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Comparative Analysis of Techno-Environmental Design of Wind and Solar Energy for Sustainable Telecommunications Systems in Different Regions of Nigeria

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Abstract- Diesel generator is generally adopted to power the telecommunication base stations (BSTs) but it releases a lot of harmful emissions into the environment. Hence, the need to adopt alternative means through the use of renewable sources such as wind energy, solar energy, biomass, etc., to power BTSs. However, ineffective design of renewable energy systems leads to its failure. Also, a renewable energy system might fail if deployed for a particular location with insufficient renewable resources for the design. In this paper, a comparative analysis of the techno-environmental design of wind and solar energy for sustainable telecommunications systems in different zones of Nigeria was carried out to determine the suitable renewable energy system for each zone based on their available renewable resources. The load profile of the six selected BTSs one from each of the six geographical zones of Nigeria was evaluated. The reported solar and wind resources of these locations were obtained from databases. Based on the load profile of the BTSs, the diesel generator, solar PV, and wind turbine were designed and simulated using Homer Pro tool. Sensitivity analysis of the diesel generator, solar PV, and wind turbine was carried out to investigate the system robustness. The simulation results demonstrated that for the selected locations namely; Amarawa, Bama, Asokoro, Awka, Bonny, and Ilaro the solar PV demonstrated its technical suitability in terms of electrical production of 3771kWh/yr, 7287kWh/yr, 22724kWh/yr, 16872kWh/yr, 34683kWh/yr, and 38988kWh/yr, respectively, and the unmet load of 0.554kWh/yr, 0.0596kWh/yr, 0.673kWh/yr, 1.440kWh/yr, 0.913kWh/yr, and 11.33kWh/yr, respectively, and its environmental friendliness through zero-emission profiles. The sensitivity analysis results have shown that it is technically optimal to operate a diesel generator at about 40% maximum load ratio (MLR), two-axis adjustment (TAA) is the preferred tracking technique for solar PV, and wind turbines is to be operated at 0% turbine performance loss for their optimal performance.

Keywords Solar PV; Wind Turbine; Diesel Generator; Telecommunication; Techno-Environmental; Sustainability.

1. Introduction

Telecommunication is pivotal to the development of any nation as it serves as the backbone for security, economic, social, and technological activities [1]. The impact of telecommunication on the national economy cannot be underestimated since it provides a platform for digital systems on which the current economy relies. In fact, it has been reported that the deregulation of Nigerian telecommunication sector has led to significant improvement in socio-economic aspects like security, healthcare, education, online trading, sporting, and entertainment [2]. The telecommunication sector has been identified to have contributed more to the GDP of Nigerian economy when compared to foreign direct investment (FDI) [2-4]. Also, there is a positive link between telecommunication and foregn direct investment (FDI) hence government should create enabling environment for the investors to attract more and sustain them for higher FDI influx into the economy [5]. Despite its successes, telecommunication presents a number of dangers to society among which include cyber-crime, cyber-bullying, blackmailing, and impaired productivity resulting from social media distractions [6-7].

Energy demand keeps growing with the growth of telecommunication networks as a result of an increased number of BTSs [8]. The growth of telecommunications infrastructure leads to a proportionate increase in the energy demand by the telecommunication sector. Energy in form of electricity for powering can be obtained from various sources such as the power grid, diesel generator, and renewable sources [9-10]. It has been reported that over 50,000 Nigerian BTSs source energy from conventional diesel generators which results in high operational cost and emissions [11]. In a country like Nigeria where the energy crisis persists the use of energy saving techniques might be a viable option [12-13]. As a result [14] explored the potential impacts of energy saving in the Nigerian telecoms industry through a literature study on energy savings that give attention to energy usage, concepts, and impacts for the benefits of energy saving practices.

The use of diesel generators to power the BTSs is a generally adopted sustainable means in Nigeria but it releases a lot of emissions harmful to both humans and animals into the environment [15]. Recent development in energy systems has seen a rise in the use of renewable sources such as wind energy, solar energy, biomass, etc., to power different systems [16-17]. However, research has shown that ineffective design of these renewable systems contributes to their failure also, use of the wrong renewable technology for a particular location that does not have enough of the renewable resources for that technology is another major challenge in the successful deployment of renewable energy systems [14]. Consequently, the design and simulation of renewable energy systems and hybrid renewable energy systems have been widely reported in the literature. Four different designs namely; photovoltaic PV/diesel generator DG, PV/battery BAT, DG/BAT, and DG-only have been compared for techno-economic analysis of powering BTS with maximum and average load of 1697 W and 39.6 kWh/day in Abeokuta, Ogun State, Nigeria [18]. The analysis which revealed that PV/BAT is most viable was based lowest life cycle cost (LCC), cost of energy (COE), and renewable fraction. It was concluded that hybrid renewable systems demonstrated superior performance when compared to traditional DG-only systems. The grid-connected hybrid renewable energy system equipped with an energy storage system has been considered by [19]. A MATLAB-based system simulation model based on load data for different locations considering different climatic conditions in Nigeria was employed. The simulation result demonstrated a significant overall energy throughput of about 4 kWh/$ added to its environmental friendliness. It was submitted that the system would improve the quality of mobile services through more reliable and cost-effective operations of GSM base stations.

Findings have it that BTSs are the most power consumers in mobile operators' cellular systems operators [17-18]. It has also been reported that the energy requirement of BTSs is a function of its size the number of online subscribers [22]. This assertion is supported by the analytical work by [23] which demonstrated that telecommunication technology could use as much as 51% of global electricity by 2030 hence, this necessitates the need to develop new energy generation techniques that would serve as alternatives and adopt energy saving techniques for these technologies. Currently, the telecommunications industry tends to generate its energy consumed through means that release a significant amount of carbon into the atmosphere [24]. It has been reported that there are 320100 off-grid and 701000 bad-grid BTSs globally and approximately 80% of these are in African and Asian nations. It's worth noting that, despite having weak grid connectivity, many of the countries in these regions have abundant solar and wind resources [25]. Though, renewable energy sources are playing a significant role in meeting the energy needs of the world growing population [26] hence, the need to intelligently develop more diversified electrical energy production resources beyond the current solar, wind, hydro, biomass, diesel, and battery technologies for microgrid systems to ensure energy sufficiency [27].

The techno-economic study is an important study in energy systems that ascertains the technical visibility of the systems and gives the economic implications of such systems while sensitivity analysis of such systems tends to identify system robustness to change in some variables [28-29]. Consequently, techno-economic analysis of energy systems is common in literature. Techno-economic analysis of hybrid photovoltaic (PV), wind, diesel generator, and battery off-grid energy systems for rural healthcare centers across the six regions in Nigeria was presented by [23]. The net present cost and a renewable fraction (RF) were used to measure the system performance and it was found that PV/diesel/battery system is the most economically viable with a net present cost and a renewable fraction (RF) ranging between $12 779 and $13,646 and 70%- 80% respectively. Masrur *et al.*, [30] presented technical and economic viability of a microgrid system through a simulation model. Sensitivity analysis was performed for different cases and the results were measured by the cost of per unit electricity and the net present cost. The result demonstrated that PV/Wind/Diesel/Battery hybrid microgrid is found to be the most viable hybrid model with 1.5 times and 28% inexpensive based on the net present cost and cost of energy, respectively. The percentage emissions reduction showed that carbon dioxide reduces by 23%. Comparative analysis of standalone wind, solar photovoltaic (PV) and hybrid PV/wind systems (LCOE) through techno-economic study was considered by [31] with Gwanda, Zimbabwe as the case study. The result of this study revealed the potential of PV/wind hybrid systems in terms of technical performance and economic benefits which increases the country's energy security. The possibility of hybrid PV-wind system powered BTSs was demonstrated by [24] through an optimal sizing and service outages possibility in three scenarios of battery capacity. The results showed that the system required a three-day backup battery in order to maintain zero hours of service outages.

