https://dx.doi.org/10.4314/dujopas.v10i4b.31
ISSN (Print): 2476-8316
ISSN (Online): 2635-3490
Dutse Journal of Pure and Applied Sciences (DUJOPAS), *Vol. 10 No. 4b December 2024*

A Techno-Economic Optimization of an Off-Grid System in Nigeria. A Case Study of Government Technical College, Eyagi, Bida

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Abstract

Prioritizing energy access for technical training institution is crucial for effective nation building. This is particularly important since most institution face challenges with unreliable power supply impending administrative, academic, practical and research activities thereby hindering their ability to provide quality education and training. This paper aimed to identify the most effective optimal configuration providing a cleaner ecofriendly environment of a Hybrid Renewable Energy System (HRES) of different combination of energy sources (Solar Photovoltaic(PV), Wind Turbine(WT), Diesel Generator(DG) and Battery System(BS)) capable of meeting the energy requirement of a technical institution in Niger State with a load demand of 453.97kWh/day and 56.280kW peak load demand while also providing benefits to the community. The HOMER Pro (Hybrid Optimization Model for Electric Renewable) software (Version 3.11) was used to stimulate and optimize system operation. The findings of the optimal hybrid system for the off-grid simulation ranked according to Net Present Cost (NPC) shows a substantial reduction in carbon dioxide emission when compared to conventional system. The convectional system has a NPC of $8,318,813.00 and a Levelized Cost of Energy (LCOE) of $0.908/kWh and the incorporation of solar PV and battery storage with the existing system to give the proposed optimal PV/DG/battery system capable of meeting the electricity demand with an annual average solar radiation of 5.49 kWh/m^2/day has reduce the NPC by 76.95% ($1,997,517.00) and the LCOE by 76% ($0.218/kWh). The study will serve as a blue print for the viability of generating electricity in promoting energy access, reduce emission and promote sustainable development.

Keywords: Renewable Energy, Hybrid System, Optimization, NPC, LCOE and Institution.

INTRODUCTION

Every nation's socioeconomic progress is fuelled and transported by its energy resources (Atoki *et al.,* 2020). Thus, the quality of essential services like health and education has been impacted by a lack of access to power (Dodo *et al.,* 2021). In order to preserve consistent growth and fortify human resources, education is a crucial instrument for any nation (Adetola, 2021).

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Energy poverty is still a serious issue in Nigerian technical institutions, posing additional difficulties that have made it harder for students to learn. Power outages have forced the cancellation or rescheduling of tutorial and practical class discussions (Adelakun and Olanipekun, 2020). Thus, in this region of our country, acquiring applied skills in technical institutions for the acquisition of practical and fundamental scientific knowledge seems unattainable due to insufficient power supply as modern technology has emerged, rendering outdated skills obsolete (Mbata, 2000).

Traditionally, these institutions have been powered by petrol and diesel generators; however, as a result of the worldwide increase in fuel prices, the majority of technical school activities have been rendered impossible because the school's operations rely heavily on fuel due to intermittent electricity (Kwa and Mahmud, 2018). The Central Bank of Nigeria (CBN) (Olalekan, 2020) estimates that Nigerians spend over $14 billion a year on fuel and generators, a sign that the country's power supply is not improving. The world is currently experiencing global warming largely due to pollution from fossil fuels which are injurious to animals and plants and also cause health problems in humans (Olatomiwa *et al.*, 2018; Yimen *et al.*, 2018). Hence, now is the ideal moment for this institution to more fully implement its renewable energy policy.

HOMER has been used in a number of studies to determine the best hybrid renewable energy system design for different locations and uses, cost of sustainable renewable energy for domestic utilization and techno – economic aspect of the hybrid renewable energy systems (Abodwair, 2023; Zereshkian and Mansoury, 2023; Taghavifar and Sadat, 2021; Bagheri *et al.*, 2019). For instance, Ohijeagbon *et al.* (2019) used Homer to design an optimal hybrid renewable energy system for providing sustainable power to isolated-grid communities in north central Nigeria. The results showed that, in Abuja and Makurdi, the hybrid generation system performed better than the standalone PV or wind energy system, while at Jos, the wind standalone system was the most effective generation technology. In an academic township in India, Baruah *et al.* (2021) assessed the techno-economic viability of a hybrid power system (HPS) for autonomous use. The system's resources included wind, solar, hydrokinetic, and syngas energy, as well as backup batteries; technical and economic data were sourced from the local Indian market. The HOMER analysis revealed that the hybrid wind-syngas–biogas–photovoltaic–hydrokinetic–battery energy system was the best combination, with an LCOE of 0.095 $/kWh.

