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Techno-economic Analysis of Hybrid Energy System Connected to an Unreliable Grid: A Case Study of a Rural Community in Nigeria

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***Abstract*—A significant number of Nigerian citizens lives in remote and rural settlements often without access to the utility grid. Even those areas connected to the grid still do experience frequent and prolonged power outages (as much as 18 hours on some days). Therefore, they have to rely on portable generators to power their electrical equipment during load shed, using firewood for cooking and burning of kerosene lamps for lighting up their homes which is not environmentally friendly. Proper sizing of multiple power sources complemented with or without a storage system has been shown to be the best long-term solution for the power challenge of Nigeria. In this paper, the technical and economic feasibility of the different combinations of energy sources (grid, wind turbine, solar photovoltaic (PV), diesel generator (DG) and battery) are carried out to meet the energy requirement of a remote village in Nigeria using HOMER (Hybrid Optimization of Multiple Energy Resources) Pro software. The aim is to determine the optimal configuration of a grid-connected Hybrid Renewable Energy System (HRES) that has the lowest net present cost (NPC) for the selected case study. It is shown from the simulation result that the incorporation of solar PV and battery storage into the existing system reduces the NPC by 32.3% and decreases the annual diesel fuel usage by 48.9%.**

Keywords — Hybrid Renewable Energy System; HOMER Pro; load shedding; unreliable grid; Levelized Cost of Energy (LCOE); Net Present Cost (NPC)

I. INTRODUCTION

Nigeria with a population of over 200 million citizens has a total installed grid capacity of 12,910.40 MW as of December 2018, available capacity is much less at about 5000 MW and only 15% of this is based on renewable energy resources (RERs) while the rest is generated from fossil fuels [1]. This ratio is indeed too small considering the potential of renewable energy utilization in Nigeria [2]–[3]. There is a significant disparity between demand and supply in Nigeria leading to frequent load shedding and power outages. According to World Bank, about 85 million Nigerians (43%) do not have access to the national grid electricity [4]. The fall of the Nigerian economy as the global oil prices dropped has been a wake-up call. Nigeria, chiefly dependent on oil and gas, felt the need to move from a mono-product economy to diversify her economy. However, the persistent unreliable energy supply in Nigeria has been a major challenge for citizens and businesses. This has led to annual economic losses of about $26.2 billion, equivalent to about 2% of the country's gross domestic product (GDP) [4].

Nigeria, being one of the most populous countries in Africa, has a strategic role to play in the realization of the United Nations' Sustainable Development Goals (SDGs) by 2030. SDG-7 (clean and affordable energy for all) is crucial, as it is linked strongly to achieving many of the other goals. In the recent decade, some studies have been carried out on the potential of RERs in Nigeria. Ajayi et al. [5], Olatomiwa et al. [7] and Bamisile et al. [8] revealed that there is a great prospect for renewable energy resources in supplementing Nigeria's energy needs and improving the power supply reliability however, little effort has been made to harness the potential due to lack of awareness and funding in this area. With the worldwide campaign on the possible depletion and the negative effect of fossil fuels on the environment, renewable energy has been proposed as a lasting and environmentally-friendly substitute for fossil fuels for a sustainable approach to development to both the developed and developing nations. Nigeria is blessed with abundant renewable energy resources, which are not yet fully exploited [9]. In previous studies most grid-connected HRESs analyses, the national grid is considered a reliable backup, where deficit or excess energy can be drawn or injected [10] – [13]. This type of scheme would be a challenge for many developing countries like Nigeria, where the grid supply can be unpredictable.

In this study, the potential of a grid-connected HRES in providing a solution to the problem of electricity blackouts in a typical rural community in Nigeria is explored. An optimal design and evaluation of different possible configurations of hybrid grid-connected energy systems for residential loads in rural Nigeria are carried out. The aim is to minimize the cost of energy for rural electrification by incorporating renewable energy resources and improving the reliability of the power supply to the area. The rest of the paper is organized as follows. Section II briefly describes the village under consideration and the grid operation schedule. Section III evaluates the renewable energy resources available at the case study site. The system components and control parameters are assessed in Section IV, while results and discussion are presented in Section V. Finally conclusions of this study are discussed in Section VI.