The mobile telecommunications industry has recently become particularly interested in energy use and carbon dioxide (CO_2) emissions. The environmental impact of BTSs cannot be underrated as they have been found to, directly and indirectly, greenhouse gases (GHGs) to the environment through the use of energy [32]. It was reported that the deployment of hybrid energy systems comprising of renewable and non-renewable energy sources significantly lowers the cost and the emission profiles of BTSs [28]. The fact that diesel-powered BTSs releases emissions that are hazardous to humans and animal into the environment necessitate the need for constant regulatory actions to ensure efficient control and management of the environment [33]. The periodic review of regulations and guidelines for the telecommunications sector without fiddling with the citizen's health would go a long way in delivering global standard services [34]. The work of [35] assessed the environmental problems arising from BTSs in Nigeria, primary and secondary data measured the ambient air quality and noise level using RASI-700 handheld air quality meter and gas detector. The work found that diesel generator-powered BTSs released Nitrogen dioxide (NO_2) and Sulphur dioxide (SO_2) gases into the atmosphere at a level that exceeded the recommended value. Co-location of BTSs by telecommunication operators was recommended to reduce the number of mast siting thereby minimizing emissions and noise pollution.

A study has been presented on techno-economic and energy efficiency analysis of optimal power supply solutions for green cellular base stations [36]. The authors presented different configurations of energy systems to supply electricity to the telecommunication system. The solar PV, wind turbine, and biomass resources-based sustainable energy supply has been considered for off-grid cellular base stations [37]. The study employed heuristic algorithm-based load balancing technique to enhance the throughput and energy efficiency (EE) of the lumped BTSs. HOMER simulation tool was employed to simulate different sizes of the energy system. The sizing of a hybrid energy storage system has been presented for a PV-based microgrid through the design space technique [38]. The authors presented optimal technical and economic analyses of the system, while another study considered fuel cell-based hybrid renewable energy systems for remote telecommunication stations [39]; the authors focused on data analysis and system optimization.

All the geographical zones in Nigeria are blessed with solar and wind resources but may not be a feasible solution in all the zones. A zone may have abundant solar resources but limited wind resources and vice versa. Hence, there is the need to determine the appropriate renewable energy solution for each zone based on the available solar and wind resources. Consequently, the aim of this paper is to design and simulate solar, wind, and diesel energy generation systems to power BTSs in each of the six (6) zones namely; north-west, north-east, north-central, south-south, south-west, and south-east of Nigeria. Hence, the remaining part of this work outline the methodology employed in section 2, the results obtained from the simulation were presented in section 3 while the work was concluded in section 4.

2. Materials and Method

This section presents the materials methods used in this work based on the flowchart presented in Fig. 1. Six BTSs were selected and used for this work by determining the load requirement of the six BTSs. The weather resources of the selected BTSs were collected and appropriate generators were sized for simulation using HOMER Pro. The technical, environmental, and economic parameters were evaluated and analysed to determine the optimal power source.

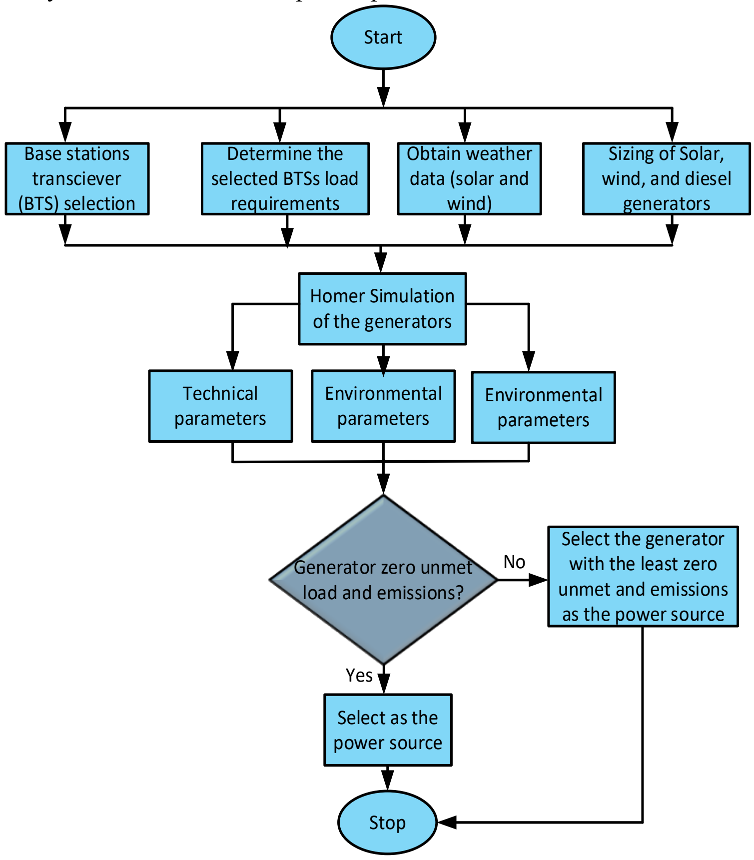

Figure. 1: System flowchart

2.1 Selection of Case Study Base Stations

Nigeria is made up of six geographical zones namely: north-west, north-east, north-central, south-west, south-east, and south-south as shown in Fig. 2. One BTS was selected from each of the six geographical zones in this study. The selection was such that the selected locations represent under developing, developing, and developed areas to capture the possibility of deploying the optimal power source in each geographical zones. Table 1 shows the information on the geographical coordinates, state, and zone for the selected locations across the country.

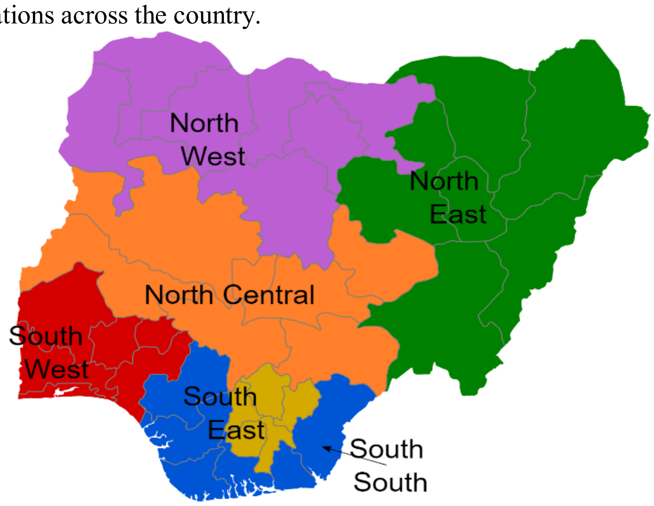

Figure 2: Map of Nigeria showing the geographical zones

Table 1: Selected case study BTSs

Location Category	Selected location	Geographical coordinates	State	Country zone
Under developed	Amarawa	13° 43' 0" N, 5° 18' 0" E	Sokoto	North-west
	Bama	11° 31' 16.82" N, 13° 41' 22.27"	Borno	North-east
Developing	Ilaro	6° 53' 10.43" N, 2° 59' 6.56" E	Ogun	South-west
	Bonny	4°26'34.19" N, 7°14'14.40" E	Rivers	South-south
Developed	Asokoro	33° 70' 92" N, 99° 79' 02" E	Abuja	North-central
	Awka	6° 12' 37.9008" N, 7° 4' 20.1972" E	Anambra	South-east

2.2 Load Requirements of the Base Station

To effectively and reliably design a power system for any system, the load requirements of the system under consideration must be determined. The BTS's daily load requirement can be determined by Eq. (1) [40]:

$$P_{td} = 0.5[p_j t_j + 2(\sum_j^{k-1} p_{1+j}\, t_{1+j}) + p_n t_n] \tag{1}$$

where p_j represents the electrical load at time t_j; p_n is the load at time t_n, while P_{td} is the total BTSs' daily load requirement. The hourly load and the daily load of the selected BTSs were estimated and presented in Table 2 which showed that four of the six selected BTSs have a constant hourly load profile round the day while others have low varying load profiles due to the population.

