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Economic Analysis of Hybrid Solar-Wind Power System for Application in Heipang Community

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Economic feasibility is one of the major criteria for selecting energy options for application in any location. One of the main drawbacks of renewable energy technology is its initial cost of investment which results in high energy tariffs making it unaffordable for low-income earners. The cost of renewable energy depends on many factors such as the potential of the renewable resources of the site and government policies on renewable energy technology. This paper aimed to determine the annualized cost of a designed hybrid solar-wind power system for the Heipang community to meet a load demand of 158.3kW and the sensitivity analysis of bank loan interest rate, inflation rate, day of autonomy, depth of battery discharge, and wind turbine rated velocity on the investment payback time. The cost of the components of the designed system was obtained from vendors and a techno-economic analysis was done using MATLAB software. Results show that the annualized cost of the hybrid solar-wind power system is ₦ 52,268,266.97, with battery, solar, and wind power systems taking 85%, 8%, and 7% of the total annualized cost respectively, and Levelized cost of energy ₦154.53/kWh. The analysis further shows that for ₦ 185.00, ₦ 160.00, and ₦ 127.00 per kWh cost of energy at a 19% inflation rate and 20% bank interest rate, the investment payback times are 8.3, 9.5 and 11.9 years respectively, and 9.8, 11.4 and 14.3 years respectively. Information from this work may help policy-makers and would-be investors make informed decisions on renewable energy technology investment.

Keywords: Annualized cost of the system (ACS); hybrid system; Payback time; Renewable energy; Levelized cost of energy (LCOE).

1. Introduction

The global concern over the environmental impact of exploration and utilization of fossil fuels as sources of energy and their finiteness has drifted attention to renewable energy (RE) technologies. RE resources such as solar and wind energy are promising in terms of power generation and are being considered as alternatives to fossil fuels due to their availability and topological advantages in local power generation and environmental friendliness. RE options are stochastic in nature, weather dependence and their variation may not match with the time distribution demand, thus, to maintain a balance between supply and demand, a high-capacity storage bank such as a battery is required which leads to high initial capital cost as well as cost of energy (COE) of system which in most literature interchangeable use levelized cost of energy (LCOE) and same is applied in this study. The high initial cost of investment has been a strong obstacle to nations' desire (especially developing nations) to move from fossil fuels to cleaner energy resources. That is why most designs on RE systems center on the maximization of system reliability and minimization of the cost of energy of the system [1].

The criteria for choosing the energy option for application in any location is not made only based on its technical feasibility but also the economic aspect of the energy generation. The economics of renewable energy systems is multifaceted. Many factors affect the unit cost of electricity produced by a hybrid solar-wind power system, which may be different from region to region. To make an intelligent investment decision, it is required to assess the net financial return from the project that is being planned. The costs involved in the generation as well as the benefits expected from the project should be estimated. The investment cost consists of the fixed and variable (i.e., operation and maintenance) costs. However, assessing the benefit is complex because the value of electricity generated depends on many factors such as the potential of the renewable resources of the site; the energy market, and incentives and exemptions. For example, the energy available in wind spectra in a site is proportional to the cube of the wind speed. This implies that when the speed of the wind at a location doubles, the energy increases by eight times. Hence, the strength of the wind spectra available at the project site is one of the critical factors in deciding the cost of wind-generated electricity. Similarly, sites with longer sunshine hours have a higher potential for generating solar power, which will eventually affect the cost of the energy generated. Cost of land, installation charges, and labor wages vary from place to place. Expenditure on the foundation depends on the strength of the soil profile as well as the extreme loads expected at the site. It only takes the government that has the political will and the desire to mitigate climate change to make policies towards encouraging renewable energy technologies. Annualized cost (ACS) of a hybrid solar-wind power system is considered in the cost analysis and is the annual repayment of loan collected for investment on the hybrid solar-wind power system, considering the inflation rate and loan interest rate. If the energy generated by the hybrid solar-wind power system is to be sold to consumers at a given approved tariff, it will generate income for the investor as cost-benefit [2].

Unlike solar power systems, the wind power system has the potential to generate power at any time of the day provided there is wind high enough to do so. Wind power system complements the solar power system in the night hours. Wind turbine-rated velocity is an important factor that determines the performance of wind turbines in a given wind speed regime. A low wind turbine-rated velocity will mean high performance as to a high wind turbine-rated velocity. This means that it will be more cost-effective to select a wind turbine that has a relatively lower rated velocity for a given wind speed regime so that more power can be harvested from the system. A deep cycle battery is the weakest link in the hybrid solar-wind power system because it has the shortest life span and is the costliest. The depth a battery system is allowed to discharge when in use affects its life span. A higher depth of discharge will mean a smaller number of battery systems to meet a given load demand and low life span of the battery. That is why for every kind of battery system, there is a recommended depth of discharge that is allowable.

