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Optimum Design, Simulation and Performance Analysis of a Micro-Power System for Electricity Supply to Remote Sites

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***Abstract*—This research paper centers on the optimum design, simulation and performance investigation of a micro-power system for off-grid locations. The objectives are to verify the monetary cost, power supply reliability and ecological benefits of the addition of wind turbines and solar photovoltaic array to a diesel generator system for electric power generation in remote sites. The optimum design configuration of the hybrid micro-power system was established on the basis of energy-balance estimations using the Hybrid Optimisation Model for Electric Renewable (HOMER) software. Simulations were carried out for a remote site in Maiduguri (lat. 11°50.9′N and long. 13°9.2′E), with a population size of 50 households, using the estimated electric load profile and 22-years meteorological data sets collected for the studied area. The results showed that a micro-power system made up of 75kW wind turbine, 46.7kW of solar photovoltaic generator and a battery bank capacity of 420.34kWh (24V, 17,514Ah) can reliably satisfy the electric power demands for a remote site at Maiduguri (with a daily peak and average consumption of 97.74kW and 563kWh/d respectively). Moreover, a monetary cost saving of over 79% in addition to a reduction of 5,125 kg/y of CO_2 emission per household energy consumption can be achieved compared with the traditional diesel-only power generation system.**

Keywords*— *micro-grid; off-grid power; optimum economical sizing; solar energy; wind energy; wind turbine

I. Introduction

African's electricity demand is blowing up due to its rapidly booming population, which is estimated to quadruple by 2100 [1]. Moreover, Africa consists of 15% of the global population but utilises only 3% of the primary energy consumption worldwide. According to the Africa Energy Sector Outlook [2], an estimate of over 93 million people cannot access electricity in Nigeria – the most populous African country – and about 80% of these people, who currently lack access to electricity grid, are rural populace. In spite of this problem, the electricity supply is highly unreliable. The reliability fluctuates between 39 and 66 percent and the grid electricity can only be accessed for an average of 6 hours per day [3], [4]. The social and economic impacts associated to the drawbacks of the grid could be very alarming. A typical example was the flooding in Nigeria that took lives, displaced so many people and destroyed properties with approximate worth over billions of Naira [5]. In addition, if much of the power required to meet the electricity demand in Africa was to come from fossil fuels, it could hamper global efforts to reducing the pace of global warming.

To resolve the problem of inadequate access to electricity, different micro-power systems have been analysed in the literature [3] – [14]. A micro-power system, such as a micro-grid, can intelligently control distributed power resources and the connected loads while operating independently from or in parallel with the grid [6]. In addition, it can efficiently supply electric power with improved reliability and power quality by integrating and optimising a mix of power sources [7], [8]. Nevertheless, the feasibility of a micro-power system depends on the hybrid energy sources, the allotted power capacity as well as the energy dispatch strategy [9]. The renewable power system design, mostly, incorporates renewable energy mixes, for example biomass, solar photovoltaic and wind [10]. Unfavourably, large landmass, water usage and social impacts frequently characterise the electric power production from biomass and further investigation is required to authenticate the techno-economic prospects of its power generation [11]. As a result, there is a shift in energy demand for other sources.

Wind and solar resources are usually utilised because of their technical and environmental merits, but these sources depend highly on the site meteorology. Hence, the range of economic and technical benefits that can be derived from renewable power systems varies from one place to another [12]. Consequently, the sustainability of micro-power systems that include renewable (wind and solar) power options should be examined as this could allow potential investors decide on the most suitable design for efficient implementation of the micro-grid technology [13]. Optimum design analysis is a pre-requisite for optimum capacity allocation of system components that can guarantee reliable and efficient operation of a micro-power system [14]. Such a design analysis considers the site meteorology and external economic conditions. In addition, correct estimates of solar and wind resources as well as appropriate choice of solar panels and wind turbines with efficient operation and management strategy are crucial factors, which affect the renewable energy potential. Africa has the highest reserves of renewable energy resources potential, to cater to future energy needs [15]. The under-utilisation of these renewable sources, perhaps, is due to technological constraints such as the enabling technology for deployment.

