210
20	Tp lodge 1	10440	11864
21	Tp lodge 2	9784	11118
22	Tp lodge 3	4337	4929
23	Tp lodge 4	11875	13332
	Total Load	**525821.6**	**606964**

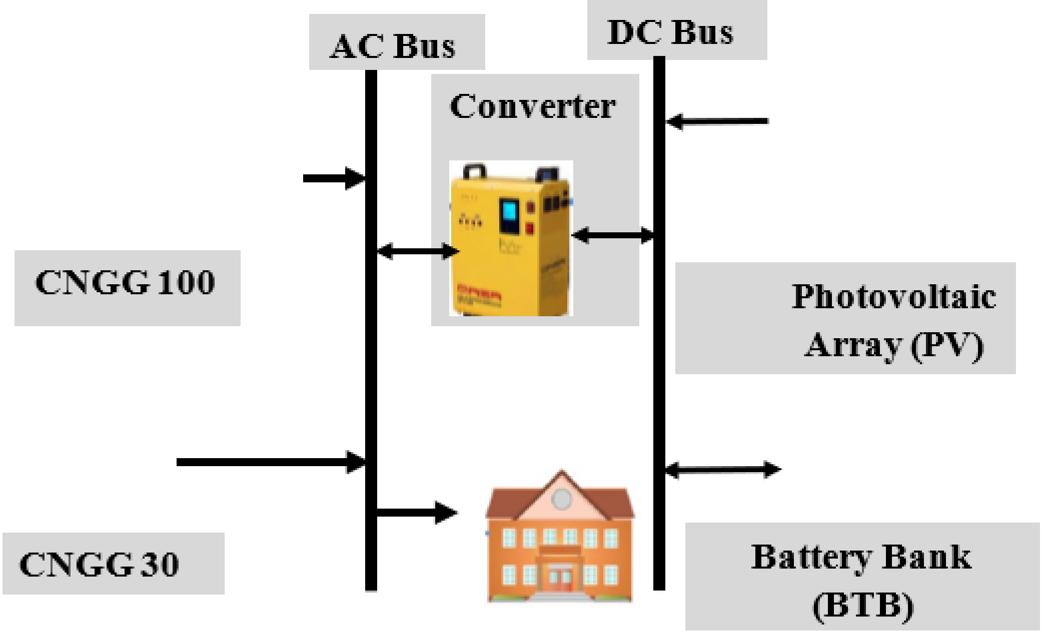


Fig. 2: Schematic block diagram of the proposed off-grid hybrid electric power system

The configuration of the power system consists of a collection of solar panels, a battery bank, a converter, and a generator powered by compressed natural gas. The hybrid power system in this study is specifically designed to only provide electricity to the load through a combination of photovoltaic panels and batteries. Additionally, the CNG generator is used during periods of low solar radiation or when battery storage is insufficient to meet electricity demand. The power capacity of the solar panel array is determined by using the following empirical equations as modified from Ghafoor and Munir (2015), Yahyaoui (2018) and Windarta et al. (2019).

$$PV_c = \frac{L_D}{G_d \text{ x } T_C \text{ x } \eta_{pv} \text{ x } \eta_{Inv} \text{ x } \eta_B} \qquad (1)$$

were PV_c is capacity of PV-cell panel arrangement, L_D is electric load demand, G_d is mean solar radiation of the particular area, Tc is temperature coefficient, η_{PV} is PV module efficiency, η_{Inv} is inverter efficiency, and η_B is battery efficiency.

The batteries bank acts as device that store the electric energy produced by the array of photovoltaic panels, and provide power to the system in the night time and during period of low or no solar irradiation such cloudy period (no sunshine). To estimate the capacity of the batteries bank, it is vital to have knowledge of the amount of electricity demand in a day, the average kilowatt hour of energy obtained from photovoltaic system per day, the number of autonomy days efficiency, the lowest value of the battery's depth of discharge (DOD), and efficiency of the inverter (Foster et al., 2010; Yahyaoui, 2018; Windarta et al., 2019). The total storage capacity of battery bank is determined by using Equation (2) (Foster et al., 2010; Yahyaoui, 2018):

$$Q_B = \frac{L_D \text{ x } N}{\text{dod x } \eta_{Inv} \text{ x } \eta_B} \text{(Wh)} \qquad (2)$$

where L_D is the electricity load demand, Q_B is the storage capacity of the battery bank (Wh), N is the number of cloudy day or number of autonomy days usually 2, DOD is depth of battery discharge use 50%, η_{Inv} is inverter efficiency (90%), and η_B is battery efficiency (85%). The battery DOD variable value is related to its capacity by the following expressions (Yahyaoui, 2018):

