Analysis of an Isolated Micro-Grid for Nigerian Terrain

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***Abstract*—The main objective of this study is to identify/determine the techno-economic and environmental merits of the inclusion of wind power to diesel power system for electricity generation in Nigeria. The optimum size of the wind-diesel micro-grid was determined by making energy-balance calculations using the Hybrid Optimization Model for Electric Renewable (HOMER) software. Analysis was performed for a typical residential area, made up of a population of 15 households, using the long-term (22-years) average wind speed data sets collected from the Nigerian Meteorological agency for Maiduguri (latitude 12.0°N and longitude 13.33°E). Sensitivity analysis was performed by varying the annual average wind speed based on the wind map and diesel price to determine the viability at other locations in Nigeria. Simulation results presented are discussed and compared with the conventional approach.**

I. Introduction

The reliability and affordability of electric power are, in particular, a critical component for sustainable development in virtually all sectors of the economy [1]. The Nigerian electric power network (grid) is characterized by high unreliability index [2]. The power supply reliability varies from 39 to 66 percent with an average duration of power access between two power outages of 4.5 hours per day [3]. At any period when the grid electric power is available, the supply voltage fluctuates mostly between 160 and 205 Volts [4] and only about 40 percent of Nigerians are connected to the grid [2].

The inadequacy of the utility grid has consistently led to load shedding. The problem has adverse effects on all sectors of the economy. Most entrepreneurs have resorted to use fossil-powered sources while diesel generators (DGs) are being used either as supplements to the grid or exclusively in remote areas [1]. The socio-economic implications associated with the use of diesel generators can be very alarming [5]. Compared to the grid, the cost of electric power generation from fossil-fuelled generators is significantly higher. The monetary cost of electric power in Nigeria is nine times higher than that of China [6]. It is to be noted that the high cost of electric power has crippled the Nigerian industrial sector. Moreover, the environmental consequences of harnessing and utilizing fossil fuels are assuming alarming proportions [7]. The most threatening of these problems, perhaps, is the greenhouse effect, where certain pollutants prevent the sun's radiation from escaping from the atmosphere. The problem has the potential of creating dangerous climate changes, with devastating effects on certain species and the ecosystem. A typical scenario of such impact is the recent flooding in Nigeria, which claimed lives, displaced citizens and destroyed properties estimated worth over billions of Naira [4].

To address the lack of electricity access in different parts of the developing world, different micro-power systems have been analyzed [8]. A micro-grid is an isolated power system, which can intelligently manage distributed energy resources, interconnected loads and is capable of operating in parallel with, or independently from, the grid. In the same vein, it can economically provide electric power while enhancing the power quality and reliability by integrating and optimizing various sources of energy. Nonetheless, the viability of a micro-grid depends on the mix of power sources, the size or allocated capacity and the dispatch strategy [1]. Wind power is a promising technology commonly used in micro-grids [8-10]. Wind is a clean source of energy that is ubiquitous and freely available, but it depends highly on site meteorology [11]. The annual average wind speeds in Nigeria range from about 2 to 9.5m/s [12]. Therefore, the sustainability of micro-grids, which includes the wind power option should be assessed to enable potential investor decide on the most suitable technology or the combination.

This paper examines the possibility of using wind power to augment fossil-power for electricity generation in Nigeria. A wind-diesel micro-grid simulated for a hypothetical area, which consists of a population of 15 households, is considered for this study. The objectives are to determine the techno-economic and environmental merits of a wind-diesel micro-grid in Nigeria. The rest of the paper is organized as follows: section II describes the methods adopted to achieve the set objectives. The results are presented and discussed in section III, while the conclusion is given in section IV.

II. Methods

The configuration of the studied micro-grid, intended to provide electrical power to a hypothetical area comprising of 15 households with an estimated daily electric load consumption of 283.94kWh/d is shown in Fig. 1. HOMER software was utilized for the design and analysis of the micro-grid as it allows for comparison with various design options. The comparison makes it easier to assess the techno-economic and environment benefits of different power system options.

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The characteristics of the wind turbine and diesel generators utilized for the micro-grid design are shown in Figs. 2 and 3 respectively. The Generic generator properties were chosen from HOMER database. The output power profile of the selected wind turbine generator (WTG) was supplied by the Anhui Hummer Dynamo Company Limited for Hummer H6.4-5kW WTG, with rotor diameter and tower height of 6.4m and 20m respectively. The wind data used for this study, as shown in Fig. 4, were adjusted to WTG hub height according to the power law. Power law is one of the ways to model wind shear [11]. The wind data, which consist of the monthly average daily wind speed measurements at Maiduguri, are measured at a height of 10m above sea level for a period of 22-years (1991–2012). The data were supplied by the Nigerian Meteorological (NIMET) agency, Oshodi, Nigeria. The main characteristics of data sets collected from NIMET are described in [11].