This paper investigates the prospects of utilising a wind-solar hybrid energy system to augment the diesel generator for electricity supply to remote locations. The specific objectives are to: (a) design and simulate a wind-solar micro-power system that can augment the fossil-power supply in isolated regions, (b) determine the optimum operating capacity of the power system for a remote area, and (c) determine the technical, economical and ecological merits of the power system for electricity supply. The inclusion of solar photovoltaic generator to the micro-power system, unlike in [5], could reduce the contribution of fossil fuels, with a corresponding decline in CO_2 emissions and thereby making the surroundings more eco-friendly and safe. In addition, the hybrid energy mix of different power sources could optimise the viability of each power source while compensating for the drawbacks of other sources. The rest of this paper is organised as follows: section II describes the micro-grid design and process simulation techniques utilised to realise the set objectives of this research paper. The results are analysed in the third section whereas the conclusion is presented in the fourth section.

II. Methods

A. The Micro-Grid Design Analysis

The design of the proposed micro-power system intended to supply electrical power to the study site with an estimated population size of 50 households is shown in Fig. 1. The total estimated daily and peak electric load consumptions are 563kWh/d and 97.74kW respectively. Power electronic converter is included for power conversion and stabilising of unpredicted voltage and frequency fluctuations. The converter – links the AC and the DC bus – allows bidirectional transfer of power, which enables the generation of proper power level between power sources and the distribution for reliably satisfying the energy demand.

The output power of a solar photovoltaic (PV) array is determined using the following equation [16]:

$$P_{PV} = f_{PV} Y_{PV} (I_T / I_S), \tag{1}$$

where, f_{PV} is the PV de-rating factor, Y_{PV} (kW) is the rated capacity of the array, I_T (kW/m^2) is the global solar irradiation incident on the surface of the array, and I_S (kW/m^2) is the standard amount of irradiation utilised to rate the power of the array. The de-rating factor accounts for the impacts of elevated temperature, wire losses as well as the effects of dust on the performance of the PV array [17].

Wind turbine (WT) designs and placement are essential parameters for optimum energy harvest but interests are mostly centred in optimising the turbine settings so as to maximise the performance of the turbines [18]. The horizontal-axis wind turbine designs for variable-speed operations utilised by modern wind turbines has higher efficiency, lower cost-to-power ratio with reduced noise and mechanical stress compared to the fixed-speed configuration [1]. The variable-speed wind turbines can trace the optimum power extraction point; hence, can generate more power than the constant-speed type, but it requires advanced power electronics, intelligent control circuitry to provide constant frequency and power factor. The power profile of WT utilised by the micro-power system design is shown in Fig. 2. The rotor diameter of the WT selected is 6.4m. The wind data were modified to the WT installation height based on the power law, which is one of the techniques utilised to model the wind shear.

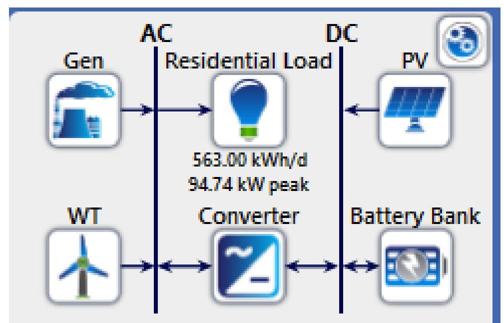


Fig. 1. Design of the proposed hybrid micro-power system

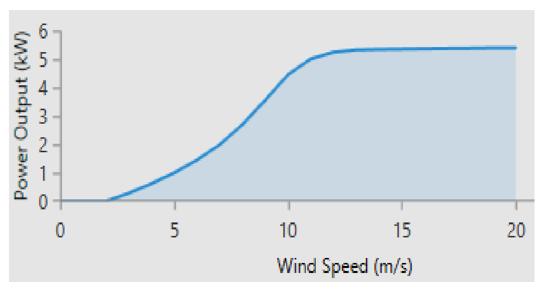


Fig. 2. Power profile of WT (H6.4-5kW) selected for this study

The fuel consumption (L) of the generator (Gen), operating at time *t*, can be computed using (2).

$$F_g(t) = a.P_r + b.P_o. \tag{2}$$

P_r (kW) is the rated power of the generator, P_o (kW) is the output power of the generator at time *t*, *a* (L/h) is the fuel curve intercept coefficient and *b* (L/h/kW$_o$) is the fuel curve slope. The minimum load ratio assumed for the generator in this study is 25%. The fuel and efficiency characteristics of the generator considered are shown in Fig. 3.