$$dod = \frac{C_R}{C_p} \qquad (3)$$

where,

$$C_p = I_B^K \times T \qquad (4)$$

K represent Peukert factor (Yahyaoui, 2018), and T is constant current time of discharge. The instantaneous battery capacity and battery current is mathematically expressed in Equations (5) and (6) as shown by Yahyaoui (2018)

$$\frac{\Delta C_R}{\Delta t} = \frac{I_B^K}{3600} \tag{5}$$

where battery current I_B is expressed by expression (Yahyaoui, 2018):

$$I_B = \frac{P_B}{V_B} \tag{6}$$

where P_B represent power supplied by battery. According to Yahyaoui (2018), batteries normally operate in DOD that ranged from 20% to 80%. However, according to Windarta et al. (2019), maximum allowable DOD for deep cycle battery is 50%. In order to estimate the appropriate capacity of a generator for a hybrid renewable energy system (HRES), it is customary to incorporate a safety margin due to potential fluctuations in energy production and unexpected increases in power demand. Besides the ability of a generator to manage high levels of demand, the ease with which it can be integrated with HRES systems is also an important factor to consider. The power required from generator is estimated using Equation (7) (Yimen et al., 2020).

$$P_{DG(t)} = P_L(t) - [\, P_B(t) + [SOC\ (t-1) - (1-DOD)] \times 1000 \times N_b \times C_b] \times ŋ_{mw} \tag{7}$$

where $P_L(t)$ is Load demand at time t, $P_B(t)$ is power from batteries, $SOC\ (t-1)$ is state of charge of battery at previous time step, DOD is depth of discharge of battery, N_b is number of batteries, C_b is capacity of each battery, and $ŋ_{mw}$ is the efficiency of the inverter. The inverter size for any HRE project should be sufficient to accommodate the maximum power output of the solar panel. In general, inverters often exhibit an efficiency of 95%. Hence, an additional capacity ranging from 10 to 25% over the panel capacity would be suitable for achieving optimal performance. Furthermore, it is essential to take into account the inverter's voltage range compatibility with the solar panel system in order to guarantee smooth integration and optimize energy output.

2.6 Homer software

HOMER software is a robust tool that enables thorough modelling and simulation of diverse renewable energy scenarios and was developed by the National Renewable Energy Laboratory to provide detailed analysis of the technical and monetary aspects of different renewable energy procedures. The software enables users to create and customize energy system models by specifying various components and features, such as solar irradiation, wind speed, and hydropower availability, to be simulated and employs sophisticated modelling techniques that precisely model the inconsistency and intermittence of these renewable sources of energy and their impact on system performance. The software also allows users to evaluate multiple system designs, sizing options, and dispatch algorithms to identify the most economically feasible and environmentally sustainable solution that fulfills the energy needs of a particular project. The software optimizes the allocation of energy-generating and storage components to satisfy the electrical demand of a project site while minimizing expenses and maximizing the efficiency of the system and permits efficient distribution of energy from renewable and non-renewable sources, taking into account their availability, system limitations, and user-defined preferences. Furthermore, HOMER enables users to perform a full financial analysis on HRES to ascertain the financial viability of the design. It does this by using complex algorithms to calculate a number of economic metrics, including NPC, LCOE, IRR, and payback period. Users have the freedom to input financial factors, such as the initial investment expenses, recurring costs, fuel expenses, interest rate, and incentives, to customize the economic assessment according to specific project requirements. The HOMER software tool facilitates the design, simulation, and optimization of various configurations of hybrid energy systems. Finally, the software generates exhaustive reports, charts, and graphs to convey results in a manner that is simple to comprehend.

2.7 Economic indicators

According to Foster et al. (2010), an economic evaluation examines the life cycle cost of a project, taking into account all expenses incurred over its life span. The initial cost of various components of the HRES, the cost of installation, maintenance, and operation, as well as the potential savings in fuel costs and the annual electricity production, are crucial elements in assessing the value of electricity generated by the hybrid electric power system.

2.7.1 Net present cost

Net present cost (NPC) is a financial metric that assesses the overall cost of a project or investment throughout its entire lifespan, taking into account the time value of money. NPC is commonly employed in the evaluation of long-term investments to compare different options. A lower NPC signifies a more cost-efficient solution, making it the preferred choice in financial decision-making. Mathematically, NPC is expressed as:

$$\text{NPC} = \sum_{t=0}^{n} \frac{C_t}{(1+r^t)} \tag{9}$$

where C_t is the cost incurred at time t, r is the discount rate, which reflects the time value of money, t is the time period (e.g., year) at which the cost is incurred, and n is the total number of periods over the project's lifetime.

