

# Optimisation of Hybrid Energy System Production Parameters for Electricity Power Generation in Nigeria

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## Abstract

Solar and wind energy are two of the most viable and sustainable sources of energy due to the tendency of renewal. The power generating supplies in Nigeria appear unreliable, rapidly diminishing and expensive. Researches are sparse on operating both energy sources alongside fossil fuel for power generation in order to take advantage of their complementary characters. The aim of this study is to explore renewable sources combined with non-renewable source to generate electricity with the objective of establishing an optimal design for a hybrid solar-wind-diesel energy plant that minimizes cost. The capacity factor of the standalone system was determined for the study area. The cost of energy for the hybrid optimal mix was determined. Levelised cost of energy was also used to determine the cost of energy for standalone power system. The result shows that the energy generated 200 MW hybrid system is 392 GWh with a cost of energy of \$0.24/kWh (47.8/kWh). The energy produced can power 39,200 homes in a year. The optimisation shows that the number of solar system, wind and diesel are 699, 1 and 300 respectively. The cost of energy for the standalone system was \$0.06/kWh, \$0.08/kWh and \$0.27/kWh for wind, solar and diesel system. The capacity factor was 56%, 21% and 80% for wind, solar and diesel system. There is a reduction in the amount of greenhouse gases released to the environment alongside with cost of energy generation. Hybrid power generation system is good and effective solution for power generation than conventional energy resources.

## Keywords

Energy Mix, Hybrid Energy, Levelised Cost, Optimal Design, Standalone Power

## 1. Introduction

Energy is considered as one of the most important resources that propels the economic development of any country. The major classes of the source of the energy are from fossil resources, such as crude oil, natural gas, coal and renewable resources like solar, wind and biogas. Nigeria as a country is a country with rich energy resource, blessed with both categories for her electricity generation. The bulk of the supply for electrical energy in Nigeria over the last 40 years is from the fossil resources which vary from gas-fired to hydroelectric power. Thus, it makes electrical energy generation in Nigeria to be unsustainable. Electricity is one factor that has perpetually maintained the status of Nigeria as a less developed country [1], as the intractable sector appears to have failed to respond to all strategies applied for improvement.

According to Oshodi [1] and NASA [2], electrical energy generation from fossil resources has been a challenge. Nigeria has spent approximately \$20 billion on electricity generation from 1999 to 2015 and up till date, still generates lower than 7500 Megawatts to over 180 million Nigerians. There is also a problem of electricity distribution according to Ogundipe and Apata [3]. A compiled table of energy generation and consumption from 1990 to 1999 showed that Nigeria lost an average of 41.4% of the Kilowatts generated due to vandalism, inadequate and worn-out electricity transmission equipment. Also the challenge of hydrological inadequacies in hydroelectric power plants especially during the dry season is another important issue.

According to Amadi [4], Nigerian needs a mixture of electric power sources from renewable source. This idea has led to the utilization of hybrid energy system. Hybrid power systems combine two or more electricity generation sources, like fossil and solar panel to reduce long term generation cost. The concept of hybridizing renewable energy sources is that the base load is to be covered by the largest and firmly available renewable source and other intermittent source should augment the base load to cover the peak load of an isolated electric mini grid system. Optimum use of the hybrid energy system provides higher system performance than a single system in terms of reliability, efficiency, less emission and low cost [5]. Energy prices, supply uncertainties and environmental concerns are driving developing nations to rethink their energy mix and develop diverse sources of clean, renewable energy for electricity generation.

The study was aimed at setting optimum production parameters for hybrid energy system with the objective of minimizing the generation cost.