The lifetime (y) of a diesel generator can be calculated using (3), where, $L_{g,h}$ (h) is the generator life span and N_g (h/y) is the hours of operation of the generator per annum [17].

$$L_g = L_{g,h} / N_g. \tag{3}$$

A battery bank is required because it cancels out unexpected power fluctuations, stabilises the voltage and frequency, improves the power supply quality, reduces the fossil fuel usage and provides security of energy supply [19]. The battery bank life span is determined by (4); given that $E_{l,tp}$ (kWh) is the lifetime throughput of a single battery, $E_{a,tp}$ (kWh/y) is the yearly battery throughput, L_b (y) refers to the life span of the battery bank, N_b is the number of batteries in the bank and $L_{b,f}$ (y) is the battery float life.

$$L_b = [(N_b E_{l,tp}) / E_{a,tp}, L_{bf}]_{\min} . \quad (4)$$

The battery bank autonomy, A_b (h), which refers to the ratio of the battery bank capacity to the electric load, is determined by (5) [20]; where N_b is the number of batteries, V_n (V) and Q_n (Ah) is the nominal voltage and the nominal capacity of a battery respectively, q_m (%) is the minimum state of charge of the storage bank and L_a (kWh/d) is the average electric load.

$$A_b = N_b V_n Q_n (1 - 0.01 q_m)(24h/d) / [L_a (1000Wh/kWh)] \quad (5)$$

B. Data, Analysis and Simulation

Figure 4 shows the topographic and aerial views of the study area. The weather data sets utilised for the case study simulation were collected from two sources. The first part consists of the ground-based monthly average daily wind speed data taken from the Nigerian Meteorological agency. These data were measured from 1991–2012 at a height of 10m above sea level. The second set of data is satellite-derived, made up of the monthly mean daily global solar radiation data, which extends from 1984 to 2005. The data were downloaded from the archives of the National Aeronautics and Space Administration (http://eosweb.larc.nasa.gov/; accessed on January 15, 2016). These data were checked for inconsistencies so as to eliminate incomplete measurement. Table I shows the monthly average meteorological data sets used in this study while Table II describes the main properties of the wind speed data.

The daily pattern of a residential household electricity consumption utilised to estimate the electric load profile of the study area is depicted in Fig. 5. HOMER software (version 3.9.1) was utilised for the simulation and analysis of the proposed micro-power system as it permits comparison with different design options. The comparison makes it simpler to calculate the techno-economical and environmental merits of various power system options [5]. The annual load profile (Fig. 6) was synthesised from the daily load profile (Fig. 5), using HOMER, by adding some uncertainty to account for the real-time daily and hourly variations considered as 10 and 15% respectively. The scaled annual daily average electric load was adjusted to 563kWh/d (i.e., the annual average per household of 11.26kWh multiplied by 50 households). The input parameters used for sizing the micro-power system is shown in Table III. The project lifetime and the expected inflation and real discount rate considered are 25 years, 2.5% and 2.44% respectively. The load-following control strategy was utilised since it can minimise excess electricity production and reduce the total Net Present Cost (NPC) of the power project. The economic analysis of different power options was assessed by the Cost of Energy per kWh (COE) and the NPC of the system. The HOMER software determines the NPC of the micro-power system using (6); where, $C_{a,tot}$ is the total annualised cost ($/y), i is the interest rate (%) and N is the project life span (y).