In order to power a building at the University of Lagos in Nigeria, Babatunde *et al*. (2021) evaluated the use of battery storage with hybrid renewable power sources. According to their findings, the best setup for the location would involve a 70 kW PV, 40 kW converter, 70, 3000 Ah batteries and a diesel engine with 20 kW. An evaluation of off grid hybrid energy systems (HES) for a university campus was carried out by Khan et al. (2017). The stand-alone diesel generator (DG), wind turbine (WT)-BS, PV-BS system and PV, WT-BS were the four configuration possibilities that were taken into consideration in the study. The PV,WT-BS system, which had the lowest NPC (US$3,054,109) and LCOE (US$0.258), was found to be the most practicable system using the Hybrid Optimization of Multiple Energy Resources (HOMER) optimization process. A hybrid PV-DG-Battery Energy Storage (BES) system and an autonomous diesel generator (DG) system were assessed by Dodo et al. (2020) for a sustainable electricity supply to a Nigerian institution. In comparison to the suggested hybrid model, it was discovered that the standalone DG had higher operating costs (30.93%), NPC, and LCOE (50%) and released more harmful gasses (90%). The design, simulation, and optimization of a hybrid renewable energy system (HRES) for Bayero University Kano, Nigeria, was proposed by Shuaibu *et al.* (2019). The results demonstrate that the HRES, which consists of PV, diesel generators, wind turbines, batteries, and inverters, is the most efficient, economical, environmentally friendly, and reliable hybrid renewable energy system available. Technical institutions in Nigeria have unique load profiles compared to residential, commercial, and industrial loads, as reported by other literatures. As a result, the amount of specific literature available regarding the most advantageous combinations of renewable power opportunities in technical institutions of Nigeria is still limited for a relevant geographical area and this is due to government's lack of critical mass concerning electricity generation from renewable energy sources for these institutions. This research will use HOMER software to optimize the hybrid power system with the goal of presenting the optimal energy mix for the institution which will differ from other related studies in terms of application, scope, location, load demand and climate data related to renewable technology. The results of this study could help energy planners, policymakers and other stakeholders adopt renewable energy more quickly in technical institutes. This would help mitigate the effects of climate change and promote the use of renewable energy sources nationwide despite the huge amount of money being spent on diesel and petrol due to unreliable national grid's power supply to this institution which has greatly reduce the teaching resources such as internet facilities, workshop equipment and classroom materials to achieve the workforce for the purpose of initiating, facilitating and implementing technological development of a nation.

MATERIALS AND METHODS

Study Location

Government Technical College, Eyagi, Bida is a public combined junior and senior secondary school located in Nasarafu Banyagi in Bida local government area, Niger State, Nigeria having longitude and latitude of $9^{o}3.8N$, $6^{o}1.4E$. It is a technical institution under the management of Niger State ministry of education. The college awards certificate in both vocational and professional education and it has ten departments which are electrical, computer, electronics, building, furniture, motor vehicle mechanics, business, fabrication and welding, catering craft practices and garment making department. It has 35 classes, 13 offices, 4 workshops, 6 laboratories, staff quarters for teachers and hostel for students.

Proposed Model

The proposed model as shown in Figure 1 is made up of a PV system, a wind system, storage energy, diesel generators, an energy system converter and a load. The PV system is DC coupled, whereas the wind and DG are AC coupled. This allows the electricity produced by the PV DC component to be converted to AC, which reduces the amount of electricity produced by the diesel generator component, which in turn affects the levelized cost of energy by reducing fuel consumption system design parameter analysis. The National Electrical Renewable Laboratory (NREL) HOMER software program was utilized for the techno economic analysis of the proposed hybrid power system. Its three primary tasks are sensitivity analysis, optimization, and simulation and because of its versatility and capability in technical, economic and pollutant gas emission assessments, HOMER has become a prominent tool in HRES design (Malik *et al.*, 2022).