## 2. Methodology

### 2.1. Study Area

Sokoto state was selected because it has one of the highest average wind speeds and temperature in Nigeria. It is located on the coordinate 13°05'N 5°15'E. The total land area is 25,973 km<sup>2</sup>. Sokoto is a dry sahel, surrounded by sandy savannah and isolated hills. Sokoto State shares borders with Niger Republic to the

North, Kebbi State to the West and South and Zamfara State to the East. Sokoto has an average temperature of 28.3°C with the maximum daytime temperature of 40°C. The warmest months are February to April when the daytime temperature reaches 45°C, during the raining season the showers rarely last long. Wind speed is the most important measure for a potential wind power. The average wind speed in Sokoto state is 7 m/s while the wind speed ranges from 2.4 m/s to 12.1 m/s [6] [7].

## 2.2. Design Considerations

The hybrid energy system consists of wind-solar-diesel energy system. Variables considered in the design include the number of photovoltaic modules, the wind turbine height, the number of wind turbines, and the rotor diameter of the turbines. These variables are used to find the optimal design of a hybrid power generation system, with the objective of maximizing power, while minimizing cost.

### 2.2.1. Model Assumption

- 1) Solar radiation is constant over the year.
- 2) The flow of air is frictionless.
- 3) The design of the hybrid wind-solar power system is considered at sea level.
- 4) The density of air is 1.23 Kg/m<sup>3</sup>.
- 5) The efficiency of the generator is 80%.
- 6) The inter-bank exchange rate (official) is \$1 = N199.05.
- 7) 1 US gallon = 3.79 litres.

### 2.2.2. Wind Energy System

There are two rudimentary reasons why wind turbine blades are able to spin in the wind. This is due to Newton's Third Law and the Bernoulli Effect. Newton's Third Law states that for every action, there is an equal and opposite reaction. In the case of a wind turbine blade, the action of the wind pushing air against the blade causes the reaction of the blade being deflected, or pushed. If the blade has no pitch (or angle) the blade will simply be pushed backwards (downwind). But since wind turbine blades are set at an angle, the wind is deflected at an opposite angle, pushing the blades away from the deflected wind. The Bernoulli Effect states that faster moving air has lower pressure. Wind turbine blades are shaped so that the air molecules moving around the blade travel faster on the downwind side of the blade than those moving across the upwind side of the blade. This shape, known as an airfoil, is like an uneven teardrop. The downwind side of the blade has a large curve, while the upwind side is relatively flat. Since the air is moving faster on the curved, downwind side of the blade, there is less pressure on this side of the blade. This difference in pressure on the opposite sides of the blade causes the blade to be "lifted" towards the curve of the airfoil. Wind turbines are machines that remove energy from the wind by leveraging the aerodynamic principles of lift and drag. Lift and drag forces move the turbine blades which convert kinetic wind energy to rotational energy. The rotational energy

can then be transformed into electrical energy. Wind turbines harness the wind to produce electrical power. A turbine consists of generator that is equipped with fan blades and placed at the top of a tall tower. The tower must be tall enough to harness the wind at a greater velocity while avoiding obstacles such as trees, hills, and buildings. As the turbine rotates in the wind, the generator produces electrical power. To justify construction of a turbine, it is recommended to have a minimum of one year of wind data to determine the feasibility of the location of interest. The wind turbine decelerates the wind, thereby reducing the kinetic energy in the wind. Wind turbines extract energy by slowing down the wind. For a wind turbine to be 100% efficient it would need to stop 100% of the wind but then the rotor would have to be a solid disk and it would not turn and no kinetic energy would be converted. On the other extreme, if a wind turbine has just one rotor blade, most of the wind passing through the area swept by the turbine blade would miss the blade completely and so the kinetic energy would be kept by the wind. Albert Betz was a German physicist who calculated that no wind turbine could convert more than 59.3% of the kinetic energy of the wind into mechanical energy turning a rotor. This is known as the Betz Limit, and is the theoretical maximum coefficient of power for any wind turbine.