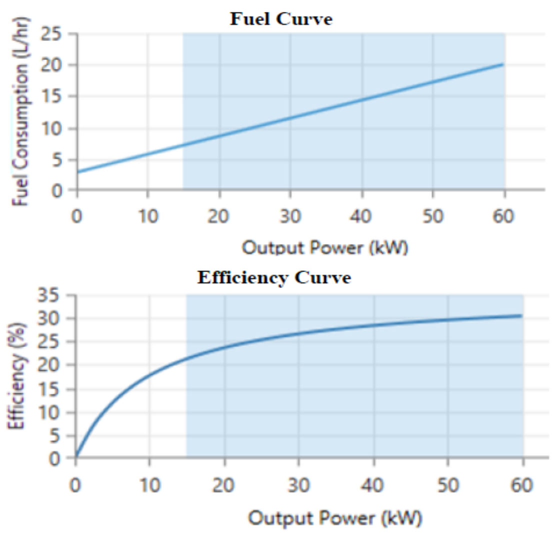
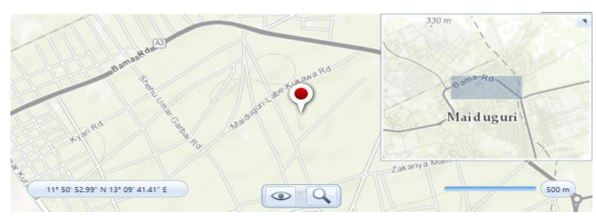
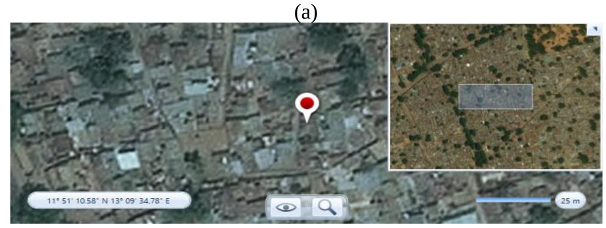


Fig. 3. Fuel and efficiency characteristics of generator used in this study



(a)



(b)

Fig. 4. Map of the study area (a) topographic view (b) aerial view

TABLE I. LONG-TERM MONTHLY AVERAGE DAILY METEOROLOGICAL DATA FOR MAIDUGURI

Resources	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
Global solar radiation (kWh/m^2/d)	5.52	6.38	6.91	6.95	6.67	6.36	5.80	5.42	5.60	5.71	5.49	5.09	5.99
Wind speed (m/s)	7.50	8.80	8.80	6.70	7.00	6.50	8.20	7.00	5.80	5.60	7.00	7.60	7.20

TABLE II. MAIN CHARACTERISTICS OF DATASETS COLLECTED FROM THE NIGERIAN METEOROLOGICAL AGENCY [21]

Instrument	**Measurement Range**	**Recording Resolution**	**Accuracy**
Wind vane (for direction)	0 – 360º	≤ 1º	± 2º
Anemometer (for speed)	0.30 – 50 m/s	≤ 0.10 m/s	± 0.30 m/s

TABLE III. INPUT PARAMETERS FOR SIZING THE MICRO-POWER SYSTEM

Option	**Parameters**	**Specifications**
PV	Model	CNSDPV150
	Size (search space)	0 – 200 kW
	Capital	$1,100/kW
	Replacement	$1,100/kW
	O&M per annum	$5/kW
	De-rating factor	95 %
	Lifetime	25 year
	Operation mode	No tracking System
WT	Model	H6.4-5 kW
	Size (search space)	0 – 200 kW
	Capital	$7,000/WT
	Replacement	$6,800/WT
	O&M per annum	$70/WT
	Lifetime	15 year
	Hub height	25 m
Gen	Model	Typical
	Size (search space)	0 – 200 kW
	Capital	$370/kW
	Replacement	$350/kW
	O&M per annum	$0.032/h
	Lifetime	15,000 h
	Diesel price	$0.75/L
	Fuel curve intercept coefficient (a)	3.36 L/h
	Fuel curve slope (b)	0.251 L/h/kW
Controller	Capital	$100
	Replacement	$100
	O&M per annum	$0
	Lifetime	25 year
Converter	Model	Typical
	Size (search space)	0 – 200 kW
	Capital	$150/kW
	Replacement	$150/kW
	O&M per annum	$2/kW
	Lifetime	15 year
	Inverter/Rectifier input efficiency	95 %