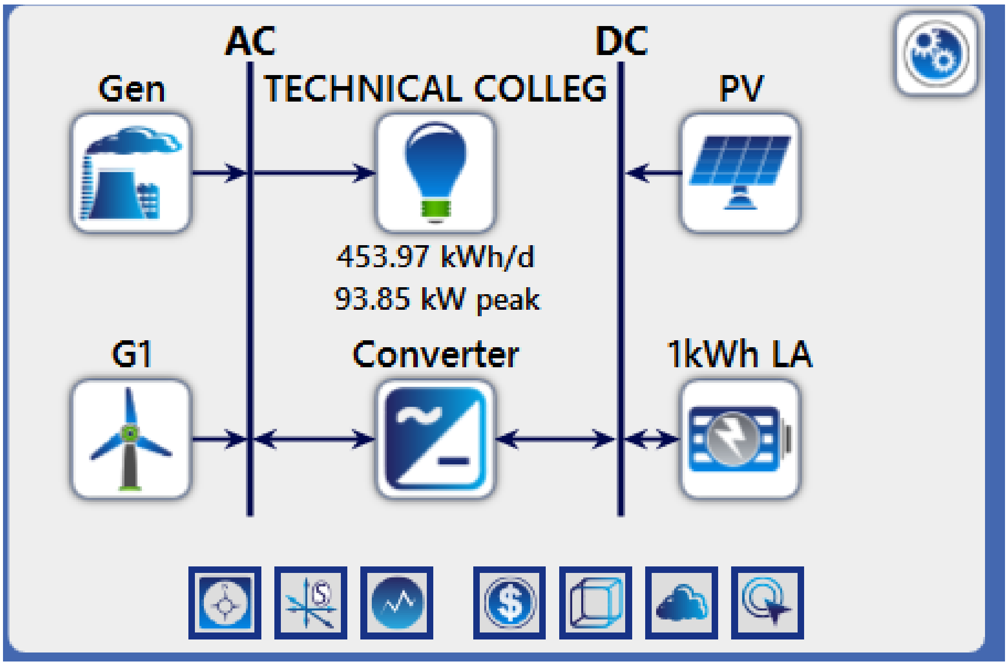

Figure 1: General Energy Simulation Model

Electrical load profile of the study location

The estimated load profile of the institution is expressed in terms of the amount, wattage and anticipated time spent using energy by each device. The Abuja Electricity Distribution Company (AEDC) Plc provides electricity to this area with a maximum peak load demand of 56.280kW in the early hours of morning, the institution uses 453.97kWh on average every day. The anticipated power system would fulfill the institution's whole daily load demands, ensuring a sustainable and dependable supply of electricity. Major load demand is shown to happen in the morning between 10 am and 2 pm and in the evening between 6 pm and 11 pm. This is because of the institution's setup, which involves workshop activities in the morning due to heavy machinery in the school and after work staff members start to return home in the evening with the evening peaking at 6 pm when multiple appliances are turned on and at 4 pm, most appliances are turned off because staff and students are gone for sports and other activities, so the load is minimal as shown in Figure 2. A 10% daily random variability and a 20% hourly random variability are specified in HOMER based on this variation. This is done to make sure that the hybrid system design is not underestimating the system's peak demand due to daily and hourly load variations.

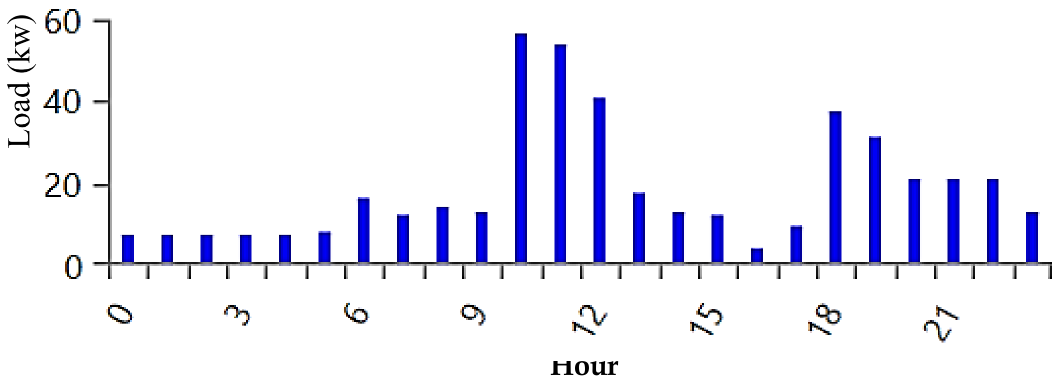

Figure 2: Daily variation of hourly load profile of government technical college Bida.

