American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-13, Issue-1, pp-01-12
www.ajer.org
Research Paper Open Access

Assessing the Feasibility of grid-connected solar photovoltaic and wind turbine systems in diverse Nigerian climates

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ABSTRACT :*This study examines the technical and economic feasibility of utilizing grid-connected 10kW rated solar photovoltaic (PV) and wind turbine (WT) systems to meet the electricity needs of a modern residential building in four distinct climatic regions in Nigeria. HOMER Pro software was employed to conduct the analysis, leveraging the available renewable energy resources in each location. The study revealed significant variations in wind speeds, global solar radiation, and temperatures among the locations, as determined by the resource potential assessment. The annual energy output (AEO) differed based on the solar radiation potential of each location. For solar PV systems, Kano and Maiduguri exhibited the highest AEO, producing 18,999 kWh/year and 17,652 kWh/year, respectively. Conversely, the wind turbine (WT) systems indicated the highest AEO in Maiduguri at 20,322 kWh/year, followed by Enugu at 14,513 kWh/year, while Abuja recorded the lowest output of 5,557 kWh/year due to variations in wind speed potential. Notably, the implementation of PV systems in the buildings led to CO2 emission savings ranging from 23% to 40%, aligning with the expectations of the International Energy Agency (IEA). Similarly, WT systems achieved a broader range of CO2 savings, spanning from 16% to 42%. Financial analysis demonstrated the profitability of installing solar PV systems, with positive net present values (NPVs) in all locations. Kano exhibited the highest profitability with an NPV of $7,156, followed by Maiduguri with an NPV of $7,038, while Enugu had the lowest NPV at $5,186. The cost of electricity (COE) inversely followed the NPV trend, with Kano having the lowest COE at $0.1056/kWh and Enugu having the highest at $0.1154/kWh. Return on investment varied across locations, with a minimum of 12.9% in Enugu and a maximum of 15.4% in Kano. In contrast, the NPV for the WT system was negative in all locations, indicating that deploying a 10 kW WT for power supply in the buildings was not financially viable.*
KEYWORDS: *Renewable Energy, Economic Analysis, Solar Photovoltaic (PV), Wind Turbines (WT), Grid Integration.*

Date of Submission: 01-01-2024 Date of acceptance: 09-01-2024

I. INTRODUCTION

Access to reliable and affordable electricity is of utmost importance for driving economic growth, fostering social development, and enhancing the overall quality of life for individuals and communities [1,2]. However, in Nigeria, the current demand for electricity for the over 210 populace stands at a staggering 100,000 megawatts, while the available supply lags far behind at an average of approximately 4,000 megawatts [3]. This glaring disparity between demand and supply has resulted in persistent power outages, widespread energy poverty, and significant obstacles to industrial productivity [4].

The implications of inadequate electricity supply in Nigeria are far-reaching. Lack of access to reliable electricity hampers the functioning of essential services such as healthcare facilities, educational institutions, and businesses, thereby hindering socio-economic progress [4]. To address these pressing challenges and pave the way for a sustainable energy future, it is imperative to explore and adopt renewable energy power sources that can significantly augment the electricity supply to buildings across the country. Renewable energy technologies offer promising solutions by harnessing abundant and environmentally friendly energy resources [5,6]. These technologies, such as solar photovoltaic (PV) systems, wind turbines, biomass, and hydropower, provide viable alternatives to conventional fossil fuel-based power generation [1,7,8]. The potential of renewable energy resources is high in Nigeria but not being utilised maximally as can be seen in Table 1.

Table 1. Nigerian Renewable Energy potential [9]

Resource	Potential	Current Utilisation
Wind	2–4 m/s (10 m height mainland)	N/A
Small Hydropower	3500 MW	64.2 MW
Large Hydropower	11,250 MW	1900 MW
Solar	4–6.5 kWh/m^2.day	15 MW (dispersed solar PV)
Biomass	Municipal Waste	0.5 kg/capita.day
	Energy Crops	28.2 million hectares of arable land (8.5% cultivated)
	Fuel Wood	43.4 million tonnes/year

Nigeria has an annual average wind speed of 4.570 m/s in the Northern region and 2.747 m/s in the Southern region at a height of 10 m [10, 11]. On solar radiation, Nigeria is endowed with intensive sunshine, with an average of 6.25 h per day, ranging between 9.0 h in the far Northern boundary and about 3.5 h in the coastal areas. The implication is that Nigeria receives average solar radiation of about 12.6 MJ/m2 /day (724 kWh/m2) at the Southern coastal latitudes and about 25.2 MJ/m2 /day (1653 kWh/m^2) in the far Northern part of the country, giving the mathematical average as 18.9 MJ/m2 /day. This translates into a PV power potential of 1248 kWh/kW$_p$ in the South and 1756 kWh/kW$_p$ in the North [12].

The global pursuit of sustainable and resilient energy solutions has become a defining feature of the 21st century. Nations worldwide are confronted with the challenge of transitioning from conventional, fossil fuel-dependent energy systems to cleaner, renewable alternatives [13, 14]. Nigeria, with its abundant renewable energy resources, has the potential to harness renewable energy solutions, specifically solar PV and wind turbine systems, to address its energy challenges and pave the way for a sustainable energy future. In recognition of this potential, a lot of studies on single and hybrid solar based power systems have been carried out by numerous authors [15–20]for Nigeria. However, a comprehensive evaluation and comparison of both solar PV and wind turbine standalone systems based on a unique climatic conditions in Nigerian locations (Enugu, Abuja, Kano, and Maiduguri) remains greatly unexplored. To fill this gap, this research investigated the feasibility of stand-alone grid-connected solar PV and wind turbine systems in diverse Nigerian climates, shedding light on the potential for a renewable energy revolution in the nation, and contributing to the global transition towards a sustainable energy future. To achieve this aim, the research is guided by the following specific objectives:

1. To carry out the solar and wind speed resource assessment of the chosen climatic regions.
2. To determine the annual energy output (AEO) of solar PV and wind turbine systems in each location.
3. To assess the carbon dioxide (CO_2) emission savings associated with the integration of PV and WT systems in the selected regions.
4. To evaluate the economic viability of installing solar PV and wind turbine systems in the location.