Table 2: Load requirements for the selected Base stations across Nigeria

Hour	Amarawa Load (kW)	Bama Load (kW)	Asokoro Load (kW)	Awka Load (kW)	Bonny Load (kW)	Ilaro Load (kW)
0	0.109	0.240	2.400	1.800	3.600	2.400
1	0.095	0.219	2.400	1.800	3.600	2.400
2	0.095	0.193	2.400	1.800	3.600	2.400
3	0.095	0.333	2.400	1.800	3.600	2.400
4	0.327	0.359	2.400	1.800	3.600	2.400
5	0.500	0.550	2.400	1.800	3.600	2.400
6	0.550	0.892	2.400	1.800	3.600	2.400
7	0.500	0.987	2.400	1.800	3.600	2.400
8	0.420	1.230	2.400	1.800	3.600	2.400
9	0.430	1.356	2.400	1.800	3.600	2.400
10	0.495	1.769	2.400	1.800	3.600	2.400
11	0.533	1.267	2.400	1.800	3.600	2.400
12	0.691	1.660	2.400	1.800	3.600	2.400
13	0.519	1.230	2.400	1.800	3.600	2.400
14	0.418	1.132	2.400	1.800	3.600	2.400
15	0.397	0.986	2.400	1.800	3.600	2.400
16	0.409	1.200	2.400	1.800	3.600	2.400
17	0.658	0.876	2.400	1.800	3.600	2.400
18	1.231	0.453	2.400	1.800	3.600	2.400
19	1.003	0.670	2.400	1.800	3.600	2.400
20	0.676	1.000	2.400	1.800	3.600	2.400
21	0.480	0.573	2.400	1.800	3.600	2.400
22	0.300	0.432	2.400	1.800	3.600	2.400
23	0.204	0.640	2.400	1.800	3.600	2.400
Total Daily Load	11.135	31.77	57.60	43.20	86.40	57.60

2.3 Weather Data

To explore the abundant renewable resources endowed by the nature, the renewable resources namely solar irradiation and wind speed data were acquired for effective design of renewable energy systems and are subsequently presented.

2.3.1 Wind Resources

The wind profile of all the selected BTSs presented in Fig. 3 was obtained from the World Weather Online database. The World Weather Online database is an online database of global weather forecasts that provide coverage to approximately 4 million cities/towns. The following data are obtainable from the database min, max, and avg temperature (ºC/ºF), Max and Avg Wind Speed (km/h, mph, knots, or m/s), Avg Wind Gust (km/h, mph, knots or m/s), Fog Days e.t.c. The country, state, and town of choice are selected based on Table 1, the historical weather averages including maximum and average wind speed for the selected town are consequently obtained.

2.3.2 Solar Resources

The solar resources of all the selected BTSs presented in Fig. 4 were obtained from the European Commission Science Hub which is a research website equipped with various scientific tools like grid-connected PV systems, off-grid PV systems, tracking PV systems, monthly, daily, and hourly radiation. To obtain the data used in this work, the location address, the latitude, and the longitude of the location are supplied according to Table 1.

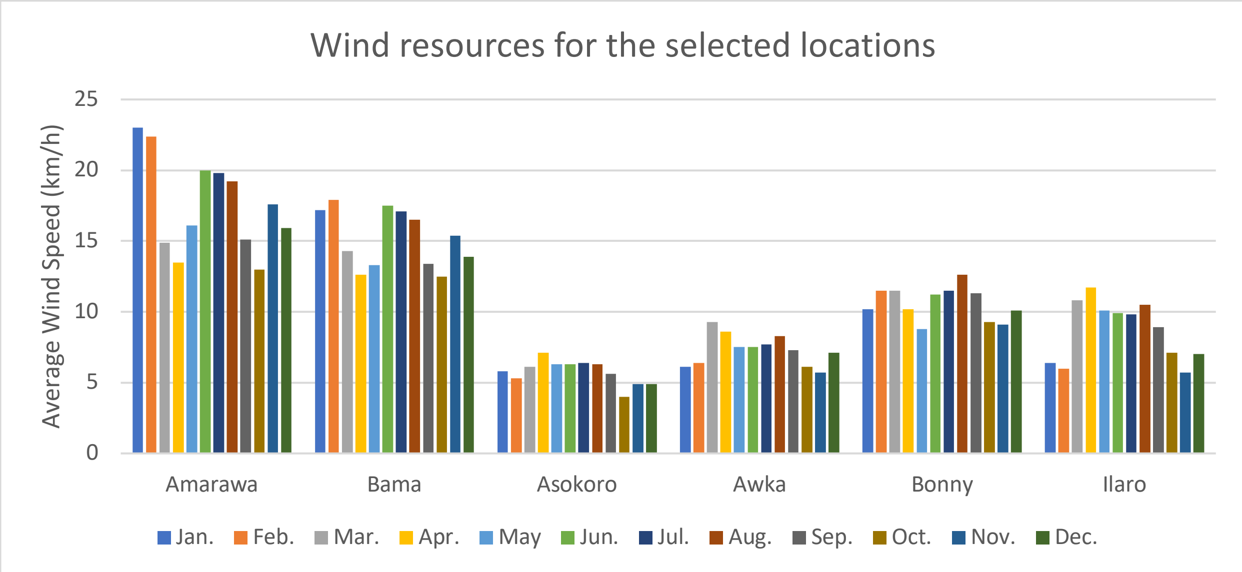

Figure 3: Wind resources for the selected locations across Nigeria

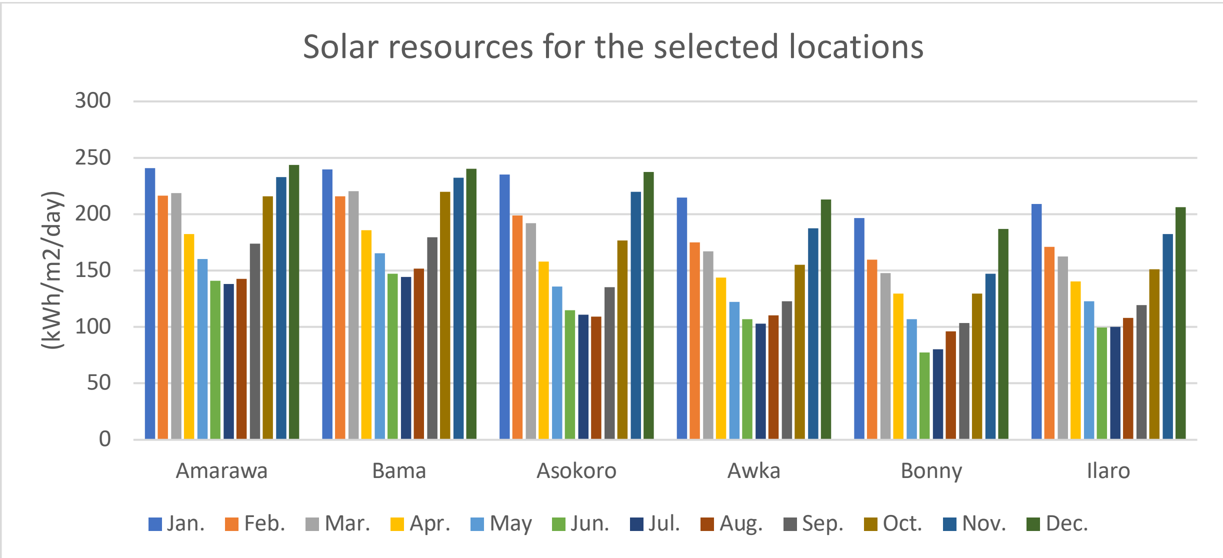

Figure 4: Solar resources for the selected locations across Nigeria

2.4 Design of Energy Generation Systems

The energy systems namely wind turbine, solar PV, and diesel generator must be designed to have efficient systems that allow for objective system assessment. The design of these systems is subsequently discussed.

2.4.1 Design of Diesel Generation Systems

The size of a diesel generator (DG) is estimated by the users' peak load requirement with just a little percentage more. This is because the DG is expected to meet the maximum load all the time. The DG capacity can be mathematically determined through the relation described by Eq. (2).

$$DG_c = D_{pk}(1+\sigma) \quad (2)$$

where D_{pk} is the peak load (kW), and σ is safety factor (%). Also, the DG fuel consumption is calculated by Eq. (3) [41]:

$$DG_{fc} = AP_o + BP_r \quad (3)$$

where P_o, P_r, A and B are the operating power output (kW), rated power (kW), fuel curve slope, and fuel curve intercept coefficient of the DG, respectively. It was on this basis that DGs were designed for the various BTS under consideration in this work. The result of the DG-powered BTSs enables the comparison with solar PV and wind turbine in terms of the emissions and levelized cost of energy.

