Comparative Study of Photovoltaic/Wind/Diesel-Powered Microgrid for Residential Load in Northern Nigeria

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Abstract: This paper discusses the design and comparative assessments of photovoltaic (PV)/wind/diesel-based microgrid (µgrid) using Tarauni in Kano State as a test case. The µgrid design is based on users' demand of 201.2 kWh/day (i.e., 73,438 kWh/yr) and the location's solar and wind data. The technical performance examines the component sizes, annual electricity, unmet load (uL), and the availability (aV), while the environmental aspect considers the carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (UH), particulate matter (PM), sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions produced. The Hybrid Optimization of Multiple Energy Resources (HOMER) Pro µgrid tool is used to simulate the systems. The size of the PV obtained is 60 kW, which produces 82,523 kWh/yr of electricity and it achieves uL and aV of 7.18 and 92.82 %, respectively. Two wind generators – WT1 and WT2, 10 kW each, are then added to the 60 kW PV. The PV and these wind systems produce 82,523, 11,739 and 11,739 kWh/yr of electricity, respectively, thus realizing uL and aV of 6.99 and 93.01 %. A 16 kW diesel generator is then added to the PV/wind µgrid and this diesel generator produces 22,164 kWh/yr of electricity, making the PV/wind/diesel µgrid to realize uL and aV of 0 and 100 %. The CO_2, CO, UH, PM, SO_2 and NO_x emissions by the PV/wind/diesel µgrid are 18,686, 118, 5.14, 0.714, 45.8 and 111 kg/yr compared to the values of 65,312, 412, 18, 2.5, 160 and 385 kg/yr when a diesel µgrid is utilized. The paper can help to address the energy shortage in unserved/underserved locations.

Keywords: Availability, diesel, emissions, microgrid, photovoltaic, wind

Introduction

Energy is one of the crucial inputs for economic development a key source of social and economic growth and advancement of the nations of the world (Asghar, 2008). In other words, energy drives the economic productivity and industrial growth, which is why it is considered to be central to a successful operation of any modern economy (Asghar, 2008). Therefore, access to the modern energy supply is instrumental to socio-economic growth of any nation, which translates to successes in all the sectors of the economy such as education, ICT, manufacturing, residential, industrial, and commercial, etc. (Akinyele *et al.*, 2014).

Having established the foregoing, the next line of thought is ascertaining the type of energy resource(s) and how they can be employed to address the mentioned energy issue. The energy resources could be conventional or non-conventional in nature. The conventional energies include the coal, diesel, petrol, natural gas resources (Twidell & Weir, 2006). The production of these energy resources involves the exploration and refining processes before they are utilized for electricity production. In addition, many industries, residential and business premises, including other sectors of the economy also utilize the conventional energy resources, especially petrol, diesel and gas resources. However, one of the major disadvantages of the conventional energy resources is that they produce carbon emissions and noise that are of concern to the entire world (Okakwu *et. al*, 2022).

On the other hand, the non -conventional energy sources are regarded as the renewable energy (RE) resources such as solar, wind, hydro, biomass, geothermal, wave and tidal (Twidell and Weir, 2006). Such energy resources are not only environment friendly but also provide clean and cost-effective alternatives to conventional power system where appreciable renewable energies such as wind and solar energy resources are available (Engin, 2013; Pehl *et al*., 2017). RE resources are suitable options for addressing energy deficit issues in several local or isolated communities in a country like Nigeria, some of which can be designed in small-scale energy supply systems referred to microgrid (µgrid). Nigeria has abundant RE resources across the six geo-political regions. Previous energy studies reveal that the country's northern part possesses a huge solar energy potential compared to the southern part (Shaaban and Petinrin, 2014). Also, the wind energy resources exist in the country in hilly terrains, coastal and offshore regions. This paper is motivated by the abundant RE resources available in the northern part of the country and the possibility of meeting the energy need of unserved or poorly served areas.

