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Design of Optimal Hybrid Renewable Energy System for Sustainable Power Supply to Isolated-grid Communities in North Central, Nigeria

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Abstract

The study analyzed the feasibility and techno-economic viability of renewable electricity generation from wind and solar standalone systems, and as hybrid facilities in six states across North-central, Nigeria. 24 years' daily solar and wind data were sourced from the Nigeria Meteorological Department, Oshodi. The dataset was analyzed and employed to design an alternative RE power supply system as a test case for university communities with an equivalent consumption of 28.9 MWh/day. The electricity load demand adopted was based on an audit of electricity generation conducted for the University of Lagos main campus. The supply architecture adopted in this study excludes the use of heavy equipment or machinery loads and only caters for the institutions' base loads. An evaluation of the design that will optimally match the daily load demand of the communities with LOLP ranging from 1 to 50% was undertaken. HOMER software was employed as the optimisation tool together with other statistical and analytical variations to determine best design for the sites with diesel standalone facility taken as the base system. The outcome showed that hybrid generation system fared better than the standalone PV or Wind energy system at Abuja, Ilorin, Lokoja and Makurdi, while the wind standalone system was the optimal generation technology at Minna and Jos. Further to this, values of the levelized cost of energy showed that adopting wind resources (as standalone or in hybrid format with PV) for power generation at the sites/institutions at Minna and Jos, is more viable than the use of diesel generators.

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Keywords: Energy; Power; Solar; Sustainability; Wind

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1.0 Introduction

Over the past two decades, Nigeria has put mechanisms in place to improve her gross energy poverty. Such mechanisms include the progressive increase in the installed generation capacity over the past decade. However, there are identified challenges in the nation's energy sector which are mainly infrastructure related and include underdeveloped natural gas resources, insufficient gas transmission networks, and old and dilapidated electrical transmission system. This has given rise to the citizenry seeking alternatives to meet their energy needs at a higher cost per kWh via the use of diesel and petrol generators. Lack of access to quality and adequate modern energy can significantly undermine the thrust to attain sustained economic growth, regional and global market competitiveness, unemployment reduction and poverty alleviation [1]. The nation's academic sector which is key to providing cutting edge research in science and technology for an improved growth in technological advancement and global competitiveness has not been spared. Government owned tertiary institutions have to depend on fossil-based generators to meet their energy demand as they are no longer assured of a specific quota assigned to them as was the case prior to the unbundling and privatisation of the then Power Holding Company of Nigeria in 2013. Based on this, power supply to the nation's tertiary institutions has dwindled and has grossly affected research output and administrative efficiency. Most of government owned tertiary institutions depend on fossil-based generators, while those that cannot afford such depends on the inadequate supply from the grid. To this end, an energy audit was conducted at the University of Lagos, Nigeria to ascertain the cost burden that alternative power from diesel generators has on the federal University [2]. The energy sources selected were the different grid systems of 132/33/11 kV substations and power from captive cummings diesel generators. The study found that the University spent about USD 1,048,500 per month on power generation, out of which 71.21% were expended on diesel generator use and the rest on grid supply. Scaling up this cost over a year shows that the University spent over USD 12.58 million on providing electricity. This is a high cost given the financial demand that is involved in building a University to its required standard in all spheres of academic and institutional endeavour. Aside this cost is the related cost of environmental degradation associated with the greenhouse gases (GHGs) emitted from a typical diesel generator. This cost connection places a huge burden on the environment when the hours of use and emission of carbon dioxide and other GHGs are considered. Hence, to improve the energy supply of such communities as a University, it is worthwhile to diversify the energy system to include embedded/microgrid generation from renewable resources of which wind and solar have been found as veritable source of sustained power supply. However, to generate power from renewable energy (RE) sources require the first step of resource assessment to ascertain the feasibility and economic viability of such generation. Moreover, a University community, despite its dynamism and differentiated lifestyle, is a typical modern community that can be used as a test case for budding modern cities. Hence, with Nigeria having a vision of becoming one of the top 20 economies by the year 2020 with energy as central tool of achievement [3], suggests that there would be several budding modern cities spread across the geopolitical zones of the nation. Therefore, studies that showcases the viability of employing RE resources for power generation in such budding cities spread across Nigeria will be a welcome idea, more so, knowing that RE resources, especially wind, are variable in time and space. Thus, this study analyzed the techno-economic viability of renewable electricity generation from wind and solar standalone systems, and as hybrid facilities in six states across North-central, Nigeria based on a test case design for university communities with an equivalent consumption of 28.9 MWh/day to cover base load for the purpose of comparison amongst the site locations. The electricity load demand adopted was based on the electricity audit conducted by Dada *et al*. [2] for the University of Lagos main campus.