2.4.2 Design of Solar PV Generation Systems

The power output of a photovoltaic power generator is represented by Eq. (4) [42]:

$$P_s = S_{rc} d_r (\frac{G_{SR}}{G_{SR,STC}})[1 + \alpha_s (T_c - T_{c,STC})] \quad (4)$$

where P_s, S_{rc}, d_r, G_{SR}, $G_{SR,STC}$, α_s, T_c, and $T_{c,STC}$ represents the power output of the solar power system, rating of solar PV modules, PV derating factor, solar irradiance incident on the PV modules, solar irradiance at standard test condition (STC), solar power temperature coefficient (%/°C), PV cell temperature (°C), and PV cell temperature at STC. The solar PV energy generation system for the various base station is designed based on Eq. (5) [43]:

$$Peak\ Power = \frac{E_d}{PSH \times \eta_{iv} \times \eta_{CR}} \quad (5)$$

where; E_d = the total load to be served, PSH = peak sunshine hours, η_{iv} = inverter efficiency, η_{CR} = charge controller efficiency. Here, it is desired that power output in Eq. 4 be sufficiently greater than the peak power in Eq. 5 for the energy system to perform reliably.

2.4.3 Design of Wind Turbine Generation Systems

The wind turbine is responsible for harnessing and converting the kinetic energy present in the wind to electrical energy. There is a need to design the wind turbine for the various BTSs under consideration in this work based on the electrical load requirement and this can be done using Eq. (6):

$$P_{available} = \frac{1}{2}\rho A v^3 C_p \quad (6)$$

Where; A = Swept Area (m^2), v = Wind Speed (m/s), Cp = Power Coefficient, ρ = Density (kg/m^3). The wind speed of any location is affected by the hub-height can be represented by the power law of Eq. (7) [44]

$$v_{hub} = v_{an} (\frac{h_h}{h_{an}})^\alpha \quad (7)$$

where v_{hub}, v_{an}, h_h, h_{an} and α are the speed at the hub-height (m/s), wind speed at anemometer height (m/s), turbine hub height (m), the anemometer height (m), and Hellman exponent which is function of topography, respectively. For this work, a hub height of 24m was considered to obtain the wind speed at the hub height using Eq. 7.

2.5 Energy Systems Simulation

The designed DGs, solar PV, and wind turbine systems were modeled and simulated in using HOMER Pro [45] based on the information provided in Table 2, Figures 3, and 4. The simulation schematics are presented in Figures 5, 6, and 6 for diesel generation systems, solar PV generation systems, and wind energy generation systems, respectively. These simulation schematics were adapted for the six BTSs being considered in this work. The simulation results were evaluated using the performance metrics presented in subsection 2.6 and reported in Tables 3, 4, and 5, for diesel generation systems, solar PV generation systems, and wind energy generation systems, respectively.

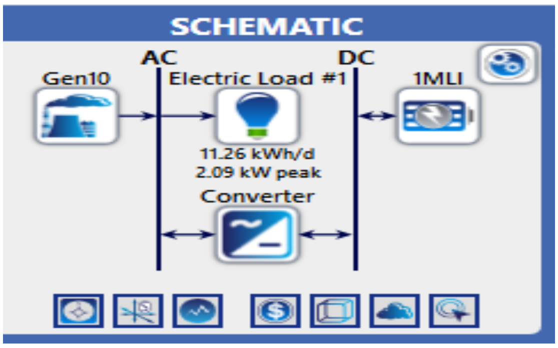

Figure 5: Schematic diagram of the diesel generator generation system for Amarawa

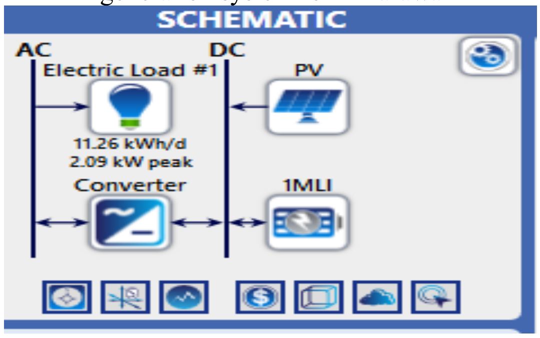

Figure 6: A schematic diagram of the solar energy generation system

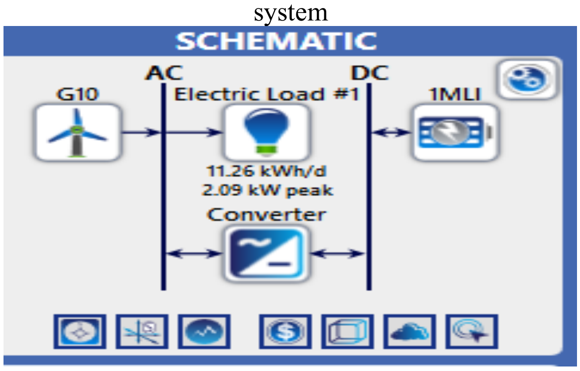

Figure 7: A schematic diagram of the wind energy generation system

2.6 Performance Parameters Evaluation

The performance of the energy systems was evaluated based on the system parameters subsequently discussed:

i. Electrical production (EP)

Electrical production (EP) can be simply defined as the amount of electrical energy produced by the power system in one year. It represents the summation of the electrical energy produced by all components of the system as follow

$$EP = \sum_{i,j}^{n,1} E_{i,j} \quad (8)$$

where integers i to n is the system components, j is the period which is always treated as one year, and $E_{i,j}$ is the energy produced by the components over a year.

The EP from all the energy sources was evaluated and analysed. This helps to determine the optimal energy source to match the demands of the BTSs.

ii. Unmet load (UL)

The UL occurs when the electrical demand exceeds the supply thereby making the power system is unable to serve some electrical load. It can be expressed as in Eq. (9)

$$Unmet\ load = Total\ load\ - Total\ load\ met \quad (9)$$

The UL from all the different energy generation systems was evaluated and analysed to determine the percentage of the total load that was not served by the system.

iii. Emissions

The emissions namely; CO, CO_2, NO, SO_2, and PM from all the different energy generation systems were evaluated and analysed to determine the energy generation system that is more or less environmentally friendly.

iv. Levelized Cost of Energy (LCOE)

The LCOE is the average cost per kWh of useful electrical energy produced by the various energy generation system [8] [41] [42]. It is determined through the relation in Eq. (10)

$$LCOE = \frac{C_{ann,tot} - c_{boiler}H_{served}}{E_{served}} \qquad (10)$$

where $C_{ann,tot}$ = total annualized cost of the system, c_{boiler} = boiler marginal cost, H_{served}= total thermal load served, and E_{served}= total electrical load served.

The energy systems were therefore compared across all the selected locations based on the EP, UL, and emissions to show the location with the most viable energy system.

2.7 Sensitivity analysis

Energy systems are characteristically sensitive to change in some system parameters. There is the need to determine the optimal parameters that affect the system performance. Consequently, the minimum load ratio, tracking techniques, and turbine performance loss for diesel generator, solar PV, and wind turbine, respectively, were varied to measure the impact on the system parameters subsequently defined.

2.7.1 Minimum Load Ratio (%)

The minimum load ratio (MLR) represents least allowable load on the generator set as a percentage of its rated output. This parameter when specified tends to prevent the generator set from running at a low load rather than preventing it from being turned off [37-47]. Consequently, the generator MLR is varied from 10% to 60% at an interval of 10% while maximum output, average electrical efficiency, total production, specific fuel consumption (SFC), and LCOE are evaluated.

2.7.2 Tracking Techniques

Tracking of the solar PV ensures that the energy available from the sun is optimally harnessed at all times. This can be achieved based on the control system used, the driving system used, the degree of freedom, and the racking strategy used [48]. For this work, the degree of freedom-based tracking techniques namely: No Tracking (NT), Horizontal Axis Monthly Adjustment (HAMA), Horizontal Axis Weekly Adjustment (HAWA), Horizontal Axis Daily Adjustment (HADA), Horizontal Axis Continuous Adjustment (HACA), Vertical Axis Continuous Adjustment (VACA), and Two-Axis Adjustment (TAA) were used while maximum output, mean output, total production PV penetration, and LCOE were evaluated

2.7.3 Turbine Performance (Loss %)

The turbine losses are a key parameter in turbine design and selection that derates the turbine performance with several different factors and may result in power loss [49]. It can be of several types like environmental losses, electrical losses, curtailment losses, Wake effect losses, turbine performance losses, availability losses, other losses with the overall loss factor calculated multiplicatively as follows:

$$L_t = \prod_{i=1}^{n} 1 + \frac{L_i}{100} \qquad (11)$$

Where L_t is the total loss by the turbine, L_i denotes the particular loss. In this work, turbine performance losses is varied to measure the impacts on parameters like maximum output, mean output, total production PV penetration, and LCOE were evaluated.

