ENERGY OPTIMIZATION AT MACRO BASE TRANSMITTER STATION SITE LOCATED IN NEMBE (BAYELSA STATE), NIGERIA

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This paper explores the best energy options by which optimized energy solution for a given GSM base station site locatied in Nembe can be made. The concept of hybridizing renewable energy sources is that the base load is to be covered by available renewable source(s) and other intermittent source(s) should augment the base load to cover the peak load of the base station site. The study is based on modeling, simulation, and optimization of the hybrid energy system located in Nembe (Bayelsa state), Nigeria. The patterns of load consumption by mobile base stations in Nembe are studied and modeled suitably for optimization using the Hybrid Optimization Model for Electric Renewables (HOMER) software. Various renewable/alternative energy sources, energy storage, and their applicability in terms of cost and performance, as well as a diesel generator were discussed. The proposed hybrid [(solar, wind & hydro) + DG] system was simulated using the model which results in eight different topologies: (solar, wind & hydro) + DG, (solar & hydro) + DG, (wind & hydro) + DG, hydro only + DG, (solar & wind) + DG, solar only + DG, wind only + DG, and DG. Total economic costs [net present cost (NPC)] and the environment impact (pollutant emissions in tons of CO_2) generated are used as indices for measuring the optimization level of each energy solution, and the option with the highest optimization value is considered to be the best energy solution for the base station site. The quantitative results of the study (as reported here) show that the hybrid power system can be more cost-effective and environmentally friendly in providing energy to a GSM base station site than diesel generators.

KEY WORDS: *energy optimization, economic cost, environmental impact, macro base transmitter station (BTS), HOMER, diesel generator (DG), renewable energy, simulation*

1. INTRODUCTION

The operation of telecommunications networks requires electrical power. The expenses on energy accounts for a significant share of the operational cost of these networks. This is particularly so in rural areas where the availability of power is uncertain. Network operators have become adept at generating their own off-grid power. This has typically been achieved by running diesel generators at each site, although the increasing number of operators are installing renewable energy equipment, such as wind turbines and solar panels, to power their base stations. The solution with the use of diesel generators to ensure continuous power supply has the disadvantage of increasing the greenhouse gas emission which has a negative impact on the environment.

The use of renewable energy solutions consists in replacing (partially or totally) the diesel generator by solar panels or a wind turbine or a hydro as the main power supply of BTS (Ani, 2015). The choice of renewable power options is partly determined by the region in which the facility is located (Solutions Paper, 2007). For instance, the performance of solar and wind energy systems (singly or in combination) are strongly dependent on the climatic conditions at the location.

The irony of this situation is that Nembe is endowed with very abundant renewable energy resources that remained unexplored and unexploited for alternative energy solutions for telecommunications. Nembe lies along the Equator, with abundant sunshine all the year round. According to Bala et al. (2000), Nigeria is endowed with an annual average daily sunshine of 6.25 h, ranging between about 3.5 h at the coastal areas and 9.0 h at the far northern boundary. Similarly, it has an annual average daily solar radiation of about 5.25 $kW/m^2/day$, varying between about 3.5 kWm^2/day at the coastal area and 7.0 $kW/m^2/day$ at the northern boundary (Chendo, 2002). Nigeria receives about 4.851×10^{12} kWh of energy per day from the sun.

There are lots of canals, several minor streams, and rivulets that crisscross the entire Nembe land mass, as well as tiny waterfalls having potentials for setting up mini/micro-hydro power units that can power GSM base station sites. Harnessing micro-hydro resources and setting up decentralized small-scale water power or micro-hydro schemes are a particularly attractive option in terrain areas without hampering the ecosystem.

Two principal wind currents affect Nigeria. The south-western winds dominate the rainy season of the year, while the north-eastern winds dominate the dry season. Depending on the shifts in the pressure belts in the Gulf of Guinea, these winds are interspersed respectively by the south-eastern and north-western winds in different periods of the year. The wetter winds prevail for more than 70% of the period due to the strong influence of the breeze from the Atlantic Ocean. Mean annual wind speed varies between 2 to 6 m/s. Speeds in the dry season (November–March) are lower. In the wet season (April–October), daily average speed could rise to 15 m/s. Values of up to 25 m/s are sometimes experienced due to inducement by convective rainfall activities and relative diffusion.

The energy derived from a biomass is not considered here due to the possibility of unwanted gas emissions as a result of combustion processes, apart from the need of the local community to minimize combustion for pristine forest reserve and tourist attraction purposes. An earlier study by Ghost et al. (2004) for a rural area in India had shown that a biomass-driven power plant could contribute to pollution gases. That power plant was reported to emit 1743 g of CO_2, 1.6 g of SO_2, and 3.4 g of NO_2 per kWh of electricity generation. The cost of the fuel cell technology is expensive due to the expensive noble metal used, notably platinum (Kreith, 2004; Flipsen, 2005; El-Sharkh et al., 2006).

The focus of this study is narrowed down to hybrid power systems.

1.1 Hybrid Power Systems (HPS)

A hybrid power system can be described as an electricity production system whose supply consists of a combination of two or more types of electricity generating sources (e.g., solar photovoltaic (PV) panels, wind turbine generators, pico-hydro plants, and/or fuel generators). Hybrid systems can include an energy storage; hybridizing solar and wind power sources together with storage batteries to cover the periods of time without sun or wind provides a realistic form of power generation. Another useful component of hybrid systems considered in this study is the diesel generator. A diesel generator can provide energy at any time, whereas energy from PV, wind or hydro is greatly dependent on the availability of solar radiation, wind speed or water flow (Wichert, 1997; Yu et al., 2005). This makes the system (generator) more reliable, and can be used to operate when PV, wind or hydro fails to satisfy the load and when the battery storage is depleted. Hybrid power systems can be a good way of providing power to many rural areas in the developing world where the costs for large-scale expansion of electrical grids is difficult and the transportation costs of diesel fuel are also very high (CEERE, 2012). The use of renewable energy sources for hybrid power generation systems would reduce the use of expensive fuels, and allow for the cleaner generation of electrical power.