The wind turbine converts 70% of the Betz Limit into electricity. Therefore, the Power coefficient ( $C_p$ ) of this wind turbine would be

$$C_p = 0.7 \times 0.59 = 0.41 \quad (1)$$

Wind turbine converts 41% of the available wind energy into electricity. This is actually a pretty good coefficient of power. Good wind turbines generally fall in the 35% - 45% range. In reality, the coefficient of power is not constant and it varies with the tip speed ratio  $\lambda$  of the turbine [8]. The relationship between the coefficient of power and tip speed ratio is given by [9]:

$$C_p = \frac{1}{2} (\lambda - 0.022\theta^2 - 5.6) \ell^{-0.17\lambda} \quad (2)$$

where  $\theta$  = pitch angle of the blades and  $\lambda$  is the blade tip speed ratio.

Tip speed ratio is given by

$$\lambda = \frac{\text{blade tip speed}}{\text{wind speed}} \quad (3)$$

$$\text{where the blade tip speed} = \frac{\text{rotational speed (rpm)} \times \pi D}{60} \quad (4)$$

where  $D$  = diameter of the rotor

The power in the wind  $P_w$  is given by

$$P_w = \frac{1}{2} C_p V^3 \rho A \quad (5)$$

where  $V$  is the velocity of the wind (m/s),  $\rho$  is the density of air and  $A$  is the swept area. The swept area is the section of air that encloses the turbine in its movement, the shape of the swept area depends on the rotor configuration, this

why the swept area of a wind turbine is circular shaped. This also limits the volume of air passing by the turbine. It can be calculated from the length of the turbine blades using the equation for the area of a circle,  $A = \pi r^2$ , where  $r$  is the radius of the blade.

### 2.2.3. Solar Power System

Photovoltaic systems harness the sun's energy by converting it into electricity via the photoelectric effect. This occurs when incoming photons interact with a conductive surface, such as a silicon cell or metal film, and electrons in the material become excited and jump from one conductive layer to the other. The excitation of electrons and their movement from the p-layer to the n-layer results in a voltage differential across the electrical circuit, causing electrons to flow through the rest of the circuit to maintain a charge balance. The system is designed so that there is an electrical load in the external circuit, permitting the current flow to perform a useful function. Solar radiation is the energy from the sun that reaches the earth. It is commonly expressed in units of kilowatts per square meter ( $\text{kW/m}^2$ ). The earth receives a nearly constant  $1.36 \text{ kW/m}^2$  of solar radiation at its outer atmosphere. However, by the time this energy reaches the earth's surface, the total amount of solar radiation is reduced to approximately  $1 \text{ kW/m}^2$ . The intensity of sunshine (*i.e.* solar radiation) varies based on geographic location. The intensity of sunlight also varies based on the time of day because the sun's energy must pass through different amounts of the earth's atmosphere as the incident angle of the sun changes. Solar intensity is greatest when the sun is straight overhead (also known as solar noon) and light is passing through the least amount of atmosphere. Conversely, solar intensity is least during the early morning and late afternoon hours when the sunlight passes through the greatest amount of atmosphere. In most areas, the most productive hours of sunlight (when solar radiation levels approach  $1 \text{ kW/m}^2$ ) are from 9:00 a.m. to 3:00 p.m. Outside of this time range, solar power might still be produced, but at much lower levels. Solar irradiance, on the other hand, is the amount of solar energy received by or projected onto a specific surface. Solar irradiance is also expressed in units of  $\text{kW/m}^2$  and is measured at the surface of the material. In the case of a PV-powered system, this surface is the solar panel. Finally, solar isolation is the amount of solar irradiance measured over a given period of time. It is typically quantified in peak sun hours, which are the equivalent number of hours per day when solar irradiance averages  $1 \text{ kW/m}^2$ . It is important to note that although the sun may be above the horizon for 14 hours in a given day, it may only generate energy equivalent to 6 peak sun hours.

To determine the size of PV modules, the required energy consumption must be estimated. Therefore, the power is calculated as

$$P_s = \frac{E}{t} = \frac{r_s \times A_s \times H \times P_r}{t} \quad 6$$

where  $r_s$  is the solar panel yield,  $A_s$  is the area of a single photovoltaic panel,  $H$  is the annual average solar irradiation on tilted panels,  $P_r$  is the performance ratio

coefficient for losses.

