Available online at: http://www.ijmtst.com/vol6issue04.html
International Journal for Modern Trends in Science and Technology
ISSN: 2455-3778 :: Volume: 06, Issue No: 04, April 2020

Feasibility Study of a Stand-alone Wind-Solar Hybrid Energy System for Off-Grid Rural Electrification in Sokoto State, Nigeria

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To Cite this Article
Gwani Mohammed, Abubakar Gado and Umar Abdullahi Bello, "Feasibility Study of a Stand-alone Wind-Solar Hybrid Energy System for Off-Grid Rural Electrification in Sokoto State, Nigeria", *International Journal for Modern Trends in Science and Technology*, Vol. 06, Issue 04, April 2020, pp.:64-72.

Article Info
Received on 06-March-2020, Revised on 26-March-2020, Accepted on 30-March-2020, Published on 03-April-2020.

ABSTRACT

The prospect of utilizing wind energy to generate electricity in developing country like Nigeria is very promising owing to high wind speeds in that region. This study investigates the feasibility of a stand-alone wind solar hybrid energy system for off-grid rural electrification in Nigeria a case study of Sokoto State. HOMER software package was used for the analysis of the simulation. Thousands of simulations were carried out to achieve optimal autonomous system configurations for the wind-photovoltaic-diesel generator-battery system. Four optimized scenarios that are considered feasible by HOMER were evaluated. The assessment criteria comprises of the Net Present Cost (NPC), Cost of Energy (COE), amount of CO_2 emitted and the Renewable Fraction (RF). Comparisons were made between the four optimized scenarios i.e. (WT-PV-DG-Battery system, PV-DG-Battery system, WT-DG-Battery system, and DG-Battery system). The results indicate that scenario 1, WT-PV-DG- Battery system is the most feasible, optimized, cost effective and environment-friendly system among other configurations. The economics analysis reveals that with scenario 1, $190,768 of the total NPC can be saved. Moreover, the cost of energy, COE for scenario 1 is $0.26/kWh lower than the other three scenarios, the results of the environmental analysis indicates that 36,649 kg/yr (54.8%) of CO_2 emitted could be reduced by the system in scenario 1 and 68% of renewable fraction can be achieved.

KEYWORDS: *HOMER, Hybrid system, wind turbine, solar PV, Renewable energy*

I. INTRODUCTION

Energy resources are among the most important assets of any nation. It is a well-known fact that the high rate of industrial growth and development of any nation is a function of the amount of energy available and the extent to which that energy is utilized [1]. Nigeria has the largest economy in Africa and the highest population growth rate. The inefficiency of the Nigerian energy industry to meet the energy demands of the nation is due to its high dependency on oil and gas as the main source of revenue [2]. Despite being the largest economy in Africa, only 48 percent of Nigerians have access to electricity while 52 percent live in total darkness[3]. The estimated electricity demand in Nigeria is 10,000 MW [4]. But currently, Nigeria power generation capacity stands at 5,500MW [5]. To attain the estimated 10,000 MW, alternative

renewable energy sources such as wind and solar should be given serious consideration.
Sokoto state, located at the North Western part of Nigeria, is situated at Longitude 13º 07' N and Latitude 5º 23'E. Sokoto is one of the states in Nigeria that is blessed with abundant renewable energy resources such as wind and solar energy which if properly harnessed and utilized can meet a reasonable percentage of the energy demand for both urban and rural dwellers. Although wind and solar energy are intermittent in nature, however, this intermittency can be overcome by using their daily and seasonal complimentary relationship [6]. Consequently, it may be possible to acquire rather constant power output through the hybrid system which combines wind powered generators and photovoltaic cells all year round [7].