Telecommunication systems require safe, long-lasting, and uninterruptible power supply in order to provide uninterrupted service (Panajotovic and Odadzic, 2010). Stand-alone homogeneous renewable power systems cannot meet the power requirements of telecommunication systems. In those cases where cell sites are scattered and will be difficult to supply with diesel power, only off grid renewable energy technologies will be appropriate for telecommunications systems deployment. Evidently, based on the current technologies, the deployment of renewable energy sources for telecommunication purposes (especially for cell sites) will require combining several renewable energy sources, conventional generators (diesel generator, LPG turbines, etc.), and energy storage systems (battery bank), which is selected based on their comparative advantage while maintaining uninterrupted supply and acceptable power quality, hence the HPS (Odadzic et al., 2011; Roskilde, 2000). Different mode of operation for the HPS is possible. Conventional system source (2) could be used simultaneously with renewable system source (1) to provide the required 10.7 kW power or, either of the two could be used as redundancy in the case of failure. Another possible mode of operation is that sources (1) and (2) would each have the capacity of 10.7 kW but the supply would alternate in such a way that source (1) will provide power for the first 12 h and source (2) will provide it for the remaining 12 h. This configuration could prove effective and may in turn cut the carbon emission by 50% when renewable (solar-PV or wind or hydro) and generator systems are deployed. It could also extend the lifetime of each system. A hybrid system uses an advanced system control logic (also known as a *dispatch strategy*) to coordinate when power should be generated by a renewable energy source and when it should be generated by sources like diesel generators. The real innovation of hybrid power generation is the realization that cost savings do not come from using the most powerful solar panels or the most efficient diesel engine, but by closely matching the cheapest energy production with the load. By coupling and coordinating sources together, the system provides more reliable and higher-quality electricity at lower costs. Faruk et al. (2012) hold an opinion that HPS provide a realistic alternative for conventional energy sources in terms of economy (fuel consumption and maintenance) and environmentally friendly although the CAPEX of such systems is high. However, the life-cycle cost is comparatively less, considering the cost of emissions.

There are different configurations — combinations of renewable and convectional energy sources — being deployed for telecommunication purposes: diesel–battery; solar–diesel–battery; wind–diesel–battery; solar–wind–diesel–battery; solar–battery, etc. (CAT, 2011). According to (Taylor, 2011), the configuration of a HPS depends on three factors: resource (renewable source), load, and cost (CAPEX and OPEX).

The major problem faced by power generation using a hybrid system is the fluctuation in load demand and renewable resources (solar radiation, wind speed, and water flowrate) (Ani, 2015). Therefore, the major concern in the design of an electric power system that utilizes renewable energy sources is the accurate selection of system components that can economically satisfy the load demand. Based on the costs of components, fuel, labor, transport, and maintenance, it is desired to evaluate the most cost-effective sizing of all components to meet the predicted peak loads. Sizing improves performance, economy, and reliability. Thus, the HPS is selected such as to optimize.

In the above optimization problem, hybrid system sizing is done with the aim of minimizing the net present costs while meeting a given demand reliably and cost-effectively. One method of doing this is to incorporate a computer simulation model for hybrid power systems.

The purpose of this study is to explore the possibility of hybridizing the diesel generator source system with renewable energy sources through design and optimization of the hybrid PV/wind/hydro/diesel system using a computer-based design optimization, to demonstrate the potential of renewable energies, and to replace (partially or totally) diesel as a source of power for mobile base station sites. This paper will provide energy system solutions that can reduce the GSM operator's dependence on a fossil fuel.

1.2 Energy Consumption at a Macro Base Transmitter Station Site

In identifying the energy consumption at GSM base station sites and assessing the impact of various operational strategies, we used a macro BTS as a model. A BTS is a tower or a mast mounted with telecommunication equipment (e.g., antenna, radio receiver and transmitters at the top of the mast) that enables the transmission of mobile signals (voice and data). At the bottom of each tower, there is a shelter with additional transmission equipment, air conditioning, battery racks and — for those that are off-grid or with unreliable electricity supply — in a separate room, a diesel generator. A BTS site load profile depends on multiple parameters including radio equipment, antenna, power conversion equipment, transmission equipment, etc. Therefore, it is important to outline an accurate power profile in order to select the energy components and their sizing. The energy consumption of various components at a typical RBS site has been categorized in (Gildert, 2006; Roy, 2008; Willson, 2009; GSMA, 2009) as follows:

1. *Radio equipment*
   - Radio unit [radio frequency (RF) conversion and power amplification] = 4160 W;
   - Base band [signal processing and control] = 2190 W.
2. *Power conversion equipment*
   - Power supply and rectifier = 1170 W.
3. *Antenna equipment*
   - RF feeder = 120 W;
   - Remote monitoring and safety (aircraft warning light) = 100 W.
4. *Transmission equipment*
   - Signal transmitting = 120 W.
5. *Climate equipment*
   - Air conditioning = 2590 W.
6. *Auxiliary equipment*
   - Security and lighting = 200 W.

This implies that a site consumes 10.7 kW·h of electricity. The diagram of the power consumption of the various components at a typical radio base station (RBS) site can be found in (Gildert, 2006).