Ajewole *et al*., (2019) discussed an optimal system design and sizing of a mini integrated power system. The authors assessed the technical and economic feasibility of PV/wind/diesel/battery power system for Osun State University main campus in Osogbo, Osun State, Nigeria. The study also included the comparison of the hybrid system with a diesel-only system. The paper used HOMER tool to select the optimal component sizes, and calculate the capital cost and the cost of energy for the electricity system considered.

Akinbomi *et al.*, (2021) discussed the optimal µgrid system for detached communities in Nigeria. The authors considered different scenarios such as diesel generator (DG) + battery, DG + WT + battery, DG + PV + battery, DG + grid, and PV + grid + battery for the study. HOMER tool was also employed for the simulation and the paper also considered the environmental and the cost aspects. The paper concluded that the µgrid based on PV + grid + battery is the best option for grid-connection for the detached communities, while the µgrid based on PV + diesel + battery is suitable for off-grid connection for the communities.

Esan *et al.*, (2019) presented hybrid µgrid for microfinance banks in rural areas. The authors considered solar, wind and gasoline resources with battery storage for Ajasse-Ipo in Kwara State using HOMER software. The µgrid was designed to meet the bank's energy demand while excess energy was utilized for community water pumping and home lighting. The paper reported that the solar PV/battery/gasoline µgrid is techno-economically feasible for the proposed application in the village and can achieve ~50 % emission reduction. Okakwu *et al*., (2020) evaluated the techno-economics of hybrid RE and non-RE systems and compared different design configurations for a base transceiver in Ogun State. The authors considered the PV/DG, PV/battery, DG/battery and DG only systems and then examine their technical and economic performances using the HOMER tool.

Sofimieari *et al.,* (2019) modelled and analyzed a PV/wind/DG µgrid for rural electrification in Kaduna State. The paper used HOMER to size different configurations such as DG, PV/DG, wind/DG, and PV/wind/DG systems and presented the technical, economic and environmental performances. The paper concluded that though the PV/DG µgrid has the least net present cost and cost per kWh of energy, the PV/wind/DG µgrid is the preferred option because it meets the load, produced the least emissions and achieves a cost-effective supply.

These studies have made useful contributions in the simulation of µgrid systems based on different resources – solar, wind, gasoline and diesel and design configurations to compare the µgrid system performances, and they provide relevant background knowledge to this current paper. This paper discusses the simulation of a microgrid system for residential application in the northern part of Nigeria, using Tarauni community in Kano as a case study. The research work presents a detailed analysis of a microgrid system based on different energy resources. The main contribution of the paper is that it simulates and discusses different energy configurations such as the PV, PV/wind and PV/wind/diesel µgrid systems; the performances of these systems are then compared with that of a diesel-based µgrid using the indices of annual energy generated, monthly average electric generation, battery state of charge, unmet load (uL), availability (aV), fuel consumption and the emissions produced.

Materials and Methods

Design requirements for wind/solar/diesel-powered microgrid

The approach employed is such that uses the wind and solar resources as the main supply sources while the diesel resource is used as backup. The microgrid uses the wind/solar resources to meet the load demand with battery being used as a storage. HOMER Pro Microgrid tool is used to simulate the energy components to determine their rated capacities. These components include the solar PV array, wind generator – WT1 and WT2, battery, inverter and the diesel generator.

Load requirements and profile

There are different kinds of appliances in an installation such as lighting bulbs, television, radio, phone chargers, refrigerators, etc. The time of operation of these appliances is important to ascertain the consumption profile over a 24-hour daily time frame. The total demand will then be summation of the demand by all the different appliances in the installation for all the households or users involved in the community. The PV/wind/diesel-powered µgrid considered in this study is designed to meet a 24-hour energy demand of 201.2 kWh/day assumed for 6 shops and 8 houses in Taurani community in Kano. The existing community load profile model in HOMER Pro µgrid will then be adjusted to the total load demand of 201.2 kWh/day to achieve the suitable µgrid sizes.

Renewable energy resources data

The solar irradiation, ambient temperature and the wind speed data used for the simulation are presented in Table 1, including the clearness index (NIMET; Weather Spark; HOMER). The solar irradiation is based on the monthly average value reported for north-west Nigeria in 2007 by NIMET.

