Modeling and optimization of hybrid microgrid energy system: a case study of University of Abuja, Nigeria

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ABSTRACT

This research work modelled and optimized the hybrid microgrid energy system for electricity generation at the University of Abuja, Nigeria, using PV, wind, diesel, and battery renewable energy resources. The model and optimization of the system are performed through HOMER software. The estimated university average annual power consumption is 2355 kWh/day, and the optimal load demand is 313.40 kWp. The PV/wind/diesel/converter/battery hybrid system has the lowest cost of energy (COE) of 0.1616 $/kWh, operating cost of $50,592, and net present cost (NPC) of $1,795,026 but diesel/wind/converter/battery hybrid system has highest COE of 0.4242 $/kWh and NPC of $4,710,983. The optimal total electricity generated is 1,272,778 kWh/yr while electricity generated by PV contribute the highest energy of 1,030,485 kWh/yr (81%), whereas diesel generator and wind produced energy of 93,927 kWh/yr (7.38%) and 148,366 kWh/yr (11.7%) respectively. The wind/diesel/converter/battery hybrid system produced carbon dioxide (CO_2) of 557,749 kg/yr. The most environmentally friendly is the wind/PV/battery and PV/battery hybrid system without pollutants emissions, but the diesel/wind/battery hybrid system has the highest rate of pollutants emissions. The result shows that PV's electrical power is extremely high from February to June, which causes a high rate of irradiance within the specified period.

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1. INTRODUCTION

Global energy consumption is rising daily, and if the traditional bulk power generation methods are not modified, it will generate serious environmental problems due to large carbon emissions, negatively impacting human health and the ecological system. The government and other stakeholders are currently shifting the mode of generating electricity from conventional methods to clean and sustainable renewable energy to avert the dangerous effects of global climate change and environmental effects [1]. Developed nations have a dependable high-power supply, unlike developing nations like Nigeria. Some states in Nigeria struggle with several problems related to poor power supplies, including regular power outages, insufficient grid strength, and significant power reduction from the distribution and transmission and network [2]. All these issues can be resolved by switching to microgrids, which offer more reliable and efficient power and give people in developing nations the chance to live better lives free from harmful and toxic emissions. There is less fossil fuel available for energy production despite an increase in environmental awareness internationally; the future electricity produced will certainly depend on conventional methods of generating power supply. These methods include power generation from unconventional sources, such as fuel cells and microturbines, and power generation from renewable sources, such as photovoltaic, wind, geothermal, and biomass. According to the system's needs, these kinds of power-generating sources typically belong to distributed generation systems that can function in grid-connected and stand-alone modes. For instance, these power sources often function in stand-alone mode when used alone or in grid-connected mode when in poor conditions or remote locations [3]. By utilizing these technologies, it is possible to achieve a number of desirable outcomes, including simple siting, minimal environmental effect, improved system efficiency, increased reliability and security, improved power quality, and minimization of congestion in distribution and transmission networks due to reduced peak shaving [4].

The main issue associated with renewable energy sources is that they are intermittent and dependent on the weather, making the operation and integration of a microgrid difficult. High-density energy storage devices, small gas turbines, diesel generators, and microturbines can all be utilized to improve system operation [5]. Energy storage technology largely depends on geography and other system parameters; therefore, its usage may not always be cost-effective. One or more distributed energy sources can be included in a microgrid, which can be deployed in a small geographic region and operate in either a grid-connected or stand-alone manner [6]. There are distinct locations that are suitable for the development of microgrids, including rural and urban areas, where there are a lot of renewable energy resources accessible for the creation of clean, green energy. The operation of microgrids can be in islanding mode to create a dependable and uninterrupted power supply when loads are attached to the dispersed energy resources present in the expected area. According to their topological structures, microgrids can be sectioned into three groups: direct current (DC), alternating current (AC), and hybrid. Microgrids act as a single, independent controlled structure from the perspective of the traditional power system network and are linked to the current power system network through a shared connection point.