1.3 Energy Optimization at BTS Sites

During the research, the author interviewed several telecom equipment vendors and operators, who made it clear that base stations account for the biggest part of the power consumption in the total mobile communication system. The electricity consumption by a BTS is on the average divided as follows: transmitters, 54%; air conditioning, 35%; other equipment, 11% (Gross, 2011; Lubritto et al., 2011). By "energy optimization" here it is meant the process of providing cheap, efficient, reliable, environmentally friendly and cost-effective power supply at GSM base station sites (Ani, 2015). This goal is pursued by selecting the best components and their sizing, and determining the best available energy option (in terms of economic and environmental costs) that will effectively power specific base station sites at chosen locations. The latter (determining the best available energy option) is the focus of this work. The selection of the best available energy option (from economic and environmental perspectives) means the design of the most effective economic configuration (combination of a number of power system components) from among a variety of options (diesel generators, PV arrays, wind turbines, micro-hydro power, batteries, converters, inverters, etc.) available at the BTS site.

1.4 Simulation and Optimization Software Tools of Hybrid Systems

Simulation programs are the most common tools for evaluating performance of the hybrid systems. By using computer simulation, the optimum configuration can be found by comparing the performance and energy production cost of different system configurations. HOMER (2012), developed by NREL (National Renewable Energy Laboratory, USA), is the most-used optimization software for hybrid systems (Bernal-Agustín and Dufo-López, 2009). The HOMER software can simulate a wide variety of micropower system configurations. A micropower system is a system that generates electricity, to serve a nearby load. Such a system may employ any combination of electrical generation and storage technologies. It is capable of optimizing hybrid systems consisting of a photovoltaic generator, batteries, wind turbines, hydraulic turbines, AC generators, fuel cells, electrolyzers, hydrogen tanks, AC–DC bidirectional converters, and boilers.

An analysis and design of distribution systems can be challenging, due to the large number of design options and the uncertainty in key parameters, such as load size and future fuel price (Baskar et al., 2012). HOMER also takes into account both seasonal and hourly load variations as well as variations in resource availability such as wind and sunlight (Lambert and Lilienthal, 2001). Renewable power sources add further complexity because their power output may be intermittent, seasonal, and nondispatchable, and the availability of renewable resources may be uncertain. This software was designed to overcome these challenges. HOMER performs three principal tasks, namely, simulation, optimization, and sensitivity analysis. The simulation process determines how a particular system configuration, a combination of system components of specific sizes, and an operating strategy that defines how those components work together, would behave in a given setting over a long period of time. Its higher-level capabilities, optimization, and sensitivity analysis rely on this simulation capability. The main disadvantage of the simulation approach is that the algorithms and calculations are not visible or accessible. HOMER is most widely used for designing and sizing hybrid systems that do not yet exist. HOMER has been used extensively in previous renewable energy system case studies (Khan and Iqbal, 2005; Zoulias and Lymberopoulos, 2007) and in renewable energy system validation tests (Dufo-López and Bernal-Agustín, 2005).

Al-Karaghouli and Kazmerski (2010) applied HOMER to study the life cycle cost of a hybrid system for a rural health clinic in Iraq. A system comprising PV/battery/inverter emerged as the most economic system. Shaahid and El-Amin (2009) performed a technical-economic evaluation of PV/diesel/battery systems for rural electrification in Saudi Arabia. They examined the effect of the increase in PV/battery on the cost of energy (COE), operational hours of diesel generators, and reduction in GHG emissions. Van Alphen et al. (2007) used HOMER to create optimal RE system designs in the Maldives. HOMER was used also by Deepak et al. (2011) to study the optimization of PV/wind/hydro/diesel hybrid power system in a rural area in Sundargarh district of Orissa state, India. They configured the power system in such a way that the PV generator and battery subsystems are connected with a DC bus. Hydro, wind energy generator, and diesel generating unit subsystems are connected with an AC bus. The electric loads connected in the scheme are AC loads. The Kansas University Magazine reported that Mahdi Sadiqi, a graduate of the Kansas State University and a native of Afghanistan, used the HOMER software to model robust, reliable energy systems for remote areas of Afghanistan (HOMER Energy, 2012). He found the most ideal solution for his site, it was a hybrid system powered by renewable resources, including micro-hydro and solar, with a battery backup.

In this paper, it was proposed to use computer software called HOMER to optimize the unit sizing and cost analysis of PV/wind/hydro/diesel hybrid power system at the GSM base station site located in Nembe (Bayelsa State), Nigeria.

1.5 Calibration of the Model

Without validating data coupled with optimization and modeling, there is little reason to believe that the conclusions stated in any paper have applicability beyond the immediate circumstances stated in each specific paper. Before using the measured data from the NASA datasets in simulating individual components of a PV/wind/hydro–diesel hybrid system, HOMER accuracy must be established. If the simulated data predicted by the software programs do not fall within the bounds of the measured data, then there is either a problem with how the models are formulated or a problem with the models that the programs use. If HOMER is proven sufficiently accurate, the software program will be used for the simulation and optimization of the hybrid PV/wind/hydro–diesel system.

Using the solar radiation and wind speed from the NASA datasets, and the measured stream flow, the bounds for the HOMER and measured parameter and the comparison between them are shown in Fig. 1a,b,c. From these graphs, it is seen that the simulated data from HOMER fall within the bounds of the measured data (solar radiation, wind speed, and stream flow).

2. METHODOLOGY

Technological options explored were solar-PV, wind turbine, hydro turbine, and diesel generator. Efforts were made to simulate and analyze a large number of alternative system configurations. Thereafter optimization analyses were carried out to arrive at the best possible sizing configurations. For this task a tool called HOMER is used.