To promote clean and locally available energy sources, several federal and state governments extend financial support to renewables in terms of exemptions and incentives. These may be in direct or indirect forms. These incentives can broadly be classified as investment, production, and policy incentives. An investment incentive, in the US, Canada, and India, for example, is that wind energy investors are allowed to deduct a fraction of the capital from their tax burden, while in Denmark and Germany, for example, direct cash grants are extended to wind energy projects [3]. Policy initiatives are other incentives by the local and national governments of some countries to promote renewable energy technology. Policies such as exemption of renewable energy systems and accessories from customs duty, and property tax on the land occupied by installed renewable energy systems are completely or partially waived. In some cases, the financing of the project is at a liberal interest rate.

This paper aims to determine the annualized cost of investment and levelized cost of energy of a designed hybrid solar-wind power system in the Heipang community (Kpang, Tapo, and Tatu) and the payback period of the investment based on the sensitivity analysis of the parameters that affect the performance of the hybrid solar-wind power system and the solar and wind energy resources potentials of the location. This will provide information to policy-makers, (NGO) investors, and utilities about the cost of investing in renewable energy technologies in the area of study.

Most of the literature reviewed in this study dwells on the techno-economic analysis of hybrid solar wind systems. [4] used a Hybrid optimization model for energy renewables (HOMER) and MATLAB as design tools to design a standalone solar/wind/micro-hydro hybrid power generation system for rural areas in Ethiopia. The LCOE for the hybrid power system is \$0.81/kWh, showing that the cost of a standalone hybrid system is significantly lower than extending the national utility grid in the study community. HOMER software was used by [5] to analyze electricity supply in Japan. The analysis was carried out in 198 stations in Japan to find the LCOE for solar wind power systems in Japan. Results show that the cost per kWh of energy varies depending on the type of system and location with LCOE ranging from \$0.339 to \$0.526/kWh. The cheapest LCOE is located in Iwojima, at \$0.339/kWh, while the most expensive in Tokyo at 0.526/kWh. [6] undertook a feasibility analysis of a hydrogen-based hybrid energy system comprising solar-hydrogen, wind-hydrogen, and solar-wind-hydrogen systems using HOMER. Results show that the LCOE for the hybrid solar-wind power system gives the lowest value of \$0.3387/kWh, while for solar alone system gives the highest LCOE with a value of \$ 0.7046/kWh. A techno-economic analysis of a grid-connected hybrid solar–wind energy system was done by [7] using the HOMER tool for the modeling of the system. Based on the results obtained, the hybrid system with 50% solar and 50% wind energy has the maximum renewable fraction with LCOE ranging from Rs. 2.92/kWh to Rs. 3.37/kWh. Using techno-economic and sensitivity analysis based on biodiesel fuel price and interest rates [8] designed an optimal hybrid system comprising of solar/biodiesel generator/battery for a load demand. Results show that the LCOE for the system is $0.0898/kWh, and is a cost-effective alternative to grid extension. [9] carried out a techno-economic comparative assessment of an off-grid hybrid renewable energy system for electrification of remote areas using pre-feasibility analysis based on economic, technical, and emission parameters. From the results obtained, the PV/WT/biomass/generator/battery hybrid system is the optimal design with the lowest LCOE of $0.1914/kWh. [10] analyzed solar-wind energy systems at a small scale for low wind topography, indicating that the proposed optimal configuration of PV/wind/battery system gives LCOE of 0.488 $/kWh. [11] designed a PV/wind/battery system for a remote island considering the saturation of each RE source involved, having an LCOE value ranging from 0.094-0.119 $/kWh. It was inferred from the research that load, wind energy, and battery cost have significant effects on COE value. A comparative analysis of the economic benefits of gas turbine, wind, and solar power generating systems for producing electricity power in Nigeria was carried out by [12]. Results show that solar and wind turbine have a simple payback period of 14 and 35 years respectively while gas turbine has a simple payback of 5 years as the preferable energy-generating technology to invest in. [13] conducted an economic feasibility study on the potential of a hybrid solar-wind power system to supply the energy demand of Telkom University. The results of their study showed that the hybrid solar-wind system can save electricity costs and has a reasonable payback period of 15 years. [14] used HOMER to find the most cost-effective combination of hybrid solar wind power systems. Results showed that the initial cost of investment of the optimal combination of the hybrid solar-wind power system is $6.58 million with a payback period of 10.11 years.