2.0 Materials and Method

The 24 years' (1987 – 2010) historical daily wind speed data at 10 m height, sunshine hours, minimum and maximum air temperature, and minimum and maximum relative humidity that were employed for this study were sourced from the Nigeria Meteorological agency (NIMET), Lagos, Nigeria. However, due to the limitation of being able to access complete data set, especially of daily global solar radiation, a model (equation (1)) developed by Ajayi *et al*. [4] was employed to generate the corresponding average daily global solar radiation over Nigeria. The model is suited specifically to Nigeria, captures the nation's unique climate and seasonal fluctuations and is less site dependent.

$$H = a\cos\phi + b\cos n + cT_{max} + d\left(\frac{\bar{n}}{N}\right) + e\left(\frac{\bar{n}}{N}\right)^3 + f\left(\frac{T_{max}}{R.H}\right) + g\left(\frac{T_{max}}{R.H}\right)^2 + h\left(\frac{T_{max}}{R.H}\right)^3 + i\cos\phi.\cos n + j\left(\frac{T_{max}}{\cos\phi}\right) + k\cos^2 n + l$$

where: ϕ = Location Latitude (^{0}), $\bar{n}$= the daily sunshine hours, N = maximum sunshine duration or day length, T_{max} =Maximum daily temperature (^{0}C), n = day number in the year, R.H. = daily relative humidity, and a, b, c, d, e, f, g, h, i, j, k, l, m are correlation coefficients (or constants).

2.1 Research Methodology

The geographical locations of the selected sites for the study are as shown in Table 1. 6 Federal universities located in North-Central, Nigeria were selected from six states. The sourced and modelled renewable energy resource dataset was analysed for use in designing an alternative RE power supply system as a test case for university communities with an equivalent consumption of 28.9 MWh/day for comparison amongst the site locations. The electricity load demand adopted was based on an audit of electricity generation conducted for the University of Lagos main campus. The daily average electric load profile is presented in Figure 1. The supply architecture adopted in this study excludes the use of heavy equipment or machinery loads and only caters for the institutions' base loads. An evaluation of the design that will optimally match the daily load demand of the communities with LOLP ranging from 1 to 50% was undertaken. HOMER was used for the multi-objective optimisation [5] together with other statistical and analytical variations to determine best design for the sites with diesel standalone facility taken as the base comparison system.

Table 1. Geographical locations of the studied sites

City	State	Latitude (° N)	Longitude (° E)
	Plateau	9.9167	8.9000
Ilorin	Kwara	8.5000	4.5500
Abuja	FCT	9.0667	7.4833
Lokoja	Kogi	7.8167	6.7500
Makurdi	Benue	7.7333	8.5333
Minna	Niger	9.6167	6.5500

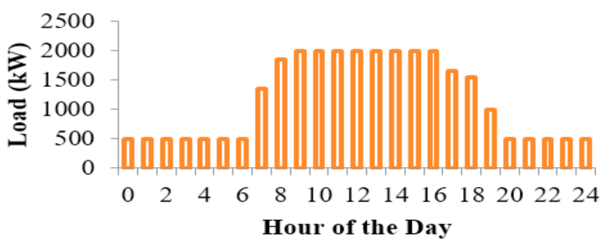

Figure 1: Average Daily Load Profile (kW) based on the experimental results of base load estimated at the University of Lagos Dada *et al*. [2]