Table 1. Solar, temperature and wind data used for the simulation

Month	Solar Radiation (kWh/m^2/day)	Clearness Index	Ambient Temperature (℃)	Wind Speed (m/s)
January	5.966	0.593	22	3.01
February	5.745	0.553	22.1	3.01
March	5.650	0.538	28.1	2.95
April	4.924	0.483	30.9	2.81
May	4.366	0.556	31.9	2.73
June	4.798	0.516	27.3	2.60
July	5.145	0.545	26.6	2.10
August	5.366	0.541	25.8	1.69
September	5.682	0.550	26.2	1.61
October	4.609	0.445	26.8	1.88
November	4.861	0.482	25.6	2.40
December	4.830	0.487	19.8	2.90

Wind generator sizing

The power in the wind is calculated by Equation (1) (Twidell and Weir, 2006):

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

where P_{in}, A, ρ, C_p and v represent the power in the wind in Watt, swept area by the wind turbine rotor in m^2, air density in kg/m^3, power coefficient and the wind speed of the location in m/s, respectively. Equation (1) shows that the output of a wind turbine is dependent upon the velocity of the wind that is Hitting its rotor blade, which implies that the power is proportional to the wind velocity. The power coefficient is referred to as the Betz limit with the value of 59.4%, indicating the maximum power that can be captured from the wind (Freris and Infield, 2008).

There is another important parameter in the wind power analysis. This is called the capacity factor, which indicates how much energy is generated by a source (i.e., wind generator in this case) relative to the maximum amount of energy it could provide. This parameter is expressed as a percentage, and the annual energy generated by the WT system is given by Equation (2) (Freris and Infield, 2008):

$$E_{wt} = CF \times P_R \times t \quad (2)$$

where E_{wt}, CF, P_R *and* t represent the annual energy generated by the wind generator in kWh/yr, capacity factor, rated capacity of the wind turbine (kW) and the total hours in the year, i.e. 8760 hours, respectively.

It is also an established convention in wind generating system that the higher the hub-height, the higher the wind speed. The new wind speed value may be calculated by using Equation (3) when the hub-heights have been increased from an initial value to new values (Ajayi *et al.*, 2013; Masters, 2004):

$$V_h = V_0 \left(\frac{h}{h_0}\right)^{\beta} \quad (3)$$

Where the wind speed (V_0) is first measured at a reference hub-height (h_0) and then adjusted to the suitable WT hub-height (h). The power law relation, i.e., Equation (3) is used to obtain the new wind speed (V_h). Also, β is the site surface roughness coefficient? This study maintains a default hub-height of 24 m in the WT model for the simulation.

Photovoltaic Array Sizing

The output of a PV array can be estimated in HOMER by Equation (4) (HOMER):

$$P_{pv} = M_{rc} D_r \left(\frac{G_L}{G_{SR,STC}}\right)[1 + \alpha_s (T_c - T_{c,STC})] \quad (4)$$

where P_{pv}, M_{rc}, D_r, G_L, $G_{SR,STC}$, α_s, T_c, and $T_{c,STC}$ represent the output power of the PV array, PV module rated capacity, derating factor, solar irradiance of the site (kW/m^2) , solar irradiance at standard test condition, which is 1 kW/m^2, PV temperature coefficient of power (%/°C), PV cell temperature (°C) and the PV cell temperature at standard test condition. The PV cell temperature can be estimated in HOMER by Equation (5):

$$T_c = \frac{NOCT - 20°C}{G_R} G_L \quad (5)$$

$NOCT$ and G_R in Equation (5) represent the nominal operating cell temperature and the reference solar irradiance of 0.8 kW/m^2, respectively. The *NOCT* of is usually provided by the PV manufacturer but a value of 47°C is used in this work, while the values used for the temperature coefficient of power, PV module efficiency and the derating factor are 13 %, -0.5 (%/°C) and 80 % (HOMER).