#### 2.2.4. Diesel Power System

The diesel generator is a compression ignition engine that uses diesel as fuel. The generator converts chemical energy to electrical energy. It is a combination of a diesel engine with an alternator to generate electricity. The fuel consumption of a diesel generator is dependent on the size of the generator and the load at which the generator is operating at. Most generators operate within 80% to 100% of the power rating.

$$E_D = \eta_D \times P_D \quad (7)$$

where  $\eta_D$  is the efficiency of the diesel generator

$E_D$  is the energy generated by the diesel generator

$P_D$  = power generated in a diesel generator

### 2.3. Development of the Optimisation Scheme

To solve an optimisation problem one needs to identify the decision variables, an objective function, and the sets of constraints which the process is subject to. The decision variables represent the adjustable input data of the problem, the objective function is the main function of the problem that is to be minimized (or maxized), and the constraints represent the physical and practical limitations of the process. In this study the energy cost is the objective function, and our task is to find the decision variables that minimize the cost while satisfying the constraints.

A general optimization model for the hybrid energy system is of the form:

$$\text{min: } C_T \quad (8)$$

Subject to the following constraints

$$g_i(x) \leq, \geq h_i, \quad i = 1, 2, 3, \dots, m \quad (9)$$

$$x \geq 0 \quad (10)$$

The objective is to minimise cost subject to energy demand, dimensional and policy constraints. The decision variables include the number of photovoltaic modules, wind turbine height, number of wind turbines, number of diesel generators and turbine rotor diameter.

#### 2.3.1. Formulation of the Objective Function

The objective function of the hybrid energy system is the total cost of generation and running the system which incorporates the cost on wind, solar and diesel. Let  $C_w$  represent the cost of wind energy system while  $C_s$  represents the cost of the solar system and  $C_D$  the cost of diesel energy system. Therefore, the total cost of the hybrid system given by [10] as

$$C_T = C_w + C_s + C_D \quad (11)$$

where the cost of wind energy is the cost incurred from operating and maintaining the wind turbines; this equation incorporates the costs of increasing the

height of the wind turbine and the rotor diameter. This cost is a multiple of the number of wind turbines installed developed by [11].

$$C_W = N_W \left[ C_{Wm} + \left[ 0.1 \left[ \frac{h}{10} - 1 \right] + 1 \right] (2.449r^{2.7} + C_{wf}) \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] \right] \quad (12)$$

where  $N_w$  is the number of wind turbine

$C_{wm}$  is the annual maintenance cost of the wind turbine.

$h$  is the wind rotor height.

$r$  is the radius of the wind turbine.

$C_{wf}$  is the installation cost and cost of the wind turbine.

$i$  is the interest rate

$n$  is the number of years

The cost solar energy is a function of the cost of capital and maintenance cost, this is given by

$$C_s = N_s C_{sm} + N_s C_{sc} \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad (13)$$

where  $N_s$  is the number of solar panel

$C_{sm}$  is the annual maintenance cost of the solar panel.

$C_{sc}$  is the capital cost of the solar panels.

The cost of the diesel generator is the cost of operating and maintaining and the capital cost.

$$C_D = N_D C_{Dm} + N_D C_{Dc} \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad (14)$$

where  $N_D$  is the number of diesel generators

$C_{Dm}$  is the annual maintenance cost of the diesel generator.

$C_{Dc}$  is the capital cost of the generator.

Adding Equation (12), (13) and (14) together and substituting it in Equation (11) we have,

$$C_T = N_W \left[ C_{Wm} + \left[ 0.1 \left[ \frac{h}{10} - 1 \right] + 1 \right] (2.449r^{2.7} + C_{wf}) \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] \right] + N_S C_{Sm} + N_S C_{Sc} \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] + N_D C_{Dm} + N_D C_{Dc} \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad (15)$$

From  $C_T = C_W + C_S + C_D$

This is the total annualized life cycle cost of the system which comprises of capital cost, operating and maintenance cost and capital recovery factor.