II. DESCRIPTION OF THE CASE STUDY SITE

A. Site Description

The location considered for this study is Sabon Daga, a rural settlement located in Niger state, north-central region of Nigeria. The village has a latitude of $9^{\circ}25'20''$N

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(9.422353°N) and a longitude of 6°23′03″E (6.384400° E). The occupation of most of the dwellers of Sabon Daga community is subsistence farming. An aerial view of the community is presented in Fig.1.

Fig. 1. Aerial view of Sabon Daga Community (*Source: earth.google.com)*

B. *Community Daily load profile*

Sabon Daga community contains about 200 households with a daily average electrical energy consumption of 957.34 kWh, a night-time peak of 65.52 kW and a load factor of 0.41. The load demand information was obtained through a semi-formal interview with the residents of the community. The electric loads are mostly residential, comprising household devices such as electric bulbs, radios, water pumps, fans, refrigerators and television (TVs).

The seasons of the year are divided into three: the dry season is from February to April, the wet season is from May to November, and the harmattan season is from December to January. The seasonal variation of the load profile is also taken into consideration as shown in Fig. 2. The energy demand of the community is highest during the dry season, this is because loads like fans and water pumps are used more frequently during this time to cushion the effects of the heat associated with this season whereas the energy demand is lowest during the cold harmattan season.

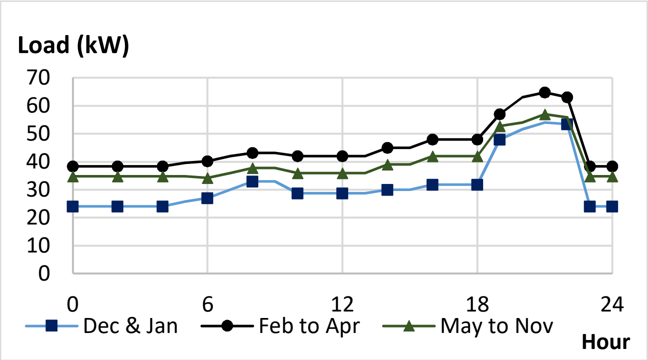

Fig. 2. Daily load profile of the village for different seasons

III. ENERGY RESOURCES ON SITE

A. *Utility Grid*

The village is connected to the national grid. However, like most of the country, power supplied to the community is very unreliable with an average daily grid supply of 6 to 8 hours and a 70% chance of electricity blackout. The annual grid outages for the community are presented in Fig. 2.

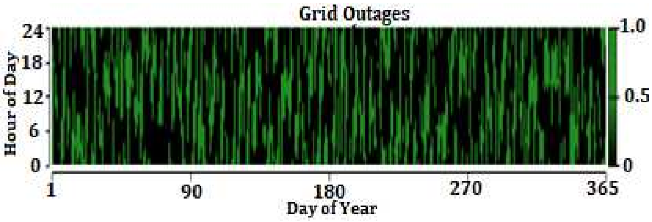

Fig. 3. Grid outages for Sabon Daga village for one year

B. *Solar Resources*

Nigeria lies within the tropical belt hence, is endowed with abundant solar energy all year round. Fig. 4 shows the average monthly variation of solar radiation and clearness index of Sabon Daga community as obtained from the national aeronautics and space administration (NASA) surface meteorology and solar energy database [14]. Solar radiation at the site is well distributed throughout the year with an annual average of about 5.49 kWh/m^2/day. The average monthly temperature is presented in Fig. 5. The power output of solar PV has a slightly negative correlation with the operating temperature [15].