Renewable resources data of the study location

Every location has a different amount of RE resources available to it. The development of a hybrid renewable energy system depends on this. Climate and geographic location affect the potential of renewable energy sources (RES) such as solar and wind power. Temperature, wind speed, solar irradiance and clearness index are among the meteorological resource data that were analysed. These data were extracted from the National Aeronautics and Space Administration (NASA) database in the HOMER software tool covering over 22 years and their average monthly values are presented graphically in Figure 3 and Figure 4.

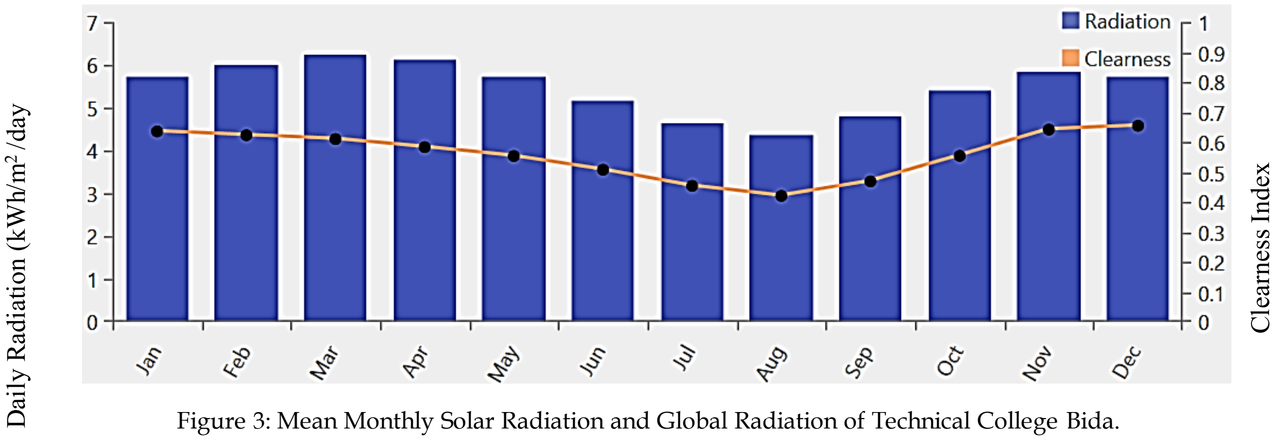

Figure 3: Mean Monthly Solar Radiation and Global Radiation of Technical College Bida.

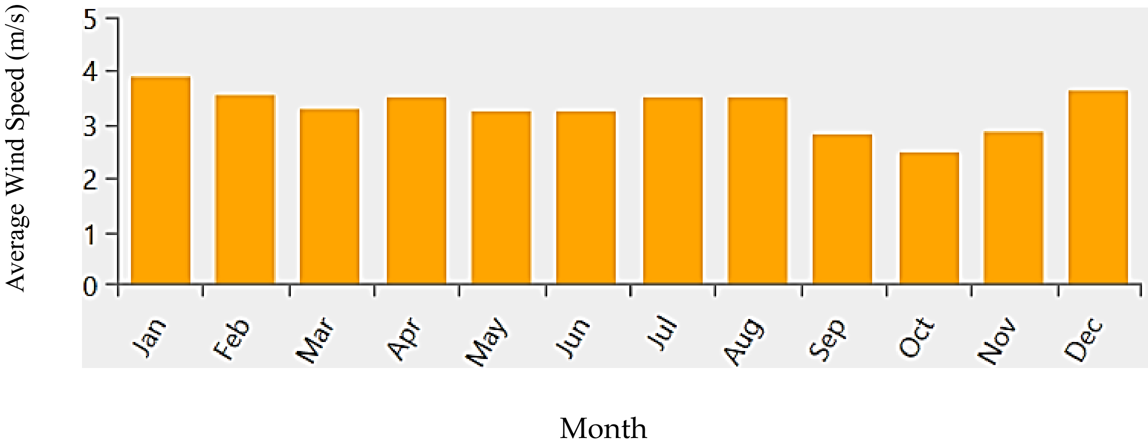

Figure 4: Yearly Mean Wind Profile

The annual average solar radiation is 5.49 kWh/m²/day indicating a significant amount of solar energy in the location. The results suggest that the location experiences bright cloud conditions throughout the year with high solar potential (Bashir *et al.*, 2022; Ndanusa *et al.*, 2014). The clearness index is highest from November to March, with a peak value of 0.654 in December and lowest clearness index value of 0.420 occurs in August, indicating a relatively lower amount of radiation during this month while the mean wind speed varies between 2.480m/s to 3.880m/s. In January, it is higher, while in October, it is lower. Literature (Olomiyesan *et al.*, 2017; Gimba *et al.*, 2019) further supports the idea that Bida is not a good fit for wind turbine applications or other wind energy initiatives.