The AC microgrids topology is the most frequently applied among the three. A bidirectional power electronic converter, such as a DC/AC inverter, is used in this topology to connect DC generators, such as PV power sources, and energy storage devices, such as batteries, to the AC bus. DC power, is generated by PV sources and batteries, and some loads can also be run directly on DC power. Although it is only conceivable in DC microgrids, a direct connection of such components to a DC bus offers many advantages but an interface like a DC/DC converter is still required. Thus, compared to DC/AC inverters, DC/DC converters are easier to construct and operate but the primary benefit of the DC microgrid structure is the removal of inverters. Hybrid microgrids, which have several advantages over conventional topologies, are microgrids that combine the usage of AC and DC buses to forms production and consumption for the power loads components and through application of few converters, energy losses and costs are both decreased [7], [8]. Khan *et al*. [9] designed grid-connected for a university campus comprising PV and battery system in Malaysia using HOMER software. El-sayed *et al*. [10] developed linear models based on dual-simplex algorithm for energy management of microgrid renewable energy. Obaid *et al*. [11] applied a PI controller for power quality improvement and PV battery energy management of a grid-connected three-phase inverter with particle swarm optimization (PSO), whale optimization (WOA), and dragonfly algorithm (DA). Khiat *et al*. [12] determine real-time microgrid digital simulation for Jordan German University and Malta College of Science, Arts, and Technology with injection of PV, energy storage, and diesel generator system. Qachchachi *et al*. [13] developed a global optimization technique for analyzing the energy problem comprising a hybrid microgrid system with a proper control algorithm.

This paper performs an optimization that focuses on techno-economic analysis for developing a hybrid electricity generation system at the University of Abuja, Nigeria. With the effect of electricity fluctuation and uncertainty faced the university currently, it is important to design hybrid microgrid energy systems for the university to improve electricity supply through sunlight and wind in the area. Thus, electricity generation is cost-effective and technically viable due to the area's high-temperature intensity. Also, wind and diesel can serve as backup for the system and increase the university community's social life.

2. MATERIALS AND METHODS

The study collected data daily and meteorological parameters of electrical load. The meteorological data were obtained from the NiMet database for the location, while the load profile was obtained from the loaded audit of the University. The peak load per day was determined using HOMER. This research work analyzed the energy demand for the University of Abuja with the integration of hybrid renewable energy resources to address power failure in the Institution. The components of the wind/PV/diesel/battery hybrid power system include PV modules, wind, diesel generators, converters, batteries, an AC bus, a DC bus, demand load, and other secondary equipment. The hybrid system's schematic diagram of the university is shown in Figure 1. In this setup, a DC bus is used to connect the PV modules, batteries, and converter, whereas an AC bus is used to connect the wind, diesel generator, electric load, and converter.

The university load profile is calculated based on the number of departments, street lamps, clinics, ICT, and hostels. The research evaluates and models the electrical demand for 48 departments, a clinic, 54 street lights, 20 rooms, and an ICT center. The analysis evaluates each device's operating time and power consumption for 24 hrs. The monthly and hourly load profile for the university is illustrated in Figure 2. In reference to the estimated university load profile, it is evaluated that the annual electricity demand of the university is 2355 kWh/day and the optimal demand is 313.40 kWp.