3. Results and Discussions

This section presents the simulation results of diesel generators, solar PV, and wind turbines for the six BTSs under consideration. The results were subsequently compared to be able select the optimal energy source for the BTSs while sensitivity analysis results were presented to demonstrate the robustness of the energy sources.

3.1 Discussion of Simulation Results

The simulation results for the locations were presented and discussed in this subsection subsequently, a comparative analysis of the across the selected locations was also presented. Figure 8 presents the comparison of the result obtained from the simulation of the diesel, solar PV, and wind turbine based on the EP, UL, emission, LCOE, and operational cost (OC) for Amarawa. From Fig. 8, it is seen that the solar PV is characterized by the lowest EP of 3771kWh/yr, the unmet load of 0.544kWh/yr as wind turbine, zero emissions, the least LCOE of 26.90USD, and OC of 38212.33USD. The diesel generator generation system has the highest EP of 18162kWh/yr, zero UL, the highest of emissions of 23,120.25 kg/yr, LCOE of 31.26USD, and an OC of 55695.05USD. From this analysis, the solar PV can be adjudged as the most suitable for Amarawa because its EP nearly matches the BTSs load demand with minimal UL, LCOE, operational cost, and zero emissions though diesel generator has zero UL, however, its emission profile is outrageous.

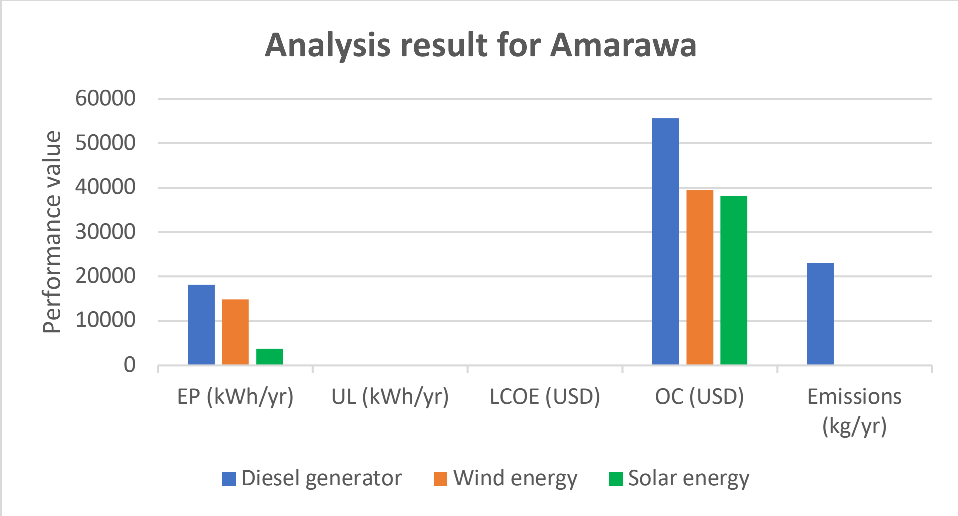

Figure 8: Performance analysis of diesel generator, solar PV, and wind turbine for Amarawa

The simulation result of the diesel, solar PV, and wind turbine based on the EP, UL, emission, LCOE, and OC for Bama is presented in Fig. 9 from which it is observed that the solar PV is characterized by the lowest EP which stands at 7287kWk/yr, UL at 0596kWh/yr, the least LCOE at 14.95USD, OC at 38,211.75USD, and zero emissions. The wind turbine has an averagely better result compared to the diesel generator has the highest EP of 52,738kWh/yr and zero UL however, it has the highest emission values of 56,745.49kg/yr, LCOE of 21.31USD, and OC of 83,983.37USD. This analysis revealed that the solar PV is technically and environmentally suitable for Bama since its EP nearly matches the BTSs load demand with minimal UL, LCOE, OC, and zero emissions.

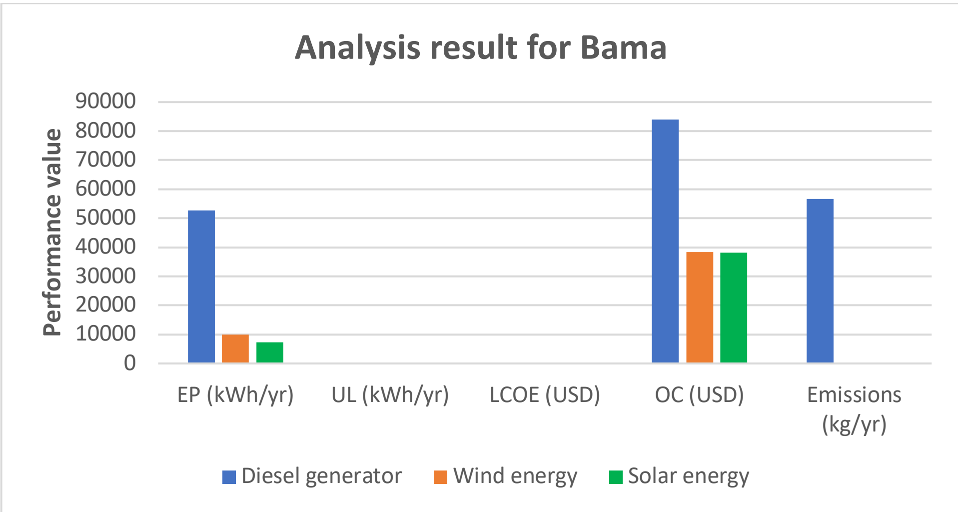

Figure 9: Performance analysis of diesel generator, solar PV, and wind turbine for Bama

Figure. 10 presented the simulation result of the diesel, solar PV, and wind turbine using the EP, UL, emission, LCOE, and OC as metrics of interest for Asokoro. Based on these metrics, it is evident that the solar PV possessed EP of 22,724kWh/yr compared to 3580kWh/yr for the wind turbine, a UL of 0.673kWh/yr compared to 17.7kWh/yr for the wind turbine, the least LCOE of 5.25USD compared to 132.57USD for the wind turbine, OC cost of 38210.47USD compared to 960280.55USD, and zero-emission profiles which are the same for the wind turbine. The diesel generator has fair results in terms of EP, LCOE, and OC however, the emission profile is outrageously high thereby making diesel generators environmentally unfriendly. Based on this analysis, it is evident that solar PV is the system of choice for Asokoro both technically and environmentally with nearly zero UL and zero-emission profile.

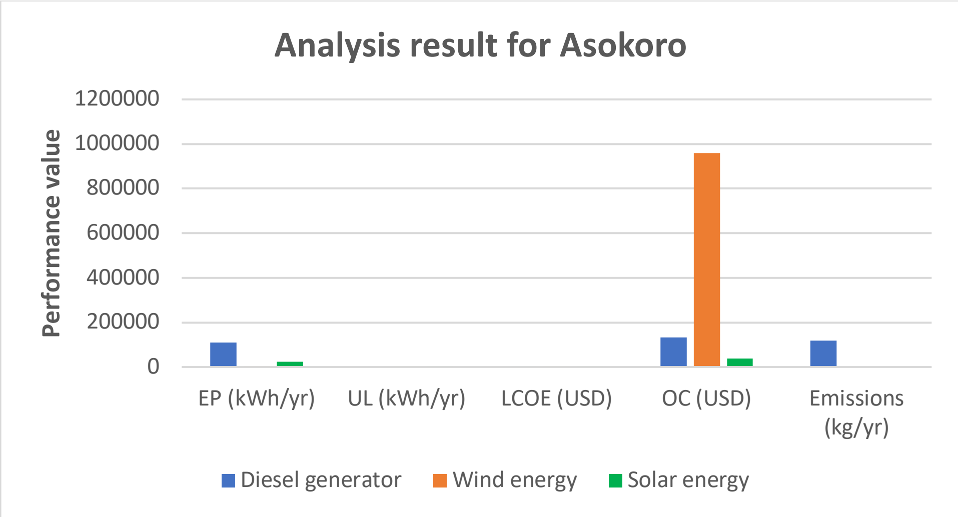

Figure 10: Performance analysis of diesel generator, solar PV, and wind turbine for Asokoro