Based on the literature reviewed, previous researchers have carried out studies on the techno-economic analysis of hybrid solar-wind power systems in different parts of the world, but to the best of the knowledge of the authors, no such work has been carried out in the Heipang community which has different renewable energy resources potentials and load demand, thus the need for this study. This study is carried out at the Heipang community (Kpang, Tapo, and Tatu) in Barkin-Ladi L.G.A of Plateau State, Nigeria. It is located between longitudes 8° 50’ E and 8° 59’ E and between latitudes 9° 34’ N and 9° 42’ N [15]. The geomorphology of Heipang can be generally classified as plain land hence giving it the vantage position for the location of the airport.

2. Materials and Methods

2.1 Materials

The data used for the design and simulation of the hybrid (solar/wind) power system is 2018 typical year weather data of hourly solar radiation, hourly ambient temperature, and hourly wind speed of the location measured at 10m height, obtained from Nigerian Meteorological Agency office Abuja and an estimated hourly load demand profile for a typical day for Heipang community not connected to the grid (Kpang, Tapo, and Tatu) as obtained from the field survey. A techno-economic method using MATLAB and Excel software tools was adopted for the analysis in this study.

2.2 Methods

2.2.1 Design of hybrid solar wind power system

2.2.1.1 Solar and wind energy potentials of the site

The available solar energy potential per unit surface area of the solar module in the Heipang community was determined using a power output model for a photovoltaic generator developed by Hybrid Optimization of Multiple Electric Renewables [16] using equation (1) to (3).

$$P_{PV} = N_{PV} \times \frac{Y_{pv}}{1000} f_{pv} \left(\frac{G_T}{G_{T,STC}}\right) \left[1 + \alpha_p (T_c - T_{c,STC})\right] kW \quad (1)$$

$$\eta_{mp,STC} = \frac{Y_{pv}}{A_{pv} * G_{T,STC}} \quad (2)$$

$$T_c = \frac{T_a + (T_{c,NOCT} - T_{a,NOCT})\left(\frac{G_T}{G_{T,NOCT}}\right)\left[1 - \frac{\eta_{mp,STC}(1 - \alpha_p \times T_{c,STC})}{\tau\alpha}\right]}{1 + (T_{c,NOCT} - T_{a,NOCT})\left(\frac{G_T}{G_{T,NOCT}}\right)\left(\frac{\alpha_p \times \eta_{mp,STC}}{\tau\alpha}\right)} \quad (3)$$

The photovoltaic module randomly selected for this research work is the WON300 mono-crystalline model selected because of its relatively higher efficiency when it was tested and compared with other monocrystalline solar panels available in the market [17].

The available wind energy potential per unit surface area of wind turbine system in Heipang community was determined using equations (4) and (5) below.

$$v = v_0 \left(\frac{H_{WT}}{H_0}\right)^{\alpha_1} \quad (4)$$

The best fit power output model for the wind turbine selected (FD21-50) as determined in the course of this research [18] is given in equation (5):

$$P_{wt} = N_{WT}\begin{cases} P_R \frac{v^{2.5}-v_C^{2.5}}{v_R^{2.5}-v_C^{2.5}} & v_C \leq v < v_R \\ P_R & v_R \leq v \leq v_F \\ 0 & v < v_C; v > v_F \end{cases} \quad (5)$$

The wind turbines selected for this design is FD21-50 model due to its higher-power output performances in Heipang wind speed regime compared with other wind turbines [18] [19].

2.2.1.2 Load sharing strategy of the solar-wind power system

According to equations (1) and (5), the power generated by the photovoltaic module per unit area is P_{pva} and the power generated by the wind turbine per unit area is P_{wta} respectively. Thus, the load shared by the solar and the wind power generation systems of the proposed hybrid system are given by the equations (6) and (7) respectively.

Load shared to photovoltaic module of the hybrid system is determined using equation (6) as given in [20]:

$$P_{sh} = \frac{P_{pva}}{P_{pva}+P_{wta}} \times P \quad (6)$$

Where, P is the total load of appliances of Heipang community not connected to the grid (Kpang, Tapo and Tatu) in kW.