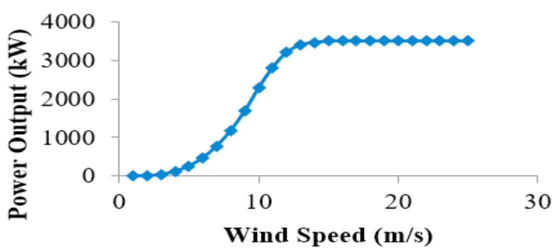

Fig. 2: Power curve for the Enercon E-101 E2 [3.5MW] Wind turbines [5]

Cumulative Enercon E-101 E2 [3.5 MW] Wind turbines, cumulative SunPower solar cells, and 5 CAT diesel generators of 550kVA (440 kW) were employed for the study as standalone or hybrid power systems. Cumulative Tesla batteries of 210 kWh nominal capacity at 380 V, 131 A and roundtrip 88% efficiency [5] was also utilised in the study. The Enercon turbine specification engaged for the study is indicated in Table 2 and the power curve is as shown in Fig. 2.

Table 2: Turbine specification [5]

V_c (m/s)	V_{Fi} (m/s)	V_{Fo} (m/s)	V_R (m/s)	P_{eR} (kW)	Available Hub Height (m)	Rotor Diameter (m)
2	2	28-34	15	3500	74	101

V_c = cut-in wind speed, V_{Fi} = low wind cut-out speed, V_{Fo} = high wind cut-out speed, V_R = rated wind speed, P_{eR} = rated power at rated wind speed.

The specification of the solar panel with a collector area of 1.6 m^2 rated at 335 W by SunPower [6] that was used in this research is presented in Table 3. Therefore, to suite the load demand, the solar collector area increases while other factors in Table 4 remain constant. Table 4 reveals components' cost as used in the design of the Energy Systems, with the installation costs embedded within each component cost.

Table 3: PV system specification [7]

Panel Power capacity	Efficiency	NOCT	Power Temperature coefficient	collector area	Miscellaneous losses
335 W	21%	45°C	-0.29% / °C	1.6 m^2	10%

Table 4: Cost of components used in the design (installation cost embedded in component cost)

Component	Nominal Discount Rate Rate (%)	Expected Inflation Rate (%)	Project Life time (years)	Cost ($/kW)	Operation & Maintenance Cost ($)	Replacement Cost ($/kW)
Wind turbine	12	2	20	1200	10,000/yr	1143
Solar panel	12	2	25	3000	0/yr	3000
Battery	12	2	10	210 / kWh	100/yr	210 / kWh
Converter	12	2	15	300	0/yr	300
Diesel generator	12	2	15,000 hrs	171	0.6/op. hr	171

The economic analysis of the diesel system for comparison is presented in Table 5.

Table 5: Diesel System economics for selected locations

	Cost/Cost Of Energy (COE) (US$)	Cost/Net Present Cost (NPC) (US$)	Production (kWh/yr)	System/Unmet load (%)	System/Excess Elec. (kWh/yr)
Diesel	0.226	21,105,870.00	10,155,069.00	3.73	100.81870

This study adopted load calculation from Dada *et al*. [2] as presented in Table 6.

Table 6: Minimum and Maximum daily energy consumption at the University of Lagos, Akoka Campus

Month/year	Min. Daily Energy Consumption (kWh)	Quantity of diesel (liters)	Base load on campus (kW)	Max. Daily Energy Consumption (kWh)	Quantity of diesel (liters)	Peak load on campus (kW)
Sept. 2010	22,220	5332.8	925.8	98,590	23661.6	4107.92
Oct. 2010	38,660	9278.4	1610.83	128,720	30892.8	5363.33
Nov. 2010	44,310	10634.4	1846.25	145,320	34876.8	6055
Dec. 2010	30,240	7257.6	1260	96,330	23119.2	4013.75
Jan. 2011	33,720	8092.8	1405	211,310	50714.4	8804.58
Feb. 2011	29,690	7125.6	1237.08	155,070	37216.8	6461.25

The Homer software and the Weibull statistical distribution were employed to estimate the power delivered by a practical wind turbine according to Ajayi *et al*. [7] and Ajayi *et al*. [8]. The unadjusted energy production was calculated based on the power curve of the chosen wind turbine and the average wind speed at hub height. Moreover, the PV array design and optimization as well as the system's economics were carried out using developed algorithms as presented and discussed in Ajayi *et al*. [9], Ajayi *et al*. [0], Ohijeagbon and Ajayi [11] and HOMER [5].