II. REVIEW OF SOLAR AND WIND ENERGY POTTENTIALS IN NIGERIA

Solar energy, in particular, holds immense potential in Nigeria. Situated near the equator, the country enjoys abundant sunshine throughout the year, making solar power an attractive option for electricity generation. According to the Nigerian Meteorological Agency (NIMET), Nigeria; Africa's biggest economy is endowed with annual daily sunshine that averages 6.25 hours. Based on the land area of the country and an average of 5.535 kWh/m2/day, Nigeria has an average of 1.804 × 1015 kWh of incident solar energy annually. This annual solar energy insolation value is about 27 times the nation’s total conventional energy resources in energy units. This means Nigeria has boundless opportunities to tap from the power of the sun for energy. [21, 22].

In addition to solar energy, Wind energy is another significant renewable energy resource in Nigeria. The country has substantial wind potential, particularly in coastal regions and northern states [23]. Wind turbines can convert the kinetic energy of the wind into electrical energy. Nigeria's wind resources can be harnessed to establish wind farms, which can contribute to the diversification of the country's energy mix and enhance its energy security. Wind speed potential varies across different states in Nigeria, with certain regions showing great potential for wind energy as shown in Fig.1. Table 2 shows the variations of solar radiation and wind speed in four geographical regions of Nigeria

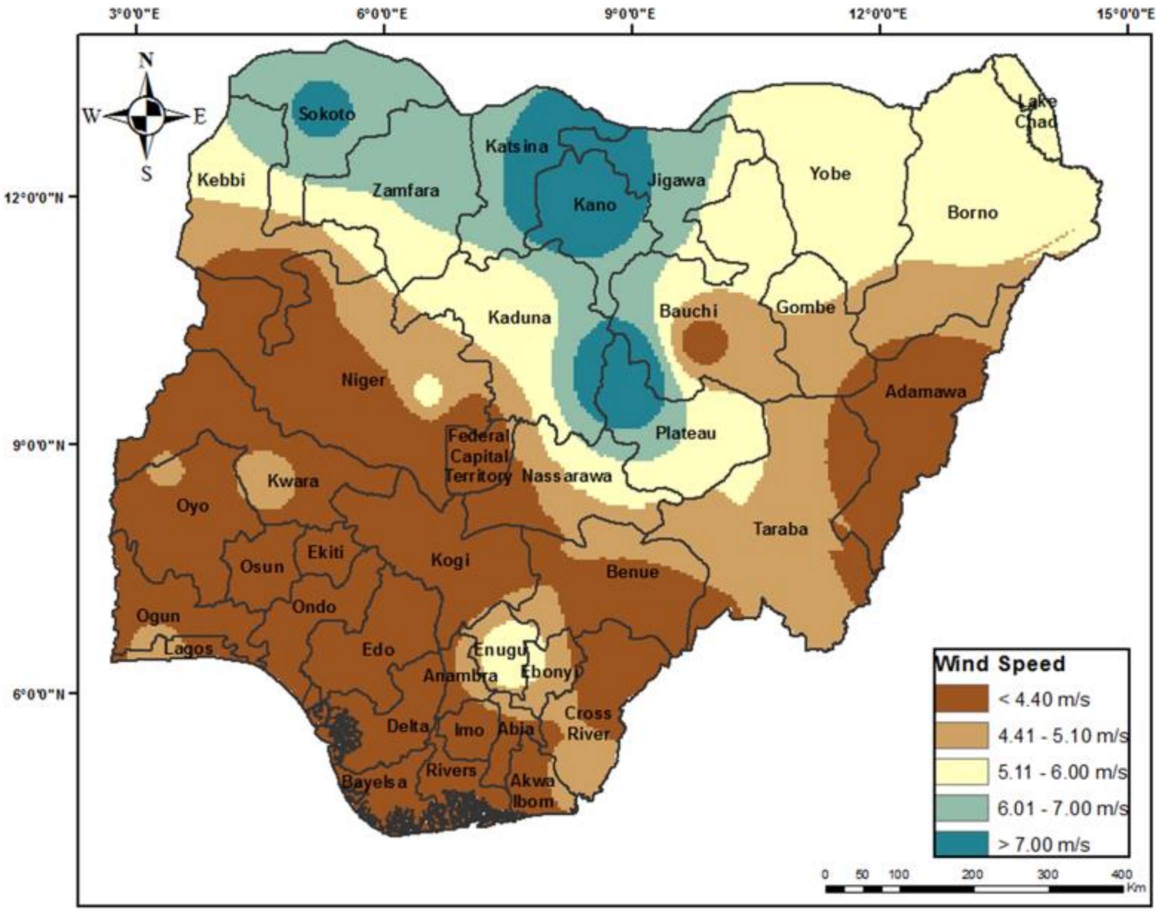


Fig. 1: Wind speed value for states in Nigeria[23]