Battery Sizing

The size of the battery bank can be determined by using Equation (6) (Okakwu *et al.*, 2020; Akinyele *et al.*, 2021; HOMER):

$$B_c = \frac{D_e A}{(n_b \times V_{DC} \times MDOD)} \quad (6)$$

Where B_c, D_e, A, n_b, V_s and MDOD represent the battery capacity in Ampere-hour, daily energy demand (Wh), days of autonomy, system's voltage (V), and the maximum depth of discharge of the battery.

Inverter sizing

For off-grid systems, the inverter is expected to be large enough to handle the total power required at any particular time. The inverter device is usually rated above the load requirements, say between 25-30 % > load. However, in the case of an appliance such as motor or inductive devices, it is reasonable to multiply the load requirement by a factor of 3 to take care of the high starting current of the motor. The inverter size for the inductive and other loads will then be the addition of the value obtained from above and the size of the other loads.

Diesel generator sizing

The size of a diesel generating set can be determined by Equation (7) (HOMER):

$$DG_s = (P_M + xP_M) \quad (7)$$

Where DG_s, P_M and x represent the diesel generator size, peak load requirement in the installation and the overrating factor (%). The overrating factor in this situation provides the gap between the size of the diesel generating set and the peak load, as it is necessary that the generator should be able to service the maximum load requirement at any time it is being operated according to the design. This is what the generator sizing is based on in HOMER tool but a value of 10.34 % is assumed for *x* in this paper.

The fuel consumption of the diesel generating set can be obtained using Equation (8) (HOMER; Akinyele, 2017):

$$DG_{FUEL} = RP_o + SP_R \quad (8)$$

where DG_{FUEL},P_o, and P_R represent the fuel consumed by the diesel generating set, operating power output of the diesel generating set in kW, the rated power of the diesel generating set, in kW. In HOMER Pro µgrid tool, R is the fuel curve slope with a value of 0.246 (Litre/kWh) while S is the fuel curve intercept coefficient with a value of 0.08415 Litre/kWh.

Results and Discussion

Load details and profile

The users' total load demand is 201.205 kWh/day, while the peak load and the load factor are 14.5 kW and 58 %. On a yearly basis, the demand of 201.205 kWh/day translates to 73,438 kWh/yr. Figure 1 shows the load profile for the Taurani community obtained from the HOMER tool. It can be seen that the base load was between the hour of 00:00 and 5:30, the load grows appreciably from 6:30 till 16:30 and there was a hike in consumption between 17:00 and 21:00 representing the peak load, and the profile returns to the base load after 22:00 hours.

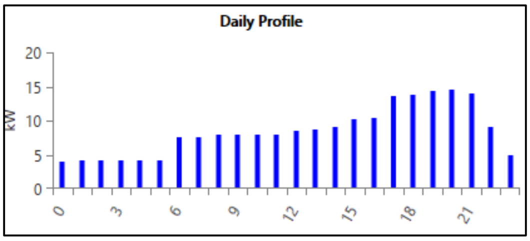

Figure 1. Load profile

PV microgrid configuration

The size of the PV array is 60 kW, which is expected to meet the users' demand assuming the PV system is the only source – PV microgrid (µgrid). This configuration is shown in Figure 2, and the system is made up of the PV, battery, inverter and the load. The PV array produces 82,523 kWh/yr, which satisfies the load demand of 68,169 kWh/yr instead of 73,438 kWh/yr. This means that there is unmet load (uL) of 5,269 kWh/yr (that is, 7.18 %) leading to availability (aV) of 92.82 % in the year. Even though the generation is greater than the demand satisfied, there are some days in the year, usually during the rainy season that the supply from the PV µgrid system will be low. The battery size is 12,328.43 Ah based on D_e, A, n_b, V_s and MDOD of 201.2 kWh/d, 1.5, 85 %, 48 V and 60 %, respectively. The monthly electric generation and the battery state of charge (BSoC) are shown in Figures 3 and 4. The battery's minimum set-point is 40 % and it can be seen that the BSoC value of < 40 % is obtained for some periods in the year showing that the users' demand will not be met at those periods.