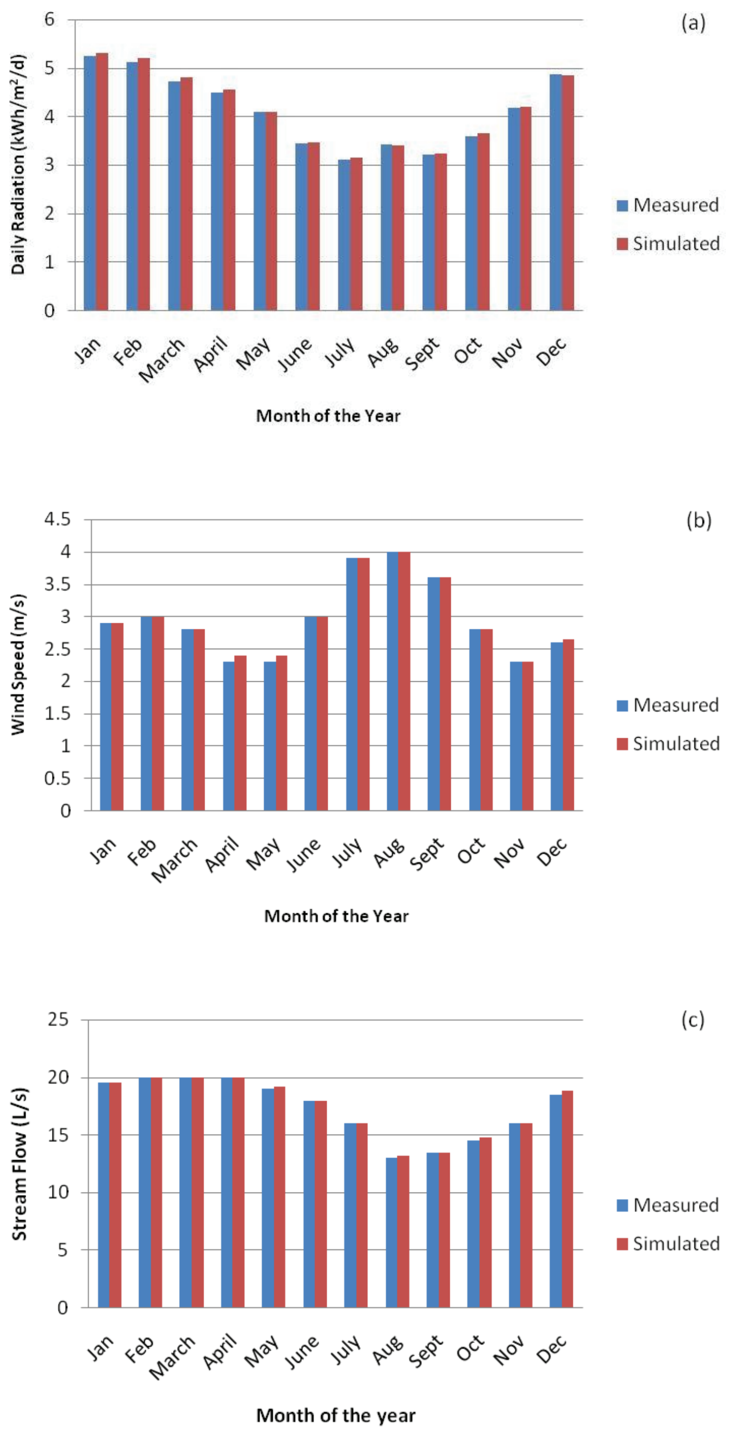


FIG. 1: Calibrated solar radiation (a), wind speed (b), and stream flow (c)

The characteristics and capabilities of HOMER have been explained in detail above and have previously been used (Khan and Iqbal, 2005; Nfah et al., 2008; Rehman et al., 2007; Georgilakis, 2005; Shaahid et al., 2004; Lilienthal et al., 2004).

3. LOAD

Hourly load demand (macro base station site perspective) has been given as an input in HOMER and then it generates daily and monthly load profile for a year. It has been found that this site consumes energy around 254 Wh/day with a peak demand of nearly 10.67 kW, as shown in Fig. 2. Table 1 shows the hourly load demand for radio base station, as well as climate and auxiliary equipment.

3.1 Renewable Resources

The data for solar and wind resources were obtained from the NASA Surface Meteorology and Solar Energy web site (NASA, 2010), while the hydro resources were measured at the site. The specific geographical location of Nembe (Bayelsa State) are of $4^{o}917'$ N latitude and $6^{o}25'$ E longitude with annual average solar (clearness index and daily radiation) of 4.12 kW·h/m^2/d, annual average wind of 3.0 m/s, and annual average stream flow of 17.3 L/s. Figure 3a,b,c shows the solar, wind, and hydro resource profile of this area.

3.2 Hybrid System Components

3.2.1 Photovoltaic module

The PV modules used were a polycrystalline photovoltaic module with 140-W maximum power connected in a series and parallel configuration. The PV module has a derating factor of 80% and a ground reflectance of 20%. The photovoltaic system was considered to have no tracking system for the purpose of the study in order to determine the worst case resource. The details of solar properties are shown in Table 2.

3.2.2 Wind turbine model

The number of Generic 10 kW wind turbines considered for simulation is one. The details of wind parameters have been given in Table 3.

3.2.3 Micro-hydro turbine model

The micro-hydro model in the HOMER software is not designed for a particular water resource. Certain assumptions are taken about the available head, design flow rate, maximum and minimum flow ratio, and efficiency to the turbines. The lifetime of the micro-hydro model in simulation is taken as 25 years. The details of micro-hydro parameters are given in Table 4.