Power components modeling

Solar photovoltaic array

The solar energy is the source of life on the planet. Solar energy is plentiful, clean renewable and sustainable energy resources which reach the globe in the form of radiation (Ndaceko *et al.*, 2014). The performance of any solar energy system in particular location largely depends on the amount of solar radiation received on a horizontal surface at that location (Nwokoye and Okonkwo, 2014). Series-parallel connections between the solar PV modules create an array or panel for the production of direct current, which is then inverted for the application of alternating current. The PV array output is calculated using Equation 1. This Equation ensures maximum output from the PV array system. (Ani and Abubakar, 2015).

$$P_{PV} = H_{PV}\, U_{PV} \left(\frac{V_T}{V_{T,STC}}\right)\left[1 + \beta_{P(T_C - T_{C,STC})}\right] \quad (1)$$

Where H_{PV} represent the PV array power capacity in kW. U_{PV} represent the derating factor of the PV. V_T and V_T, STC represent the incident solar radiation upon the PV array on kW/m^2 and based on standard testing conditions respectively β_P represent the coefficient of temperature based on power T_C, STC represent the cell temperature and that based on standard temperature conditions. A generic flat plate PV was considered for the design and it has a capital cost of $2,000/kW, a replacement cost of $2,000/kW, operation and maintenance cost of $5/year, derating factor of 80% and life time of 25 years with no tracking system and grand reflectance were taking as 20%. (Muhammed *et al.*, 2022).

Wind Energy System

The indirect kind of solar energy that the sun constantly replenishes is known as wind energy. The process of converting energy takes place when the abundant natural resource is used to produce power or electricity (Okedu, 2018). The wind potential is measured using the power law based on 10m height by the following Equations;

$$\left(\frac{W_2}{W_1}\right) = \left(\frac{Y_2}{Y_1}\right)^{\alpha} \quad (2)$$

Where W_2 represent the wind speed at height Y_2 and W_1 represent the wind speed at heightY_1. α represent the power law exponent. A generic 1kw wind turbine was chosen for the design and it has a capital cost of $3,200/kW, a replacement cost of $3,000/kW and operation and maintenance cost of $30/year (Dodo and Ashigwuke, 2023). A hub height of 17 meter, a life time of 20 years and cut in wind speed at 4m/s and a working speed between 4m/s to 24m/s. The wind turbine power curve is shown in the Figure 5 below.