Many studies have been conducted on feasibility and optimization analysis of different hybrid energy systems using the HOMER software in Africa. Feasibility study on renewable energy-based microgrid system in Somali land's urban center was reported by Abdilahi, Abdul Halim [8] in the study, 58% renewable energy penetration, 30% reduction in cost of energy, COE and 25% reduction in net present cost, NPC could be achieved when compared to current diesel-only microgrid. A similar study was conducted by Khan and Iqbal [9], a case study of Newfoundland.Tao, Hongxing [10]reported that it is feasible to implement a stand-alone solar-wind-battery system to supply power for remote island. Munuswamy, Nakamura [11], reported that the cost of powering a rural health care center using decentralized renewable energy system is both feasible and cost effective compared to the grid source. Further studies on the application of HOMER for off-grid hybrid renewable electricity generation were reported in [12-15]. The present study investigates the feasibility of wind-solar hybrid energy system for electricity generation for remote area application in Sokoto State Nigeria. HOMER (hybrid optimization model for electric renewable) is used for this analysis. HOMER is optimization software that simplifies the task of evaluating designs of both off-grid and grid-connected power systems for a variety of applications.Its flexibility makes it useful in the evaluation of design issues in the planning and early decision-making phase of rural electrification projects [16]. Thousands of cases are simulated and compared based on the NPC, COE, carbon dioxide (CO_2) emissions and renewable fraction (RF). The study evaluates the impact of increase in diesel price and wind speed with respect to the NPC; the robustness of the economic analysis and the identification of the variable with the greatest impact on the system are also evaluated through the sensitivity analysis.

II. Description of the Hybrid system

The sustainability and reliability of uninterrupted power supply can only be realized by the design of hybrid renewable energy system. Various studies conducted on hybrid energy systems show that the systems are viable and reliable both economically and environmentally for electricity generation in rural areas.

2.1 Modeling of the system

2.1.1 Electric load

For successful design of hybrid renewable energy systems, a reliable load consumption profile is very important. In this study, the daily load requirement is carefully estimated for fifty households. The estimated loads for the fifty households are 291 kWh/day, and 28 kW peak, the load was synthesized by adding some randomness for different days and months.

2.2 Configuration of the System

The proposed wind-solar hybrid energy system comprises of a wind turbine, solar PV array, diesel generator, battery and converter. The backup system for this hybrid energy system is the Diesel generator whose function is to back up the renewable energy system during odd times when the renewable system is limited [17]. The architecture of the system obtained from HOMER is as shown in Fig. 1.

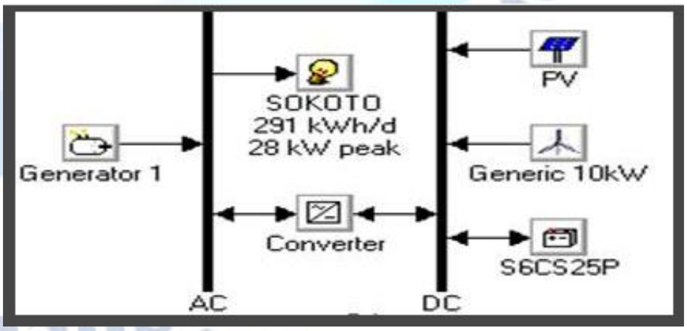

Fig. 1: HOMER diagram for the system architecture for the hybrid energy system

III. Resource Assessment

3.1 Solar Resource

The solar radiation data for this study was obtained from HOMER through the NASA surface meteorological and Solar Energy web site given the location of the site [18]. The input data for the solar radiation is shown in Fig. 2, the solar radiation ranging from 5.38 kWh/m²/day to 6.51 kWh/m²/day.

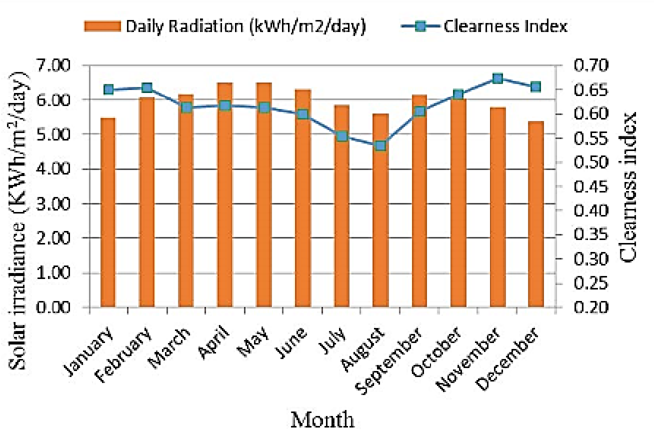

Fig. 2: Solar irradiance for the study site [18]

From Fig. 2, it can be observed that solar irradiance is high from February to June and September to November, while solar irradiance is low in the months of January, July, August and December.