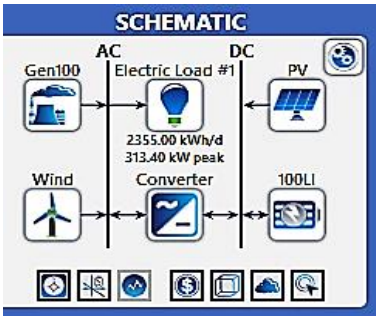

Figure 1. Microgrid system schematic diagram

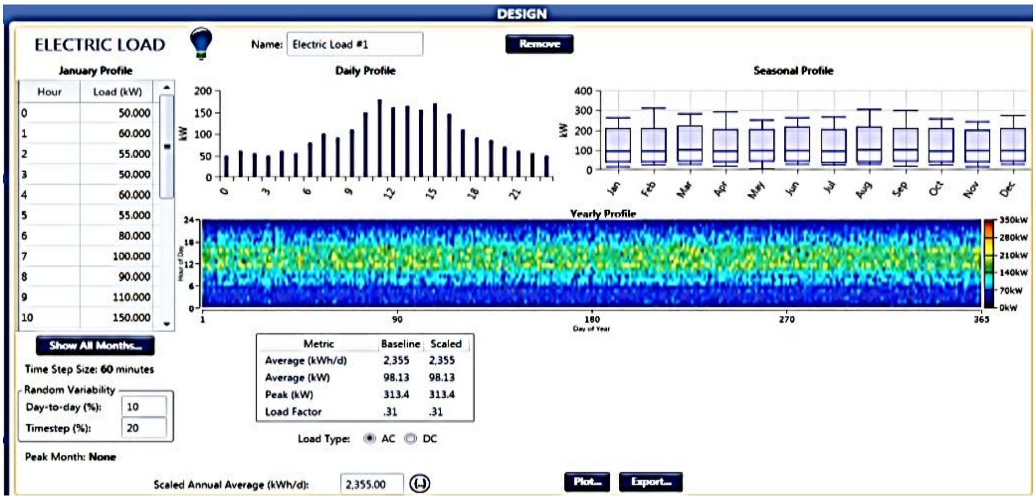

Figure 2. University load profile

2.1. Mathematical modeling of solar photovoltaic (PV) system

The PV panels power output equation applied in HOMER is shown in (1) [14].

$$P_{pv} = Y_o V_{pv} \frac{I_T}{I_S} \tag{1}$$

Where Y_o is the PV derating factor, V_{pv} is the rated PV array capacity (kw), I_T is the PV array global radiation solar incident (kW/m^2), I_s is the standard capacity of PV array radiation (1 kw/m^2).

2.2. Mathematical modeling of wind turbine system

The wind turbine power output equation applied in HOMER is shown in (2) [15].

$$P_w(t) = \begin{Bmatrix} 0, V(t) < V_d \\ qV(t^3) - wP_n, V_d < V(t) < V_n \\ P_n, V_n < V(t) < V_{dc} \\ 0, V(t) > V_{dc} \end{Bmatrix} \tag{2}$$

Where P_n is the rated mean power, V_d is the wind speed cut-in, V_{dc} is the wind speed cut-out, and V_n is the estimated wind speed.

2.3. Mathematical modeling of diesel generator system

The diesel generator power output equation applied in HOMER is shown in (3) [14].

$$F_{Gen} = C_{om} + \frac{C_r}{R_L} + F_n X_{Gen} C_{eff} \quad (3)$$

Where C_{om} is the maintenance and operational cost ($/hr), C_r is the replacement cost ($), F_n is the intercept fuel curve coefficient (fuel/hr/kw), R_L is the generator lifetime (hrs), X_{Gen} is capacity of generator (kw), and C_{eff} is the effective fuel price ($/L).

2.4. Modeling of the battery storage system (BSS)

The state of charge (S_oC) at a definite time (t) is determined considering the demand balance between the load and the PV hybrid system. It is expressed using (4) and (5) [16].

$$E_{bb}(t+1) = E_{bb}(t)(1-\sigma) + surplus\ power * \eta_{BC} \text{ Charging mode} \quad (4)$$

$$E_{bb}(t+1) = E_{bb}(t)(1-\sigma) - \frac{deficit\ power}{\eta_{BD}} \text{ Discharging mode} \quad (5)$$

Where, E_{bb} is the output energy of the battery bank, η_{BC} is the battery charging efficiency, and η_{BD} is the battery discharging efficiency. Finally, σ is the self-discharging rate of the battery; it is taken as 0.2% per day for most batteries.