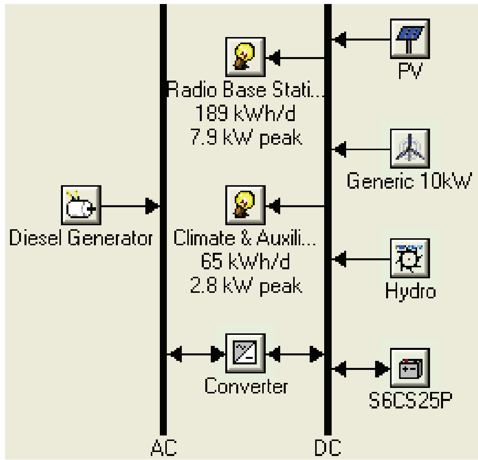


FIG. 2: The proposed energy system for GSM base station site

TABLE 1: Load inputs for radio base station as well as climate and auxiliary equipment

Hour	Radio base station baseline data load (kW)	Climate and auxiliary equipment baseline data load (kW)
00:00-01:00	7.860	2.790
01:00-02:00	7.860	2.790
02:00-03:00	7.860	2.790
03:00-04:00	7.860	2.790
04:00-05:00	7.860	2.790
05:00-06:00	7.860	2.790
06:00-07:00	7.860	2.790
07:00-08:00	7.860	2.590
08:00-09:00	7.860	2.590
09:00-10:00	7.860	2.590
10:00-11:00	7.860	2.590
11:00-12:00	7.860	2.590
12:00-13:00	7.860	2.590
13:00-14:00	7.860	2.590
14:00-15:00	7.860	2.590
15:00-16:00	7.860	2.590
16:00-17:00	7.860	2.590
17:00-18:00	7.860	2.790
18:00-19:00	7.860	2.790
19:00-20:00	7.860	2.790
20:00-21:00	7.860	2.790
21:00-22:00	7.860	2.790
22:00-23:00	7.860	2.790
23:00-00:00	7.860	2.790
Average (kWh/d)	189	65.0

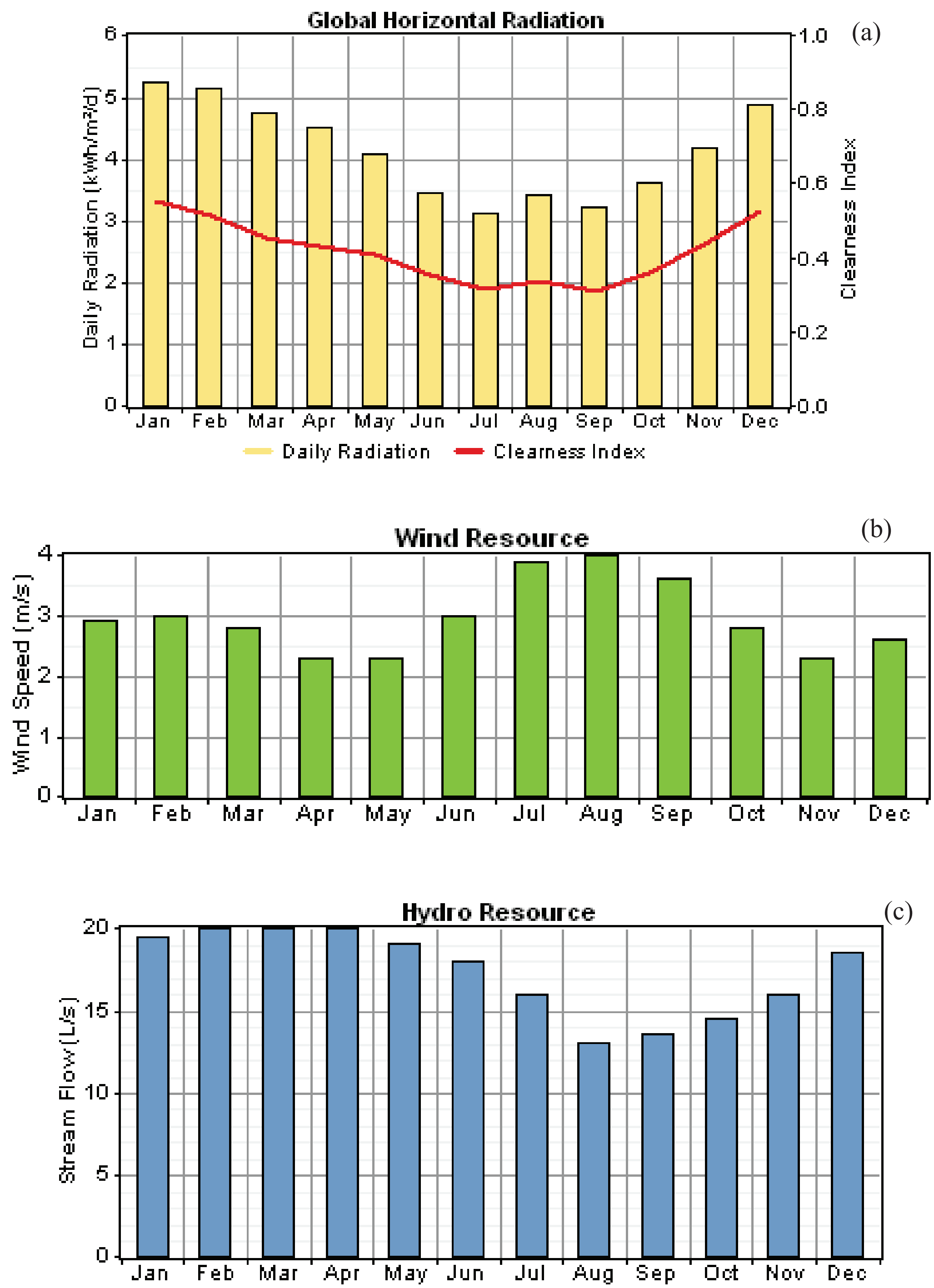


FIG. 3: HOMER output graphic for Nembe for: a) solar (clearness index and daily radiation) profile; b) wind speed profile, and c) stream flow profile