The daily pattern of domestic electricity consumption used for this study, with an estimated daily electric load consumption of 283.94kWh/d is given in Fig. 5. The electric load profile is similar to that described in [1]. HOMER synthesized the annual hourly load profile from the daily profile by adding some randomness to account for real-time hourly and daily variations taken in this study as 15 and 10%, respectively. Nevertheless, real-time electric load tend to jump around randomly. As a result, an operating reserve is needed. A micro-grid, which includes wind as a source of power requires more operating reserve to guard against random decreases in the renewable power supply. In the case of a rise in energy demand or decrease in wind speed, the operating reserve prevents the micro-grid from going down. This study considered an operating reserve of 40% of load demand.

The main input parameters used for sizing the micro-grid are described in [10]. The project lifetime and annual interest rate considered are 20 years and 3.3%, respectively. The rate corresponds to the current cost of borrowing in terms of dollars. The load-following strategy was employed as it can minimize excess electricity generation and reduce the total NPC (Net Present Cost) of the system. The economic analysis was assessed by the COE (Cost of Energy per kWh) and the NPC of the system. The HOMER software determines the NPC of the micro-power system using the following equation:

$$NPC = C_{ann,tot} / [i(1+i)^N / ((1+i)^N - 1)] \quad (1)$$

where, $C_{ann,tot}$ is the total annualized cost ($/y), i is the interest rate (%) and N is the project lifetime (y). An option or mix of power sources is feasible if the power option can satisfy the load demand subject to the pre-defined constraints. The feasible option with the lowest total NPC and COE is considered as the most viable option.

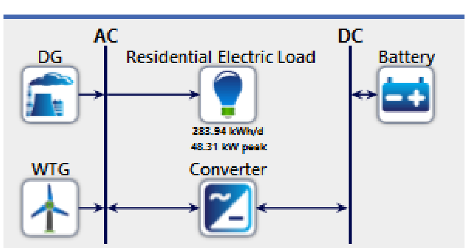

Fig. 1. The wind-diesel micro-grid system architecture

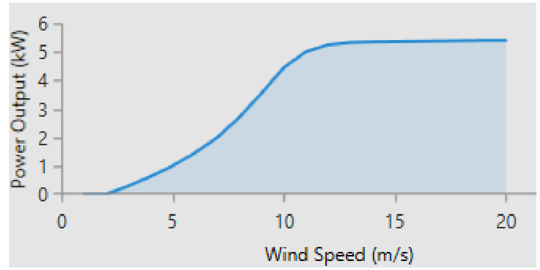

Fig. 2. Power characteristics of Hummer H6.4-5kW wind turbine generator

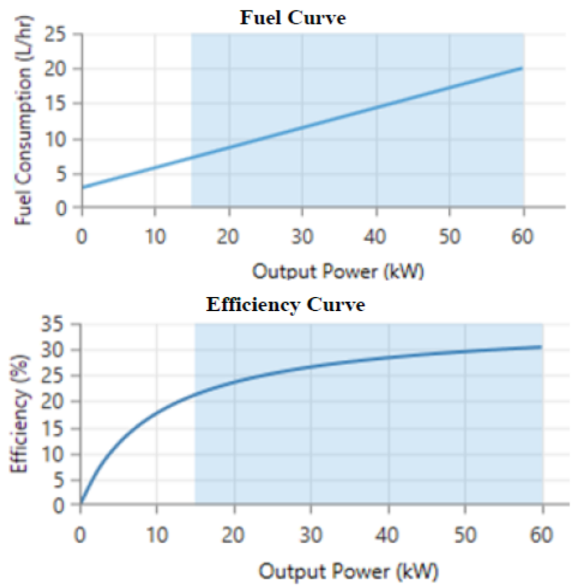

Fig. 3. Fuel and efficiency curves of selected diesel generator

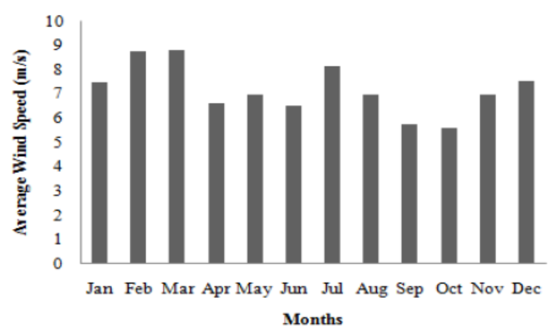

Fig. 4. Long-term (1991 –2012) monthly average wind speed data for Maiduguri, Nigeria