3.0 Results and Discussion

Tables 7-12 presents the technical and economic details of the optimisation analysis at each site location that best meets the electrical load demand profile captured in Figure 1. From Table 7, it is observed that the Wind Standalone System (WSS) at Jos meets the required load profile at an availability of 95% all through the year. The WSS fared better than the Diesel Standalone without batteries (DSS) at 46% of DSS cost per kWh. The Wind-PV system followed closely at 47% of DSS cost per kWh. From Table 8, Minna was found to also have a high potential to transit to the WSS at a COE that fared better than the conventional DSS, which was proportional to 59% of DSS and a hybrid PV-Wind system that was found to have an optimal value of 63% of the DSS. In relation to the other four sites (Ilorin, Abuja, Makurdi and Lokoja) (Tables 9 – 12), the DSS still remained the most viable cost-effective alternative to the erratic power supplied by the utility grid system at the north central region. Presently, the commercial rate for the utility grid system stands at about US$ 0.1/ kWh, which is at par with the WSS at Jos. None of the PV standalone systems (PSS) at each location were able to compete economically with the DSS. This may be chiefly attributed to the total number of sunshine hours equalled in the north central region per year (Figure 4).

Table 7: Techno-economics of different technologies at Jos

	Cost/COE (US$/kWh)	Cost/NPC (US$)	Production (kWh/yr)	System/Unmet load (%)	System/Excess Elec. (kWh/yr)
Wind	0.104	9,599,763.00	18,524,030.00	5.08	8,059,025
PV-Wind	0.105	9,379,740.00	19,964,487.00	8.14	10,006,940
PV	2.305	169,193,800.00	10,088,070.00	24.50	1,269,126
Diesel	0.226	21,105,870.00	10,155,069.00	3.73	100.81870

Table 8: Techno-economics of different technologies at Minna

	Cost/COE (US$/kWh)	Cost/NPC (US$)	Production (kWh/yr)	System/Unmet load (%)	System/Excess Elec. (kWh/yr)
Wind	0.133	11,861,170.00	26,727,300.00	8.53	16,743,480
PV-Wind	0.141	12,560,520.00	15,704,284.00	8.35	5,634,532
PV	2.924	255,983,500.00	11,716,290.00	9.95	1,276,532
Diesel	0.226	21,105,870.00	10,155,069.00	3.73	100.81870

Table 9: Techno-economics of different technologies at Ilorin

	Cost/COE (US$/kWh)	Cost/NPC (US$)	Production (kWh/yr)	System/Unmet load (%)	System/Excess Elec. (kWh/yr)
Wind	0.286	24,968,000.00	28,459,770.00	10.09	18,499,650
PV-Wind	0.245	21,844,090.00	18,212,124.00	8.25	8,087,127
PV	2.554	212,588,700.00	10,314,780.00	14.39	1,204,383
Diesel	0.226	21,105,870.00	10,155,069.00	3.73	100.81870

Table 10: Techno-economics of different technologies at Abuja

	Cost/COE (US$/kWh)	Cost/NPC (US$)	Production (kWh/yr)	System/Unmet load (%)	System/Excess Elec. (kWh/yr)
Wind	0.321	25,000,050.00	16,660,640.00	19.83	7,655,910
PV-Wind	0.291	23,492,820.00	12,014,170.00	17.01	2,743,413
PV	2.692	210,951,500.00	10,314,780.00	19.39	967,489
Diesel	0.226	21,105,870.00	10,155,069.00	3.73	100.81870