TABLE 2: Details of solar properties

Solar module type: Solar World SW 140 poly R6A	
Size	0.140 kW
Sizes considered	0, 10.7 kW
Lifetime	20 yr
PV control	
Derating factor	90%
Tracking system	No tracking
Slope	40^o
Azimuth	0^o
Ground reflectance	20%

TABLE 3: Details of the wind parameters

Wind turbine type: Generic 10 kW	
Nominal power	10 kW
Quantities to consider	0, 1
Lifetime	20 yr
Wind turbine control	
Weibull k	2.00
Autocorrelation factor	0.850
Anemometer height	10 m
Altitude	0 m
Wind shear profile	Logarithmic
Surface roughness length	0.01 m
Hub height	25 m

TABLE 4: Details of micro-hydro parameters

Hydro turbine	
Nominal power	10.3 kW
Quantities to consider	0, 1
Lifetime	25 yr
Hydro turbine control	
Available head	56 m
Design flow rate	25 L/s
Minimum flow ratio	25%
Maximum flow ratio	100%
Turbine efficiency	75%
Pipe head loss	10.5%

3.2.4 Diesel generator model

The diesel generator technology is widespread and the siting of a power plant is relatively easy. The price of a diesel fuel is ₦165 ($1.0/L) based on the federal government approved pump price in Nigeria as of July, 2012. This price varies considerably based on the region, transportation costs, and the current market price. The details of the diesel generator model parameters aregiven in Table 5. The diesel back-up system is operated at times when the output from wind, hydro, and solar systems fails to satisfy the load and when the battery storage is depleted.

3.2.5 Storage battery

The variations of solar and wind energy generation do not match the time distribution of the demand. The storage battery chosen was Surrette 6CS25P. These batteries were configured such that each string consisted of two batteries, with a total of forty-eight strings. This means that the total batteries used were 96 units. From the datasheet given by the HOMER software, the minimum state of charge of a battery is 40%. Its round trip efficiency is 80%. Batteries are considered as a major cost factor in small-scale stand-alone power systems. The details of storage battery model parameters are given in Table 6.

TABLE 5: Details of diesel generator model parameters

AC generator type: 20 kVA diesel generator	
Size considered	16 kW
Quantity considered	1
Lifetime	20,000 h
Diesel generator control	
Minimum load ratio	30%
Heat recovery ratio	0%
Fuel used	Diesel
Fuel curve intercept	0.08 L/h/kW
Fuel curve slope	0.25 L/h/kW
Fuel: diesel	
Price	₦165 ($1.0/L)
Lower heating value	43.2 MJ/kg
Density	820 kg/m^3
Carbon content	88.0%
Sulphur content	0.330%

TABLE 6: Surrette 6CS25P battery properties

Battery type: Surrette 6CS25P	
Quantities to consider	96, 192
Lifetime throughput	9645 kWh
Battery: Surrette 6CS25P control	
Nominal capacity	1156 Ah
Voltage	6 V

3.2.6 Converter

Here a converter is used which can work as both an inverter and rectifier depending on the direction of the flow of power. In the present case, the size of the converter ranges from 0 to 50 kW for simulation purposes. The details of converter parameters are given in Table 7.

3.3 Hybrid System Control Parameters and Operating Strategies

Two types of dispatch strategies are available in HOMER. In the ‘load following’ strategy, the generators supply just enough power to service the loads whenever there is insufficient renewable energy contribution. In the "cycle charging" strategy, a generator (if present) runs at full power and excess electricity is used for charging the batteries. In the present work, the dispatch strategy is "cycle charging" and an 80% state of charge was set for this strategy.

When the renewable sources produce less energy than demanded (wind speed, water flow, and solar radiation are low), the deficit power should be supplied by the battery bank. When the state of charge of the battery bank reaches its minimal level (40%), the diesel generator starts to function. The surplus of energy produced by the

TABLE 7: Details of converter parameters

Converter	
Sizes to consider	25, 50 kW
Lifetime	20 yr
Converter control	
Inverter efficiency	85%
Inverter can parallel with AC generator	Yes
Rectifier relative capacity	100%
Rectifier efficiency	85%

TABLE 8: System control inputs

Simulation	
Simulation time step (min)	60
Dispatch strategy	
Allow systems with multiple generators	Yes
Allow multiple generators to operate simultaneously	Yes
Allow systems with generator capacity less than peak load	Yes
Generator control	
Check load following	No
Check cycle charging	Yes
Setpoint state of charge	80%

diesel generator and the renewable energy sources (variation of the climatic data) is stored in the battery bank.

The storage batteries is a key factor in a hybrid system of renewable energy, it allows one to minimize the number of starting/stopping cycles of the diesel generator, which reduces the problem of its premature wear, and to satisfy the request of the load in spite of renewable sources fluctuations. The system control inputs used are shown in Table 8.

3.4 Economics and Constraints

The project lifetime is estimated at 25 years. The annual interest rate is fixed at 6%. There is no capacity shortage for the system and operating reserve is 10% of hourly load.

The operating reserve as a percentage of hourly load was 10%. Meanwhile, the operating reserve as a percentage of solar power output and wind power output was 25% and 50%, respectively. The operating reserve is the safety margin that helps one to ensure the reliability of the supply despite variability in electric load, solar power supply, and in the wind power supply. The constraints inputs required by software are given in Table 9.