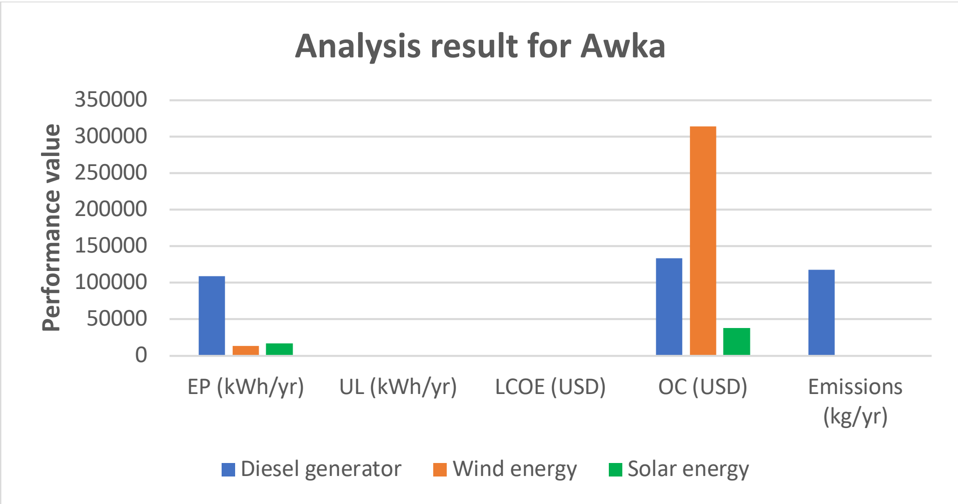

Figure 11: Performance analysis of diesel generator, solar PV, and wind turbine for Awka

The performance analysis of the diesel, solar PV, and wind turbine with EP, UL, emission, LCOE, and OC as metrics for Awka is presented in Fig 11. The result revealed that the solar PV has an EP of 16,812kWh/yr compared to 13,542kWh/yr for the wind turbine, a UL of 1.440kWh/yr compared to 11.5kWh/yr for the wind turbine, the LCOE of 7.01USD compared to 58.55USD for the wind turbine, OC of 38,210.68USD compared to 31,3943USD for the wind turbine, while the two has zero-emission profiles. Comparatively, the diesel generator presented better results based on of EP, UL, emission, LCOE, and OC. It is observed that the emission profile of diesel generators is significantly high thus making it environmentally unfriendly. This analysis demonstrated that solar PV is preferred for Awka.

In Fig. 12, the simulation result of the diesel, solar PV, and wind turbine showing the EP, UL, emission, LCOE, and OC is presented in Fig. 11 for Bonny. The simulation result showed that the solar PV is a viable system with an EP of 34,683kWh/yr, an UL of 0.913kWh/yr, an LCOE of 3.51USD, the OC of 38210.68USD, and a zero-emission profile. The wind turbine has a comparatively better result than the diesel generator based on LCOE, OC, and emission profile of 4.24USD, 43136.79USD, and 0kg/yr, respectively, for the wind turbine, compared to 8.69USD, 197675.12USD, and 211,164.19kg/yr, respectively, for diesel generator. Analytically, solar PV is preferred for Bonny with nearly zero UL and a zero-emission profile.

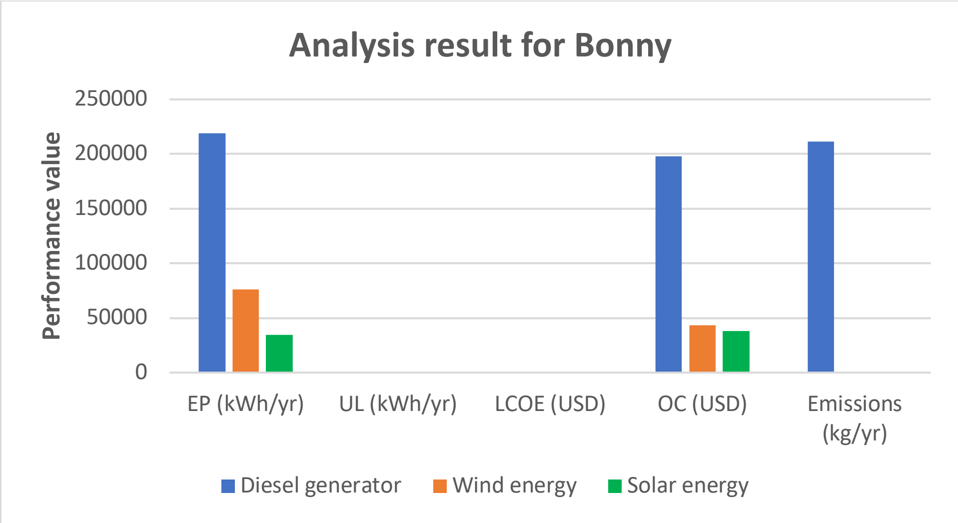

Figure 12: Performance analysis of diesel generator, solar PV, and wind turbine for Bonny

The simulation result of the diesel, solar PV, and wind turbine using the EP, UL, emission, LCOE, and OC for Ilaro is presented in Fig. 13 from which it can be seen that the solar PV possessed EP of 38988kWh/yr compared to 35,529kWh/yr for the wind turbine, an UL of 11.53kWh/yr compared to 55.4kWh/yr for the wind turbine, the least LCOE of 0.832£ compared to 8.77USD for the wind turbine, OC of 7657.01USD compared to 44497.49USD, and zero-emission profiles for the two systems. The diesel generator presented unfavourable results in terms of LCOE, OC, and emission profile thereby making it environmentally unfriendly. This analysis has revealed that the solar PV is the system viable for Ilaro both technically and environmentally based on the unmet load and zero-emission profile.

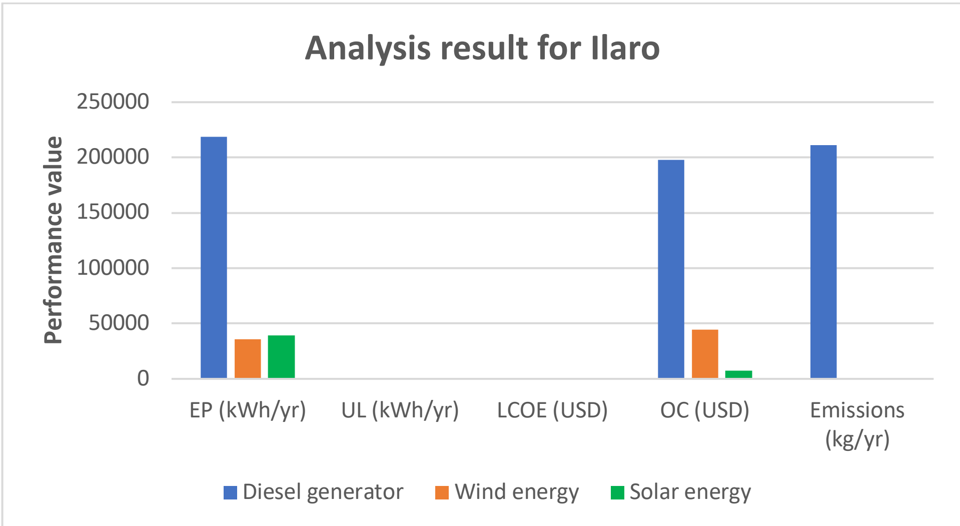

Figure 13: Performance analysis of diesel generator, solar PV, and wind turbine Ilaro

The summary of the simulation results for diesel generator, solar PV, and wind turbine are presented in Tables 3, 4, and 5, respectively. The summary of the simulation results for a diesel generator for the selected locations are presented in Table 3 where Bonny and Ilaro have the highest EP and emission profiles of 218975kWh/yr and 211164.19kg/yr, respectively, while Amarawa possessed the least EP and emission profiles of 18162kWh/yr and 23,120.25kg/yr, respectively. This implies that with a diesel generator, Bonny and Ilaro are at more risk environmentally while Amarawa is at less risk environmentally. It is observed from the Table that all the selected locations have zero UL with the highest and lowest LCOE of 31.26USD for Amarawa and 8.69USD for Bonny, respectively. The implication of this is that Amarawa residents will have to pay more for the same communication services compared to Bonny residents.

Table 4 summarizes the simulation results for solar PV for all the selected locations. Firstly, it is observed from the Table that all the selected locations have zero-emission profiles which make this system environmentally friendly. It is also noted that Ilaro have the highest EP and UL of 38988kWh/yr and 11.30kWh/yr, respectively and the least LCOE and OC of 1.11USD and 7657.01USD, respectively. Also, Amarawa possessed the least EP and UL of 3771kWh/yr and 0.544kWh/yr, respectively, and the highest LCOE and OC of 26.90USD and 38,212.33USD, respectively. The results presented in this work implied that this system is technically viable and environmentally friendly. The summary result of the wind turbine simulation is presented in Table 5 for all the selected locations.