2.7.2 Levelized cost of electricity

The LCOE represents the value of the electricity generated by the hybrid electric power system and is calculated as a fixed amount during the system's lifespan, which is estimated to be 25 years. The levelized cost of electricity can be estimated using Equation (10). The evaluation of cost of electricity serves as a criterion for assessing the economic viability of the hybrid power systems, particularly when juxtaposed with the cost of electricity derived from alternative sources, such as a power utility company or the operation of a diesel generator. The utilization of a levelized cost of electricity as a measure of viability of electricity projects has been a prevalent approach among hybrid power system designers (Dykes, 2020). The measurement of COE allows for a more accurate comparison of the overall cost of energy production over the lifetime of the system.

$$\text{LCOE} = \frac{IC \times FCR + AOM}{A\,Kwh} \tag{10}$$

where IC is the initial capital expenditures of the system adjusted for a fixed charge rate (FCR), AOM is the expected annual operational expenditures over the system lifetime, and A kwh is the expected annual electricity production delivered to the load.

2.7.3 Internal rate of return

Internal Rate of Return (IRR) is a financial metric used to evaluate the profitability of an investment. It represents the discount rate at which the net present value (NPV) of an investment becomes zero. By comparing the IRR of different investment options, decision-makers can determine which option will yield the highest return on investment. An investment proposal is approved or rejected based on whether the IRR exceeds the cut off or hurdle rate (r). The cut off or hurdle rate (r) is the minimum rate of return that an investment must meet in order to be considered acceptable. If the IRR of an investment exceeds the hurdle rate, it indicates that the investment is expected to generate a higher return than the minimum required. Therefore, decision-makers often use IRR as a key factor in determining which investment proposals to approve or reject. Mathematically,

$$\Sigma NPV_{end} - C_{investment} - \Sigma NPV_{om} - \Sigma NPV_{r} = 0 \tag{11}$$

Where NPV_{end} is the currently discounted reward of income from the residual value of the subsystems at the end of the life of the system, $C_{investment}$ is the initial investment cost, NPV_{om} is the present value of future exploitation and maintenance costs during the life of the system, and NPVr is the present value of future replacement costs to replace components during the lifetime of the system.

2.7.4 Payback period

The Payback Period (PP) is an economic indicator that calculates the time it takes for the net cash inflows from an investment to equal or exceed the initial investment expenditures. The payback period is commonly employed as a convenient and efficient method to assess the level of risk associated with an investment. Projects with shorter payback periods are generally seen as less risky. Estimating payback period entails evaluating the number of years it takes for cash flow into the investment in this case, investment in an HRES, will be equal to the initial investment. It can be determined by applying the following formula:

$$\text{Simple payback period} = \frac{\text{Initial Investment}}{\text{Annual Net Cash Inflow.}} \tag{12}$$

The expression to determine the simple payback period in years based on annual electricity production (AEP) as found in (Foster et al., 2010) is given as:

$$\text{SP} = \frac{IC}{A\,(Kwh) \times \frac{\$}{Kwh}} \tag{13}$$

where SP is the simple payback in years, IC is the initial cost of installation ($), A (Kwh) is the energy produced annually (kWh/year), and $/kWh is the price of energy displaced.

3. Results and discussion

3.1 Analysis of the capital, maintenance and operational cost

The summary of the cost component of the HRES is presented in Table 4. The initial capital cost of the CNGG 100 generator is estimated at Forty-Eight Million Naira (N48, 000,000.00), while the replacement cost after a period of fifteen (15) years is estimated at One Hundred and Thirty-Three Million Naira (N133, 000,000.00). The operation and maintenance cost over the fifteen (15) year's period is estimated at Eight Thousand Naira (N8, 000.00) per hour. The initial capital cost of the CNGG 30 generator is estimated at Eighteen Million Naira (N18, 000,000.00), while the replacement cost after a period of fifteen (15) years is estimated at Fifty Million Naira (N50, 000,000.00). The operation and maintenance cost over the fifteen 15 years period is estimated at Two Thousand Seven hundred naira (N2, 700.00) per hour. The initial capital cost of the photovoltaic solar panels is estimated at Forty Million Naira (N40, 000,000.00), while the replacement cost after a period of twenty-five (25) years is estimated to be zero Naira (N0.00) as the panel has a life span of 25 years. The operation and maintenance cost over twenty-five, 25 years period is estimated at Five Hundred Thousand Naira (N500, 000.00) annually. The initial capital cost of the energy storage battery bank is estimated at Six Hundred Million Naira (N600, 000,000.00), while the replacement cost after a period of fifteen (15) years is estimated at One Billion Six Hundred and Sixty-Five Million Naira (N1, 665, 000,000.00). The operation and maintenance cost over the fifteen (15) year period is estimated at Fourteen Million, Five Hundred Thousand Naira (N 14, 500, 000.00). The initial capital cost of the system converter is estimated at fifty six million, seventeen thousand, four hundred and twenty one naira, thirty two kobo (₦56,017,421.32). While the replacement cost after a period of Twenty-five (25) years is estimated at one hundred and fifty five million, five hundred and ninety nine thousand, seven hundred eighty eight naira fifty two kobo (₦154,599,788.52).