3.5 System Economics

The capital costs for all system components including a PV module, wind turbine, hydro turbine, diesel generator, inverter, battery, and the balance of system prices are based on quotes from PV system suppliers in Nigeria (Solarshopnigeria, 2012). These costs are estimates based on a limited number of internet enquiries and prices. They are likely to vary for the actual system quotes due to many market factors. The figures used in the analysis are therefore only indicative.

TABLE 9: Constraints inputs

Maximum annual capacity shortage	0%
Minimum renewable fraction	0%
Operating reserve as percentage of hourly load	10%
Operating reserve as percentage of annual peak load	0%
Operating reserve as percentage of solar power output	25%
Operating reserve as percentage of wind power output	50%

The replacement costs of equipment are estimated to be 20–30% lower than the initial costs, but because decommissioning and installation costs need to be added, it was assumed that they are the same as the initial costs.

The PV array, wind turbine, hydro turbine, diesel generator, inverter and battery maintenance costs are estimates based on approximate time required and estimated wages for this sort of work in a remote area of Nembe. This optimal system has been obtained with particular capital, replacement, operation, and maintenance costs for each component. HOMER bases its optimization process on costs calculations, so it is obvious that changes in these costs would generate different results and therefore a different optimal system. However, these costs seem quite logical and are in accordance with the prices of the market. All initial costs including installation and commissioning, replacement costs and operating and maintenance costs at a site are summarized in Table 10. All costs presented are in Nigerian currency, Naira (₦).

TABLE 10: Summary of initial system costs, replacement costs, as well as operating and maintenance costs

Item	Initial system costs	Replacement costs	Operating & maintenance costs
PV modules	₦ 324/W ($2)	₦ 291.6/W ($1.8)	₦ 16,200/kW/yr ($100)
Generic 10 kW wind turbine	₦ 4,374,000 ($27,000)	₦ 3,402,000 ($21,000)	₦ 48,600 ($300)
Hydro turbine	₦ 8,100,000 ($50,000)	₦ 6,480,000 ($40,000)	₦ 162,000 ($1000)
20 kVA diesel generator	₦ 2,106,000 ($13,000)	₦ 2,106,000 ($13,000)	₦ 405/h ($2.5)
Surrete 6CS25P battery	₦ 185,490 ($1145)	₦ 162,000 ($1000)	₦ 16,200 ($100)
Converter	₦ 324/W ($2)	₦ 324/W ($2)	₦ 16,200/kW/yr ($100)
Labor	₦ 6,480,000 ($40,000)	N/A	N/A

NA: Not Applicable

The input parameters (the technical and economic data of all the components of the hybrid system) and system constraints, as described above, were used to simulate hybrid systems and perform optimization analysis. HOMER determines the optimal system by choosing suitable system components (system configuration) depending on the parameters like solar radiation, water flowrate, wind speed, diesel price, and maximum annual capacity shortage. The feasibility of a configuration is based on the NPC and hourly performance. The results are presented in graphical form.

4. METHOD

Based on the energy consumption of a mobile base station and the availability of renewable energy sources, it was decided to implement an innovative stand-alone hybrid energy system (Celik, 2002; Nema et al., 2010) combining solar photo-voltaic panels, small wind turbine-generator, pico-hydro turbine-generator, diesel generator, battery storage, and bidirectional converter. The system architecture employed in the hybrid system is DC coupled where the renewable energy sources and the conventional diesel generators all feed into the DC side of the network as depicted in Fig. 2.

The total net present cost (NPC) for economic and environmental evaluation of hybrid (solar, wind & hydro) + DG, hybrid (solar & hydro) + DG, hybrid (wind & hydro) + DG, hydro only + DG, hybrid (solar & wind) + DG, solar only + DG, wind only + DG, and DG system have been developed and simulated using the model which results in eight different topologies:

- wind–diesel system;
- solar–diesel system;
- hydro–diesel system;
- PV/hydro–diesel system;
- PV/wind–diesel system;
- hydro/wind–diesel system;
- wind/hydro–diesel system;
- PV/wind/hydro–diesel system.

From the outlined design above, the cost-effectiveness of adding renewable energy components to the existing energy (diesel) were compared:

1. The standard diesel generator configuration with renewable hybrids (wind & solar), (wind & hydro), (solar & hydro), and (wind/solar/hydro).
2. The standard diesel generator configuration with pure wind, pure hydro, and pure solar models.

In the optimization process, the proposed system was simulated with many different system configurations in search of the one that satisfies the technical constraints at the lowest life-cycle cost.

5. RESULTS OF THE ANALYSIS

5.1 Simulation Results

This is to carry out eight energy component configurations for power supply to the GSM base station site located in Nembe (Bayelsa) for the project lifetime of 25 years. The simulation results are collated and classified according to these three major factors, namely: the total economic costs (NPC in ₦), the environmental impact (pollutant emissions in tons of CO_2), and the electric energy (kWh) generated by each hybrid system type. The results are presented below in Tables 11–13, respectively. More detailed analysis of these results highlights the following major findings of this study: 1) the superiority of the PV/wind/hydro/diesel hybrid system over any of the other seven configurations; 2) the more renewable energy components in a hybrid system, the higher the initial capital cost, but the lower the total net present cost (NPC) in the long run; 3) similarly, the more renewable energy components in a hybrid system, the lower the environmental impact by the hybrid system type; 4) the percentage of energy generated by the hydro component of the hybrid systems is consistently higher than that of each of the other two components (solar, wind) and that of their combination (PV + W).

TABLE 11: Economic costs

Hybrid system type	PV/W/H + DG	PV/H + DG	H/W + DG	H + DG	PV/W + DG	PV + DG	W + DG	DG only
NPC in billions of Naira (₦) [10^{-9}]	**0.62**	0.88	1.37	1.63	2.78	3.03	3.46	*3.69*

Note: The figures in the table are classified from the least cost (in bold) to the highest cost (in italic) per hybrid type. For instance, PV/W/H + DG hybrid system type has the least NPC (0.62), while DG only has the highest NPC (3.69) as shown in the table.