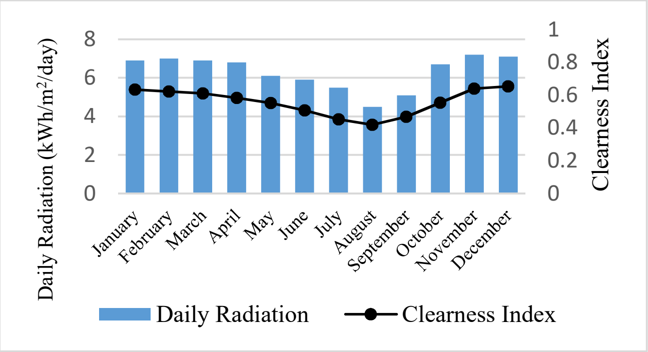

Fig. 4. Monthly average solar radiation chart for Sabon Daga

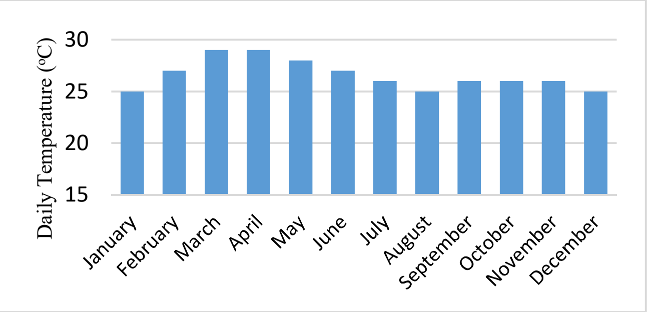

Fig. 5. Average monthly temperature data for study site

C. *Wind Resources*

Wind speed data is a vital resource in energy system analysis. The kinetic energy of the wind is converted to electrical energy with the aid of a wind turbine. Ground wind speed data for Sabon Daga settlement were not available hence, the monthly wind speed data were considered from NASA renewable energy resource website [14] and are presented in a chart in Fig. 6. The power output of the wind turbine is a function of the wind speed. There is a minimum (cut-in) speed and a maximum (cut-out) speed where the power output from the wind turbine is zero. This relationship is presented in Fig. 7.

IV. SYSTEM COMPONENTS AND CONTROL PARAMETERS

Grid-PV-wind-diesel hybrid system with battery storage system configuration is proposed for this study as seen in Fig. 8. Solar and wind are the primary energy sources however, the power output from solar and wind are intermittent, therefore some kind of energy storage facility is necessary for storing energy during times of excess production to improve the efficiency and stability of the system [15]. The grid is used to serve the load deficit during times when the power from the renewable energy source is not enough to meet the energy demand.

TABLE I. CONTROL PARAMETERS

Project lifespan	20 years
Simulation time step	60 minutes
Annual capacity shortage	0%
Inflation rate	15%
Interest rate	10%
Dispatch strategy	cycle charging (CC) strategies or Load-following (LF)
Minimum renewable fraction	0%

TABLE II. ECONOMICS AND TECHNICAL SPECIFICATION OF VARIOUS COMPONENTS OF THE HRES

Grid	
Grid capital cost	$0
Import energy tariff	$0.06/kWh
Export energy tariff	$0/kWh
Solar PV	
Capital cost	$1200 /kW
Replacement cost	$1000/kW
Operation and Maintenance cost	$5/year
Lifetime	25 years
Efficiency	20.4%
De-rating factor	88%
Temperatur coefficient	-038%/°C
Wind turbine	
Power output type	AC
Rated capacity	10 kW
Initial cost per unit	$50,000
Replacement cost	$50,000
Operation and Maintenance cost	$50/year
Hub height	24 m
Lifetime	20 years
Diesel generator	
Initial cost per unit	$195/kW
placement cost	$190/kW
Operation and Maintenance cost	$0.03/hour
Lifetime	15000 hours
Maximum load ratio	25%
Diesel price	$0.5/L
Battery	
Type	Lead-Acid
Rating	12 V, 83.4 Ah, 1 kWh
Initial cost per unit	$300
Replacement cost	$250
Operation and Maintenance cost	$5/year
Battery string	2 batteries
Depth of Discharge	30%
Throughput	800 kWh/year
Converter	
Capital cost	$300/kW
Replacement cost	$250/kW
Operation and Maintenance cost	$5/year
Lifetime	15 years
Inverter efficiency	95%
Rectifier efficiency	90%

The diesel generator is activated as a last resort when there is a grid outage and the energy from the battery is low. A bidirectional converter is connected between the AC and DC components, to maintain the flow of energy. An optimal combination of the grid, solar PV, wind, diesel generator and battery storage, supplementing one another to provide a steady and continuous power supply thereby making the HRES more efficient and reliable. Table I shows the simulation control parameters and Table II presents the technical assumption data of various system components selected in this study.