The constraints on the system's battery bank at any time are represented using (6) and (7).

$$E_{bb,min} \le E_{bb}(t) \le E_{bb,max} \quad (6)$$

$$E_{bb}(t+1) = E_{bb}(t)(1-\sigma) \quad (7)$$

Where, $E_{bb,max}$, is the maximum acceptable battery storage capacity, while $E_{bb,min}$ is the minimum acceptable battery storage capacity. $E_{bb,min}$ can be obtained with (8).

$$E_{bb,min} = D_o D \times E_{BR} \quad (8)$$

Where, D_oD is the battery bank's maximum discharge depth, while $E_{.B.R.}$ is the battery bank's total nominal storage capacity.

2.5. Modeling and optimization with HOMER

Homer software is an optimization hybrid model for electrical renewable, which was formed by the National Renewable Energy Laboratory (NREL) for the energy generation analysis and economic performance of the energy systems configuration. HOMER designs hybrid models of energy that evaluate the system performance and its corresponding system cost analysis [17]. This software analyzes and evaluates various renewable energy to determine the best system based on technical, economic, and environmental benefits. Also, HOMER can perform the modelled system when varying the input parameters. Hence, HOMER performed three functions effectively: analysis, optimization, and simulation. During the analysis process, HOMER determines the effect and proximity of change in the input parameter for future purposes. Thus, the input parameter is designed to have multiple optimizations in a specific range. The optimization process determines the visibility control of optimal variable value for the system, which includes the combination of the component in the system and evaluation of various energy that will specifically meet the desired objectives (technical, environmental, and economic) to minimal total net present cost (NPC).

To analyze the levelized cost of energy (LCOE), HOMER evaluates the cost by dividing the annual cost of producing electricity (annual total cost minus thermal load integration cost) [18].

$$COE = \frac{C_{at} - C_{bt} H_{Load}}{E_{Load}} \quad (9)$$

Where C_{at} is the total annual cost ($/year), C_{bt} is the marginal boiler cost ($/kWh), H_{Load} is the total thermal load served (kWh/yr), and E_{Load} is the electric total load served (kWh/yr).

In (10) shows the profit after the discount of an initial investment with a typical net present value (NPV) equation [19]–[21]. Therefore, the total net present cost (TNPC) is the present value worth of the system expenses for a specific period minus the present value income generated at a specific period. This income is the cumulative capital costs, operation costs, cost of replacement, maintenance costs, and the costs of fuel in a specific lifetime [22]–[26].

$$Net\ present\ Cost = \frac{C_{at}}{R(i,N)} \quad (10)$$

Where C_{at} is the total annual cost, N is the system lifetime, i is the annual interest rate, and $R(i,N)$ is the capital recovery factor.

$$R(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (11)$$

3. RESULTS AND DISCUSSION

3.1. Result of COE and NPC

The university has average annual global solar radiation of 4.0 kWh/m^2/day, an average annual wind speed of 3.79 m/s, and a diesel price of 1.4 $/L. The hybrid system configuration comprises a PV module of 834 kWp, wind of 95 kW, a diesel generator of 100 kW, batteries of 100 (34 strings), and a converter of 304 kW. As a result, the PV/wind/diesel/converter/battery hybrid system has the lowest COE of 0.1616 $/kWh, operating cost of $50,592, and NPC of $1,795,026 but wind/diesel/converter/battery hybrid system has highest COE of 0.4242 $/kWh and NPC of $4,710,983. Table 1 shows the configuration schemes of hybrid microgrid system.

Therefore, the application of PV and wind hybrid system integration can significantly reduce the effect of pollutant emissions, as shown in Table 2. Hence, operating on diesel generators is not advisable due to high fuel consumption costs and environmental effects. The effect of CO_2 emissions is exceptionally high among other pollutants. The environmentally friendly is the PV/wind/battery and PV/battery hybrid system without pollutants emissions. Still, wind/diesel/battery hybrid system has the highest rate of pollutants emissions of CO_2, SO_2, CO, and NOx.