### 2.3.2. Formulation of the Optimisation Constraints

#### 1) Power Demand Constraint

The hybrid power mix that meets the power demand of the loads, using the power generated from the hybrid system from wind turbines, solar rays and diesel generators. This is given by

$$(N_W \times P_w) + (N_S \times P_S) + (N_D \times P_D) \geq P_{Demand} \quad (16)$$

where  $P_{Demand}$  is the power demand

The power generated by the wind considered in this section is in terms of the number of wind turbine, height of the rotor, diameter of the rotor, co-efficient of power and wind speed according to the [11]:

$$P_w = N_w \left[ 1 + 0.814 \ln(h)^{-1.92} \left( \frac{1}{2} C_p V^3 \rho A \right) \right] \quad (17)$$

Therefore, Equation (16) becomes

$$N_w = \left[ 1 + 0.814 \ln(h)^{-1.92} \left( \frac{1}{2} C_p V^3 \rho A \right) \right] + [N_S \times P_S] + [N_D \times P_D] \geq P_{Demand} \quad (18)$$

## 2) Height and Radius Constraint

Here the height of the wind turbine is at least 70 meters, while the limit of the rotor radius is at least 30 percent of the tower height. The reason for this is that the higher you go, the windier it gets and a larger swept area is needed according to this expression:

$$h \geq 70 \quad (19)$$

$$r \geq 0.3h \quad (20)$$

## 3) Renewable and Non-Renewable Policy Constraint

The policy adopted for this study suggest that at least 60% of the energy should come from the renewable while the rest should be from non-renewable.  $N_R$  is 60% of  $N_T$ .

$$N_w + N_s + N_D = N_T \quad (21)$$

$$N_w + N_s \geq N_R \quad (22)$$

$$N_D \geq N_T - N_R \quad (23)$$

## 4) Wind Speed

The wind speed for heights  $h$  can be modeled using this

$$V = v \left[ \left( \frac{h}{H} \right)^{0.143} \right] \quad (24)$$

### 2.3.3. Formulation of the Problem Statements

The problem can therefore be written as

$$\begin{aligned} \text{Min} C_T = N_w & \left[ C_{wm} + \left[ 0.1 \left[ \frac{h}{10} - 1 \right] + 1 \right] \left( 2.449 r^{2.7} + C_{wf} \right) \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] \right] \\ & + N_s C_{sm} + N_s C_{sc} \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] + N_D C_{Dm} + N_D C_{Dc} \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] \end{aligned} \quad (25)$$

Subject to

$$N_w = \left[ 1 + 0.814 \ln(h)^{-1.92} \left( \frac{1}{2} C_p V^3 \rho A \right) \right] + [N_S \times P_S] + [N_D \times P_D] \geq P_{Demand}$$

$$\begin{aligned}
h &\geq 70 \\
r &\geq 0.3h \\
V &= v \left[ \left( \frac{h}{H} \right)^{0.143} \right] \\
N_W + N_S + N_D &= N_T \\
N_W + N_S &\geq N_R \\
N_D &\geq N_T - N_R \\
N_W, N_S, h, r &\geq 0
\end{aligned} \tag{26}$$