Table 2. Average solar radiation and wind speed in some zones in Nigeria

S/N	Zone	Solar irradiance ($kWh/m^2/d$)	Sun hours (h/d)	Wind speed (m/s)
1	North Central (NC)	5.32 – 5.72	6.0	< 4.0 – 6.0
2	North East (NE)	5.73 – 6.24	5.5	4.4 – 6.0
3	North West (NW)	5.73 – 6.24	5.0	6.0 – 7.5
4	South East (SE)	4.83 – 5.3	5.0	< 4.4

III. METHODOLOGY

The methodology for evaluating the feasibility of grid-connected solar photovoltaic (PV) and wind turbine (WT) systems in diverse Nigerian climates follows a comprehensive four-step process. This method entails the selection of study locations, data collection and load assessment, energy generation analysis and environmental impact assessment, along with an economic feasibility analysis. The research integrates field data collection, simulation, modeling, economic analysis, and environmental assessment. The detailed methodology is as follows:

3.1 Study area

Four specific locations with diverse climatic conditions in the four Geopolitical zones of Nigeria were chosen for the study, offering a localized and region-specific analysis. The chosen locations with their geographical coordinates is summarised in Table 3.

Table 3. The Geographical Coordinates of the case-study Sites.

S/N	Geopolitical Zone	Sites	Latitude (^oN)	Longitude (^oE)
1	South East (SE)	Enugu	$6^{\circ}26.9'$	$7^{\circ}30.8.9'$
2	North Central (NC)	Abuja	9.27	7.03
3	North West (NW)	Kano	12.05	8.53
4	North East (NE)	Maiduguri	11.85	13.08

3.2 Data Collection and load assessment

The historical meteorological and climatic data for each selected location, encompassing solar radiation, wind speed, temperature, was obtained from the NASA database in HOMER Pro for the locations. Table 4 summarised the data for the locations.

Table 4. Mean monthly average wind speed, solar radiation and temperature

Month	Wind speed (m/s)				Global solar radiation (kWh/d/m^2)				Air Temperature (°C)			
	Enugu	Abuja	Kano	Maiduguri	Enugu	Abuja	Kano	Maiduguri	Enugu	Abuja	Kano	Maiduguri
Jan	3.83	4.58	5.81	4.58	5.68	5.88	5.49	5.61	24.02	23.49	20.850	23.35
Feb	3.76	4.18	5.85	4.18	5.74	6.09	6.33	6.3	25.68	25.6	23.670	26.16
Mar	4.14	3.68	5.48	3.68	5.57	6.27	6.79	6.7	26.6	27.31	27.560	29.98
Apr	4.4	3.6	4.65	3.6	5.25	6.06	6.96	6.62	26.62	27.17	30.640	32.77
May	4.18	3.31	4.18	3.31	4.94	5.58	6.76	6.36	26.16	26.08	31.140	32.77
Jun	4.55	3.3	4.19	3.3	4.54	5.06	6.42	5.97	25.29	24.99	29.870	30.94
Jul	5	3.57	3.77	3.57	4.14	4.44	5.81	5.43	24.6	24.04	27.800	28.17
Aug	5.03	3.55	3.21	3.55	3.91	4.19	5.41	5.14	24.58	23.78	26.400	26.61
Sep	4.41	2.9	3.23	2.9	4.19	4.73	5.67	5.57	24.78	24.33	26.720	27.23
Oct	3.65	2.66	3.65	2.66	4.57	5.31	5.9	5.89	25.05	24.77	26.580	28.22
Nov	2.83	3.4	4.72	3.4	5.11	5.98	5.72	5.84	25.27	24.2	23.900	26.16
Dec	3.33	4.34	5.58	4.34	5.46	5.86	5.27	5.35	23.92	23.11	21.160	23.64
Avrg	4.09	3.59	4.53	5.5	4.93	5.45	6.04	5.9	25.21	24.91	26.4	28

A typical unit three bed modern family house in Nigeria had been assumed as a representative housing for load analysis. The load in the building consist typically of lighting fixtures and small power consumption gadgets as shown in Table 5. The electric load of the building was estimated based on the appliance ratings and duration of use each day according to the following equation:

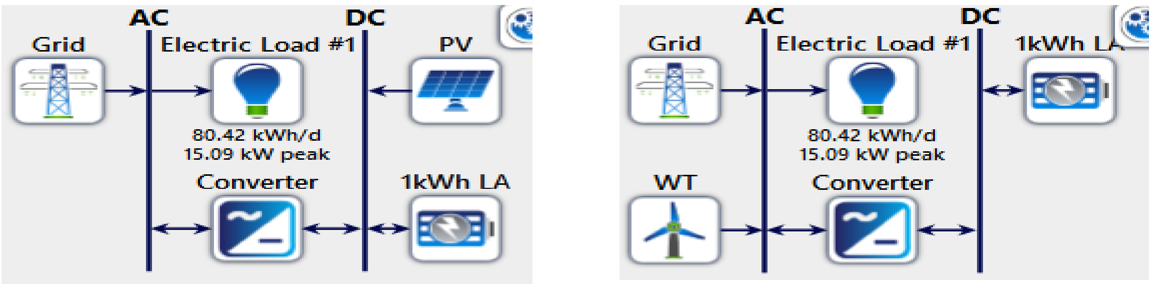
$$Load = No\ of\ Fixtures \times Power\ Consumption\ per\ Fixture \times duration\ of\ use \quad (1)$$

Table 5. Average Electric load demand of a unit 3-bed modern family house [24]