Therefore, aV of 92.82 % requires the addition of another power source to improve the system's reliability. There are no emissions for the PV µgrid configuration.

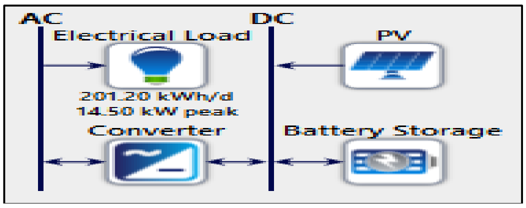

Figure 2. PV µgrid configuration

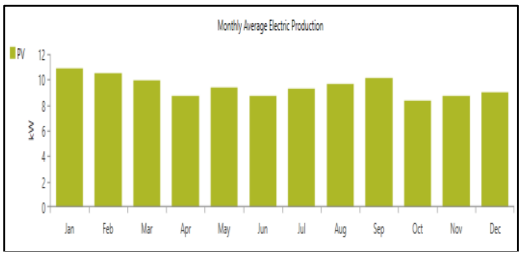

Figure 3. Monthly average electric generation by the PV µgrid configuration

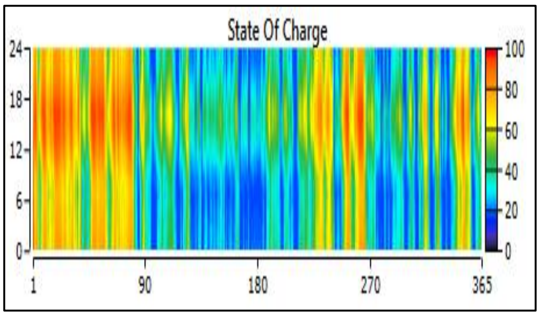

Figure 4. Battery state of charge with the PV µgrid configuration

PV/wind microgrid configuration

The PV/wind µgrid is shown in Figure 5. The two wind generators (WTI and WT2) are 10 kW each, which are added to the existing 60 kW PV array. The PV array, WT1 and WT2 produce 82,523; 11, 739; and 11, 739 kWh/yr of electricity; these translate to 77.9, 11.1 and 11.1 % respectively. This electricity generated by the PV/wind µgrid satisfies a demand of 68,305 kWh/yr, which leads to uL of 5,133 kWh/yr (i.e., 6.99 %) and aV of 93.01 %. This demonstrates that apart from low generation by PV during the rainy season, there are also days in the year that there is no wind. This is why 100 % availability is not achieved in the case of PV/wind µgrid system. The monthly electric generation and BSoC are shown in Figures 6 and 7. The results show that there is an improvement in Figure 7 compared to Figure 4. The addition of WTs to the PV array could not totally compensate for the uL due to unavailability of wind. This justifies the addition of another power system – diesel generating system in this case. There are no emissions in the PV/wind µgrid configuration.