3.2 Wind Energy Resource

Sokoto state is one of the states in Nigeria which experiences high wind speeds. The average annual wind speeds available in this region is appropriate for wind power generation [19]. The geographic location of Sokoto State placed it at an advantage of high wind speeds especially during the winter season. The wind data obtained from the Nigeria Meteorological Agency for the site was measured at 10 m height. For an average wind turbine, the height is estimated to be between 20 to 50 m height. In this study, the wind data was extrapolated to 40 m height using equation 1 as shown in Fig. 3.

$$V(z) = Vr= V_r\left(\frac{Z}{Z_r}\right)^{\propto} \qquad (1)$$

Where;

V(z) is the speed at the extrapolated height, Vr is the wind speed at the reference height, z is the extrapolated height, Z_r is the reference height and $\propto$ is the ground roughness coefficient which is given a value of 0.31.

Fig. 3 shows the average wind speed for Sokoto state. From the Fig., high wind speed is observed in the early month of the year from January to March.

The Weibull probability distribution function is used to describe the wind speed distribution for Sokoto State.

$$F\,(v) = \left(\frac{K}{C}\right)\left(\frac{V}{C}\right)^{K-1}\exp\left[-\left(\frac{V}{C}\right)^{K}\right] \qquad (2)$$

Where k is the shape parameter and c is the scale parameter (m/s), as shown in Fig. 4.

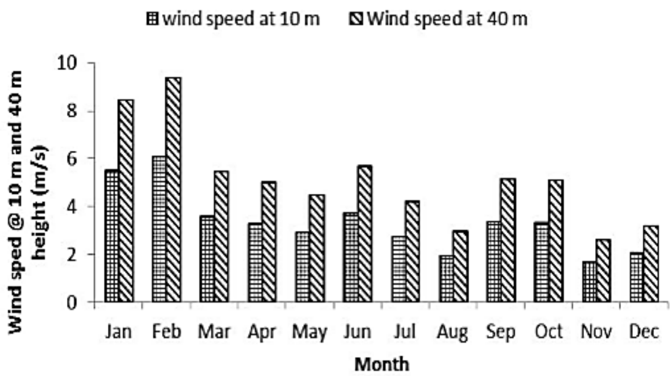

Fig. 3: Monthly average wind speed in Sokoto at 10 m and 40 m height

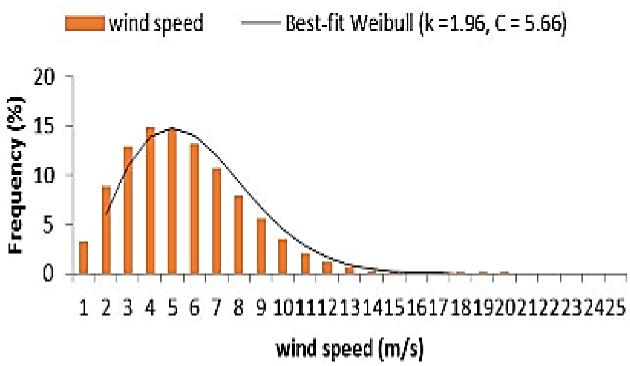

Fig. 4: Probability distribution of wind speed data synthesized by HOMER

The relationship between the k and c parameter and the average wind speed is given by

$$\bar{V} = \text{cr} = \left(\frac{1}{K} + 1\right) \qquad (3)$$

Where r is the gamma function

IV. Assessment of Components

4.1 Solar PV modules

The solar PV modules used for this study is the Sunmodule plus SW 280 mono black (33mm frame). The power generated by the solar PV module is expected to be high because there is better insulation of solar radiation at the site. The details of the PV modules are presented in Table 1.

Table 1: Details of PV Module [20]

PV Panel	Value
Manufacturer	Solar world
Model /model number	Sunmodule plus SW 280 mono black
Max. Power (W)	280 W
Optimum circuit voltage (voc)	39.5V
Efficiency	16.7%
Short circuit current	9.71A
Maximum power point current	31.2 V
Capital cost ($)	$ 12000/kW
Replacement cost ($)	$12000/kW
Operation and Maintenance ($)	0.00
lifetime	20 years

The energy output for the PV module is calculated using

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right)\left[1 + \alpha_p\left(T_c - T_{c,STC}\right)\right] \quad (4)$$

Where

Y_{PV} = rated capacity of the PV array,

f_{PV} = PV derating factor (%)

$\bar{G}_T$ = solar radiation incident on the PV array in the current time step (kW/m²)

$\bar{G}_{T,STC}$ = incident radiation at standard test conditions (1kW/m²)

α_p = temperature coefficient of power (%)

T_c = PV cell temperature in the current time step (°C)

$T_{c,STC}$ is the PV cell temperature under standard test conditions (25°C)

In this study, a derating factor of 80% is used [17].