TABLE III. CONTINUATION

Option	**Parameters**	**Specifications**
Battery	Model	Lead-Acid (Generic)
	Nominal voltage	12 V
	Nominal capacity	83.4 Ah (1.0 kWh)
	Lifetime throughput	800 kWh (10 y)
	Round trip efficiency	80 %
	Maximum charge rate	1 A/Ah
	Size (search space) strings (2 batteries per string)	0 – 2000 kWh
	Capital	$135/ battery
	Replacement	$135/ battery
	O&M per annum	$10/ battery
System control and constraints	Simulation step	60 min
	Dispatch strategy	Load following
	Maximum yearly capacity shortage	2 %
	Minimum renewable fraction	0 %
	Percent of hourly load	10 %
	Percent of annual peak load	0 %
	Percent of hourly solar output	15 %
	Percent of hourly wind output	20 %

Note: $1 ≈ ₦ 305.5 (Central Bank of Nigeria, accessed June 9, 2017)

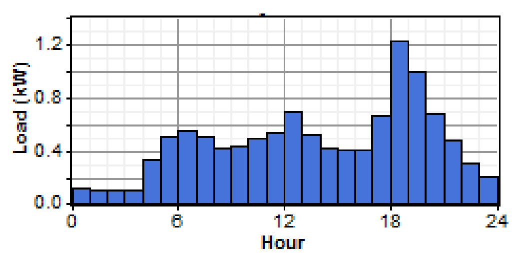


Fig. 5. Daily pattern of residential electricity consumption per household

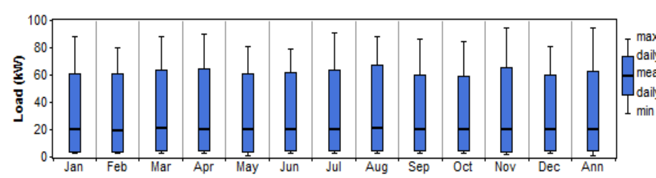


Fig. 6. Yearly load profile of study area with 50 households in Maiduguri

$$NPC = C_{a,tot} / [i(1+i)^N / ((1+i)^N - 1)] \qquad (6)$$

An option or a mixture of energy sources is possible if the power option can satisfy the load demand subject to the pre-defined constraints. The feasible option with the lowest NPC is considered as the most realistic option.

III. RESULTS AND DISCUSSION

Table IV shows the simulation result. The optimum hybrid micro-power system design, which can enable reliable and efficient electric power supply to off-grid sites at Maiduguri is made up of 75kW wind turbine, 46.7kW solar photovoltaic array and a battery bank with a capacity of 420.34kWh (24V, 17,514Ah).

As noticed, a comparison of the optimal wind-solar-battery system with other feasible power options (wind-solar-diesel-battery, wind-diesel-battery and solar-diesel-battery) shows that the wind-solar micro-power option lowered the COE by 6.75, 14.01 and 42.74 % respectively but with 1.51% deficit power supply. The installation of the optimal operation size of the wind-solar-battery system at remote areas in Maiduguri can save over 79% of electricity bills compared to the diesel-only energy system. The high reduction in costs is an indication of the potential of wind-solar micro-grid within the region.

The economics of different hybrid-power system options are compared with the traditional diesel-only (base case) system in Table V, taking into account the monetary costs of installation, operation and maintenance of each system. As observed, the positive values of the present worth shows that a significant amount of money ranging from $1,535,529.0 to $1,900,912.0 can be saved by installing the various hybrid power system options as a substitute to the diesel-only power system.