Appliance	No	Rating(W)	Duration of use (hours/day)	Load (kWh/day)
Lights (LED)	10	15	8	1.2
32 Inch LED TV	3	60	5	0.9
Air-Conditioner (1HP)	3	746	3	6.714
Standing Fan	3	70	3	0.63
Fridge / Freezer	1	400	8	3.2
Small Toaster	1	750	0.5	0.375
Washing Machine	1	600	0.285	0.171
Small domestic Water Pump	1	746	0.285	0.21261
Total				**13.40261**

3.3. Energy Generation Analysis

HOMER Pro software tool was employed to conduct simulations and optimisation for energy generation potential of solar PV and wind turbine systems in each location. These simulations incorporate local climate patterns, Technical parameters, system specification/costs, and performance characteristics. In the HOMER Pro has inbuilt-modules for electric load, power components, and energy resources that were utilized for the modelling and optimisation of the power systems based on the resources occurring the each location. The monthly demand load of the hypothetical modern building was imported into the load module of the HOMER Pro software. The respective system configurations, as depicted in Fig. 2 (a and b), were the set up using the appropriate in-built power generating components and ancillaries, such as PV, WT, Battery bank (BB), Converter (Conv), and grid.



(a) PV system **(b) WT system**

Fig. 2. Configuration of solar PV and WT system in HPMER Pro

The energy resources required by the power generating components, such as ambient temperature, solar irradiation, and wind speed specific to the study areas, were obtained from the inbuilt library of NASA meteorological data in HOMER Pro for the selected site. The technical specifications of the different components of the hybrid renewable energy system (HRES), including costs and the combined dispatch strategy, were inputted into the HOMER software. HOMER was then utilized to optimize the systems for the site, aiming to minimize the net present cost (NPC).

3.3.1 Design of Solar PV

Solar energy is harnessed through the conversion of sunlight into electricity through the use of solar cells in solar panel. This system is called Photovoltaic (PV) system. The direct current (DC) required to be generated by the PV system to meet the load can be estimated as follows:

$$P_{array} = \frac{E_{load}}{PSH \times \eta_{system}} (kW) \tag{2}$$

Where PSH is peak sun hour, The System conversion efficiency (η_{system}) is a product of the Temperature loss efficiency (η_{Tl}), Inverter efficiency (η_{inv}), and battery efficiency (η_{B3})The PV module area (A_{module}) required is determined from:

$$A_{array} = \frac{P_{array}}{I_P \times \eta_m} \ (m^2) \tag{3}$$

Where η_m denote the module or PV efficiency and $\boldsymbol{I_P}$ is the maximum normal surface irradiance (1 kW/m^2) [25]. The Number of Panels required to meet the load can be estimated as follows:

$$\text{Number of Panels} = \text{Array size } (P_{array}) \times 1000 \ / \ \text{Solar Panel rating (W)} \tag{4}$$

The actual power generated by the PV panels depends on solar radiation and ambient temperature. With these, the power that can be harnessed using solar PV panel is calculated as follows:

$$P_{PV}(t) = H_G(t) \times A_{PV} \times \eta_{mp} \tag{5}$$

Where $P_{pv}(t)$ is the power output from the PV-panel (W), $H_G(t)$ is the total solar irradiance data at time t (W/m^2), A_{pv} is the area of a single PV-panel (m^2) and η_{mp} represents the PV generator efficiency and is given as [4]:

$$\eta_{mp} = \eta_{mp,STC} . \left[1 + \alpha_P \left(T_C - T_{C,STC}\right)\right] \tag{6}$$

Where, α_P denote the temperature coefficient of power and $\eta_{mp,STC}$ and $T_{C,STC}$ are the max power point efficiency and cell temperature under standard test conditions (25°C) respectively. The cell temperature (T_C) is calculated from the ambient temperature (T_a) and the incident irradiation as follows:

$$T_C = T_a + .\bar{G}_T \left(\frac{T_{c,NOCT} - 20}{0.8}\right)\left[1 - \frac{\eta_{mp}}{0.9}\right] \tag{7}$$

Where = $T_{c,NOCT,}$ *and* η_{mp} denote the nominal operating cell temperature (°C) and the efficiency of the PV array at its maximum power point (%).

3.3.2 Wind Turbine (WT)

Based on the wind resource available at the specific location and the power curve characteristics of the chosen wind turbine model, HOMER utilizes a linear interpolation to calculate the output power (P_{WT}) of the wind turbine at intervening points. In the absence of the power curve, the following three-step process can be used to calculate the output power (P_{WT}) of the wind turbine (WT) in each time step:

$$P_{WT} = N_W \times \sum_i f_i(v) P_{WT,i}(v_{hub}) \quad \times \frac{\rho}{\rho_0} \tag{8}$$

$$P_{WT}(v_{hub}) = N_W \times \frac{1}{2}\rho A {v_{hub}}^3 Cp(\lambda, \beta)\, \eta_m \eta_G \tag{9}$$

$$v_{hub} = v_{anem}\left(\frac{h_{hub}}{h_{nem}}\right)^{\alpha} \; or \; v_{anem}\frac{\ln\left({h_{hub}}/{h_0}\right)}{\ln\left({h_{anem}}/{h_0}\right)} \tag{10}$$

Where N_W is the number of WT; $f_i(v)$is the probability of duration at site wind speed v; $P_i(v_{hub})$ is the hub height power production from the turbine from its power curve at the time i (kW), ρ is the actual air density (kg/m^3); ρ_0 *is*the air density at standard temperature and pressure (1.225 kg/m^3); α is the wind shear coefficient for the site and h_0 is the surface roughness length (m), η_m *and* η_G is the mechanical and generator efficiency of the WT; $C_p(\lambda, \beta)$ is the power coefficient which is determined by the WT blade angel (β) and the tip speed ratio (λ) and A is the swept area of the WT blades (m^2) [4].