4.2 Wind Turbine

A Generic 10 kW horizontal axis wind turbine manufactured by Saiam power was considered for the analysis. The availability of high wind speeds at the study site determines the amount of power that could be generated by the wind turbine. The details of the wind turbine are presented in Table 2.

Table 2: Details of Wind turbine [21]

Wind Turbine	Value
Rated power	10kW
Peak Power	15000W
Startup wind speed	3 m/s
Working wind speed	4-35m/s
Survival wind speed	45 m/s
Rotor diameter	7 m
Swept area	38.47m²
Blade length	2m
Blade	3 pcs reinforced fiber glass
Rated RPM	220
Capital cost	$20000/kW
Replacement cost	$20000
Operation and maintenance	$10/year
Lifetime	20 years

The available power in the wind can be calculated from

$$P_A = \tfrac{1}{2}\rho A V^3 \quad (5)$$

Where

P_A (W) = available power in the wind,

ρ = density (kg/m³),

V = wind speed (m/s)

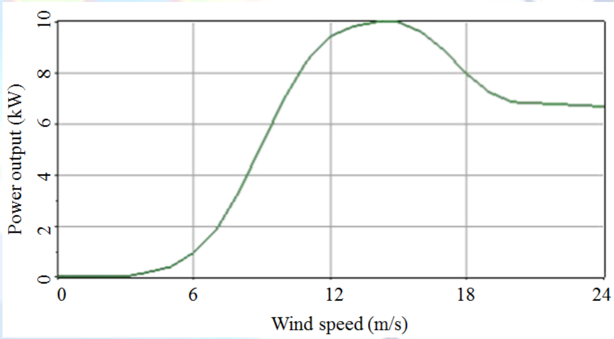

Fig. 5: Power curve for the wind turbine HOMER ;National Renewable Energy Laboratory (NREL)[17]

The extractible power from the wind turbine can be calculated from

$$P_{ext.} = C_P \tfrac{1}{2}\rho A V^3 \quad (6)$$

Where

C_p = power coefficient of the wind turbine

4.1.3 The Battery

In off-grid renewable energy applications, a deep cycle battery is often used. In this study, a Surette

S6CS25P battery is chosen. The battery has a 6V and 1156-Ah (6.94KWH) capacities with a lifetime throughput of 9,645kWh per battery as shown in Table 3.

Table 3:Details of Battery (NREL)

Battery	Value
Model	Surette 6CS25P
Nominal capacity	1156Ah
Nominal voltage	6
Roundtrip efficiency	80%
Min. state of Charge	40%
Lifetime through put	9,645kWh
Max. capacity	1155Ah
Capital cost	$400
Replacement cost	$400
Operation and maintenance	$0.5/year

4.1.4 Diesel Generator (DG)

The role of a backup generator is to provide electricity during odd times when the availability of the renewable energy system is limited. It also helps to reduce the overall costs of the hybrid systems. In this study, a 30 kW capacity generator was used and modeled by HOMER. Operating performance and cost of the diesel generator is shown in the Table 4.

Table 4: Detail of Diesel Generator (DG) [22]

Diesel generator	Value
Model	PF8GF
Rated Power	30 kW
Output power	30 kW
Output type	A.C single Phase
Rated frequency	50Hz
Frequency	Less than 5s
Engine	178 F
Power	3.0 kW
Capital cost	$ 12000
Replacement cost	$ 12000
Operation and Maintenance	$ 0.5

V. Results And Discussion

5.1 Simulation results

In this section, the simulation results are discussed. Based on the meteorological data and load consumption, thousands of combinations were simulated to achieve an optimal system configuration. HOMER estimates their technical feasibility and scales them in terms of the net present cost, (NPC), cost of energy (COE), amount of CO_2 emitted and renewable energy penetration.