Table 1. Categorized system configuration schemes

Architecture	PV (Kw)	Wind (Kw)	Diesel (Kw)	Battery (No.)	Converter (Kw)	COE ($/kwh)	NPC ($)	OC ($/yr)	Fuel (L/yr)
PV/wind/diesel/converter/battery	834	95	100	34	304	0.1616	1,795,026	50,592	26,600
PV/diesel/converter/battery	1,072	0	100	42	309	0.1801	2,000,787	47,105	23,319
PV/wind/converter/battery	1,401	95	0	76	455	0.1998	2,218,908	20,725	0
PV/converter/battery	1,760	0	0	77	324	0.2228	2,475,010	19,693	0
Wind/diesel/converter/battery	0	95	100	27	199	0.4242	4,710,983	340,427	213,241

Table 2. Emitted emissions from all the hybrid systems

Architecture	CO_2 (kg/yr)	CO (kg/yr)	SO_2(kg/yr)	NO_X (kg/yr)
PV/wind/diesel/converter/battery	69,574	473	171	37.9
PV/diesel/converter/battery	75,993	512	192	41.2
PV/wind/converter/battery	0	0	0	0
PV/converter/battery	0	0	0	0
Wind/diesel/converter/battery	557,749	3,794	1,367	304

Figure 3 shows the average monthly variation of solar irradiance and clearness index of the University of Abuja. From the figure, it is worthy of notice that the monthly average variation of solar radiation ranges from 2.5 kWh/m^2/day in October to 5.3 kWh/m^2/day in March, and the clearness index occurs between 0.241 in October to 0.539 in May. The average annual clearness index and solar radiations are 0.4 and 4.0 kWh/m^2/day, respectively. The university demand load has been evaluated in two different seasons, i.e., rainy (April to October) and Harmattan (December to March). The university's average annual wind speed is 3.79 m/s. Figure 4 illustrates the wind speed variation in the area.

3.2. Electrical generation outputs

The electrical consumption and production of the renewable energy comprised of wind/PV/diesel/battery hybrid microgrid system are illustrated in Table 3. The optimal total electricity generated is 1,272,778 kWh/yr while electricity generated by PV contribute the highest energy of 1,030,485 kWh/yr (81%), whereas diesel generator and wind generate an energy of 93,927 kWh/yr (7.38%)

and 148,366 kWh/yr (11.7%) respectively. The excess generated electricity and capacity shortages are 346,211 kWh/yr and 767 kWh/yr, respectively.

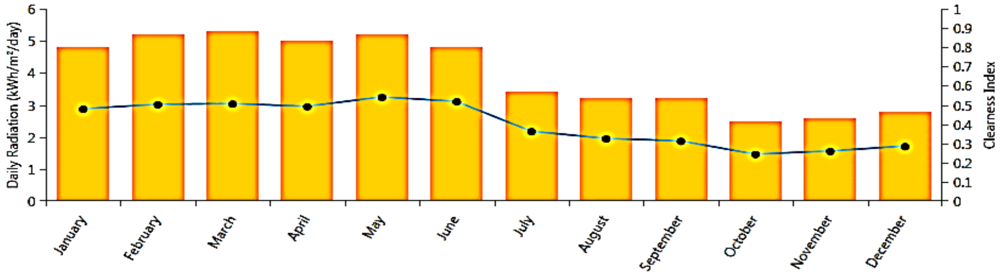

Figure 3. Average monthly variation of solar irradiance

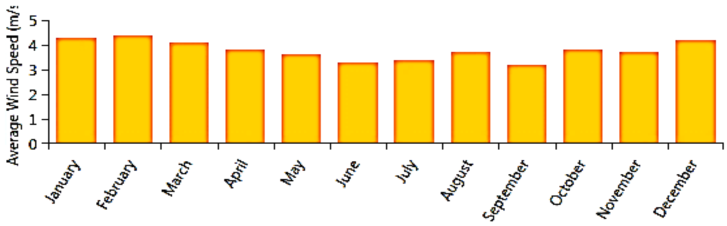

Figure 4. Average monthly variation of wind speed

Table 3. The electrical consumption and production of microgrid

Production	kWh/yr	Percentage (%)
PV	1,030,485	81
Diesel generator	93,927	7.38
Wind	148,366	11.7
Total	1,272,778	100
Consumption		
AC primary load	859,445	100
DC primary load	0	0
Total	859,445	100
Excess electricity	346,211	
Capacity shortage	767	