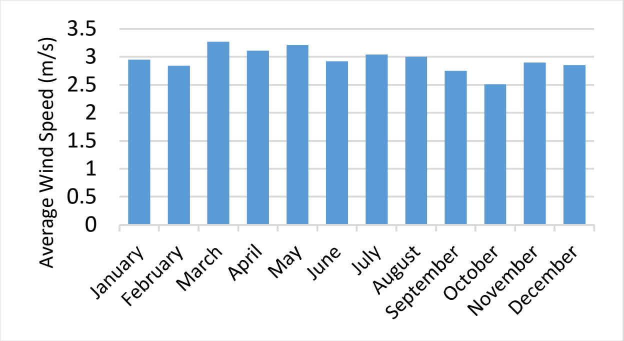

Fig 6. Average monthly wind speed data for the study site

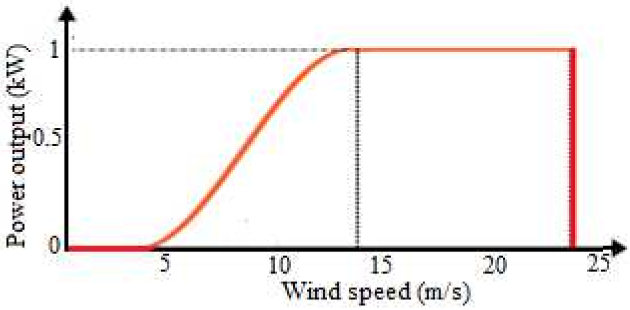

Fig 7. Wind speed vs wind turbine power output

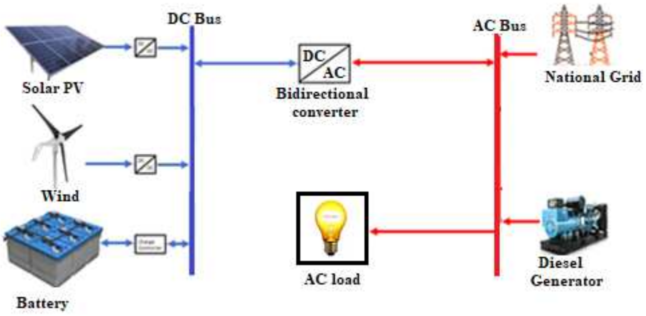

Fig. 8. Proposed HRES configuration for the study site.

V. SIMULATION RESULT AND DISCUSSION

A. *Optimal System Analysis*

The system analysis is performed every tmestep of 1 hour by HOMER Pro software throughout the lifecycle of the project for various system combinations of solar/wind/DG/grid/converter/battery that meet the load requirement of the study site. A list of these feasible system configurations and component sizes is presented in a table as shown in Table III arranged according to increasing net present cost (NPC). It shows that a grid-connected HRES with the combination of a 241 kW Solar PV array, 120 kW

TABLE III. SIMULATION RESULT OF FEASIBLE SYSTEM COMPOSITION

Components						**Component Size**							**Cost**				**System**	
						Solar (kW)	**WT (10kW)**	**DG (kW)**	**Batt. (kWh)**	**Grid (kW)**	**Converter (kW)**	**Dis-Patch**	**LCOE ($/kWh)**	**NPC ($)**	**Operation Cost ($)**	**Capital Cost ($)**	**Renew Fractn. (%)**	**Fuel usage (L/yr)**
✓		✓	✓	✓	✓	241		120	252	999,999	72.5	LF	0.136	1.70 M	39,269	410,168	49.9	41,127
✓	✓	✓	✓	✓	✓	238	1	120	258	999,999	74.2	LF	0.140	1.75 M	39,305	458,092	50.2	40,966
✓			✓	✓	✓	563			1,716	999,999	131	CC	0.157	2.24 M	30,793	1.23 M	80.5	0
✓	✓		✓	✓	✓	574	1		1,710	999,999	124	CC	0.162	2.29 M	30,483	1.29 M	80.6	0
✓		✓		✓	✓	552		120		999,999	66	CC	0.182	2.30 M	48,457	705,017	39.0	59,476
✓	✓	✓		✓	✓	548	1	120		999,999	67.7	CC	0.185	2.35 M	48,600	750,964	39.4	59,501
		✓		✓				120		999,999		CC	0.218	2.51 M	75,501	23,400	0	80,447
		✓	✓	✓	✓			120	4	999,999	0.214	CC	0.218	2.51 M	75,569	24,664	0	80,447
	✓	✓		✓			1	120		999,999		CC	0.222	2.56 M	75,466	73,400	0	80,316
	✓	✓	✓	✓	✓		1	120	30	999,999	0.289	CC	0.225	2.59 M	75,972	82,487	0	80,316
	✓		✓	✓	✓		6		8,002	999,999	546	CC	0.718	8.26 M	163,792	2.86 M	0	0
			✓	✓	✓				8,772	999,999	574	CC	0.751	8.64 M	177,038	2.80 M	0	0