5.2 Optimization results

The categorized optimization results of the system simulation performed by HOMER based on an annual real interest rate of 10% and a projected lifetime of 25 years are summarized in Table 5

Table 5: Categorized optimization results for the study area

Combination	WT (KW)	PV (KW)	DG (KW)	Batt.	Total Capital cost($)	Total NPC ($)	Total O & M cost $/yr	Operating cost($/yr)	COE ($/KWh)	Renewable Fraction (%)	CO_2 Emissions (kg/yr)
WT-PV-DG-Batt.	1	30	30	88	74,200	396,168	1,606	25,186	0.261	68	44,374
PV-DG-Batt.	0	30	30	72	47,800	586,936	1,709	42,175	0.387	37	81,023
WT-DG-BATT	1	0	30	64	58,600	648,758	2,342	46,166	0.428	30	87,190
DG-Batt.	0	0	30	56	35,400	873,818	2,496	65,587	0.576	0	128,052

HOMER simulates thousands of combinations and categorizes the best four scenarios that are feasible, cost effective and environment-friendly. The categorized form of the optimization results is shown in Table 5. The four scenarios considered feasible by HOMER are the WT-PV-DG-Battery system, PV-DG-Battery system, DG-Battery system and WT-DG-Battery system.

5.2.1 Scenario 1; Hybrid Wind-PV-DG-Battery

The system simulation performed based on the meteorological data has shown that wind-PV-DG-Battery system is the most optimized and cost effective system among other configurations, the total NPC for this system over the projected life time is USD 396,168, the system has the lowest cost of energy (COE) of 0.26 $/kWh and 68% renewable energy penetration when compared to other combinations on the optimization results. The system comprises of 1 unit of 10 kW wind turbine, 30 kW PV panel, 30 kW diesel generator and 80 units of 6 strings of Surette battery bank. The amount of CO_2 emitted by this system is 44,374 kg/yr. The monthly average electricity production for this wind-PV-DG-Battery hybrid energy system is shown in Fig. 6 and the summary of the electric power production by each component is presented in Table 6.

Table 6: Summary of electric power production scenario 1

Production	kWh/yr	%
Wind turbine	44,422	31
PV array	52,904	37
DG	46,168	32
Total	143,495	100

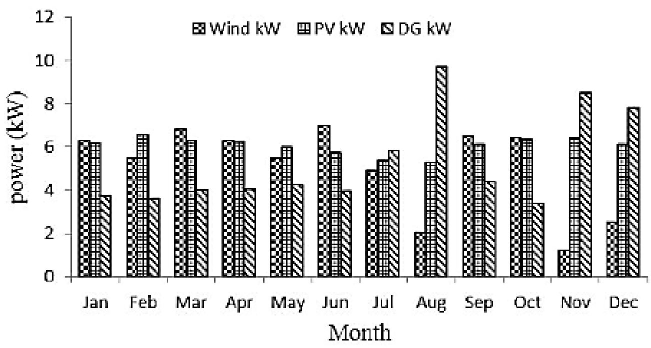

Fig. 6: Monthly average electricity production for hybrid WT-PV-DG-Battery system, Scenario 1

5.2.2 Scenario 2: Hybrid PV-DG-Battery system

The second best optimal system from the categorized optimization results according to Table 5 is the PV-DG-Battery system. The system consists of 30 kW PV panel, 30 kW diesel generators, and 72 units of 6 string battery banks. The system has a total NPC of USD 586,936 and \$0.387/kWh cost of energy (COE). The renewable fraction for this configuration is 37% and the amount of CO_2 is 81,023 kg/yr which is twice the amount CO_2 emitted in scenario 1. Fig. 7 shows the monthly average electricity production for this hybrid configuration and the summary of the electric power produced by each component for scenario 2 is shown in Table 7.

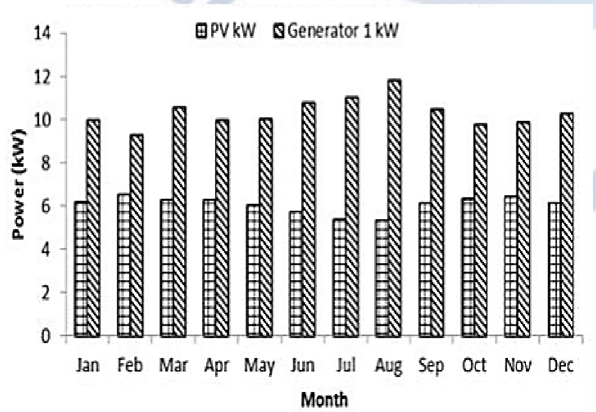

Fig. 7: Monthly average electricity production of hybrid PV-DG-Battery energy system, scenario 2