Load shared to wind turbine of the hybrid system i determined using equation (7) as given in s [20]:

$$P_{wh} = \frac{P_{wta}}{P_{pva}+P_{wta}} \times P \quad (7)$$

The power from the photovoltaic module should be able to meet the percentage of load allotted to it based on the solar potential in the site. If the load allotted to the photovoltaic system is P_{sh}, then the number of photovoltaic modules required to serve the load is determined using equation (8):

$$N_{PV} = \frac{P_{sh}}{P_{rs}} \quad (8)$$

From equation (7) the load allotted to the wind turbine system is P_{wh}, thus, the number of wind turbines required to serve the load is determined using equation (9):

$$N_{WT} = \frac{P_{wh}}{P_{rw}} \quad (9)$$

Where; $P_{rw}$is the power rating of the selected wind turbine.

2.2.2.2 Battery capacity model

The initial storage capacity of the battery is computed as in [21] using equation (10):

$$C_{wh} = C_{bat}(t-1) = N_{BT} \times \frac{E_L \times S_D}{\eta_{bat}} \quad (10)$$

In the case when the battery capacity reaches a maximum value, C_{batmax}, the control system stops the charging process.

During the charging process, when the total output of PV module and wind generators is greater than the load demand, the available battery bank capacity at a time t can be determined as in [22]

$$C_{bat}(t) = C_{bat}(t-1).(1-\sigma) + \left(P_{PV}(t) + P_{WT}(t) - \frac{P_{load}(t)}{\eta_{inv}}\right).\eta_{batC} \quad (11)$$

Charging constraint

$C_{bat}(t) \leq C_{bat\ max}$

$C_{batmax} = 1{,}512kWh$

On the other hand, when the load demand is greater than the available energy generated, the battery discharges to meet the supply deficit. Thus, the capacity of the battery at a time t can be expressed as:

$$C_{bat}(t) = C_{bat}(t-1).(1-\sigma) - \left(\frac{P_{load}(t)}{\eta_{inv}} - (P_{PV}(t) + P_{WT}(t))\right)\eta_{batD} \quad (12)$$

Discharging constraint

$C_{bat}(t) \geq C_{bat\ min}$

$C_{bat\ min} = DOD \times$ (13)

The storage battery selected for the design is Hoppecke 5 OPzS solar power 350 - 48V. It is optimal for application in sectors with high charge and discharge operation load such as solar and other off-grid applications [23]:

2.2.3 Sizing of inverter

The DC/AC converter, also known as inverter is used to convert DC signal from the battery to AC signal to supply to load.

Inverter power $P_{INV}(t)$ is determined using the corresponding load power requirements, as follows [24]:

$$P_{INV}(t) = \frac{P_{load}(t)}{\eta_{INV}} \quad (14)$$

SKU- ATO-OGI 200kW Pure sine wave inverter was selected because it was relatively cheaper and has high efficiency of 94% [25]>

2.2.4 Economic model of hybrid solar-wind power system based on annualized cost of system

The cost of generating electricity using solar and wind power system depends on the capital cost, discount rate, operation and maintenance cost;

potentials of solar and wind energy resources and the efficiencies of the photovoltaic (PV) module and wind turbine systems. The capital cost comprises of the cost of the PV modules and wind turbines, the Balance of System (BOS) cost and tasks. For small-scale PV system, the BOS and installation costs comprise 60% of total PV system costs, cost of operation and maintenance is 10% of the cost of the PV system [26]. For the wind power system, the cost of tower is 26.3% of the total cost of wind turbine [27] and the cost of installation and operation and maintenance is 30% and 2% of the wind turbine cost respectively [3]. Solar and wind energy projects investments last for 20 to 30 years [3]. Cash flows in and out during all these years in the form of benefits and costs related to the project. Therefore, to get the real picture of the project economics, costs and benefits over the entire life span of the project has to be considered.

The following assumptions are made for the analysis of the system: The inflation rate of 21.34 % per annum considered is assumed to be constant over a period of 20 years [28]; the loan interest rate from banks of 17.01 % per annum [29] is constant over a period of 20 years; the salvage value of the solar and wind power system is negligible;

The net present value (NPV) approach is used to find the total cost of the hybrid power system per kW of power generated by solar and wind power systems; per meter height of wind turbine tower and per kWh of battery capacity. The annualized cost of the hybrid system (including PV array and support frame, wind turbine, battery, wind turbine tower and balance of system) expressed as the annuity of net present value of the project over its life span is determined using equation (15):

$$ACS = [P_{PV} \times NPV_{PV} + P_{WT} \times NPV_{WT} + C_{wh} \times NPV_{BT}] \times \left[\frac{i(1+i)^N}{(1+i)^N-1}\right] \quad (15)$$