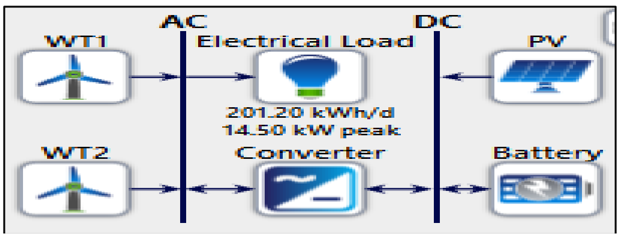

Figure 5. PV/wind µgrid configuration

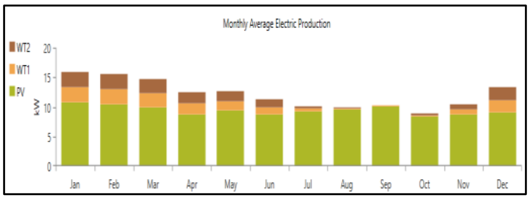

Figure 6. Monthly electric generation by the PV/wind µgrid configuration

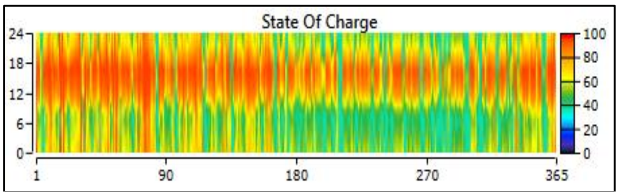

Figure 7. Battery state of charge with PV/wind µgrid configuration

PV/wind/diesel microgrid configuration

The PV/wind/diesel generating (Gen) µgrid configuration is shown in Figure 8. The size of the diesel generator is 16 kW, which is added to 60 kW PV, 10 kW WTI and 10 kW WT2. The PV array, WT1, WT2 and the Gen produce 82,523; 11, 739; 11, 739; and 22, 164 kWh/yr of electricity; this is essentially 64.4, 9.16, 9.16 and 17.3 % contribution, respectively. This electricity generation satisfies a total demand of 73, 438 kWh/yr which leads to uL and aV of 0 and 100 %, respectively. The diesel generator that is included to the system has helped to balance the load. The monthly average electric generation and the BSoC profile for the PV/wind/diesel gen µgrid of the energy system are shown in Figures 9 and 10. The BSoC is well improved compared to Figures 4 and 7.

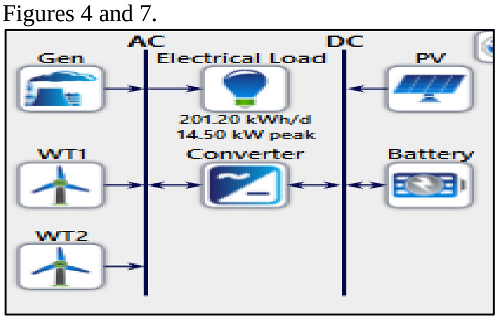

Figure 8. PV/wind/diesel gen µgrid configuration

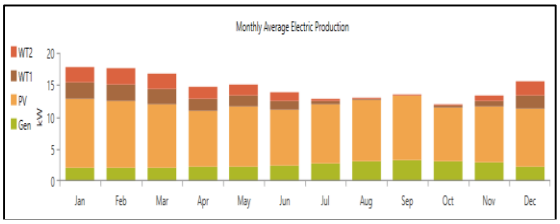

Figure 9. Monthly average electric generation by the PV/wind/diesel gen µgrid configuration

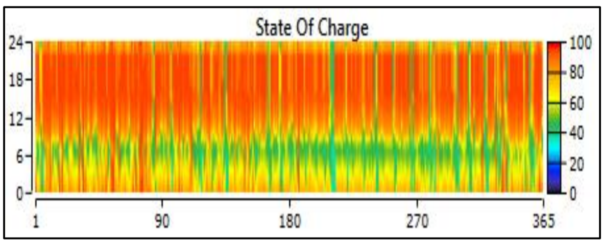

Figure 10. Battery state of charge with PV/wind/diesel gen µgrid configuration

The values of respective emissions for CO_2, CO, UH, PM, SO_2 and NO_x by the PV/wind/Gen µgrid configuration are18, 686, 118, 5.14, 0.714, 45.8 and 111 kg/yr.

Diesel-based microgrid configuration

Figure 11 shows the diesel-based µgrid configuration for the users' load. The generating set produces 73,438 kWh/yr., which is able to completely cater for the users' load demand with uL and aV of 0 and 100 %, respectively. Figure 12 confirms that the monthly average electric production remains constant in as much as the generating set is fueled appropriately. The diesel fuel consumed is 24,951 L as shown in Figure 13. The values of emissions for CO_2, CO, UH, PM, SO_2 and NO_x by the diesel-based µgrid configuration are 65,312, 412, 18, 2.5, 160 and 387 kg/yr, respectively, which are very much higher than the emissions produced by the PV/wind/Gen µgrid configuration.