Figure 5 shows the average monthly electric production for the renewable energy of wind/PV/diesel/battery systems. The result shows that PV electrical power is extremely high from February to June; due to high rate of irradiance within the specified period. Also, there is low PV electrical power generation from July to December due to low solar irradiance within the specified periods. Thus, the diesel generator compensates the system between July to December at low PV irradiance. As a result, the demand load drastically reduced in the months of July to November because there was a steady power supply from the national grid between the period of rainy and due to low demand load and low radiation, the production from PV, diesel generators, and wind turbine system is enough for meeting the load demand. The microgrid system is operated at optimal capacity to determine load demand and continuous battery charging using cyclic charging (CC) and load following (LF). Therefore, the system can operate automatically and independently supply electricity to the load without continuously charging the battery using LF techniques.

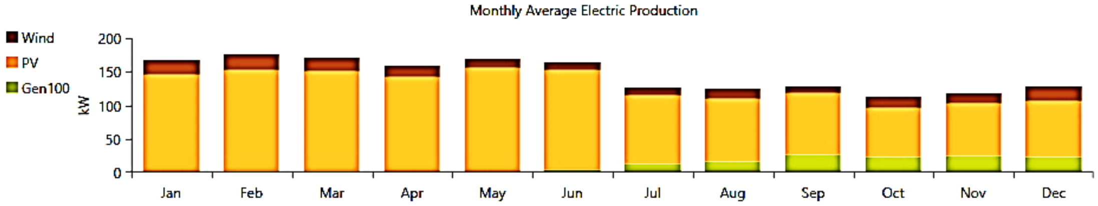

Figure 5. Average monthly electricity production

4. CONCLUSION

This research work model and optimized the hybrid microgrid energy system for the generation of electricity in the University of Abuja, Nigeria, using PV, wind, diesel, and battery renewable energy resources. The model and optimization of the system are performed through HOMER software. The sensitivity analysis of technological and economic input parameters is set to meet the 98.13 kW average loads of 313.40 kWp and 2355 kWh/day. The University load profile is calculated based on the number of departments, street lamps, clinics, ICT, and hostels. The research evaluates and models the electrical demand for 48 departments, a clinic, 54 street lights, 20 rooms, and an ICT center. The analysis evaluates each device's operating time and power consumption for 24 hrs. The university has average annual solar radiation of 4.0 kWh/m^2/day, an average annual wind speed of 3.79 m/s, and a diesel price of 1.4 $/L. The optimal total electricity generated is 1,272,778 kWh/yr while electricity generated by PV. contribute the highest energy of 1,030,485 kWh/yr (81%), whereas diesel generator and wind generate an energy of 93,927 kWh/yr (7.38%) and 148,366 kWh/yr (11.7%) respectively. The excess generated electricity and capacity shortages are 346,211 kWh/yr and 767kWh/yr, respectively. The PV/wind/diesel/converter/battery hybrid system has the lowest cost of energy (COE) of 0.1616 $/kWh, operating cost of $50,592, and net present cost (NPC) of $1,795,026 but wind/diesel/converter/battery hybrid system has highest COE of 0.4242 $/kWh and NPC of $4,710,983. The wind/diesel/converter/battery hybrid system produced carbon dioxide (CO_2) of 557,749 kg/yr. The result shows that PV's electrical power is extremely high from February to June; this causes a high rate of irradiance within the specified period. Also, there is low PV electrical power generation from July to December due to low solar irradiance within the specified periods.

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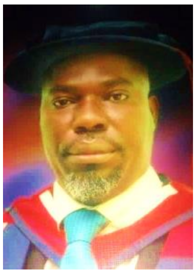

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