The annual real interest rate i is related to the nominal interest rate i' (the rate at which you could get a loan from banks or other financial institutions) and the annual inflation rate f by the equation (16), assuming is constant over the period of consideration:

$$i = \frac{i'-f}{1+f} \quad (16)$$

The Levelized Energy Cost (LCOE) is one of the parameters used in measuring the cost of energy generated by a system. It is defined as the net present value of the total cost incurred by the power generating system over the lifetime divided by the net present value of the total power generation over its lifetime. It is determined using equation (17):

$$LCOE = \frac{\sum_1^N (ACS \times CRF)}{\sum_1^N (P_{PV} + P_{wt}) \times CRF} \quad (17)$$

Where CRF is the capital recovery factor and is computed using equation (18):

$$CRF = \frac{((1+i)^N - 1)}{(i \times (1+i)^N)} \quad (18)$$

2.2.4.1 Replacement cost of Battery

Based on the selected battery that has a life cycle of 10 years (Europe Solar store. 2023), it would require the battery be replaced once throughout the project life span. The future cost of battery considering the effect of inflation f was determined using equation (19):

$$FC_{rep} = C_{rep} \times (1+f)^{N_b} \quad (19)$$

2.2.4.2 Operation and Maintenance cost of solar wind power system

The operation and maintenance cost of the solar and wind power system is often expressed as a percentage of the initial investment of the systems [26], [3] and was determined as the accumulated present value over the lifetime of the project, considering the effect of inflation f using equation (20):

$$APV_{Nop} = mC_I \times \left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] \quad (20)$$

2.2.4.3 Payback time of hybrid solar-wind power system

Payback time (PBT) is the year in which the net present value of all costs equals with the net present value of all benefits. The annual benefit from sales of energy generation is computed using equation (21):

$$B_A = \left(\sum_{t=1}^{T} \left(\left(P_{PV}(t) + P_{WT}(t)\right). \Delta t + C_{bat}(t-1) - C_{batmin} \right) \eta_{inv} \right) \times \varepsilon \quad (21)$$

Where, ε is the kWh cost of energy generated. Therefore, the payback period of the hybrid solar-wind power investment is computed from:

$$n = -\frac{ln\left[1 - \frac{i(P_{PV}C_{PV} + P_{WT}C_{WT} + C_{wh}C_{BAT})}{B_A - (P_{PV}m_{PV} + P_{WT}m_{WT})}\right]}{ln(1+i)} \quad (22)$$

2.2.5 Sensitivity analysis of hybrid solar-wind power system

The desire of any would-be investor on renewable power system is to have a very low payback time in order to maximize profit on the investment made. Thus, sensitivity analysis on parameters that affect the payback time of the hybrid solar-wind power system was carried out to determine the extent of their impact on the payback time. The payback time is affected by factors such as the cost of investment, cost of energy, which depends on the tarrif-regime; inflation rate of the country, bank loan interest rate, system design adopted such as day of autonomy, depth of battery discharge and wind turbine rated velocity.

3. Results and Discussion

Table 1 shows the Annualized cost of system (ACS), Levelized cost of energy (LCOE) and

Payback time (PBT)) of the designed hybrid solar-wind power system, with ACS ₦52,268,266.97, LCOE ₦154.53/kWh and the payback time 10.5 years as shown in Table 1. The LCOE of the hybrid solar-wind power system as compared with the LCOE of solar power system for the six-geopolitical regions of Nigeria ranges from ₦ 306.70 - 376.44 ₦ /kWh from Northern to the Southern part of Nigeria [30] and for wind system 13.23 ₦ /kWh to 153.51₦/kWh respectively [31], which shows that the LCOE in Haipang is relatively cheaper compared to other parts of Nigeria signifying high potential of solar and wind energy resources potententials.

Table 1. Annualized cost of hybrid solar-wind power system

System	ACS ₦	LCOE ₦/kWh	PBT year
Hybrid solar-wind power	52,268,266.97	154.53	10.5

The total annualized cost of the hybrid solar-wind power system is ₦ 52,268,266.97as shown in Table 1; with battery, solar and wind power systems taking 81%, 10% and 9% of the total annualized cost respectively as shown in Figure 1. The cost of the battery system is more than the cost of the other components because it has a shorter lifespan of 10 years compared to solar panel and wind turbine which are 20 years each,which implies that the battery has to be replaced once in the life span of the project, and also because the cost of manufacturing kWh of battery is much higher than that of solar and wind power systems. Similarly, solar power system requires a large land area for installation, thus, its cost is relatively higher than that of the wind power system because land cost was captured into its cost.