Table 4: Summary of the cost of investment of the hybrid renewable electric power system components

Component	Parameter	Total cost (₦)	Cost per unit
CNGG 100	Initial Capital	48,043,800.00	
	Replacement cost	132,554,359.54	
	O & M (₦ /hr)	8,128.875	213
	Fuel price (₦ /m^3)		15
	Lifetime (years)		
CNGG 30	Initial Capital cost	18,016,425.00	
	Replacement cost	49,707,884.83	
	O & M (₦ /hr)	2,704.000	213
	Fuel price (₦ /m^3)		15
	Lifetime (years)		
PV: Studer Vario Track VT-65 with Generic PV	Initial Capital cost	39,800,000.00	50,507 (₦ /kW)
	Replacement cost	0.0	0.0 (₦ /kW)
	O & M (₦ /yr)	500,600.00	

	Lifetime (yrs)		25
Battery: Lithium-ion battery	Initial Capital cost	600,000,000.00	761,421(₦ /unit)
	Replacement cost	1,665,418,924.00	2,113,475 (₦ /unit)
	O & M (₦ /yr)	14,500,000.00	
	Lifetime (yrs)		15
Converter: Leonics GTP519S 900	Initial Capital cost	56,017,421.32	
	Replacement cost	154,599,788.52	
	O & M (₦ /yr)	560,174.21	
	Lifetime (yrs)		25

3.2 Economic evaluation of the proposed HRES

The evaluation of the economic viability of the proposed hybrid electric power system was carried out using HOMER pro software. Fig. 3 shows a summary of the economic optimization of the HRES. The HRES requires an initial investment of ₦233,840,186.91, which covers the purchase and installation of CNG generators, storage systems, PV systems, and converters. Over its lifetime, the system is projected to have a replacement cost of ₦552,707,368.29, mainly due to the pricey replacement of the battery storage system. The operation and maintenance cost (O&M) cost is ₦120,088,422.33, representing the continuous expenses necessary to maintain the system's efficient operation. Most of these expenses are related to the storage system and the PV system. The entire fuel cost amounts to ₦69128.26, which is comparatively low due to the utilization of compressed natural gas (CNG) in the generators. The system primarily depends on solar photovoltaic (PV) technology and battery storage, reducing its reliance on fuel. The negative salvage value of -₦489,246,654.72 represents the estimated remaining worth of the components at the end of their useful lives. This negative value is substantial, particularly for the CNG generators and storage system, which affects the overall cost negatively. The salvage value denotes the remaining worth of an object after it has reached the end of its productive lifespan. If the salvage value is negative, it means that there is an expense involved in getting rid of, shutting down, or reusing the equipment. The significant salvage value (-₦196,196,159.24) of the 100 kW CNG generator indicates potential difficulties in environmentally responsible disposal of the equipment. Moreover, the 30 kW CNG generator possesses a substantial salvage value (-₦75,334,294.48), which might potentially complicate the environmentally responsible disposal of the equipment. Additionally, the salvage value indicates that there may be a more profitable alternative to simply disposing of the equipment, such as selling it for parts or repurposing it for another use. This salvage value should be taken into consideration when making decisions about the end-of-life management of the generators. The NPC of ₦417,458,451.07 represents the total cost of the HRES over its lifetime, accounting for all expenses and salvage values. In terms of greenhouse gas emissions and dependency on fossil fuels, the low fuel cost and reliance on solar PV point to a positive environmental impact.