Table 3: Results summary for diesel generator for the selected locations across Nigeria

elected Locations	EP kWh/yr	UL kWh/yr	LCOE (USD)	OC (USD)	CO kg/yr	CO_2 kg/yr	UH kg/yr	PM kg/yr	SO_2 kg/yr	NO kg/yr
Amarawa	18162	0	31.26	55695.05	22,681	172	6.25	10.4	55.6	195
Bama	52738	0	21.31	83983.37	55,914	349	15.4	2.09	137	328
Asokoro	109488	0	9.89	133310.82	116,083	725	31.9	4.35	284	681
Awka	109488	0	13.20	133310.80	116,083	725	31.9	4.35	284	681
Bonny	218975	0	8.69	197675.12	209,053	1422	57.5	5.69	512	114
Ilaro	218975	0	13.05	197982.22	209,053	1422	57.5	5.69	512	114

Table 4: Results summary for solar PV for the selected locations across Nigeria

Selected Locations	EP kWh/yr	UL kWh/yr	LCOE (USD)	OC (USD)	CO kg/yr	CO_2 kg/yr	UH kg/yr	PM kg/yr	SO_2 kg/yr	NO kg/yr
Amarawa	3771	0.544	26.90	38,212.33	0	0	0	0	0	0
Bama	7287	0.596	14.95	38,211.75	0	0	0	0	0	0
Asokoro	22724	0.673	5.25	38,210.47	0	0	0	0	0	0
Awka	16812	1.440	7.01	38,210.68	0	0	0	0	0	0
Bonny	34683	0.913	3.51	38,210.47	0	0	0	0	0	0
Ilaro	38988	11.30	1.11	7657.01	0	0	0	0	0	0

Table 5: Results summary for wind turbine for the selected locations across Nigeria

Selected Locations	EP kWh/yr	UL kWh/yr	LCOE (USD)	OC (USD)	CO kg/yr	CO_2 kg/yr	UH kg/yr	PM kg/yr	SO_2 kg/yr	NO kg/yr
Amarawa	14908	0.753	28.47	39,592.16	0	0	0	0	0	0
Bama	9836	3.17	15.11	38,457.85	0	0	0	0	0	0
Asokoro	3580	17.7	132.57	960280.55	0	0	0	0	0	0
Awka	13542	11.5	58.55	313943.53	0	0	0	0	0	0
Bonny	76273	15.8	4.24	43136.47	0	0	0	0	0	0
Ilaro	35529	55.4	8.77	44497.49	0	0	0	0	0	0

Like, in Table 4, the emission profile is zero for all the selected locations thus making the system environmentally friendly. It is also noted that Ilaro has the highest EP and UL of 38988kWh/yr and 11.30kWh/yr, respectively, and the least LCOE and OC of 1.11USD and 7,657.01USD, respectively. Also, Amarawa possessed the least EP and UL of 3771kWh/yr and 0.544kWh/yr, respectively, and the highest LCOE and OC of 26.90USD and 38,212.33USD. This result implied that this system is technically viable and environmentally friendly.

Figure 14 presents the comparison of EP for diesel generators, solar PV, and wind turbines for all the selected locations. Generally, it is observed from the figure that diesel generators produced more electricity compared to solar PV and wind turbines. Also, the figure showed that the highest electricity is generated from solar PV in Ilaro while the highest electricity is generated from wind turbines in Bonny which revealed the abundance of solar resources and wind resources at these locations, respectively. It is also evident that Amarawa has the lowest solar EP while Asokoro has the lowest wind EP.

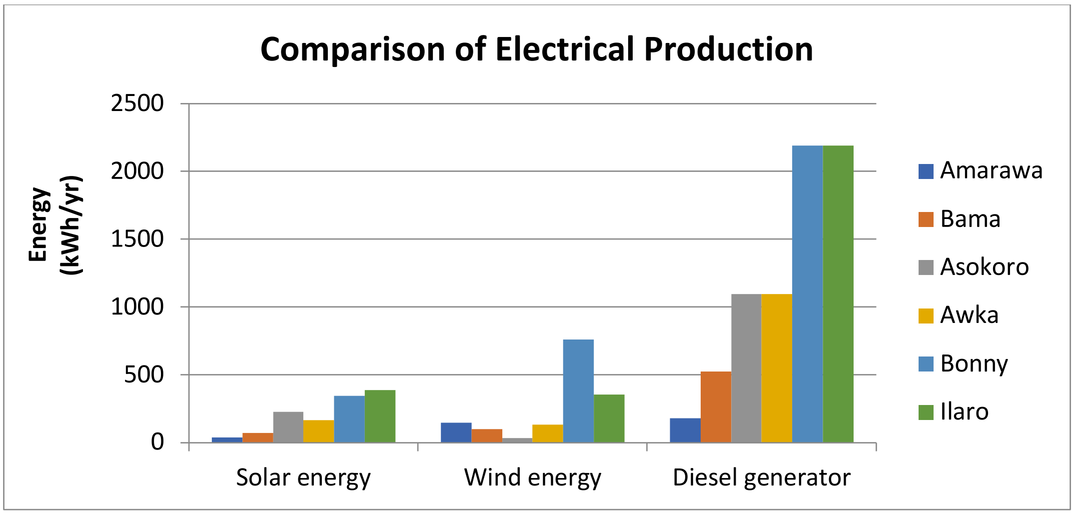

Figure 14: Comparison of electrical production of diesel generator, solar PV, and wind turbine across the selected locations

The comparison of UL for diesel generator, solar PV, and wind turbine for all the selected locations is presented in Fig. 15. It is observed that the diesel generator has zero UL while the wind turbine has the highest UL load. Technically, solar PV is a feasible solution in terms of UL for all the selected locations.

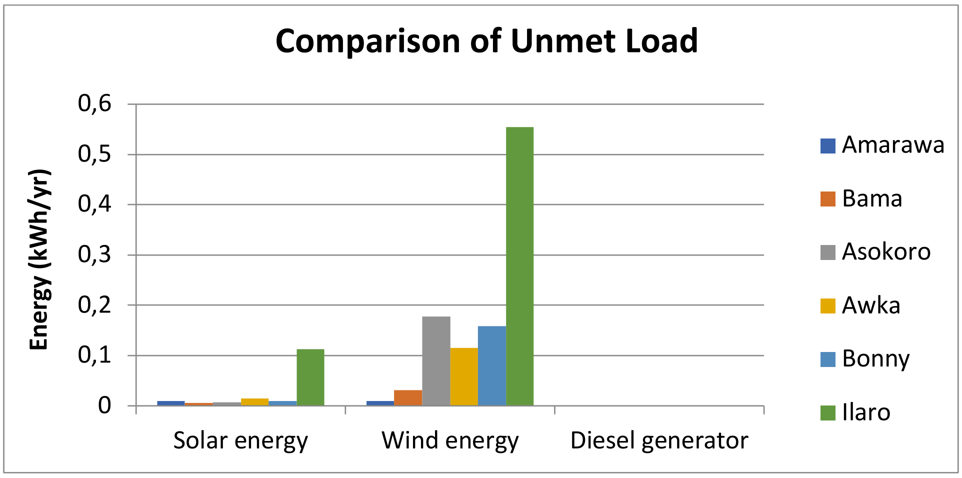

Figure 15: Comparison of unmet load of diesel generator, solar PV, and wind turbine across the selected locations

The comparison of emissions for diesel generators, solar PV, and wind turbines across the selected locations is presented in Figure 16. It is observed that the solar PV and wind turbine have zero-emission profiles while the diesel generator has the highest emission profiles across the selected. Environmentally, the solar PV and wind is feasible solution in terms of UL for all the selected locations. Conclusively, the solar PV can be recommended as viable means of powering the BTSs across the selected location both technically and environmentally with respect to UL and emission profiles, respectively.