Diesel Generator, 252 Lead-acid 12 V, 83.4 Ah battery bank is the most cost-effective as it has the lowest NPC at $ 1.7 million and levelized cost of energy (LCOE) of $ 0.136/kWh. The village of Sabon Daga presents a significant solar energy potential but a low average wind energy thus, the simulation result indicates that including a wind turbine in the system is suboptimal for the selected location. The cost constituent based on the component of this optimal system configuration is presented in Fig. 9. It is noted that the DG contributes 100% of the fuel cost ($ 677,655.96) which is the highest cost constituent and also accounts for 64% of the Operation and Maintenance (O&M) cost. However the DG has the advantage of being dispatchable; hence, it can be activated to meet the energy shortfall of the HRES at any time. On the other hand, solar PV has the highest initial capital cost but little O&M cost making the system cost-effective in the long run. An optimal combination of these two energy sources, with the grid, offers reliability and cost-effective HRES.

When the economics of the optimal system is compared with the existing system of Grid and DG backup, the NPC of the optimal system is 32.3% less and has a discounted payback period of 8.42 years at a return on investment (ROI) of 4%. Also, annual diesel fuel usage decreases from 80,447 litres per year to 41,127 litres per year reducing the CO2 emission by 48.9%. Load following (LF) where the DG is used to serve the net load but is not used to charge the battery is chosen over cycle charging (CC) as this dispatch strategy takes optimum advantage of the renewable energy source; reserving the battery capacity for storing excess energy from the solar PV.

It can be observed in Fig. 10, that a significant quota of the energy requirements of the load is met by the solar PV. An assessment of the annual average energy production and consumption of the system is presented in Table IV. It shows that Solar PV supplied 68% of total energy production, 20.8% is served by the DG and the remaining 11.2% is purchased from the national grid. The system is noted to produce excess electricity of 199,233kWh per year. Since there is no facility and policy available that allow for the sale of excess energy to the grid, this excess supply may be used to serve dump loads like water pumps.

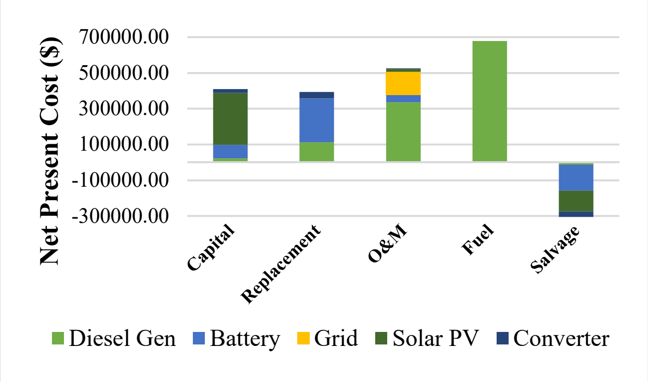

Fig. 9. Cost constituent based on the system component

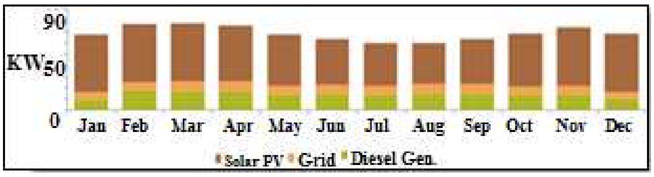

Fig. 10. Monthly average electric production by the selected optimal system.