### 2.3.4. Solution to the Optimisation Problem

#### 5) Cost of Energy

The absence of accurate and reliable data on the cost and performance of renewable power generation technologies and non-renewable technologies is a significant barrier to the uptake of these technologies. Providing this information will help governments, policy-makers and investors make informed decisions about the role renewable can play in their power generation mix. Cost can be measured in a number of different ways, and each way of accounting for the cost of power generation brings its own insights. It is important to adopt a metric that estimates the dollar per kilowatthours of these alternative sources of energy. The study adopts the simplified levelised cost of energy. Different cost measures are useful in different situations; the levelised cost of energy is a widely used measure by which renewable and non-renewable energy technologies can be evaluated for modeling or policy development. The United States Energy Information Administration [12] defined the levelised cost of energy as a stream of equal payments, normalized over expected energy production that would allow a project owner to recover all costs, including financing and an assumed return on investment, over a predetermined financial life. It can also be defined as the constant unit cost (per kWh or MWh) of a payment stream that has the same present value as the total cost of building and operating a generating plant over its life. This gives an effective price per unit of energy and it can be used to compare different types of generation systems. The formula for the simplified levelised cost of energy is given below;

$$\text{LCOE} = \frac{\text{Total life cycle cost}}{\text{annual energy output}} \times \text{CRF} \tag{27}$$

where CRF is the capital recovery factor and this is given as

$$\text{CRF} = \frac{i(1+i)^n}{[(1+i)^n] - 1} \tag{28}$$

## 3. Results and Discussion of Results

### 3.1. Power Generated in the Wind Turbine

Power generated in the wind turbine is described in the following sub-sections:

### 3.1.1. Modeling Wind Speed with Height

The wind speed is the most important input when considering a wind turbine. At the height of 10 m in Sokoto the average wind speed was found to be 7 m/s over a period of 40 years. The study therefore seeks to estimate the wind speed at the height of 60 m using the height of 10 m as a reference. The most commonly used expression is the Hellmann exponential law (Power law) which correlates the wind speed readings at two different heights. The expression extrapolates the wind speed to a certain height using;

$$V_2 = V_1 \left( \frac{H_2}{H_1} \right)^\alpha \quad (29)$$

where  $V_2$  = wind speed at height  $H_2$

$V_1$  = wind speed at height  $H_1$

And  $\alpha$  = friction coefficient or Hellman exponent

The friction coefficient  $\alpha$  is a function of the topography at a specific site and frequently assumed as a value of 1/7 (0.143) for open land and 0.2 for forested region. However, it is important to note that this parameter can vary for one place with 1/7 value during the day up to 1/2 during at night time [12]. A terrain description of many trees and occasional buildings has a friction coefficient of 0.22. Sokoto will have friction coefficient of 0.143.

Therefore,

$$V_2 = 7 \left( \frac{60}{10} \right)^{0.143}$$

$V_2 = 9$  m/s

The estimated average wind speed at height of 60 m is 9 m/s.

### 3.1.2. Energy Output

An SRC 29.8 - 225 kw wind turbine with three blades was selected. It has a swept area of 697 m<sup>2</sup>. Blade length is 13.4 m. Rated output power is 225 kW. Air density at sea level is 1.23 kg/m<sup>3</sup>. Using equation 4 the power in the wind is given by

$$P(\text{output}) = \frac{1}{2} \times 1.23 \times 697 \times 9^3 \times 0.4 = 125 \text{ kw}$$

Power output of a 225 kW wind turbine is 125 kW at an average wind speed of 9 m/s.

The annual capacity factor is defined as the ratio energy generated in a time period to the energy produced if the wind turbine had run at rated power over that period. This is given by

$$\text{Annual capacity factor} = \frac{\text{Power Generated/yr (kw)}}{\text{Turbinerated Power (kw)}}$$

$$\text{Capacity Factor} = \frac{125}{225} = 0.556$$

Therefore, the capacity factor = 55.6%

In order to calculate the energy produced the annual generation hours is required. This is given by Annual Generation = 8760 × Capacity Factor

$$\text{Annual Generation hours} = 8760 \times 0.556 = 4870.56 \text{ hours}$$

The turbine is expected to run for 4870.56 hours this is due to the erratic nature of the wind. The energy produced will be

$$\text{Energy} = 125 \times 4870.56 = 608820 \text{ kWh}$$

The amount of energy the turbine is expected to generate in a year is 609 MWh.