Table 11: Techno-economics of different technologies at Makurdi

	Cost/COE (US$/kWh)	Cost/NPC (US$)	Production (kWh/yr)	System/Unmet load (%)	System/Excess Elec. (kWh/yr)
Wind	0.286	25,000,050.00	26,655,970.00	10.09	16,631,800
PV-Wind	0.263	23,492,820.00	17,034,326.00	8.28	6,845,809
PV	3.141	259,258,000.00	10,337,640.00	15.08402	494,630
Diesel	0.226	21,105,870.00	10,155,069.00	3.73	100.81870

Table 12: Techno-economics of different technologies at Lokoja

	Cost/COE (US$/kWh)	Cost/NPC (US$)	Production (kWh/yr)	System/Unmet load (%)	System/Excess Elec. (kWh/yr)
Wind	0.460	22,348,460.00	8,021,646.00	50.04	2,509,631
PV-Wind	0.323	19,487,790.00	7,909,480.00	37.91	1,050,747
PV	2.573	212,588,700.00	10,916,240.00	15.02	1,045,284
Diesel	0.226	21,105,870.00	10,155,069.00	3.73	100.81870

Figure 3 presents the average monthly solar radiation profiles covering the period of 24 years. The figure shows that the 24 years monthly average solar radiation ranged between 3.2 ($kWh/m^2/d$) in August for Abuja and 5.8 ($kWh/m^2/d$) in March for Minna. It shows that the period between June and September experiences the least solar radiation across the sites/states. Minna, Ilorin, and Lokoja appear to be the sites/states with the better solar profiles and Jos with the worst in terms of 24-year monthly average.

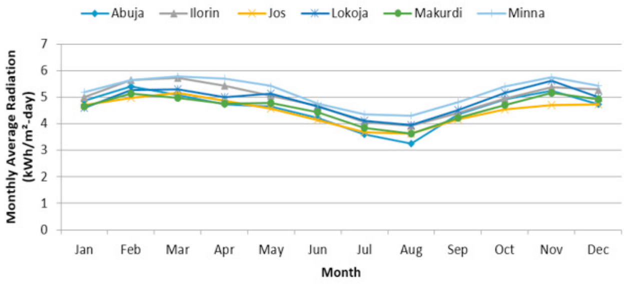

Figure 3: 24- Year Monthly Average Radiation (kWh/m²-day) for sites in North-Central Nigeria

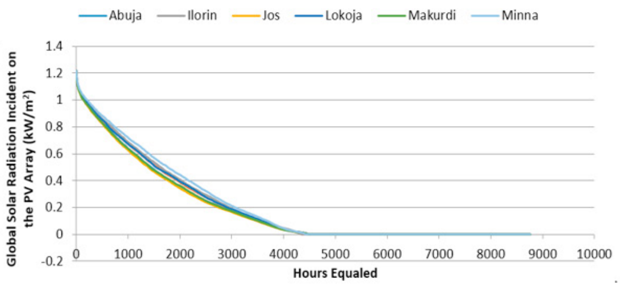

Figure 4: Plot of 24 Years' Annual Average Hours Equalled for North-Central Nigeria

Considering the hours equalled for a series of mean measured solar radiation (Figure 4) across the studied period revealed that power may only be generated for each site between 4333 hours for Ilorin and 4616 hours for Minna out of the 8760 hours in a year. This corresponds to about 49.5% to 52.7% of the hourly duration in a whole year. This however is because solar radiation, unlike wind speed, is in occurrence only during the daytime alone.