TABLE IV. ANNUAL AVERAGE ENERGY PRODUCTION AND CONSUMPTION

Constituent		**Quantity (kWh/yr)**	**Percentage (%)**
Production	Solar PV	403,349	68.0
	DG	123,426	20.8
	Grid purchases	66,466	11.2
	Total	593,241	100
Consumption	AC primary load	349,430	92.1
	Excess electricity	199,233	33.6
	Capacity shortage	0	0

B. *Sensitivity Analysis*

In this study, sensitivity analysis is carried out to reveal the effect that the increase in diesel fuel price and inflation rate have on the cost of the optimal system and renewable energy penetration. It was observed that the effect on the optimal system is not that significant when the diesel price changes from $0.5 to $0.75 but when the price of diesel gets higher the effect on the initial capital cost, O&M cost, fuel

TABLE V. SENSITIVITY ANALYSIS RESULT OF VARIATION IN DIESEL PRICE

Inflatn Rate (%)	**Diesel Price ($)**	**Solar PV (kW)**	**DG (kW)**	**No. of Batt.**	**Grid (kW)**	**Converter (kW)**	**LCOE ($/kWh)**	**NPC ($)**	**Initial Cap. Cost ($)**	**O&M Cost ($/yr)**	**Fuel Cost ($/yr)**	**Renew Fractn (%)**
15	0.50	241	120	252	999,999	72.5	0.136	1.70M	410,168	15,990	20,564	49.9
15	0.75	269	120	864	999,999	73.5	0.158	1.95M	627,963	13,447	16,123	64.4
15	1.00	308	120	1,452	999,999	80.9	0.166	2.05M	852,737	12,835	4,421	79.1
15	1.25	339	120	1,580	999,999	95.5	0.163	2.07M	933,225	13,076	2,481	81.8
15	1.50	340	120	1,584	999,999	97,6	0.164	2.09M	936,360	13,122	2,759	82.0

TABLE VI. SENSITIVITY ANALYSIS RESULT OF VARIATION IN RATE OF INFLATION

Inflatn Rate (%)	**Diesel Price ($)**	**Solar PV (kW)**	**DG (kW)**	**No. of Batt.**	**Grid (kW)**	**Converter (kW)**	**LCOE ($/kWh)**	**NPC ($)**	**Initial Cap. Cost ($)**	**O&M Cost ($/yr)**	**Fuel Cost ($/yr)**	**Renew Fractn (%)**
13	0.50	205	120	274	999,999	73.6	0.146	1.48M	373,414	16,203	20,749	49.0
14	0.50	211	120	268	999,999	74.5	0.141	1.59M	379,782	16,160	20,723	49.3
15	0.50	241	120	252	999,999	72.5	0.136	1.70M	410,168	15,990	20,564	49.9
16	0.50	269	120	240	999,999	73.5	0.131	1.83M	440,763	15,889	20,456	50.7
17	0.50	283	120	234	999,999	73.7	0.126	1.97M	455,781	15,835	20,392	43.8

cost and renewable energy penetration gets substantial. Table V shows that an increase in diesel cost from $0.5 to $1.00 (55% higher) caused a 107.9% increase in the capital cost and a 20.6% increase in NPC but the fuel cost decreased by 78.5%. This is because as the diesel price gets higher operating the DG becomes less cost-effective hence, the need to involve more solar PV, battery storage and converter capacity to meet the load demand. This explains the increase in renewable energy penetration as the diesel price increases. Higher renewable energy penetration increases the initial capital cost but decreases the O&M and fuel cost. On the other hand, Table VI indicates that a variation in the inflation rate has little effect on the O&M cost, fuel cost and renewable energy penetration. However, the NPC increases noticeably as the inflation rate increases.

VI. CONCLUSIONS

In this study, a techno-economic analysis of a HRES connected to a grid with frequent outages in a Nigerian rural community has been explored. The study shows that the solar PV-DG-grid-battery system is a suitable combination to cost-effectively and reliably serve the energy demand of the studied location in the long term. The existing system of the utility grid with DG backup used by the community has a lower initial capital cost but a high fuel cost, O&M cost and also is not environmental friendly. Utilizing solar PV and battery bank in combination with the existing system to power the studied community is cost-effective and will decrease the operating hours of the DG and therefore reduce the diesel fuel consumption, thereby reducing the harmful emission to the environment.

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