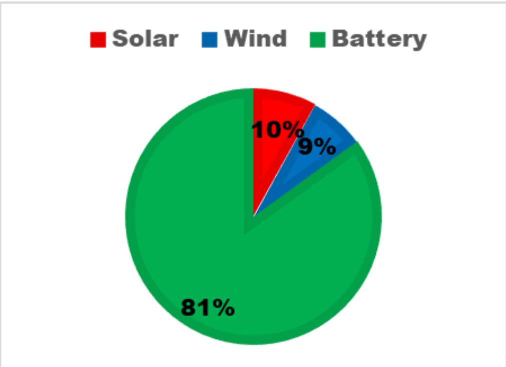

Figure 1: Percentage annualized cost distribution for hybrid solar/wind power system

Figure 2a shows a plot of investment pay back time against inflation rate for different cost per kWh of energy. As shown in Figure 2a, for a given cost of energy, the higher the inflation, the greater the pay back time. Similarly, for a given rate of inflation, the higher the cost of energy, the lower the pay back time. The figure shows that for ₦ 185.00, ₦ 160.00 and ₦ 127.00 per kWh cost of energy at 20% inflation rate, the investment payback times are 8.8 and 10.1 and 12.6 years respectively. Inflation rate can be controlled by good monetary policy of the Government of a country.

The plot of investment pay back time against bank loan interest rate is shown in Figure 2b. The figure shows that for ₦ 185.00, ₦ 160.00 and ₦ 127.00 per kWh cost of energy at 20 % bank interest rate, the investment payback times are 9.8, 11.4 and 14.3 years respectively. This shows that the payback time is more sensitive to bank loan interest rate than the chang in inflation rate rate. Bank loan interest rate for renewable energy technologies depends on the economic and renewable energy policies of a country. The cost of energy depends on the tarrif-regime of a country. High tarrif-regime will make renewable energy generation unaffordable for most rural consumers. For countries that want to promote renewable energy technologies, governments extend financial support to renewables in terms of exceptions and incentives. These may be in direct or indirect forms in order to encourage investors and consumers. Such supports make the renewable energy option more attractive. Providing incentives and exemptions reduces the energy tarriff to the level that it is affordable to consumers and also motive investors to key into renewable energy technologies.

Providing financial supports for the renewable energy projects are justifiable as many conventional energy sources like natural gas and coal have enjoyed subsidies in hidden forms. For example, in US, the Government had spent $ 35 billion in a span of 30 years for the treatment of coal miners who suffer from black lung [3]. Also, the cost of scavenging the atmosphere of its harmful chemical released to it by fossil fuel-based power plant ought to be added to the cost of energy produced through these technologies. The cost of many conventional sources may appear to be higher than they appear today if all these hidden financial favors are accounted. As reported in [32] the Federal Government spends ₦ 30 billion to subside electricity every month. Similarly, report has shown that, the federal

Government of Nigeria expends ₦ 102.5 billion monthly to reduce the retail cost of petrol [33].

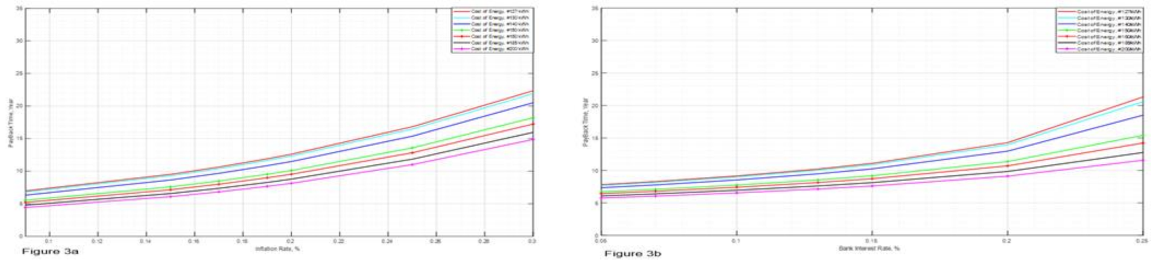

Figure 2: Plot of solar-wind power system investment payback time against (a) Inflation rate (b) bank interest rate

Solar and wind energy technology are stochastic, thus the need for battery backup system for steady and uninterrupted power supply. Day of autonomy is the number of days the battery backup can supply uninterrupted power when there is no solar and wind power generation. Uninterrupted power supply is the desire of consumers but it certainly comes with cost implication. Figure 3b shows a plot of investment pay back time against day of autonomy for different cost per kWh of energy. From the figure, for ₦ 185.00, ₦ 160.00 and ₦ 127.00 per kWh cost of energy for 3 days of autonomy, the investment payback times are 9.8, 11.1 and 13.5 years respectively and 10.6, 12.0 and 14.6 years respectively for 5 days of autonomy. This implies that the the higher the day of autonomy, the higer the reliability of the system in terms of meeting the power demand and the higher the payback time.