3.4 Economic Analysis

The financial performance of the systems in the locations are analysed using the following economic indicators:Simple Payback (SPB), Discounted payback period (DPB), Return on investment, Net present cost (NPC), cost of electricity (COE) and present worth or net present value (NPV).

3.4.1 Payback period

The Simple payback period (PBP) measures the time it takes for the energy savings to payback the initial cost of the project. It can be estimated as follows:

$$PBP = Estimated\ project\ cost \,/\, Estimated\ energy\ saving\ per\ period \tag{11}$$

3.4.2 Return on Investment (ROI)

Return on Investment (ROI) evaluates the profitability of the investment relative to its cost. It can be calculated as follows:

$$ROI = \frac{Net\ profit}{Cost\ of\ investment} \times 100 \tag{12}$$

3.4.3 Net present cost (NPC)

The Total Net Present Cost (NPC) represents the total present value of costs associated with a project or investment. It takes into account all the expenses and costs related to the investment over its entire lifetime, accounting for factors like operating costs, maintenance, initial investment, and any other relevant expenses. NPC is calculated by summing up all these costs after discounting them to their present value using a chosen discount rate as follows [26]:

$$NPC = \frac{CF_n}{(1+d)^n} \tag{13}$$

Where CF is cash flow (costs-revenue) and d is real discount rate. Inflation is factored out of the analysis by using the real discount rate. If the cash flow is constant every year of the plant life, the NPC is simply estimated by the using the capital recovery factor (CRF) as follows:

$$CRF(\$) = \frac{\times (1+d)^N}{(1+d)^N - 1} \tag{14}$$

$$d = \frac{r-e}{r+e} \tag{15}$$

Where; C_A is the total annual cost ($); *CRF* is the capital recovery factor; *n* is the annual project lifetime; *N* is the number of years; *d* is the annual real interest rate (%); *r*, *is* the nominal interest rate; *e* is the annual inflation rate.

3.4.4 Net Present Value (NPV)

The Total Net Present Value (NPV) takes into account both costs and revenues or cash flows associated with an investment. It represents the total present value of the projected cash inflows (revenues, savings, earnings) minus the present value of all outflows (costs, expenses, investments). Before tax NPV is calculated by discounting all these cash flows to their present value using a chosen discount rate as follows:

$$NPV = \sum \frac{CF_n}{(1+d)^n} = CF_o + \frac{CF_1}{(1+d)^1} + \frac{CF_2}{(1+d)^2} + \cdots . + \frac{CF_N}{(1+d)^N} \tag{16}$$

Where CF_0 = the cash flow at time zero (Initial investment), CF_n = the cash flow at time period n (Energy savings), d = the discount rate (Based on risk of project), n = time period of cash flow from time zero (Number of years).

NPV after tax can be calculated as follows [27]:

$$NPV = (1 - Tax)\{Rev_{PV} - (F_{PV} + O\&M_{PV} + R_{PV})\} - T \times Dep_{PV} - I_{PV} \tag{17}$$

Where Rev_{PV}present value of all revenues is in year n, F_{PV} is the present value of fuel cost,$O\&M_{PV,}R_{PV}$ is the present value of O&M cost, and $Dep_{PV}$is the present value of depreciation expense.

3.4.5 The Internal Rate of Return (IRR)

Internal Rate of Return (IRR) is the intrest rate that makes the NPV equal zero.

$$NPV = -CF_0 + \sum \frac{CF_n}{(1+IRR)^n}) = 0 \tag{18}$$

3.4.6 Cost of Electricity (COE)

Cost of electricity (COE) is the average cost of energy generated by the system. It can be expressed as the net present value of total life cycle costs (TLCC) of the project divided by the quantity of annual energy produced (AEP) over the system life as follows [28]:

$$COE = \frac{TLCC}{\left({}^{AEP_n}/_{(1+d)^n} \right)} \tag{19}$$

The TLCC for a commercial or industrial investor can be estimated as follows [27]:

$$TLCC = \frac{I + \sum_{n=1}^{N} \frac{Dep}{(1+d)^n} \times T + \sum_{n=1}^{N} \frac{Annual\ costs^n}{(1+d)^n} \times (1-T) - \frac{Residual\ value}{(1+d)^n}}{\sum_{n=1}^{N} \frac{AEP}{(1+d)^n} \times (1 - system\ degradation\ rate)^n} \tag{20}$$

$$TLCC = [I + (1 - Tax)\{O\&M_c + R_c + F_c\} - Tax \times Dep]_{present\ value} \tag{21}$$

Where I is investment cost at year zero, T is tax rate, $O\&M_c$ is operation and maintenance, R_c is replacement cost, F_c is fuel cost and AEP is energy output or saved in year, n; d=discount rate and N = analysis period. For a utility sector the TLCC is divided by (1-Tax) to arrive at the before tax revenue required to cover all costs. Tables 6 and 7 show the technical and cost parameters of the PV and WT architectures. The lifetime of the project is assumed 25 years, at a nominal (real) discount rate of 25% (8.7%) and an expected inflation rate of 15%.