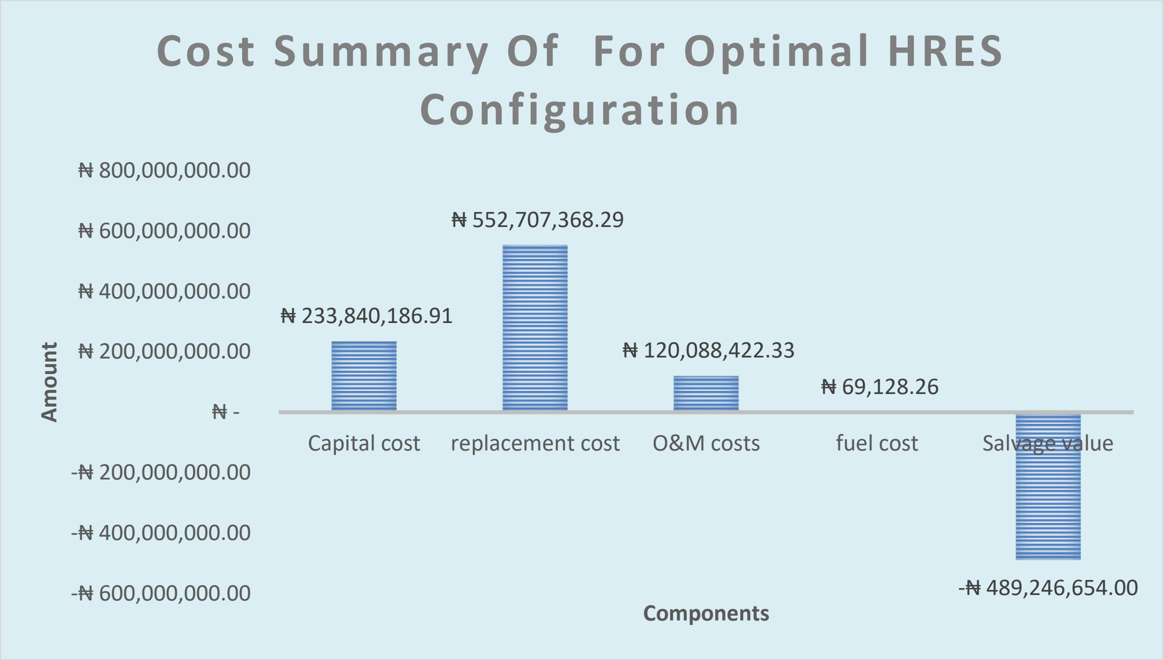


Fig. 3: Cost summary for optimal HRES configuration.

Table 5 highlights the comparative analysis of different system configurations for the HRES suggested for NMU. Each arrangement offers a distinct combination of components, comprising photovoltaic (PV) panels, compressed natural gas (CNG) generators, battery storage, and converters. The table indicates that the most economical choice is configuration C1, which comprises a mix of photovoltaic panels, a 100 kW compressed natural gas generator, a 30 kW compressed natural gas generator, a battery bank, and a converter. This configuration has the most favorable levelized cost of electricity at ₦220.96/kWh and the lowest net present cost of ₦417 million. The second most feasible alternative is configuration C2, which eliminates the smaller CNG generator from the arrangement. The NPC is ₦470 million, the LCOE is ₦249/kWh. Configuration C3 consists solely of a single smaller CNG generator, combined with PV panels and battery storage, yielding a net present cost (NPC) of ₦556 million and a levelized cost of electricity (LCOE) of ₦229/kWh. Configuration C4 is a hypothetical situation in which only battery storage and PV panels are employed. It has an annual operating cost of ₦14.5 million, an LCOE of ₦328/kWh, and an NPC of ₦620 million. Configurations C5 to C8 denote progressively less inexpensive alternatives, characterized by escalating NPCs, operating expenses, and LCOEs. Configuration C8, which depends solely on a single 30 kW CNG generator, serves as the baseline scenario. Its initial capital cost is ₦18 million, the lowest among options, although it incurs the highest total lifetime cost, with a net present cost (NPC) of ₦2.03 billion, a levelized cost of electricity (LCOE) of ₦1077/kWh, and yearly operational costs of ₦64.4 million. Configuration C8 may seem cost-effective at first due to its low initial capital cost, but the high operating expenses and LCOE make it the most expensive option in the long run. This highlights the importance of considering total lifetime costs when evaluating different configurations for energy generation.

The economic indices of the most profitable HRES is shown in Table 6. It indicates that the proposed system configuration has a present worth of approximately N417 million and an annual worth of about N34.8million. The system’s return on investment was estimated to be 22 %; the internal rate of return was estimated to be 25%; the simple payback was estimated to be 3.8 years period; while the discounted payback time was estimated to be 3.6 years period. Judging from this result, it can be seen that the cost of investment for this proposed hybrid electric power system can be recovered within four (4) years. This suggests that the proposed hybrid electric power system has a short time investment recovery period and proves to be economically viable.

Table 5: Comparison of different system configurations

Combination	Configuration	NPC (₦)	COE (₦/kWh)	Operating cost (~~N/Y~~)	Initial capital (₦ million)
C1	PV–CNGG100–CNGG30–BTB–CVT	417 Million	220	5.87	234
C2	PV–CNGG100–BTB–CVT	470 Million	249	8.13	216
C3	PV–CNGG30–BTB–CVT	556 Million	229	12.1	186
C4	PV–BTB–CVT	620 Million	328	14.5	167
C5	PV–CNGG100–CNGG30–CVT	1.26 Billion	665	35.1	159
C6	PV–CNGG30–CVT	1.04 Billion	743	41.3	111
C7	CNGG 30, CNGG 100	1.89 Billion	998	58.2 Million	66.1
C8	CNGG 30	2.03 Billion	1,077	64.4 Million	18.0

Table 6: Economic metrics of the proposed HRES

Metric	**Value**
Present worth (N)	417,458,700
Annual worth (N / year)	34,750,000
Return on investment (%)	22%
Internal rate of return (%)	25%
Simple payback (year)	3.8