Table 7: Summary of electric power production scenario 2

Production	kWh/yr	%
PV array	52,904	37
Generator 1	90,257	63
Total	143,162	100

5.2.3 Scenario 3: Hybrid WT-DG-Battery system

In this scenario, hybrid WT-DG-Battery system is considered as the third best option for the system. The main energy components of the system are 1unit of 10kW wind turbine, 40kW diesel generator, and 64 string batteries with 20kW power converter. The total NPC and cost of energy (COE) for this system is \$648,758 and 0.428\$/kWh respectively, the system has 30% of renewable fraction and emitted 87,190 kg/yr of CO_2. The total electricity production for the system is shown in Fig. 8 and the summary of the electricity production by each component is shown in Table 8.

Table 8: Summary of electric power production scenario 3

Production	kWh/yr	%
Wind turbine	44,422	31
DG	97,082	69
Total	141,505	100

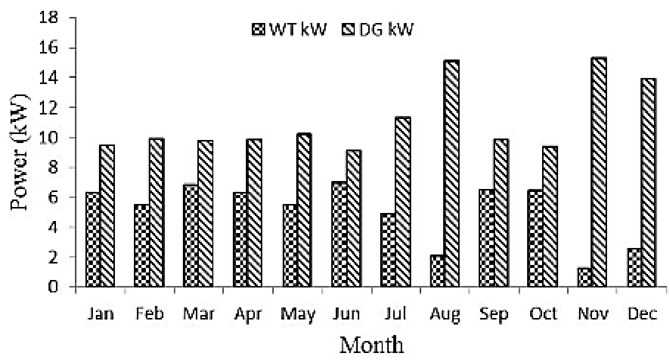

Fig. 8: Monthly average electricity production for hybrid WT-DG-Battery energy system, scenario 3

5.2.4 Scenario 4; Hybrid DG-Battery system

The fourth best scenario for the hybrid system according to HOMER is the hybrid DG-Battery energy system. This system consists of a 40kW diesel generator and 80 strings Surette battery. The total NPC and COE for this system is \$ 873,818 and 0.576\$/kWh respectively. It has 0% of renewable fraction; this shows that the source of electricitysupply to the load is only on diesel generator and 128,052 kg/yr of CO_2 emitted. The electric power production for this system is shown in Fig. 9 and the summary of electric power produced by each component is shown in Table 9.

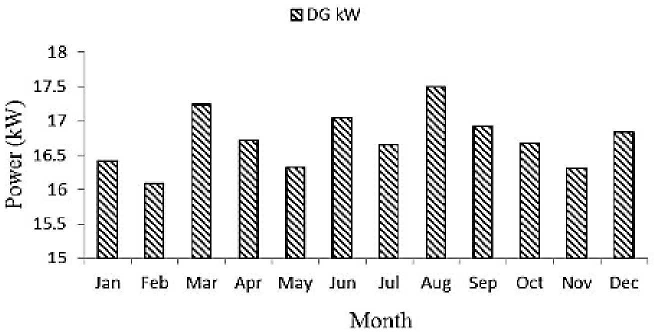

Fig. 9: Monthly average electric power production DG, scenario 4

Table 9: Summary of electric power production scenario 4

Production	kWh/yr	%
DG	146,601	100
Total	146,601	100

5.3Sensitivity analysis

Several important variables that directly or indirectly affect the overall cost as well as the feasibility of the proposed systems are modeled using sensitivity analysis. HOMER eliminates all the non-feasible combinations/configurations through the sensitivity analysis. It also considers feature development such as increase or decrease in load demands, resources, increase in wind speed, or diesel price using optimal system type graph (OST) and the line graph options. It can be observed from the sensitivity results in Fig. 10 that the optimal system which HOMER considers feasible is the WT-PV-DG-Battery energy system. It is the most feasible and optimized system among the other configurations.