Figure 3a shows a plot of investment payback time against depth of discharge of battery for different cost per kWh of energy. From the figure, for ₦ 185.00, ₦ 160.00 and ₦ 127.00 per kWh cost of energy for 50% depth of battery discharge, the investment payback times are 8.9, 10.7 and 12.4 years respectively and 6.7, 8.1 and 9.5 years respectively for 80% depth of battery discharge. This implies that the the higher the depth of battery discharge the lower the payback time and the lower the life-span of the battery.

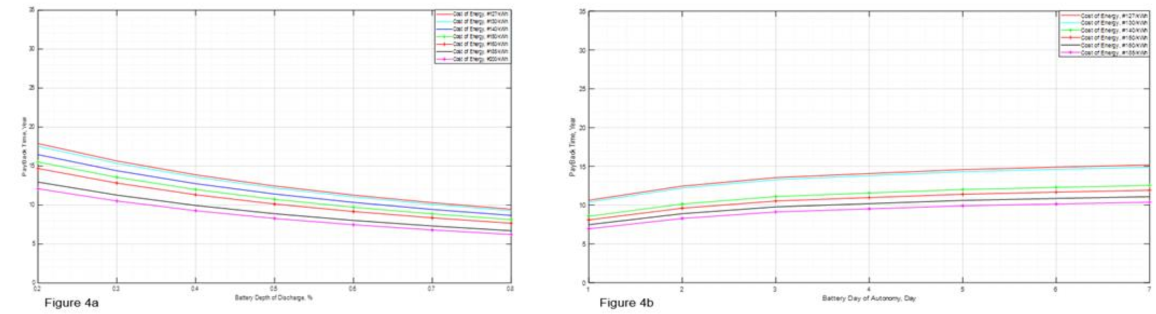

Figure 3: Plot of solar-wind power system investment payback time against (a) Battery depth of dischage (b) Battery day of autonomy.

The plot of investment payback time against wind turine rated speed is shown in Figure 4. The figure shows that for ₦ 185.00, ₦ 160.00 and ₦ 127.00 per kWh cost of energy at 10m/s wind turbine rated-velocity, the investment payback times are 10.0, 11.4 and 13.9 years respectively. Also from the figure, for ₦ 127.00 per kWh cost of energy, the payback time increased by 1.5 years as the wind turbine rated-velocity increased from 10m/s to 11m/s, but increased by 3.1 years as the wind turbine rated-velocity increased from 11m/s to 13m/s, showing how sensitive payback time is to change in wind turbine rated-velocity. This implies that a right choice of wind turbine for application in a given wind speed regime is key to viable investment in wind power technology.

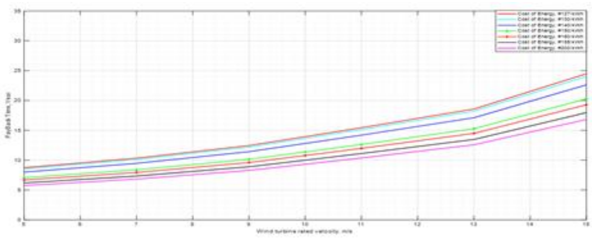

Figure 4:A plot of solar-wind power system investment payback time against wind turbine rated velocity

4. Conclusion

The ACS and the LCOE of a hybrid solar-wind power system was determined using techno-economic analysis. The LCOE is ₦154.53/kWh which falls between the range of ₦127 to ₦185/kWh for commercial and residential respectively of the solar cost of energy for solar mini-grid electrification projects at Demshin and Angwan-Rina in Shendam Local Government Area of Plateau State [34]. The payback time of the hybrid solar-wind power system investment is 10.5 years, which falls within the range of 10 to 15 years as reviewed in the literature [12], [13], [14]. The pay-back time of hybrid solar-wind power system investment depends on economic and technical factors. Based on the sensitivity analysis, the pay-back time is more sensitive to the technical factors. The technical factors such as battery depth of discharge, system day of autonomy and the rated wind turbine velocity depend on the optimal design of the system, while the economic factors such as the bank interest rate and inflation rate depend on the monetary policy of the Government. As stated in [35] the cost of installing a non-renewable power plant is higher than the cost of installing same capacity of renewable power system which will certainly result to high energy tariff. Thus, to promote renewable energy technology Government will have to develop policies that will encourage renewable energy subsidies to encourage low-income earners and investors key into renewable energy technology for sustainable development.