The results of wind profile analysis at the site are as shown in Figures 5 and 6. The figures demonstrate that the 24 years monthly average wind speeds ranged between 2.3 m/s in December for Lokoja and 10.1 m/s in December for Jos. Additionally, the hours equalled for a range of mean measured wind speeds (Figure 6) across the period revealed that 43.4% of the data spread are values above 3.0 m/s for the poorest site (Lokoja) in terms of wind profile, and 92% for the best wind profile in Jos. Thus, this values proof that most of the sites are compatible with modern wind turbines for power generation throughout the year. Following the results presented in Tables 7-12, it is apparent that the relative wind speed profiles for each site location is directly proportional to the energy harvestable and consequently also directly impacts on the cost of energy (COE) at each location. Figures 7 - 9 presents the best location in North Central Nigeria by COE in comparison to the DSS. For the ranking under WSS (Figure 7), only the WSS at Jos and Minna fared better than the DSS at \$0.104/kWh and \$0.133/kWh respectively. Ilorin, Makurdi, Abuja and Lokoja stood at 27%, 27%, 42% and 104% respectively above the DSS in terms of COE. For the ranking under the PSS (Figure 8), none of the sites fared better than the DSS. This may be attributed to the efficiencies of the solar cells. Additionally, the cost of PV (though less efficient in terms of wattage panel rating) is higher per kW than that of Wind energy. Also, solar radiation typically is only available for less than 50% of the hours in a day, hence, more expensive deep cycle battery storage capacities are required to cushion energy supply during night hours and periods of lower solar irradiation due to increased cloud cover. On the other hand, wind energy is available throughout a 24-hour day. Hence, would only require batteries to smoothen out supplies during steep wind speed fluctuations period. For the ranking under the RE hybrid (Figure 9), only the hybrids at Jos and Minna fared better that the DSS at \$0.105kWh and \$0.141/kWh respectively. Ilorin, Makurdi, Abuja and Lokoja stood at 8.5%, 17%, 29% and 43% respectively above the DSS in terms of COE. From the outcome of the hybrid optimisation, it was clear that hybridization improved the wind COE at all sites, except those at Jos and Minna, which have very good wind profiles. The percentage of COE above that of the DSS dropped for all four sites from 27% to 8.5% for Ilorin, 27% to 17% for Makurdi, 42% to 29% Abuja and 104% to 43% for Lokoja as an aftermath of hybridisation.

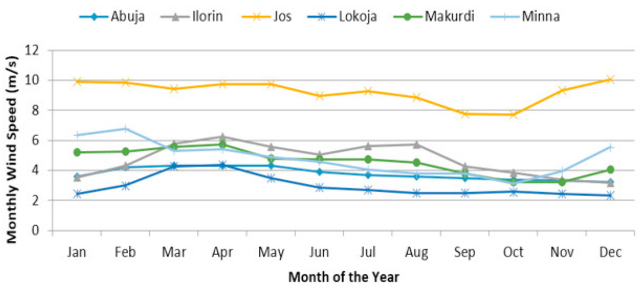

Figure 5: Plot of 24 Years' Monthly Average Wind

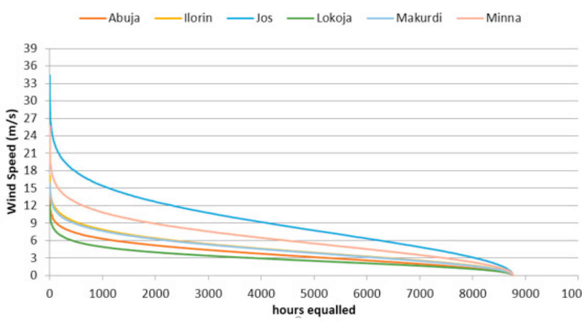

Figure 6: Plot of 24 Years' Annual Average Hours Equalled for different wind speeds

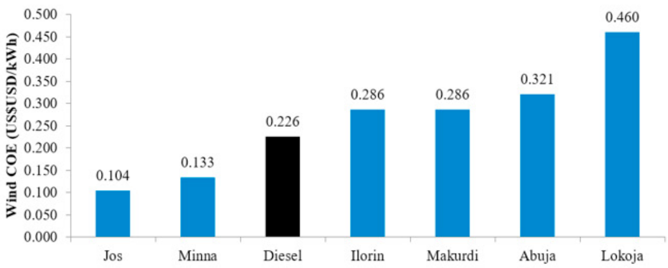

Figure 7: PV COE for daily electric energy demand of 29.8MWh/day at Tertiary Institutions in North Central Nigeria