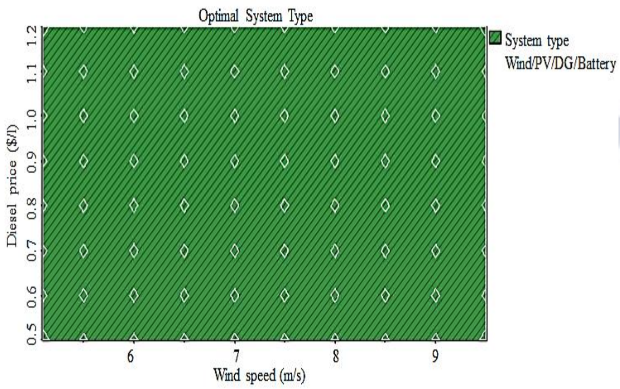

Fig. 10: Sensitivity analysis of the WT-PV-DG-Battery system

5.3.1 Effect of variation in diesel price on the Net Present Cost and Levelized Cost of Energy

The sensitivity results for the system design of varying diesel price are presented in Fig. 11. As can be observed from the Fig., the increase in diesel price greatly affects the total Net Present Cost (NPC) and the Levelized Cost of Energy (LCOE) of the system. As the price of the diesel increases, both the total NPC and the LCOE also increase respectively.

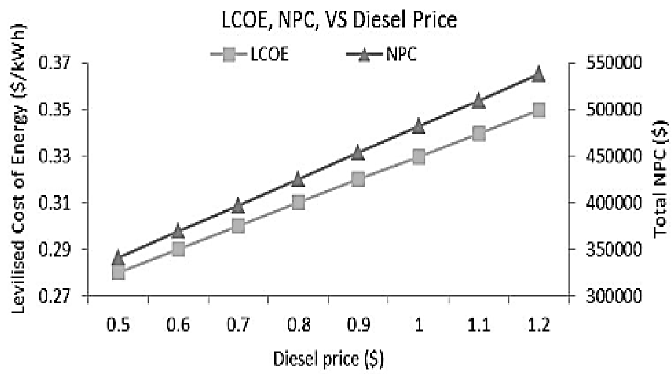

Fig. 11: Effect of increase in diesel price on the LCOE and the NPC

5.3.2 Effect of variation in wind speed on the Net Present Cost and Levelized Cost of Energy

The effect of variation in wind speed on the NPC and LCOE of the system is presented in Fig. 12. The Fig. shows the sensitivity results for the system design for varying wind speed. As can be observed from the Fig., increases in wind speed have positive effects on the total NPC and the LCOE of the system because as the wind speed increases, the LCOE and the total NPC decreases respectively.

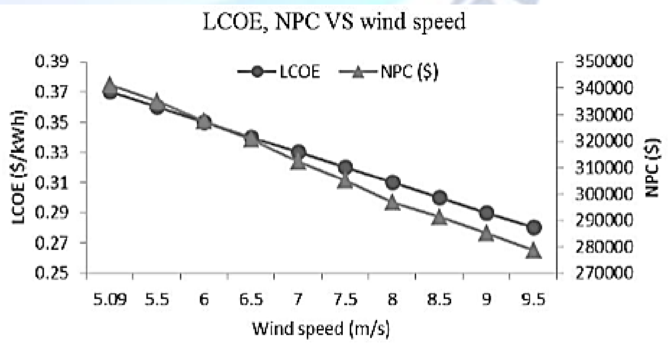

Fig. 12: Effect of changes in wind speed on the LCOE and the NPC

5.3.3. Effect of Variation in wind speed on Renewable Fraction and CO_2 emission

High percentage of renewable fraction and less CO_2 Emission is an indication of an environmentally friendly system. The effect of variations in wind on the renewable fraction and CO_2 emission is presented in Fig. 13. From the Fig., it can be observed that as the wind speed increases, the CO_2 emission released to the environment is reduced, this shows that increase in wind speed has positive effects on the amount of CO_2 emitted to the surrounding by the system. Moreover an increase in wind speed can also increase the renewable energy fraction of the entire system.

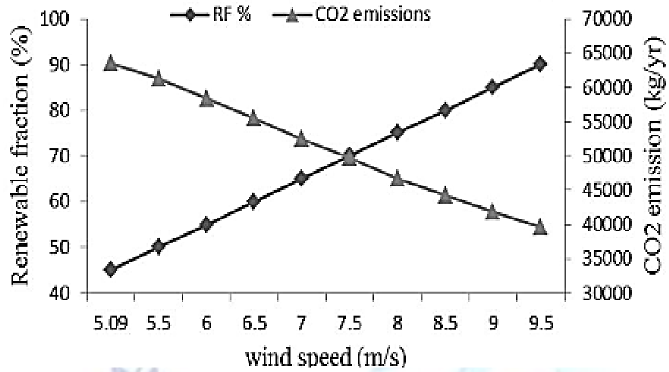

Fig. 13: Effect of changes in wind speed on Renewable fraction and CO_2 emission.