### 3.2. Solar Power

The inputs for this system are the solar panel yield  $r_s$ , area of the solar panel  $A_s$ , annual average solar irradiation  $H$ , performance ratio  $P_r$ . The performance ratio or coefficient for losses is 0.75, solar panel yield is 15% and the area of a 200 W Kyocera Japanese solar panel is 1.45 m<sup>2</sup> (Dimension 1.46 m by 0.992 m). A 22-year average solar isolation incident for Sokoto state (latitude 13.083 and longitude 5.25) according to NASA surface meteorology and solar energy [2] is 6.24 kWh/m<sup>2</sup>/day. Using equation 6 the energy derived is given as

$$E = 1.45 \times 0.75 \times 0.15 \times 6.24 = 1.02 \text{ kWh/day}$$

The energy consumption is 1.02 kWh/day or 372.3 kWh per annum.

### 3.3. Diesel Power System

The energy from a diesel generator can be calculated as follows. Using equation 7 the efficiency of a diesel generator is 0.8. A 220 kW Yorpower YXP275RSC open set generator with a power factor of 0.8 operating for 8760 hrs will produce

$$E = 220 \times 0.8 \times 8760 = 1541760 \text{ kWh}$$

### 3.4. Optimal Mix and Cost of Energy

According to the USA solar and wind inc. [2] a 200 kW wind turbine with the following specification (Rated power: 200 KW, Rated voltage: 690 v DC, Rotor diameter: 30 m, Start-up wind speed: 3 m/s, Rated wind speed: 13 m/s, Security wind speed: 60 m/s, Yawing type: electronic, Rated rotating rate: 85 r/m, Generator work way: magnetic saturation, Generator material: steel, Blade material: fibre glass, Blade quantity: 3 pcs, Free stand tower height: 32 m, Matched inverter type: grid connected inverter) would cost \$1046,976 or N208400,572.8 (Wind generator price \$629411.10, Blade price \$69664.70, Controller price \$69664.70, On-grid inverter price \$129412.00 and Free stand tower price \$148823.80) or \$5.23 per watt. The operating and maintenance cost of the wind turbine is \$0.10/W.

A 20 kW solar panel (solar kit Canadian 310p, power-one inverters, product code is CS6X-310P-20kW) cost \$30,000 (\$1.5/W) or N5, 971,500. Theoretically a 200 kW solar panel will cost \$300,000 or N59, 715,000. The operating and maintenance cost of solar power systems is 5% of the investment cost which is

\$0.075/W.

The cost of a 200 kW Perkins diesel generator is \$23,975, sound proof enclosure cost \$2359 and a 250 gallon sub-base fuel tank cost \$1795. The total cost of the generator is \$28,129 (N5599, 077. 45) or \$0.14 per watt. This is a 6 cylinder 4 stroke engine with fuel consumption of 9.8 gallons/hr (37.1 litres per hour) at 3/4 load. At full load it consumes 12.6 gallon/hr. The cost of diesel in Nigeria is \$0.72 or N143 per litre. The cost of diesel is N5, 305.3 /hr or \$26.71/hr. The lubrication oil capacity is 26.4 litres. 26.4 litres of semi-synthetic oil every six months, the cost is N8000 per 4 litres. Therefore, the cost of engine oil is N52, 800 or \$265.3 for the diesel engine every six months. Every year about N105,600 or \$530.52 will be spent on engine oil and N37, 179, 542.4 or \$186784.94 on diesel. Therefore, the total operating and maintenance cost is N37, 285, 142.4 or \$187315.46 (\$0.9 per watt) per annum.

The model (equation 22) was run using Lingo 14 on a 4 GB ram Dell Inspiron computer. The installed capacity of the hybrid system was 200 MW with a single power source of 200 kW. Therefore, there can be only 1000 units of these power sources. The optimal number of the mix was determined and the following variables were calculated has shown in **Table 1**.