Table 6. Technical parameters

System	Parameters
PV	Rated capacity 10 kW
	Derating factor 80%
	Efficiency 95%
WT	Rated capacity 10 kW
	Cut in speed 4 m/s
	Rated speed 14 m/s
	Cut out speed 25 m/s

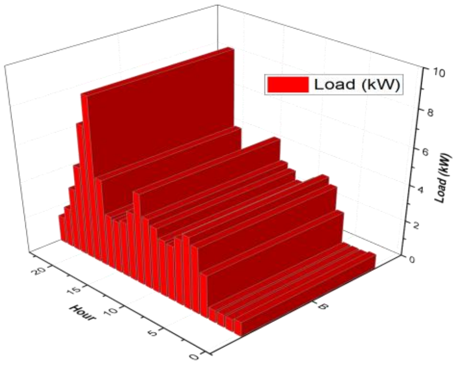
Table 7. Cost parameters of the system [4]

Components	parameter	Specification
	Capital cost ($/kW)	600
PV	Replacement cost ($/kW)	500
	O&M ($/kW/yr)	10
	Lifetime (yrs)	25
WT	Capital cost ($/kW)	2000
	Replacement cost ($/kW)	1750
	O&M ($/kW/yr)	10
	Lifetime	20
	Capital cost ($/unit)	168
Battery	Replacement cost ($/unit)	168
	O&M ($/kW/yr)	10
	Lifetime (yrs)	10
	Capital cost ($/kW)	300
Converter	Replacement cost ($/kW)	300
	Lifetime (yrs)	15
Grid tariff	Tariff ($/kWh)	0.14

IV. RESULTS AND DISCUSION

This paper reports on a comprehensive technical and economic evaluation and comparison of both wind turbines (WTs) and solar PV standalone systems (SPVs) connected to the grid for firming energy supply in a hypothetical modern buildings of six household cluster in different Nigerian geographic locations (Enugu, Abuja, Kano, and Maiduguri).

The electrical load demand of a building and the quantity and variability of the energy resources (Solar, wind, biomass and temperature) determines the size of power system (PV and WT) that can be installed to meet the load. Based on the load analysis carried out in this work, the average electrical load demand of a modern 3 bedroom household (having modern gadgets) with a kitchen, living and dining areas in the analyzed location is 13.40 kWh/day per household. The determined daily hourly load variation of profile is presented in Fig. 3, while the monthly load profile is presented in Fig. 4.



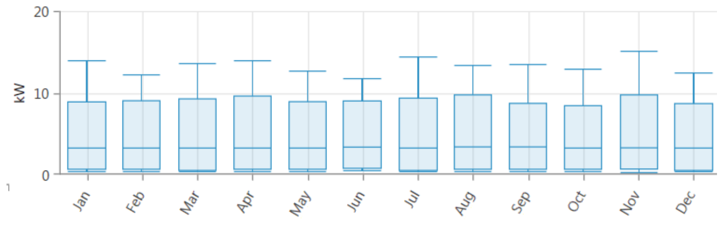


Fig. 4.Monthly load profile

Fig.3. Daily load profile

Based on the six household clusters considered, the total electric alternating current (AC) load demand required to be served is 80.42 kWh/day or 29,353 kWh/year, with a peak load reaching 15.09 kW and a load factor of 0.22. The grid CO2 emission to meet the load is about 18,551 kg/yr. Table 8 presents system sizing results for the WT and PV power system considered for meeting the loads in a grid mode for the four locations in this study.

It can be observed that for the same PV capacity of 10 kW for the different locations, the mean power output, capacity factor (CF), renewable fraction (RF), hours of operation and CO2 emissions varies based on the location. The mean solar PV output is highest (2.05 kW) in Kano closely followed by Maiduguri (2.02 kW) and least in Enugu (1.05 kW). The annual energy output (AEO) mirrors this trend, with Kano generating the highest (17,999 kWh/year) and Enugu producing the least (8,876 kWh/year). This variation is attributed to differences in solar radiation and clearness index among the locations. Locations with higher solar radiation exhibit more operating hours, leading to higher capacity factors compared to those with lower solar resources, thus making power plants installed in the locations with lower solar resource potentials to buy more power from the grid when compared to the ones installed in the locations with higher resource potential.

For WT systems, the trend in annual energy output differs. Maiduguri records the highest AEO (20,322 kWh/year), followed by Enugu (14,513 kWh/year), and Abuja with the lowest (5,557 kWh/year). This discrepancy is due to varying wind speed potential, with Maiduguri having the highest (5.5 m/s) and Abuja the lowest (3.59 m/s). Interestingly, despite Kano having a higher average wind speed of 4.53 compared to Enugu's 4.09 m/s, Enugu's AEO (14,153 kWh/year) exceeds Kano's (12,123 kWh/year) due to the smaller standard deviation of the average wind speed in Enugu (0.65) compared to Kano (0.98).

Table 8. Technical results of 10 kW rated systems

Location		Conv rating (kW)	Mean output (kW)	CF (%)	AEO (kWh/yr)	Grid purchases (kWh/yr)	RF (%)	CO_2 emission (kg/yr)	excess power (%)	Hours of operation (hrs/yr)
Enugu	PV	4.55	1.01	10.1	8,876	22704	28.1	14,349	0	4,487
	WT		1.66	16.6	14,513	19499	37.4	12,323	6.64	
Abuja	PV		1.85	18.5	16222	18768	40.7	11,862	7.68	4471
	WT		0.634	6.34	5,557	24788	18.3	15,666	0	5685
Kano	PV		2.05	20.5	17,999	18,038	44	11,400		4,449
	WT		1.38	13.8	12,123	21,078	36.5	13,322	0	6,715
Maiduguri	PV	4.97	2.02	20.2	17,652	18,121	43.5	11,453	8.24	4361
	WT		2.32	23.2	20,322	17134	54.3	10,828	0	7,348

*CF: Capacity factor, RF: Renewable Fraction, AEO: Annual energy output

Since the system is connected to the grid, any shortfall in the load demand is met by electricity supplied from the grid. As it can be seen from Table 8 the grid purchased electricity varies inversely with the AEO in all the four locations. The hourly and monthly power contribution of the grid and the solar PV/WT in meeting the load of the buildings varies across the locations. A typical plot for the hourly and monthly power contribution of the grid and the solar PV/WT in meeting the load of the building in Enugu and Maiduguri is depicted in Fig. 5 and 6 respectively.