VI. Economics Analysis

The ultimate aim of HOMER is to reduce the cost and to optimize the system. Therefore, the economics of the system plays a vital role in the simulation. HOMER uses the total NPC and the cost of energy as an indicator for comparing different combinations /configurations of the system in terms of increasing NPC. The total NPC is calculated using,

$$\text{NPC} = \frac{TAC}{CRF} \qquad (7)$$

Where TAC is the total annualized cost and CFR is the capital recovery factor which is given by

$$\text{CFR} = \frac{i(1+i)^N}{(1+i)^N - 1} \qquad (8)$$

Where the number of years is denoted by N and i is the annual real interest rate in (%) [23].

6.1 Economic Merits

To ascertain the economic merit of the best system which is the Wind-PV-DG-Battery system (current system), a comparison was made with the second best system that is the PV-DG-Battery system (base system). The results of the comparison are presented in Table 10. The comparison is based on their initial capital cost and the total NPC. The difference between the two systems is presented in Fig. 15.

Table 10: Comparison between the current system and the base system

Energy System	PV (kW)	WT (kW)	DG (kW)	Battery	Conv. (kW)	Initial Capital ($)	Total NPC ($)
Current system (Wind-PV-DG-Battery)	30	1	30	88	20	74,200	396,168
Base System (PV-DG-Battery)	30		30	72	20	47,800	586,936

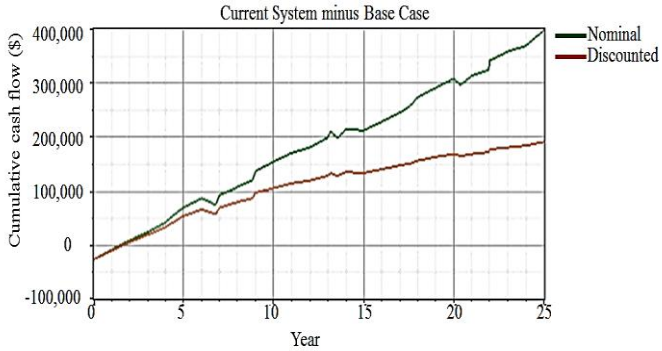

Fig. 14: Current systems minus base system

The summary of the economic merit of the current system (optimal system) is presented in Table 11. This includes the present worth, annual worth and simple payback of the system.

Table 11: Summary of the economic analysis

Metric	Value
Present worth	$ 190,768
Annual worth	$ 14,923/yr
Return on investment	64.2 %
Internal rate of return	66.2 %
Simple payback	1.57 yrs
Discounted payback	1.71 yrs

VII. Environmental Analysis

Atmospheric CO_2 has been a global challenge as the global economy grows, hence the need to take appropriate measures. From the environmental analysis, the WT-PV-DG-Battery system has the lowest CO_2 emission into the surroundings when compared with other scenarios. In comparison with the second best system PV-DG-Battery system, 36,649kg/yr (54.8%) of CO_2 could be reduced. Furthermore with the Wind-PV-DG-Battery system, 68% of renewable energy penetration could be achieved thus making the system in scenario 1 to be more environmentally friendly than all the other scenarios.

Table 12: Summary of CO_2 emitted and renewable fraction achieved

Component	CO_2emitted kg/yr	Renewable Fraction (%)
WT-PV-DG-Battery system	44,374	68
PV-DG-Battery system	81023	37
WT-DG-Battery system	87,190	30
DG-Battery system	128,052	0

VIII. Conclusion

As the main finding of this study, the Wind-PV hybrid energy system has been introduced as a reliable solution for rural electrification in Sokoto State, Nigeria. From the analysis of the results the optimized hybrid energy system that is considered to be more feasible for remote area application in Sokoto State Nigeria is the WT-PV-DG-Battery system. The system is more cost effective and environment friendly option compared to other scenarios. The results from the economics analysis reveal that $ 190,768 of the total NPC could be saved. Furthermore, result of the environmental analysis indicates that with the WT-PV-DG-Battery system, 36,649 kg /yr (54.8%) of CO_2 emitted can be reduced and 68% of renewable penetration can be achieved. These results are an indication that that wind-solar hybrid energy systems could help to overcome the challenges of electricity supply in that part of the country.

Acknowledgment

The authors would like to thank the Kebbi State University of Science and Technology, Aliero for providing the enabling environment for the study

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