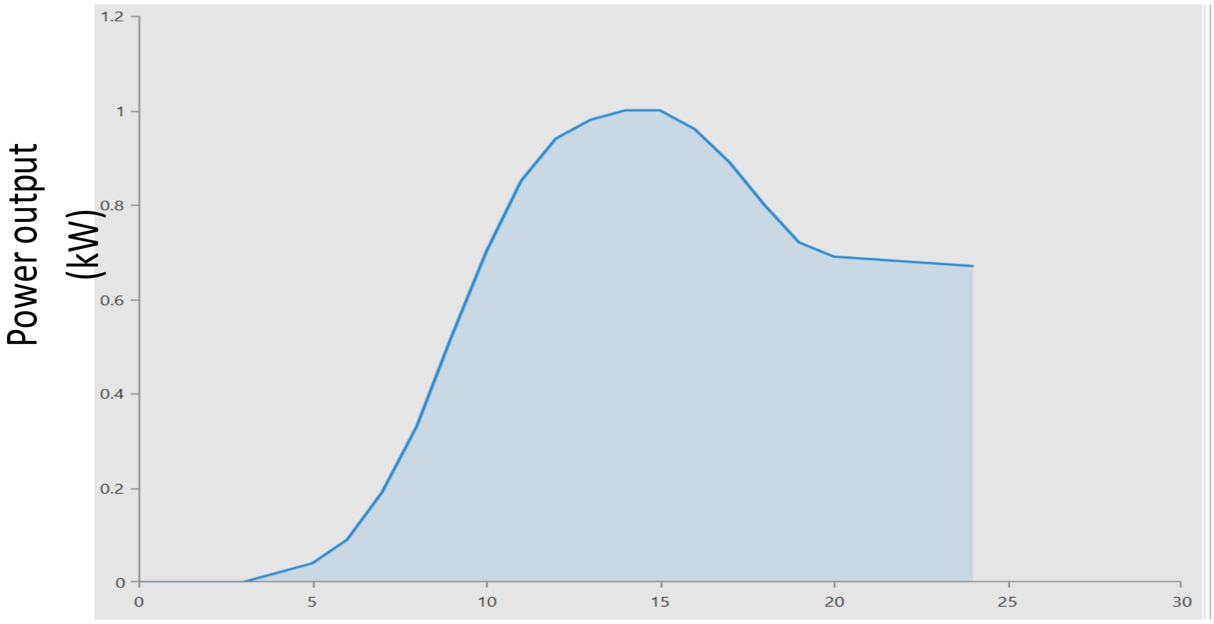

Figure 5: Wind turbine power curve

Battery Storage System

A hybrid energy system requires a lot of batteries because of the unpredictable nature of renewable energy sources and the variable weather, which cause the batteries' capacity to fluctuate continually. To store extra energy produced by renewable sources for use at a later time, a battery is necessary. When the energy production of the PV modules and the wind turbine exceeds the load demand, the battery begins to charge. For modelling a battery, it is essential to determine the capacity (kW) which is carried out by applying the following equation (Sinha and Chandel, 2018).

$$C_b = (E_l \times AD)/(n_{inv} \times n_{batt} \times DOD) \quad (3)$$

Where E_l is the average daily load energy (kWh/day), AD is the battery's days of autonomy (3-5 days). DOD is the battery depth of discharge while n_{batt} and n_{inv} are the battery and inverter efficiency respectively. Lead acid battery was chosen for the system due to its reasonable cost maturity and high performance over cost ration. A 12v nominal capacity voltage was selected with capital and replacement cost of $200/unit, operation and maintenance cost of $10/year (Dodo and Ashigwuke, 2023) with 1kWh nominal capacity, 80% roundtrip efficiency and 40% minimum state of charge is considered for this study.

Power converter

A converter is needed to maintain flow of energy between direct current (DC) and alternating current (AC). It functions as a rectifier when it converts AC to DC and as an inverter on the other way by converting DC to AC. The initial and capital cost of the converter were taken as $300/kw. The operation and maintenance cost are taken as $10/year, the efficiency of the converter is 95% while the life term span was 15 years (Rashid *et al.,* 2023).

Diesel generator

Renewable energy systems' ability to produce and supply electricity to meet energy demand is dependent on the prevailing weather conditions, which are characterized by intermittent output. As a result, diesel generators must be integrated with conventional power sources to guarantee continuous power output. The homer software applies the following Equation to obtain the generators fuel consumption as follows (Sinha and Chandel, 2018).

$$F = F_O Y_{GEN} + F_1 P_{GEN} \quad (4)$$

Where F_O represent the fuel curve intercept coefficient, Y_{GEN} is the generator rated capacity in kW, F_1 is the fuel slope curve and P_{GEN} represent the electric output in kW.

Hybrid Power System Economic

Power system planning requires the use of economic data such as fuel prices, inflation rates, replacement costs, capital costs, operation and maintenance (O&M) costs, etc. These statistics provide valuable economic indicators that aid in the HRES study. The life cycle cost is one of them; HOMER refers to it as the net present cost (NPC). All expenses incurred throughout the course of the project are covered by NPC. The levelized cost of energy (LCOE), which is the ratio of the system's yearly energy production to its total annualized cost, is another economic metric. The NPC and LCOE are expressed in equations (5) and (7), respectively (Dodo and Ashigwuke, 2023):

$$NPC_{Tot} = \frac{C_{ann,Tot}}{\boldsymbol{CRF}} \quad (5)$$

Where, CRF is capital recovery factor, and can be evaluated in terms of interest rate (i) and project lifetime (n) as:

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (6)$$

$$\text{LCOE} = \frac{NPC_{Tot}}{P_L(kW)/(8760h|yr)} \times \text{CRF} \quad (7)$$

In this study, the project lifetime is considered 25 years and the discount rate and inflation rate were taken as 6% and 12% respectively (Dodo *et al.*, 2022). For this system 100% reliability is required for the intended application, hourly load variation of 10% is considered in the simulation and 25% reserve is considered for PV panel output due to its inherent dependence on solar irradiance leading to unpredictable output.