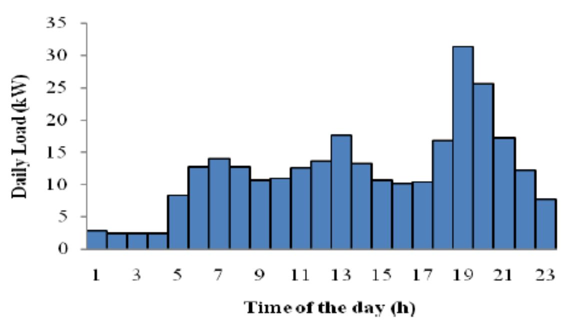

Fig. 5. Daily electric load profile for the residential area consisting of 15 households in Nigeria

III. RESULTS AND DISCUSSION

A comparison of the optimized wind-diesel micro-grid with the wind-battery, diesel-battery and the diesel-only system is shown in Table I. The optimum size of the isolated micro-grid, which consists of 60kW wind turbine, 10kW diesel generator and 172.8kWh (48V, 3600Ah) battery banks enabled reliable and cost-effective energy supply at Maiduguri. As observed, the optimum wind-diesel micro-grid option reduced the COE by 12.89, 73.84 and 79.76 percent compared to the wind-battery, diesel-battery and the diesel-only option respectively without compromising the power supply reliability of the system. In particular, the installation of the optimum capacity of the wind-diesel micro-grid at isolated sites in Maiduguri can save more than 79% of electricity payments. The high reduction in monetary costs shows the potential of wind power within the region. The result suggests that either the wind profile or cost of diesel, or both can significantly influence the range of financial benefits of the wind-diesel micro-grid.

The electrical properties of various power options are compared in Table II. The electricity characteristics vary for different options. A significant change in energy production and consumption is observed for options, which include wind power. The variation is due to the intermittent nature of the wind as a source of power. The wind-battery option gives the highest excess energy percent (69%). It is worth mentioning that the power system, which includes renewable such as wind always produces excess energy for few moments to guarantee, continues power supply. The inclusion of diesel generator to provide power at such periods can reduce the COE, since the cost of excess generation is accounted for in the total NPC. As shown, the inclusion of the diesel generator with operation time of 902 hours per annum reduces the COE of the wind-battery option by 12.9%, from \$0.194 to \$0.169 (₦38.51 to ₦33.55; note that \$1 ≈ ₦198.53, Central Bank of Nigeria, accessed June 19, 2016).

The optimum capacity of the wind-diesel micro-grid reduces the excess capacity from 69 to 60.9% but with the release of pollutant emission into the environment. Augmenting the wind-battery option with 8% of the electric power production from diesel generator emits 7,638.9 kg of CO_2 per annum, in addition to other harmful gases as shown in Table III. When compared with the exclusive use of diesel generator as a power source in remote locations, the use of the optimum capacity of the wind-diesel micro-grid can reduce the CO_2 emission per annum from 153,114 to 7,638.9 kg/y. A significant reduction of over 95% in CO_2 emission from residential energy consumption can make the environment "greener" and more eco-friendly. The high percentage reduction in both monetary costs of energy and pollutant emission is a clear indication that the wind-diesel micro-grid if optimally sized can be more viable compared to the conventional (diesel-only) power system at isolated regions in Maiduguri (Nigeria).

The effect of varying interest rate on the optimum configuration of the micro-grid (with diesel price fixed at 1.0 US dollar per liter) is shown in Table IV. As noticed, increase in interest rates increases the COE of the micro-grid, but reduces both the optimum capacity and energy contribution of the renewable power source. The reason is that the lower the capacity/contribution of wind power, the higher the fossil-powered source needed to reliably power the electric loads. The potential of the wind-diesel micro-grid at other locations across Nigeria, with similar load profile, was assessed on the basis of sensitivity analysis.

Sensitivity analysis is performed on the system by varying both the cost of diesel and the annual average wind speed according to the wind speed distribution in Nigeria. The analysis can assist either potential investors or energy consumers, or both in selecting the most viable micro-grid option at other locations with a similar energy consumption pattern. The two most viable micro-grid options are wind-diesel-battery and the diesel-battery systems as shown in Fig. 6. As observed, the COE reduces with a decrease in diesel price and a rise in annual average wind speed. In contrast, the COE increases with the increase in diesel price and the decrease in the annual average wind speed.