Notations

A_{pv}- surface area of the solar module
B_A- annual benefit from sales of energy generated
C_{ah}- ampere-hour rating of the selected battery
C_{BAT}- battery investment cost per kWh
$C_{bat}(t)$- battery bank capacity (Wh) at hour t
$C_{bat}(t-1)$- battery bank capacity (Wh) at hour $t-1$
$C_{bat\,min}$- minimum capacity of battery
C_{batmax}-maximum battery capacity
CF_{Hybrid}- capacity factor of the hybrid power system
C_I- initial cost of investment
C_{PV}- solar power investment cost per kW
C_{rep}- replacement cost of battery
C_{wh}- capacity of battery
C_{WT}- wind power investment cost per kW
DOD- depth of discharge
DOD_{max}- maximum depth of discharge of battery
E_L- electrical load
$EEGP(t)$- Excess Energy Generated Percentage
f- annual inflation rate
FC_{rep}- future cost of replacement of the battery
f_{pv}- photovoltaic derating factor
G_b- beam radiation on a horizontal plane
G_d- diffuse solar radiation
G_E-Hourly extraterrestrial solar radiation
G_m- Measured daily global solar radiation on horizontal surface
G_{sc}-Solar constant
G_T- solar radiation at inclined plane in W/m^2
$G_{T,NOCT}$- Solar radiation at nominal operating solar cell temperature
$G_{T,STC}$- incident solar radiation at standard test condition
H_0- reference height for measuring wind speed
H_{WT}- Wind turbine Hub height
i- annual real interest rate
i'-Bank interest rate
K_T- clearness index
n- investment payback period in years
N- project lifetime
N_{bp}- number of batteries in parallel
N_{bs}- number of batteries in series
N_{BT}- number of strings of battery
n_d-Number of the day in a year
N_{PV}- number of photovoltaic modules
NPV_{PV}- Net present value of solar panel/kW
NPV_{WT}- Net present value of wind turbine/kW)
N_{WT}- number of wind turbine
m- percentage of operation and maintenance cost based on cost of initial investment,
m_{PV}- solar power annual operation and maintenance cost per kW
m_{WT}- wind power annual operation and maintenance cost per kW
P- Total load demand
P_{Hybrid}-Hybrid (solar wind) power generated
$P_{INV}(t)$- Inverter capacity
$P_{load}(t)$- power consumed by the load at hour t
P_{pva}- power generated by photovoltaic per unit area
$P_{PV}(t)$- power generated by solar system at time t
p_R- Rated power of the wind turbine
P_{rs}- power rating of the selected photovoltaic module
P_{rw}- power rating of the selected Wind turbine
P_{sh}- Solar power system load share
P_{wh}- wind turbine power system load share
$P_{WT}(t)$- power generated by wind turbine at time t
P_{wta}- power generated by wind turbine per unit area
R_b- ratio of beam radiation on an inclined surface to that on the horizontal surface
T -operation time of hybrid solar wind power system
$T_{a,NOCT}$- ambient temperature at nominal operating temperature
T_c- solar cell temperature in degree Kelvin
$T_{c,NOCT}$- nominal operating solar cell temperature
$T_{c,STC}$- solar cell temperature under standard test condition
v- wind speed at hub height
V_B- nominal voltage of the selected battery
v_C- cut-in wind speed
v_F- cut-out wind speed
v_0- wind speed measured at the reference height
v_R- rated wind speed
V_{system}- system voltage
SD- battery day of autonomy
Y_{pv} -Rated capacity of the solar module

GREEK SYMBOLS

α_p- temperature coefficient of power
α_1- power law exponent.
δ-Angle of declination
ϕ- latitude of the location
ω- hour angle
$\acute{\beta}$- inclined angle of solar panel to the horizontal plane
ρ_g- diffuse reflectance of the surroundings
σ- self-discharge rate of the battery bank
η_{bat}-efficiency of battery
η_{INV}-Inverter efficiency
η_{batC}- battery efficiency during charging process
η_{batD}- battery efficiency during discharging process$\eta_{mp,STC}$-maximum power point efficiency under standard test conditions

Δt- Time step used for the calculations
$\tau\alpha$- solar transmittance-absorptance factor of solar module cover
ε- cost of energy generated per kWh

Conflict of interest

The authors declare no conflict of interest.

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