RESULTS AND DISCUSSION

This study used the HOMER software to design power generation systems for electrifying Government Technical College, Bida. During the simulation, HOMER determined the optimal components combination to meet the electrical load demand of the study location and ranked the results in increasing NPC and COE values. Table 1 presents the optimization results of the institution which were extracted from HOMER output.

Table 1: The optimization results of the institution

System Architecture	PV (kW)	WT (kW)	Gen (kW)	BS 1kWhLA	Conv (kW)	NPC ($)	COE ($)	RF (%)
PV/Gen/BS/Conv	172		110	1080	90.3	$2.00m	$0.218	97.8
PV/WT/Gen/BS/Conv	172	1	110	1100	88.6	$2.00m	$0.219	97.7
PV/BS/Conv	425			1070	130	$2.51m	$0.275	100
PV/WT/BS/Conv	428	1		1060	135	$2.53m	$0.276	100
WT/Gen/BS/Conv		134	110	610	72.7	$4.88m	$0.533	7.02
Gen/BS/Conv			110	550	67.6	$5.15m	$0.562	0
PV/Gen/Conv	597		110		88.3	$6.49m	$0.709	5.95
PV/WT/Gen/Conv	596	1	110		90	$6.50m	$0.709	5.93
Gen			110			$8.32m	$0.908	0

In table 1 above, the uppermost row represents the characteristics of the systems in terms of component type, economic parameters and dispatch strategy. Each of the subsequent rows is treated as a case of an energy system to be considered for electrification and is determined through simulation. The system in the top row is the optimal one. About 5,635 solutions were simulated, out of these, 4273 were feasible and 1,362 were infeasible due to capacity shortage constraints since the system were modeled to have no capacity shortage. The hybrid renewable energy system that is best suited for the study location is a hybrid of PV/diesel/battery with a total initial capital cost of $620,303 and operating and maintenance costs of $24,917/yr for a 25-year period; it has a total net present value (NPC) of $1,997,517.00 and a levelized cost of energy (COE) of $0.218/kWh. Based on the results of the simulation, the configuration comprising 172kW of PV modules, a 110kW diesel generator, a 90.3kW system converter, and 1080 batteries is determined to be the most desirable option that can satisfy the technical institution's load demand. In this region, there is high solar radiation for clean energy facilities installation although the wind speed in the location is suboptimal (Olomiyesan *et al.*, 2017; Gimba *et al.*, 2019). According to Figure 6, the integrated system's total energy output from all RE sources is 280,272 kWh per year, of which 98.7% is attributed to the PV system. The remaining 1.30% is derived from the diesel generator and from this result the optimal hybrid system has reduced carbon and other pollutant emission, due to minimal use of the diesel generator, thus preventing environmental pollution and increasing the carbon credit.

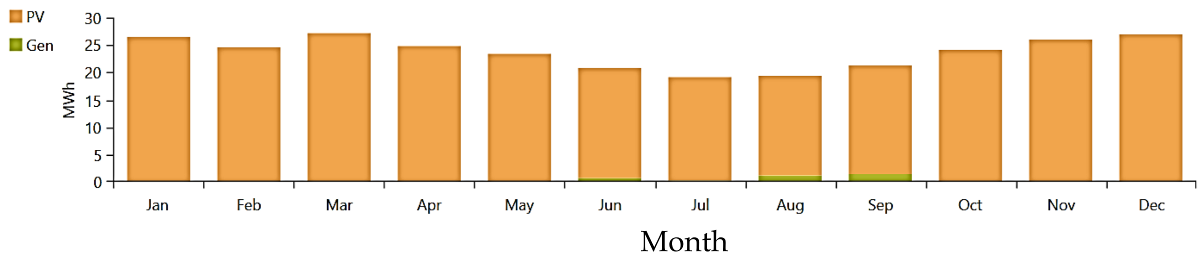

Figure 6: Hybrid Power System Electricity Production

In August and September, the diesel generator kicks in to meet the institution's demand due to the low potential of the RE source. This causes the batteries to run down to their minimum state of charge before the generator kicks in to supply the load and recharge the batteries. These months in the region is considered as rainy season months due to the large amount of rainfall during this period, hence cloudy sky leading to low solar radiation potential that adversely affects PV power production. Evaluating the current study alongside existing research is difficult due to varying renewable resources, system configuration and electricity demand. However, the levelized cost of energy and renewable fraction provide a useful basis for evaluating the performance of HRES. Notably, the optimal system in this study exhibits favorably LCOE and RF compared to other HRES as reported by Dodo et al. (2022) calculated a LCOE of $0.292/kWh and RF of 99.1%. Rashid et al. (2023) obtained an LCOE of $0.629/kWh for a PV/diesel/battery design and RF of 95%.