The minimum and maximum percentage of PV supplied electricity occurred in Enugu and Kano/Maiduguri respectively which is 43% and 50 % while in the WT system, it is 28.1 and 54.3 % in Enugu and Abuja respectively. The CO2 emission from the considered systems is far much lower than the CO2 emitted by the grid to supply the load which stands at 18,551 kg/yr. The CO2 emitted by the PV systems varies from a minimum value of 11,400 kg/year in Kano to a maximum value of 14,349 kg/year in Enugu. This means that implementing the PV systems in the buildings could lead to percentage CO2 emission savings of 23 to 40%. Similarly the use of the WT systems in the locations leads to a minimal and maximal CO2 emissions of 10,828 kg/year and 15,666 kg/year in Maiduguri and Abuja respectively. This is equivalent to percentage CO2 savings in the range of 16 to 42 %.

Table 4.2 summarizes the financial benefits of integrating the analyzed grid systems (WTs and solar SPVs) to stabilize energy supply in various geographic locations for the studied building type. Factoring in the estimated load for the six building clusters and the current operating costs for grid electricity supply standing at $4,109 per year, the installation of either the proposed solar PV or WT systems in the buildings is projected to lower operating costs, depending on the location and the power plant installed.
A positive NPV highlights the profitability of employing solar PV for commercial power generation in the four locations. Kano demonstrates the highest profitability with an NPV of $7,156, followed closely by Maiduguri at $7,038. Enugu trails with the least profitability at an NPV of $5,186. The Cost of Electricity (COE) mirrors an inverse trend, ranging from the lowest in Kano (0.1056 $/kWh) to the highest in Enugu (0.1154 $/kWh). The observed COE aligns with the average COE currently charged to residential consumers in Nigeria, ranging from $0.14 to $0.17 per kWh.