The total cost of the hybrid energy is \$95,291,920. The diameter of the wind turbine blade is 42 m, the height is 70 m and the speed of the wind is 9.23 m/s. The total energy produced is 392 GWh. Therefore the cost of energy can be calculated and given as \$0.24/kWh (N47.8 per kWh). The cost of energy for the 200 kW solar system, 200 kW diesel and wind turbine standalone systems can be calculated below using the levelised cost of energy (LCOE).

The LCOE is the cost, if assigned to every unit of energy produced (or saved) by the system over the analysis period, will equal the total life cycle cost when discounted back to the base year. **Table 2** shows the total life cycle cost and the cost per kWh (LCOE) of electricity from three alternative sources. The levelised cost of energy for solar, wind and diesel generator is \$0.06 per kWh, \$0.08 per kWh and \$0.27 per kWh respectively. The lowest was recorded for solar system and the highest was the diesel generator. The levelised cost of \$0.08 per kWh for wind energy is the minimum amount of energy that must be sold for the project to break even. This also applies to the other levelised cost for solar and diesel generator of \$0.06 per kWh and \$0.27 per kWh. The cost of energy by the hybrid system is much lower than the cost of energy for the standalone diesel system.

**Table 1.** Result of the optimal mix.

Energy type	Cost of power (\$/W)	Cost of operating and maintaining (\$/W)	Capacity factor	Annual generation hours (hr)	Optimal number	Power produced (kW)	Energy produced (GWh)
Solar	1.5	0.075	0.21	1840	699	29707.5	54.6
Wind	5.23	0.10	0.556	4871	1	110	0.535
Diesel	0.14	0.9	0.80	7008	300	48,000	336.4

**Table 2.** The levelised cost of energy.

	200 kW solar system	200 kW diesel generator	200 kW wind turbine
Nameplate capacity (megawatts)	0.20000	0.2	0.2
Capacity factor	21.0%	80%	56%
Total annual output (megawatt hours)	367.92	1402	974
Cost to build	\$350,000	\$23,975	\$1,046,975
Number of employees	2	4	4
Average annual salary of employees	\$1000	\$1005	\$2000
Annual salary costs	\$2000	\$4019	\$8000
Annual maintenance and upkeep costs	\$1500	\$180,000	\$20,000
Fuel costs to generate one megawatt hour	\$0	\$134	\$0
Annual fuel costs	\$0	\$187,114	\$0
Total annual operating costs	\$3500	\$371,133	\$28,000
Total operating costs for 20 years	\$70,000	\$7,422,656	\$560,000
Total costs to build and operate for 20 years	\$420,000	\$7,446,631	\$1,606,975
Total power output in 20 years (megawatt hours)	7358.40	28,032	19,482
Levelized cost per kilowatt hour for 20 years	\$0.06	\$0.27	\$0.08
Levelized cost per kilowatt hour for 40 years	\$0.03	\$0.27	\$0.06

## 4. Conclusions

- 1) The cost of energy of the optimal mix is N47.8 per kWh.
- 2) The cost of a typical 225 KW turbine is about N208, 400, 572.8 (using \$1 = N199.05) while a 20 kW solar panel cost N5, 971, 500. On the other hand, a 200 kW diesel generator would cost N4, 772, 223.75. Operating and maintaining the diesel engine is much more costly.
- 3) The levelised cost of energy for solar, wind and diesel generator is \$0.06 per kWh, \$0.08 per kWh and \$0.27 per kWh respectively for twenty years.

Using the Lingo, the optimum number of solar arrays, diesel generators and wind turbines, as well as the optimum rotor diameter and height were determined. Hybrid power generation system is good and effective solution for power generation than conventional energy resources. It is important to note that the cost of energy of the hybrid system is low.

## 5. Recommendation

The study therefore recommends that since the scope of this project is limited to the optimal mix of renewable energy, the design of a micro-grid station is recommended for further studies.

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