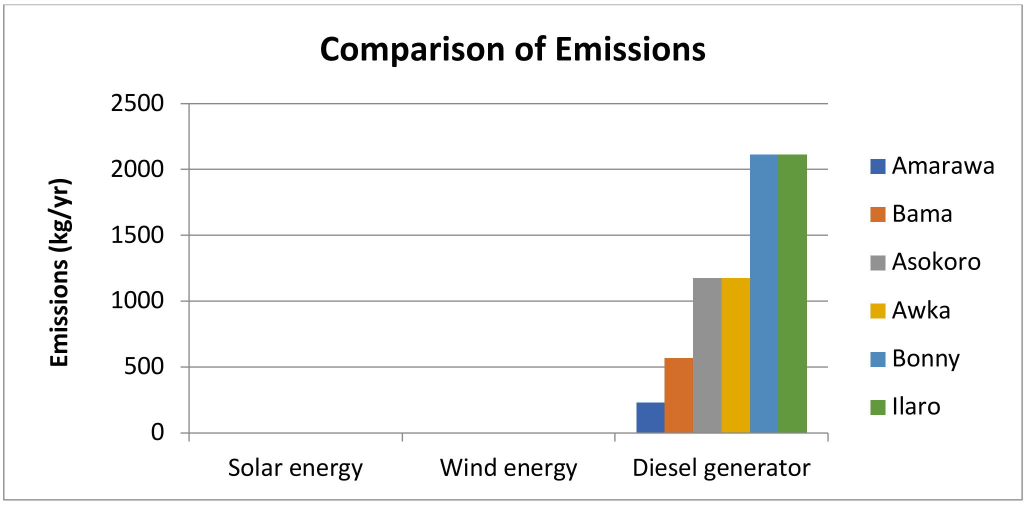

Figure 16: Comparison of emissions of diesel generator, solar PV, and wind turbine across the selected locations

3.2 Discussion of Sensitivity Analysis Results

The results of the sensitivity analysis of diesel generators, solar PV, and wind turbines are presented in Tables 6, 7, and 8, respectively. The sensitivity analysis of the result of the diesel generator is presented in Table 6 where the Minimum Load Ratio (MLR) is varied to reflect the variation in maximum output, average electrical efficiency, total production, SFC, and LCOE. It is observed from the table that the maximum output, average electrical efficiency, total production, and LCOE increase with an increase in MLR except for SFC that decreases with an increase in MLR. Technically, it is viable to operate a diesel generator at about 40% MLR as the generator gave reasonable results of 20kW, 28.60%, 175,180kWh/yr, 0.356L/kWh for maximum output, average electrical efficiency, and total production, respectively at 11.04USD/kWh LCOE. The significance of this result is that the diesel generator can be safely and optimally operated.

Table 7 presents the solar PV sensitivity analysis result showing the change in maximum output, mean output, total production, PV penetration, and LCOE as a result of the change of the tracking techniques namely; NT, HAMA, HAWA, HADA, HACA, VACA, and TAA. It is observed from the table that NT and VACA produced exactly the same result in terms of maximum output, mean output, total production, PV penetration, and LCOE of 29.0kW, 107kWh/d, 38,988kWh/yr, 193%, and 0.0085USD/kWh, respectively. It can be seen that HAWA and HADA also demonstrated the results except for the total production where HAWA has 40,902kWh/yr while HADA has 40,894kWh/yr. Based on the result presented in this table, TAA is recommended as the tracking technique of choice due to its ability to optimally harness available solar energy. Generally, it can be concluded from the result that the change of tracking technique yields a significant change in the variables been considered.

Table 6: Diesel generator sensitivity analysis result

Minimum Load Ratio (%)	Maximum Output kW	Average Electrical Efficiency	Total Production kWh/yr	Specific Fuel Consumption L/kWh	LCOE USD/kWh
10	5.00	16.9	43,795	0.630	8.76
20	10.00	23.20	87,590	0.438	9.52
30	15.00	26.50	131,385	0.383	10.28
40	20.00	28.60	175,180	0.356	11.04
50	25.00	30.00	218,975	0.339	11.79
60	30.00	31.00	262,770	0.328	12.55

Table 7: Solar PV sensitivity analysis result

Tracking Technique	Maximum Output kW	Mean Output kWh/d	Total Production kWh/yr	PV Penetration %	LCOE USD/kWh
NT	29.0	107	38,988	193	0.0085
HAMA	30.7	111	40,674	201	0.0082
HAWA	30.9	112	40,902	202	0.0082
HADA	30.9	112	40,894	202	0.0082
HACA	31.5	115	42,102	208	0.0081
VACA	29.0	107	38,988	193	0.0085
TAA	32.6	136	49,617	245	0.0069

In Table 8, the result for wind turbine sensitivity analysis is presented where the turbine performance loss is varied 0% to 60% at an interval of 10% to reflect the variation in maximum output, mean output, total production, wind penetration, and LCOE. It observed that an increase in turbine performance loss generally leads to a decrease in the maximum output, mean output, total production, and wind penetration except for LCOE that increases with an increase in turbine performance loss. Consequently, it is recommended that wind turbine be operated at 0% turbine performance loss since the maximum output, mean output, total production, and wind penetration is highest and LCOE is lowest at this value.

Table 8: Wind turbine sensitivity analysis result

Turbine Performance Loss %	Maximum Output kW	Mean Output kWh/d	Total Production kWh/yr	Wind Penetration %	LCOE USD/kWh
0	186	4.06	35,529	169	0.67
10	175	3.82	33,430	159	0.75
20	169	3.69	32,299	154	0.84
30	172	3.74	32,784	156	0.96
40	102	2.21	19,379	82.2	1.13
50	102	2.21	19,379	92.2	1.35
60	98.3	2.14	18,733	89.1	1.69

4. Conclusion and Future Directions

This work was facilitated by the need for a technically viable and environmentally friendly power system for a sustainable telecommunication system. Traditionally, diesel generator serves as the means of powering the BTSs in Nigeria however, it is environmentally unfriendly due to high emission profiles. It has been identified that diesel generator is cost-ineffective when compared to the use of renewable energy systems for powering BTSs. These renewable energy systems might fail for several reasons if not properly designed. Consequently, a comparative analysis of the techno-environmental design of wind and solar energy was considered in this work for sustainable telecommunication systems in Nigeria.

The simulation result analysis has revealed that the solar PV is the most suitable for Amarawa, Bama as its electrical production nearly matches the BTSs load demand with minimal UL, LCOE, OC, and zero emissions compared to a diesel generator that has zero UL but with outrageous emission profile. Also, the analysis has shown that both technically and environmentally, solar PV remains viable for Asokoro with nearly zero UL and zero-emission profile. For Awka and Bonny, Analytically, the solar PV is preferred based on minimal UL and zero-emission profile. Solar PV was also identified through analysis as the system viable for Ilaro both technically and environmentally. However, for these locations, diesel generators showed unfavourable results in terms of LCOE, OC, and emission profile thereby making them environmentally unfriendly. From the comparative analysis of the diesel generator, solar PV, and wind turbine, it is evident that Bonny and Ilaro are at more risk environmentally while Amarawa is at less risk environmentally based on the emission profiles at these locations. The comparative analysis of these systems has shown that Amarawa residents will have to pay more for the same communication services compared to Bonny residents based on LCOE and OC. The solar PV is convincingly recommended as a viable alternative source of powering the BTSs in all the selected locations both technically and environmentally with respect to UL and emission profiles, respectively.

It can be concluded from the sensitivity analysis that MLR is an important diesel generator parameter that leads to an increase in the maximum output, average electrical efficiency, total production, and LCOE when it is increased. However, SFC was found to have decreased with an increase in MLR. Also, it was concluded from the sensitivity analysis of solar PV that the change of tracking technique produced a significant change in maximum output, average electrical efficiency, total production, and LCOE. The turbine performance loss has been found to be a key parameter of wind turbines that must be kept at 0% for optimal maximum output, mean output, total production, wind penetration, and LCOE.

From the results, it can be inferred that Nigeria has more solar resources than wind resources. All the regions in the country have demonstrated the potential of solar PV. This work helps to determine the suitable renewable energy systems either wind or solar for each zonal region of the country based on their renewable resources. It is applicable in all the states in the country to maximize available natural resources and reduce emissions on the environment. The use of fuel cells and biomass technologies would be tested for deployment suitability to achieve sustainable telecommunication systems in future works. Consequently, the following are the main contributions of this work:

1. The renewable resource sufficient to power BTSs in different zones of Nigeria have been identified through simulation.
2. The environmental friendliness of the energy systems was determined through the emissions.
3. The cost implications of the energy systems and the effect on the BTS subscribers was indicated.
4. The technical parameters for optimal operation of the energy systems were investigated.

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