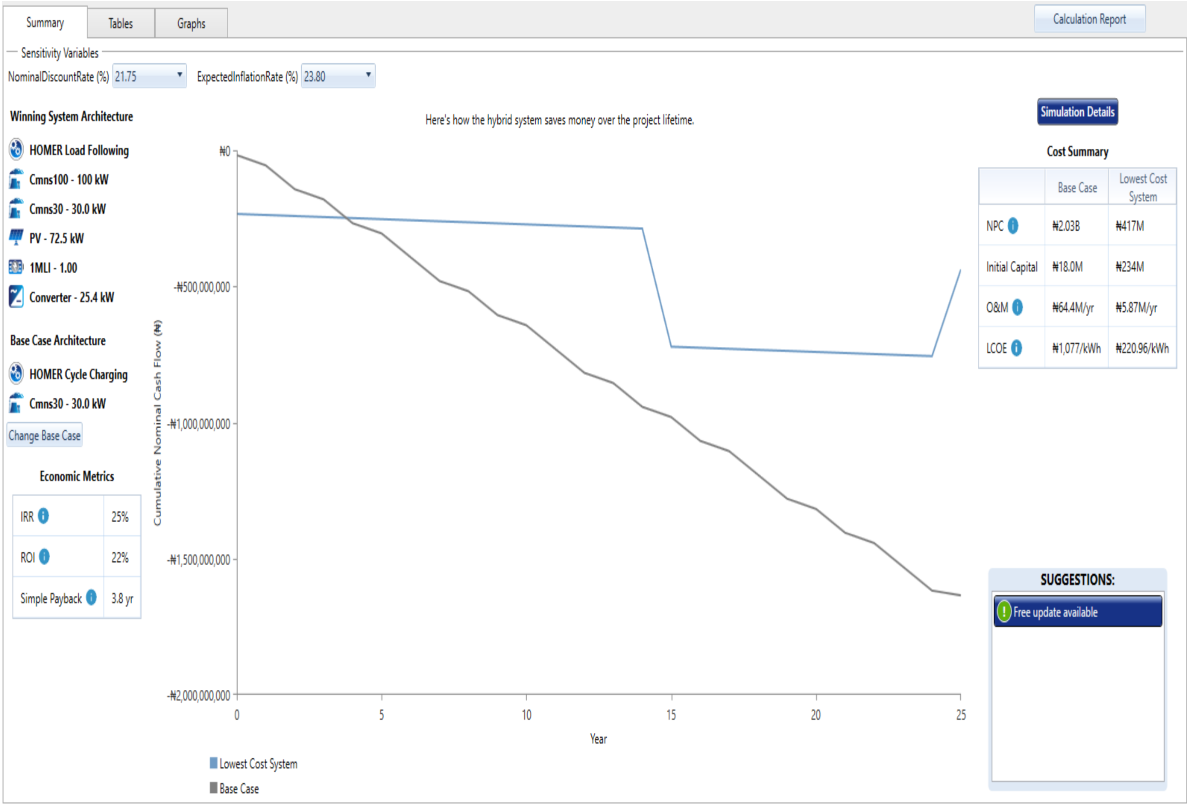
The economic indices of the base case (C8) and the lowest cost system (C1) were compared and result as shown in Table 7. A comparison of both cases as shown in the table indicates that the NPC of the base scenario is ₦2.03 billion, whereas the NPC of the lowest cost solution is ₦417 million. The lowest-cost system exhibits a significantly reduced overall lifetime cost in comparison to the base case. The initial cost of the base case is ₦18.0 million, while the lowest cost system is ₦234 million, demonstrating that the initial investment for the lowest cost system is considerably higher than that of the base scenario. The yearly operation and maintenance cost for the base case is ₦64.4 million, but the lowest cost system incurs ₦5.87 million; the much-reduced annual operation and maintenance expenses of the lowest cost system confer a long-term economic benefit over the base scenario. The LCOE for the baseline scenario is ₦1077 per kilowatt-hour, whereas the LCOE for the most economical system is ₦220.96 per kilowatt-hour. Demonstrating that the least expensive system is more economical and efficient over the long term.