Comparison of the optimal hybrid system with the base system (Diesel alone)
The diesel alone system is the most cost-effective configuration in the study. It has a capital cost of $33,000, a replacement cost of $1,006,127.46, operation and maintenance cost of $1,917,358.21, a fuel cost of $5,414,612.37 and salvage value of $52,285.09. It has a total NPC of $8,318,813.00 at a diesel price of $1.0/L and the levelized cost of energy for the stand-alone diesel is $0.908/kWh. The annual mean electricity demand is estimated as 165,699kWh/yr and the diesel alone could generate 271,671kWh/yr with surplus electricity of 105,972kwh/yr which represents 39% of the annual electricity demand. When compared to the initial investment in a renewable energy source like a solar or wind system, the initial capital required to operate a diesel generator is often lower. The difficulty is in the high maintenance and running costs of the diesel generator, which are caused by the need to continually provide fuel, as well as the need for regular engine inspection and maintenance during the generator's operational life. Comparing the suggested ideal hybrid system to the diesel generator system alone, the system's net present cost has been lowered by more than 75%. Table 2 show the comparison of the optimal hybrid system with the base system.

Table 2: Comparison of the optimal system with the base system

System	Architecture	PV (kW)	Gen (kW)	BS (No.)	Converter (kW)	NPC ($)	Initial Capital ($)
Base system	Gen		110			$8.32m	$ 33,000
Proposed system	PV/Bs/Gen/Conv	172	110	1080	90.3	$2.00m	$ 620,303

Pollutant Emission Analysis
Generally, reduction of pollutant emission from power generating units has always been an important concern for researchers, scientist and government authorities. Table 3 shows the pollutant emission analysis for the optimal configuration in comparison with diesel alone system configuration.

Table 3: Pollutant emission analysis of the optimal system with the base system

Pollutant	Emission kg/yr Optimal System	Emission kg/yr Diesel Generator
Carbon Dioxide	3,562	256,430
Carbon Monoxide	22.5	1,616
Unburned Hydrocarbons	0.980	70.5
Particular Matter	0.136	9.80
Sulfur Dioxide	8.72	628
Nitrogen Oxides	21.1	1,518

From the given table the optimal hybrid renewable system configuration has curtailed over 98.6% of the total emission when compared to the diesel system alone. Based on this result, it can be observed that the optimal hybrid system has reduced carbon and other pollutant emission, due to minimal use of the diesel generator, thus preventing environmental pollution and increasing the carbon credit, maintenance cost and cost effective due to minimum running hours of the generator. It can be concluded that the optimal hybrid renewable system is the most effective strategy to adopt in addressing the high cost of fossil fuel-based electricity generation and it provides a clean energy to the environment as reported in a number of similar studies for sustainable renewable energy systems (Bishnoi and Chaturvedi, 2022; Singh and Basak, 2022; Abodwair, 2023).

CONCLUSION

The study explored the viability of an off-grid renewable energy in providing reliable power source to a technical institution in Niger state. The lack of electricity in this institution has crippled the institution ability to provide quality education and training which is essential for developing the skilled workforce needed to drive technological development and national progress. To this aim, the potential of solar and wind energy for the study location were analyzed followed by a comprehensive assessment of the techno-economic feasibility of the hybrid renewable energy system for electrifying the technical institution and the result finding of this study revealed that the selected site has sufficient monthly global solar irradiance for sustainable power but the wind energy is sub-optimal for sustainable power and the PV/diesel/battery storage system was found to be the most cost effective power system for the location with various cost indices being cheaper to diesel by as much as 76% and emission significantly reduce due to reduce fuel consumption of diesel leading to a lower carbon foot print and other poisonous gases. The implementation of the proposed hybrid renewable energy in technical training institution will lead to sustainable electrification of educational institution and provide a safer and healthier environment.

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