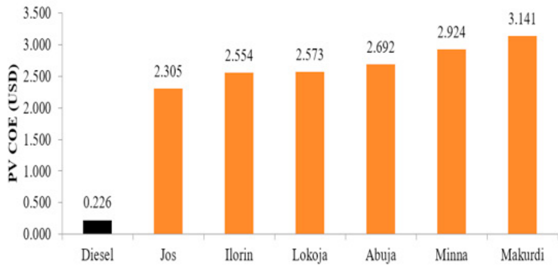

Figure 8: PV COE for daily electric energy demand of 29.8MWh/day at Tertiary Institutions in North Central Nigeria

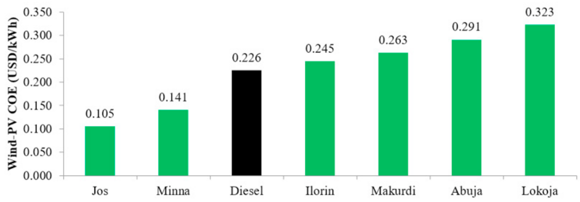

Figure 9: Wind-PV hybrid COE for daily electric energy demand of 29.8MWh/day at Tertiary Institutions in North Central Nigeria

Conclusion

The study assessed the potential of wind and solar power generation at six selected sites of North Central region of Nigeria. It evaluated the design that will suit the adoption of the renewable resources either as standalone or as hybrid facilities. The focus of the study was to use the load profile of University of Lagos to replicate the likelihood and determine the feasibility and economic viability of having budding cities of the like of a modern university in the region. It found that wind and solar resources can be a viable option, especially as hybrid facility in the selected. Cities.

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References

[1] Ajayi, O.O. Fagbenle, R.O. and Katende, J. 2011. Wind profile characteristics and econometric analysis of wind power generation of a site in Sokoto State, Nigeria, *Energy Science and Technology*, 1 (2), 54-66

[2] Dada O. M., Daniyan I. A, Azeez T. M, Adaramola O. O, 2016: Audit of Electricity Generation in University of Lagos, Nigeria, *International Journal of Energy and Power Engineering*, 2016; 5(2), 29-33

[3] National Technical Working Group, 009. Report of the Vision 2020 National Technical Working Group on Energy Sector

[4] Ajayi, O.O. Ohijeagbon, O.D.**;** Nwadialo, C.E.; Olasope, O. 2014: New model to estimate daily global solar radiation over Nigeria, *Sustainable Energy Technologies and Assessments* 5, 28–36

[5] HOMER Pro Software, Available online at http://homerenergy.com/, downloaded July 2018

[6] SunPower, 2016. X-Series Residential Solar Panels. Available online [https://us.sunpower.com/sites/sunpower/files/media-library/data-sheets/ds-x21-series-335-345-residential-solar-panels.pdf, accesed 18/08/2018

[7] Ajayi, O.O., Fagbenle, R.O., Katende, J., Omotosho, O.A and Aasa, S, 2012. Analytical predictive model for wind energy potential estimation: a model for pre-assessment study, *Journal of Applied Sciences*, 12 (5), 450-458

[8] Ajayi, O.O., Ohijeagbon, O.D., Ogbonnaya, M. and Attabo, A, (2016). Wind power mapping and NPV of embedded generation systems in Nigeria, *International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering* 10, 5, 394-405

[9] Ajayi, O.O., Ohijeagbon, O.D, Ogbonnaya, M., Attabo, A., 2016. Potential and econometrics analysis of standalone RE facility for rural community utilization and embedded generation in North-East, Nigeria, *Sustainable Cities and Society*, 21 (2), 66 – 77

[10] Ohijeagbon, O.D. Ajayi, O.O, 2015. Solar regime and LVOE of PV embedded generation systems in Nigeria, *Renewable Energy*, 78, 226 – 235

[11] Ajayi, O.O., Fagbenle, R.O., Katende, J., and Okeniyi, J.O. 2011. Availability of wind energy resource potential for power generation at Jos, Nigeria, *Frontiers in Energy*, 5 (4), 376 – 385