Table 7: Summary of base case and lowest cost system

Parameter	Base case (₦)	Lowest Cost system (₦)
NPC	2.03B	417M
Initial capital	18.0M	234M
Operation and maintenance	64.4M/yr	5.87M/ year
LCOE	1,077/kWh	220.96.00/kWh

A summary of financial analysis of the base case and the lowest cost solution for a hybrid power system over a period of 25 years is presented in Fig. 4. It provides information about the economic performance of the hybrid system and potential cost savings. The y-axis represents the total accumulated nominal cash flow in Nigerian Naira (₦), while the x-axis represents the duration in years, ranging from 0 to 25. The graph displays two distinct curves. The gray curve represents the baseline scenario, whereas the blue curve indicates the most cost-effective system. The gray line shows a consistently low level of cost recovery throughout the 25-year period, leading to a high NPC. In contrast, the blue line represents a substantial initial investment but also significant cost savings over time, resulting in a substantially reduced NPC after 25 years. The most cost-effective system design comprises two generators, an array of solar systems, four units of 1 MW lithium-ion batteries, and a converter. However, in the basic scenario, only a generator is utilized. The base scenario consists of an NPC of ₦2.03 billion, an initial capital of ₦18.0 million, an O&M cost of ₦64.4 million per year, and an LCOE of ₦1,077 per kilowatt-hour. On the other hand, the lowest cost system has an NPC of ₦417 million, an initial capital of ₦234 million, an O&M cost of ₦5.87 million per year, and an LCOE of ₦220.96 per kilowatt-hour. The hybrid system yields a 25% internal rate of return (IRR) and a 22% return on investment (ROI), demonstrating a profitable investment with a payback period of 3.8 years.

The sensitivity analysis tests the system's reliability, performance, and responses to changes in discount and inflation rates. Fig. 4 depicts the sensitivity analysis for total net present cost at varying electricity prices and nominal discount rates. It indicates that as the discount rate increases from 21.75 % to 24.75 %, the total capital cost of the system increases from N401 M to N424 M at expected inflation rate of 23.8 %, and the total net present cost increases from N250 M to N390 M. It can be observed from Fig. 5 that an increase in the nominal discount rate will cause a correspondent increase in both the total net present cost and the cost of energy, with an equilibrium nominal discount rate of 22.75 %. It is also observed that while the cost of energy remains constant at varying nominal discount rates, the annual electricity consumption increases with increasing nominal discount rates, with an equilibrium nominal discount rate of 22.75 %. This suggests that the annual electricity consumption is also sensitive to the nominal discount rates. In other words, nominal discount rates affect the level of electricity consumption annually. Economic factors such as inflation and interest rates will tend to impact on the operating cost during the operation of the power system, thereby increasing the total cost of energy



Sensitivity Variables
NominalDiscountRate (%) 21.75
ExpectedInflationRate (%) 23.80

Winning System Architecture

- HOMER Load Following
- Cmns100 - 100 kW
- Cmns30 - 30.0 kW
- PV - 72.5 kW
- 1MLI - 1.00
- Converter - 25.4 kW

Base Case Architecture

- HOMER Cycle Charging
- Cmns30 - 30.0 kW

Economic Metrics

IRR	25%
ROI	22%
Simple Payback	3.8 yr

Cost Summary

	Base Case	Lowest Cost System
NPC	₦2.03B	₦417M
Initial Capital	₦18.0M	₦234M
O&M	₦64.4M/yr	₦5.87M/yr
LCOE	₦1,077/kWh	₦220.96/kWh

SUGGESTIONS:

Free update available

Fig. 4: Comparison between base case and lowest cost system

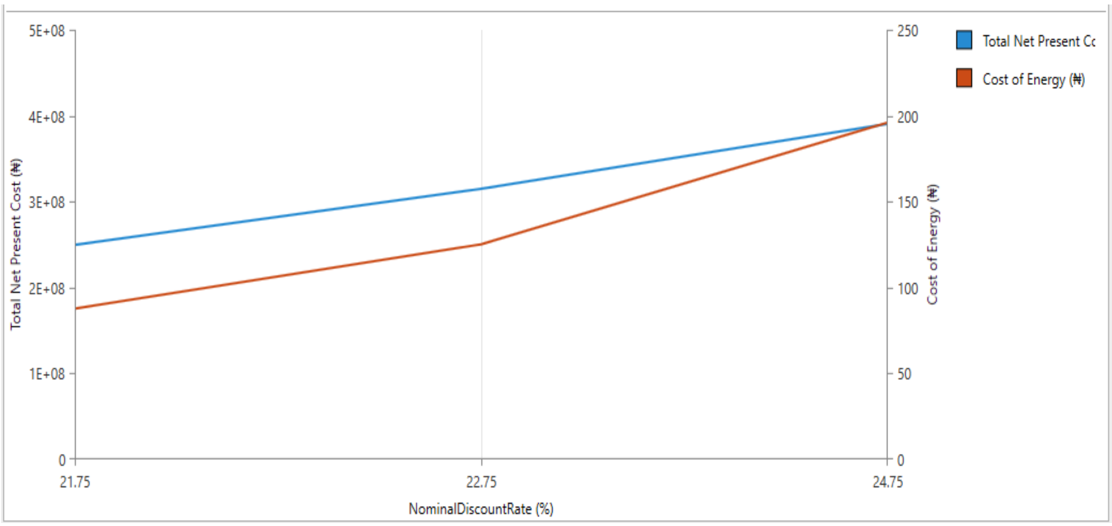


Fig. 4: Sensitivity analysis for total net present cost at varying cost of energy and nominal discount rates