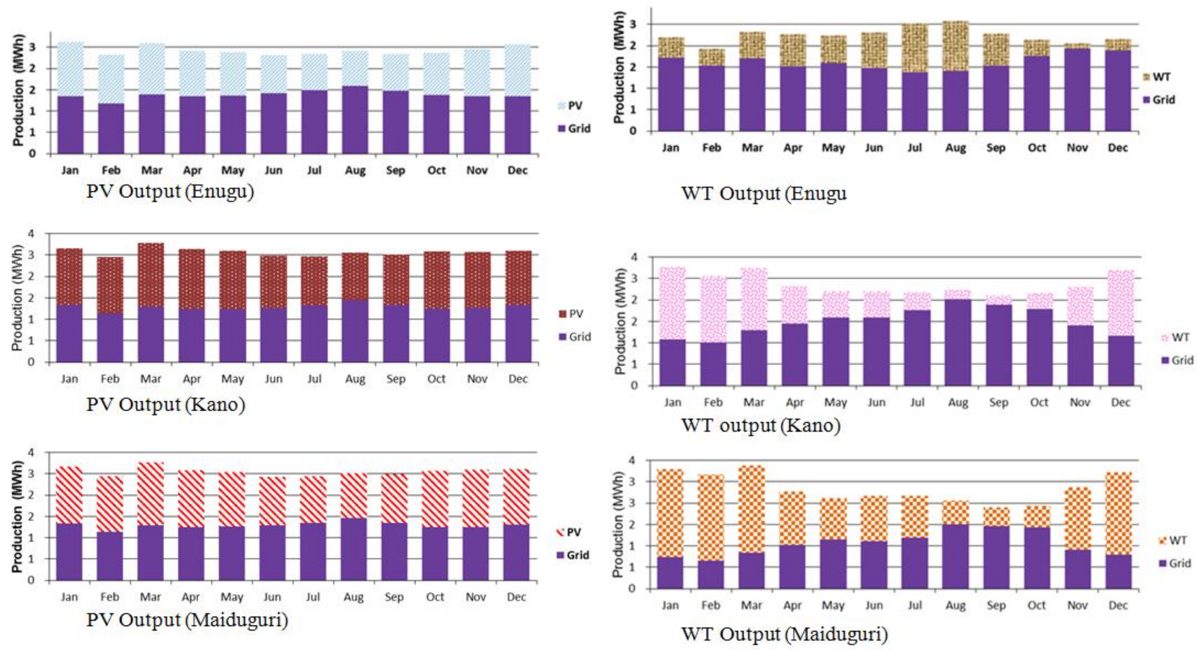


Fig.5. Monthly generated power in the locations

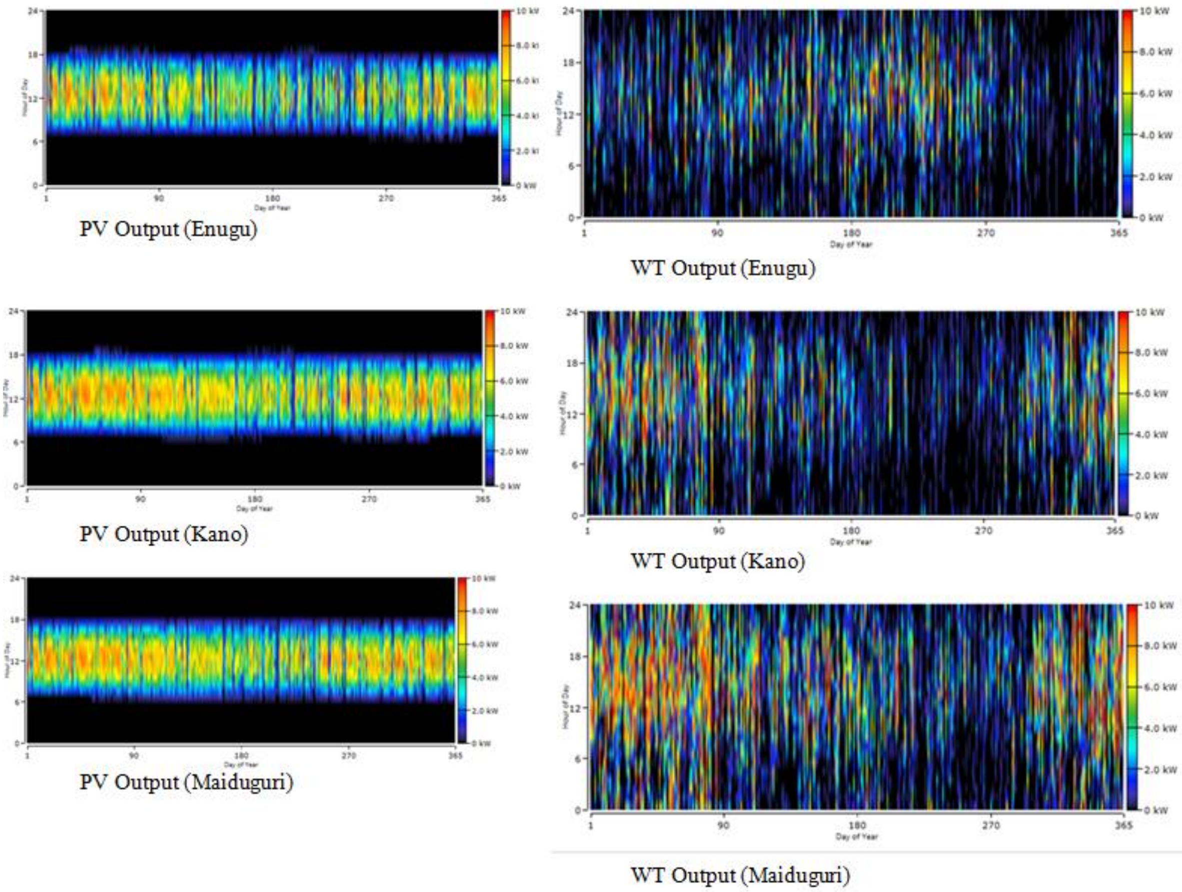


Fig. 6. Hourly output of the generators

V. CONCLUSION

In conclusion, this research paper focused on the comparative analysis between solely using 10 kW grid connected wind turbine (WT) or solar photovoltaic (PV) systems for firming electric power supply to six three-bedroom household clusters in four different geographic location in Nigeria. The resource potential assessment revealed varying wind speeds, global solar radiation, and temperatures across the different locations studied.

The technical results highlighted the electrical load demand of a modern three-bedroom household and the quantity and variability of energy resources, which influenced the sizing of the power systems. The average electrical load demand for a three-bedroom household was determined to be 13.40 kWh/day per household, with a total alternating current (AC) load demand of 80.42 kWh/day or 29,353 kWh/year for the six-household cluster.

For the solar 10 kW rated PV systems, the mean power output and annual energy output varied based on the location's solar radiation potential, with Kano and Maiduguri exhibiting higher values of 18,999 kWh/year and 17,652 kWh/year respectively. In contrast, the 10 kW rated wind turbine (WT) systems showed the highest annual energy output in Maiduguri (20, 322 kWh/year), followed by Enugu (14,513 kWh/year), with Abuja having the lowest output (5,557 kWh/year) due to variations in wind speed potential.

The CO2 emissions from the considered systems were significantly lower than the emissions from the grid supply. Implementing PV systems in the buildings resulted in CO2 emission savings ranging from 23% to 40%, while the use of WT systems led to CO2 savings in the range of 16% to 42%.

Financial analysis demonstrated that the installation of the 10 kW rated solar PV systems was profitable, with positive net present values (NPVs) observed in all locations. Kano had the highest profitability (NPV of $7,156), followed by Maiduguri (NPV of $7,038), while Enugu had the least (NPV of 5,186). The cost of electricity (COE) inversely followed the trend of NPV, with Kano having the lowest COE (0.1056 $/kWh) and Enugu the highest (0.1154 $/kWh). The return on investment varied across locations, with a minimum value of 12.9% in Enugu and a maximum value of 15.4% in Kano.

In contrast, the NPV for the 10 kW rated WT system was negative in all locations, indicating that deploying a 10 kW WT for power supply in the buildings was not profitable.

Based on these results, it is recommended that future research focus on improving the financial viability of the systems especially the WT systems and exploring hybrid systems that combine both wind, solar and other related technologies to maximize renewable energy generation and cost-effectiveness. Additionally, conducting more detailed studies on the environmental impacts and long-term performance of these systems would provide valuable insights for sustainable energy planning and decision-making in Nigeria

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