The return on investment (ROI) is an index, which specifies the financial benefits an investor derives from an investment. This index is used to compare the efficiencies of different projects. A high ROI indicates that the benefits of a project compare favourably to its monetary cost. As shown (Table V), the wind-solar-battery micro-power system has the highest ROI (61.4%) while the solar-diesel-battery hybrid system has the least ROI (38.8%) compared to the diesel-only system. On the other hand, the internal rate of return (IRR) considers the time value of fund in assessing an investment. The higher the IRR index the better the investment. The payback period (y) indicates the duration it would take to recover an investment (i.e., the difference in monetary cost between the current power project and the base case system). The simple payback is derived using the nominal cash flow while the discounted payback is computed using the discounted cash flow.

The electrical characteristics of the different power architectures are compared as shown in Table VI. The properties differ for different system architectures. A significant change (> 43%) in the electric power generation and consumption was observed for options with wind power. The disparity in the electricity is as a result of the high irregular

TABLE IV. SIMULATION RESULT FOR DIFFERENT POWER SYSTEM ARCHITECTURES AT MAIDUGURI

Architecture						**Cost**				**Battery Bank**		**Gen**	
Options	***WT (kW)***	***PV (kW)***	***Gen (kW)***	***N_b***	***Converter (kW)***	***COE ($)***	***NPC ($)***	***Operating Cost ($)***	***Initial Capital ($)***	***Autonomy (h)***	***Annual Throughput (kWh)***	***Fuel (L)***	***Operation (h)***
Wind-PV-battery	75	46.7	-	420.0	69.7	0.1258	472,356	13,407	223,600	10.8	40,997	-	-
Wind-PV-diesel-battery	70	37.8	110	340.0	54.6	0.1349	514,144	15,074	234,464	8.7	36,337	3,782	274
Wind-diesel-battery	105	-	110	322.0	56.3	0.1463	557,832	17,146	239,719	8.24	35,445	4,200	340
PV- diesel-battery	-	140	110	622.0	64.7	0.2197	837,822	29,616	288,292	15.9	99,552	8,947	587
Diesel-only	-	-	110	-	-	0.6225	2,373,267	125,716	40,800	-	-	97,902	8,760

TABLE V. COMPARISONS OF ECONOMICS AMONG DIFFERENT HYBRID-POWER SYSTEM OPTIONS WITH DIESEL-ONLY (BASE CASE) SYSTEM AT MAIDUGURI, NIGERIA

Compare Economics	**Present Worth ($)**	**Annual Worth ($/y)**	**ROI (%)**	**IRR (%)**	**Simple Payback (y)**	**Discounted Payback (y)**
Wind-PV-battery versus Diesel-only	1,900,912	134,874	61.4	62.2	1.61	1.66
Wind-PV-diesel-battery versus Diesel-only	1,859,124	131,909	57.2	57.2	1.73	1.78
Wind-diesel-battery versus Diesel-only	1,815,436	128,810	54.7	55.4	1.77	1.83
PV-diesel-battery versus Diesel-only	1,535,529	108,950	38.8	39.6	2.36	2.48

TABLE VI. COMPARISON OF ELECTRICAL CHARACTERISTICS OF VARIOUS MICRO-POWER SYSTEM ARCHITECTURES AT MAIDUGURI, NIGERIA

Power Options	**Electricity Production (kWh/y)**	**Electricity Consumption (kWh/y)**	**Renewable Fraction**			**Shortage Capacity (%)**	**Unmet Electric Load (%)**	**Excess Electricity**	
			Wind (%)	***PV (%)***	***Total (%)***			***(kWh/y)***	***(%)***
Wind-PV-battery	429,350	202,388	76.2	23.8	100	2.08	1.51	199,939	48.0
Wind-PV-diesel-battery	387,929	205,495	74.4	20.1	94.5	0.00	0.00	169,712	43.7
Wind-diesel-battery	456,780	205,495	94.1	-	94.1	0.00	0.00	237,377	52.0
PV-diesel-battery	324,196	205,495	-	86.5	86.5	0.00	0.00	87,097	26.9
Diesel-only	272,566	205,495	0.00	0.00	0.00	0.00	0.00	67,071	24.6