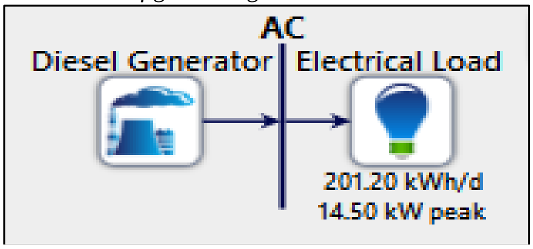

Figure 11. Diesel-based µgrid configuration

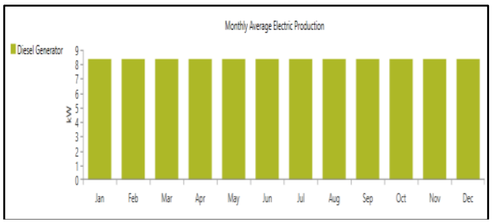

Figure 12. Monthly average electric generation by the diesel-based µgrid configuration

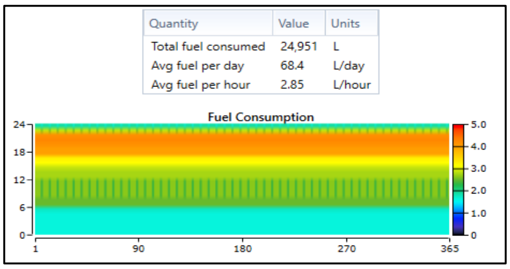

Figure 13. Fuel consumption by the diesel-based µgrid configuration

The PV/wind/Gen µgrid configuration is selected as a suitable choice in this study from the point of view of reliability and relatively low emissions. This is because it achieves a 100 % availability, implying that the users' load demand requirements will be satisfied for 24-hours per day over the year (Olabode *et al.*, 2021), compared with the PV and PV/wind µgrid configurations. Though the PV and PV/wind µgrid configurations produce no emissions, results still demonstrate that the PV/wind/Gen µgrid configuration also produces lower emissions compared to the diesel-based µgrid configuration.

Conclusion

This study has considered the comparative assessments of PV/wind/diesel-powered µgrid system for residential load in Northern Nigeria using the Tarauni in Kano State as a test case. The µgrid has been designed for a total demand of 73,438 kWh/yr assumed for 8 residential homes with 6 shops in the mentioned location. The paper simulated the µgrid configurations based on the location's solar irradiation, ambient temperature and wind speed data using the HOMER Pro µgrid software. The technical performance was considered in terms of the µgrid component sizes, annual electricity generated, unmet load, and the availability, while the environmental performance was evaluated in terms of the carbon dioxide, carbon monoxide, unburned hydrocarbons, particulate matter, sulfur dioxide and nitrogen oxides emissions generated. For the first configuration – PV µgrid system, a 60 kW PV array was obtained to power the load, and an electricity of 82,523 kWh/yr was generated with the unmet load and availability of 7.18 and 92.82 %, respectively. In the second configuration, two wind generators WTI and WT2 rated 10 kW each were added to the 60 kW PV. This µgrid – PV/WT1+WT2 produced 82,523, 11,739 and 11,739 kWh/yr of electricity with unmet load and availability of 6.99 and 93.01 %, respectively. For the third configuration, a 16 kW diesel generator was integrated with the PV/wind µgrid; this system generated 22,164 kWh/yr of electricity with unmet load and availability of 0 and 100 %. The battery state of charge profiles showed a better battery charging in PV/wind/diesel compared to the PV and PV/wind µgrid systems. The results of the study further demonstrated that PV/wind/diesel µgrid produced CO_2, CO, UH, PM, SO_2 and NO_x emissions of 18,686, 118, 5.14, 0.714, 45.8 and 111 kg/yr, respectively, compared to the values of 65,312, 412, 18, 2.5, 160 and 385 kg/yr obtained when a diesel µgrid is employed to supply the load demand. The PV/wind/Gen µgrid configuration is selected as a suitable choice in this study from the point of view of reliability; though it has higher emissions compared with the PV and PV/wind µgrid configurations, it is cleaner than the diesel-based µgrid system. This study provides useful insights into addressing the energy poverty or shortage situations in unserved and underserved locations in Nigeria through the available renewable and non-renewable resources.

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