Fig. 5 depicts the sensitivity analysis for cost of energy at varying nominal discount rates and fixed annual electricity consumption. The x-axis depicts the nominal discount rate, ranging from around 21.75% to 24.75%. The y-axis on the left side, which corresponds to the blue line, displays the cost of electricity in Nigerian Naira (₦). The orange line on the right y-axis depicts the yearly electricity consumption measured in kilowatt-hours (kWh). The blue line depicts the relationship between the cost of electricity and fluctuations in the nominal discount rate. As the discount rate rises, the cost of power also rises. This suggests that when assessed in terms of current value, greater discount rates result in a higher COE. The positive gradient of the blue line indicates that an increased present value of future costs, hence raising the COE. The orange line is horizontal, demonstrating that the annual electricity consumption is consistent regardless of the discount rates. This suggests that the fluctuations in energy prices are solely attributed to fluctuations in the discount rate, rather than changes in consumption. The increasing trajectory of the blue line emphasizes the responsiveness of electricity costs to changes in the nominal discount rate. When the discount rate increases, the cost of electricity also increases. This is because the higher discount rate reflects the higher cost of future expenses when they are discounted at a higher rate.

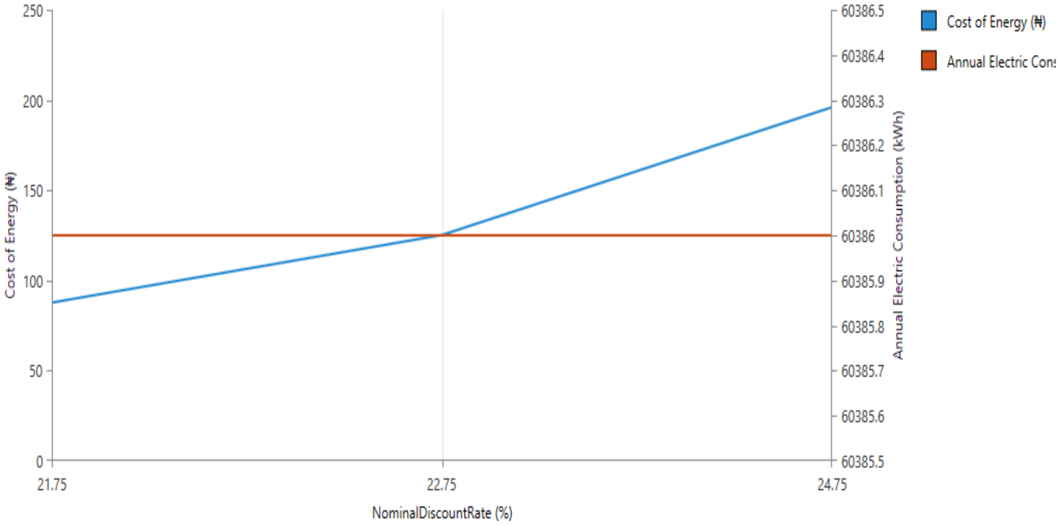


Fig. 5: Sensitivity analysis for cost of energy at varying nominal discount rate and fixed annual electricity consumption

4. Conclusion

The economic evaluation of the hybrid renewable energy system (HRES) suggested for the Nigerian Maritime University (NMU) clearly illustrates its financial viability. The ideal HRES configuration, which consists of two compressed natural gas generators (CNGG 100 and CNGG 30), solar photovoltaic panels, battery storage, and a converter, provides significant cost savings over the base scenario of just utilizing a generator to power the university. The research indicates that the ideal configuration has a net present cost (NPC) of₦417 million, whereas the base case scenario has an NPC of₦2.03 billion, representing a cost reduction of ₦1.613 billion throughout the system's lifespan. The ideal system has a payback period of 3.8 years and a significantly lower levelized cost of energy (LCOE) of ₦220.96/kWh, in comparison to ₦1077/kWh for the baseline scenario. The initial capital investment of ₦234 million exceeds the base scenario; however, it is mitigated by reduced yearly operational and maintenance costs of ₦5.87 million. Sensitivity study indicates that electricity prices exhibit more sensitivity to fluctuations in the discount rate compared to the nominal rate, underscoring the resilience of the HRES under diverse economic conditions. The proposed optimal HRES has a return on investment (ROI) of 22% and an internal rate of return (IRR) of 25%. In light of these findings, it is recommended that NMU adopt the HRES to secure a dependable and sustainable energy supply while realizing long-term cost savings of ₦1.613 billion. The implementation of this system will markedly enhance the university's energy reliability and environmental sustainability, establishing a benchmark for other institutions in Nigeria confronting energy supply challenges.

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