TABLE VII. COMPARISON OF POLLUTANT EMISSIONS FOR VARIOUS POWER SYSTEM ARCHITECTURES AT MAIDUGURI

Power Options	Emissions (kg/y)					
	CO_2	***CO***	***Unburned Hydrocarbon***	***Particulate Matter***	***Sulfur Dioxide***	***Nitrogen Oxides***
Wind-PV-battery	-	-	-	-	-	-
Wind-PV-diesel-battery	9,889	62.4	2.72	0.378	24.2	58.6
Wind-diesel-battery	10,995	69.3	3.02	0.42	26.9	65.1
PV- diesel-battery	23,914	148	6.44	0.895	57.3	139
Diesel-only	256,269	1,615	70.5	9.79	628	1,517

TABLE VIII. PERFORMANCE COMPARISON OF PROPOSED WITH PREVIOUS MICRO-POWER SYSTEM AT MAIDUGURI

Index	**Previous [5]**	**Present Study**	**Enhancement (%)**
COE ($)	0.1690	0.1258	25.56
Power supply reliability (%)	99.00	98.49	0.52
CO_2 emission per household (kg/y)	509.3	-	100
Renewable fraction (%)	92	100	8.70

nature as well as the high operating reserve of the wind power option. It is worthy of note that a power system that includes renewable (e.g., wind and solar) produces surplus electricity occasionally to ensure, continuous power supply. The wind-diesel-battery option generates the largest excess energy percent (52%).

The inclusion of a solar photovoltaic array to supply electricity at such times can lower the COE; this is because the cost of surplus production is accounted for in the NPC. In particular, the optimum capacity of the wind-solar-diesel-battery micro-power reduces the excess capacity of the wind-diesel-battery power system from 52% to 43.7% (see Table VI) with a monetary cost reduction from $0.1463 to $0.1349 as shown in Tables IV. Also, the annual CO_2 emission from the wind-diesel-battery system was reduced by 10% (from 10,995 to 9,889 kg/y) as shown in Table VII.

On the other hand, the inclusion of 23.8% of electric power production from a solar photovoltaic generator as an alternative source to diesel reduces the COE of the wind-diesel-battery system from $0.1463 to $0.1258 without polluting the environment, as the mix of energy sources does not require diesel generator. When compared with the exclusive use of fossil fuel generator in off-grid sites, the installation of the optimum size of the wind-solar-battery hybrid power system can reduce the CO_2 emission per annum by 256,269 kg/y (Table VII), which correspond to 5,125 kg/y of CO_2 emission per household. The significant reduction in CO_2 emission can make the surroundings "greener" and more eco-friendly. The high percentage reduction in the COE (>79%) as well as the significant reduction in pollutant emissions indicates that the wind-solar micro-power system if optimally configured can be a more viable alternative to the diesel-only power generation system at off-grid sites in Maiduguri (Nigeria).

Table VIII shows the performance comparison of the proposed wind-solar hybrid power system with the previous design [5] for Maiduguri, Nigeria. The performance comparison is based on the same electric load profile. The result shows that the installation of the proposed micro-grid design architecture at Maiduguri can bring about a cost benefit exceeding 25% per kWh consumption but with a down time of 0.52% (≈ 46 h/y) compared to the previous technology [5]. Moreover, over 509kg of CO_2 emission can be mitigated annually per household.

IV. CONCLUSION

This study focused on the optimum design, simulation and performance analysis of a micro-power system for off-grid regions. The overall aim was to investigate the prospects of utilising a wind-solar hybrid energy system to augment the diesel power generation system at remote locations. This research paper assessed the economical, technical and the ecological impacts of hybrid power systems at a remote location in Nigeria. The results showed that a wind-solar-battery hybrid power system made up of 75kW wind turbine, 46.7kW of solar photovoltaic generator and a battery bank capacity of 420.34kWh can reliably satisfy the electric power demands for a remote site at Maiduguri (with a daily peak and average consumption of 97.74kW and 563kWh/d respectively). Also, a monetary cost saving of more than 79% as well as a reduction of 5,125 kg/y of CO_2 emission per household energy consumption can be achieved compared to the regular generator power system. The implementation of the proposed micro-grid design can help in solving the energy problems in Nigeria as well to enhance the standard of living of the citizenry.

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