TABLE I. COMPARISONS AMONG DIFFERENT MICRO-GRID OPTIONS AT MAIDUGURI, NIGERIA

Micro-Grid Architecture					Cost				System		DG	
Options	***WTG (kW)***	***DG (kW)***	***Battery (kWh)***	***Converter (kW)***	***Initial Capital (\$)***	***Operating Cost (\$)***	***Total NPC (\$)***	***COE (\$)***	***Renew. Fraction***	***Capacity Shortage***	***Fuel (L)***	***Operation (h)***
Wind-diesel-battery	60	10	172.80	30	140,800	7,714	252,109	0.169	0.92	0.001	2,901	902
Wind-battery	80	-	328.32	40	199,200	6,265	289,594	0.194	1.00	0.001	-	-
Diesel-battery	-	40	-	10	42,200	64,054	966,448	0.646	0.00	0.001	44,752	7,492
Diesel-only	-	50	-	-	25,000	84,820	1,248,882	0.835	0.00	0.000	58,145	8,760

TABLE II. COMPARISONS OF ELECTRICAL PROPERTIES OF DIFFERENT MICRO-GRID OPTIONS AT MAIDUGURI, NIGERIA

Power Options	**Electricity Production (kWh/y)**	**Electricity Consumption (kWh/y)**	**Excess Electricity**	
			(kWh/y)	***(%)***
Wind-diesel-battery	276,800	103,615	168,639	60.9
Wind-battery	357,561	103,603	246,676	69.0
Diesel-battery	106,178	103,625	398.9	0.4
Diesel-only	129,783	103,638	26,145	20.1

TABLE III. COMPARISONS OF POLLUTANT EMISSIONS AMONG DIFFERENT OPTIONS AT MAIDUGURI, NIGERIA

Power Options	**Emissions (kg/y)**					
	CO_2	***CO***	***Unburned Hydrocarbon***	***Particulate Matter***	***Sulfur Dioxide***	***Nitrogen Oxides***
Wind-diesel-battery	7,638.90	18.86	2.09	1.42	15.34	168.25
Wind-battery	-	-	-	-	-	-
Diesel-battery	117,846.00	290,89	32.22	21.93	236.66	2,595.60
Diesel-only	153,114.00	377.94	41.86	28.49	307.48	3,372.40

TABLE IV. IMPACT OF INTEREST RATES ON OPTIMUM MICRO-GRID ARCHITECTURE AT MAIDUGURI, NIGERIA

Interest Rates	**Micro-Grid Architecture**				**Cost**				**System**		**DG**	
	WTG (kW)	***DG (kW)***	***Battery (kWh)***	***Converter (kW)***	***Initial Capital ($)***	***Operating Cost ($)***	***Total NPC ($)***	***COE ($)***	***Renew. Fraction***	***Capacity Shortage***	***Fuel (L)***	***Operation (h)***
2.50	60	10	172.80	30	140,800	7,710	260,958	0.162	0.917	0.001	2,901	902
3.33	60	10	172.80	30	140,800	7,714	252,109	0.169	0.920	0.001	2,901	902
4.50	50	10	224.64	30	134,600	8,161	240,808	0.179	0.903	0.001	3,371	1,048
7.00	50	10	224.64	30	134,600	8,095	220,356	0.201	0.903	0.001	3,371	1,048

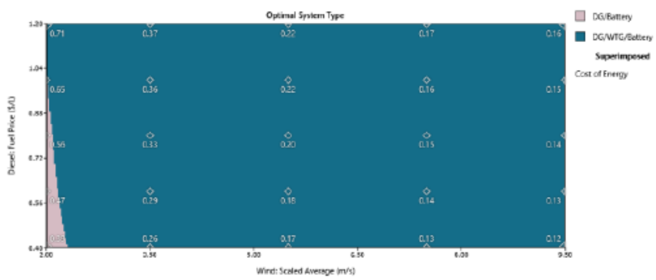

Fig. 6. Optimum cost of micro-grid at interest rate of 3.3% and maximum capacity shortage of 0.0% at different sites across Nigeria.

Compared with interest rate, the variation of the annual average wind speed has greater impact on the COE of the micro-grid. At the range of annual average wind speed from 2.5 to 9.5 m/s and the fixed interest rate of 5.5% and the diesel price greater than or equal to 0.5$/L, for example, the wind-diesel-battery hybrid system is the most viable

IV. CONCLUSION

Techno-economic analysis is very vital in the design of the optimum capacity for reliable and cost-effective operation of micro-grids. Such an analysis must consider the meteorological data of the site and external economic condition. The present study assessed the techno-economic and environmental impacts of micro-grids at isolated regions. Analysis was performed based on the HOMER software using daily profile of domestic electricity consumption and the long-term average wind speed data for Nigeria. The results proved that the proposed wind-diesel micro-grid can bring about the benefits of improved power reliability and cost saving, but the range of financial benefits depends on the geographical coordinates. In particular, the installation of a micro-grid, which consists of 60kW wind turbine, 10kW diesel generator and 172.8kWh (48V, 3600Ah) battery bank can reliably supply the electric load requirements of an isolated area (with an estimated daily average and peak load consumption of 283.94 kWh/d and 48.31kW respectively) at Maiduguri, and can save more than 79% of electricity costs, compared with the conventional diesel-only power system. Moreover, a significant reduction of over 95% in CO_2 emission from residential energy consumption can make the environment “greener” and more eco-friendly.

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