TABLE 12: Environmental impact

Hybrid system type	PV/W/H + DG	PV/H + DG	H/W + DG	H + DG	PV/W + DG	PV + DG	W + DG	DG only
Pollutant emissions in tons of CO_2 (10^{-3})	**14.63**	21.99	35.33	42.64	73.49	80.49	92.24	*98.50*

Note: Similarly, the figures in this table are classified from the least environmental pollution (in bold) to the highest environmental pollution (in italic) per hybrid type. For instance, PV/W/H + DG hybrid system type has the least environmental pollution (14.63), while DG only has the highest environmental pollution (98.50) as shown in the table.

TABLE 13: Percentage of energy generated by the renewable energy hybrid systems components [contributions made by the hybrid system components are demarcated by forward slashes (/)]

Hybrid system type	PV/W/H + DG	PV/H + DG	H/W + DG	H + DG	PV/W + DG	PV + DG	W + DG	DG only
Percentage of energy generated	**20/7/56/17**	20/55/25	54/7/39	53/47	18/6/76	17/83	*6/94*	100

Note: The same applies to the figures in this table. They are arranged from the highest energy generated by the renewable energy (in bold) to the least energy generated by the renewable energy (in italic). For instance, PV/W/H + DG hybrid system type has the highest energy generated by the renewable energy (20/7/56/17), while W + DG has the least energy generated by the renewable energy (6/94), as shown in the table.

As stated above, Tables 11–13 show the classification of the simulation results according to: i) the total net present economic costs (NPC in Naira ₦) (Table 11), ii) the environmental impact (pollutant emissions in kg of CO_2) (Table 12), and iii) the electric energy (kWh) generated by each hybrid system type (Table 13).

These results are further illustrated with line graphs in Figs. 4 (NPC), 5 (environmental impact), and 6 (energy generated).

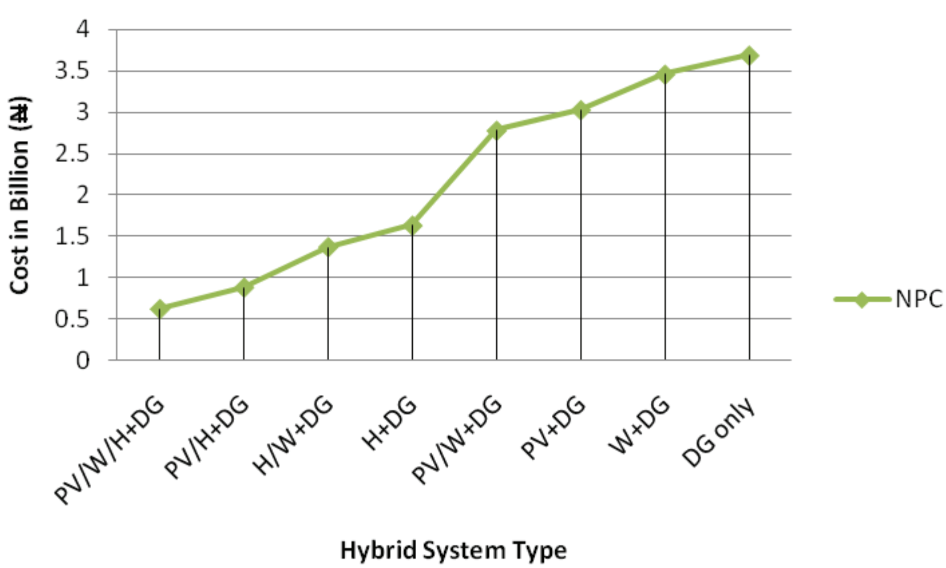


FIG. 4: Economic costs [NPC in billions of Naira (₦)]

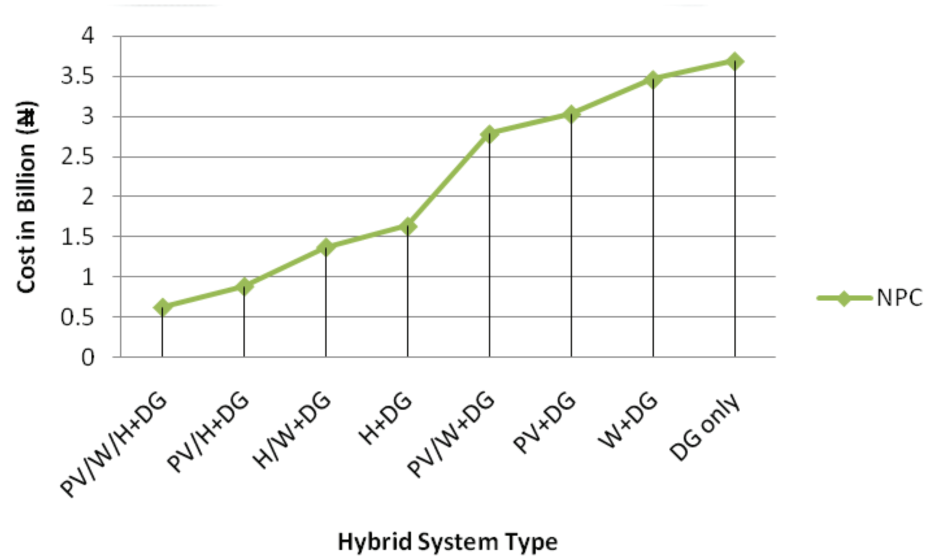


FIG. 5: Environmental impact (pollutant emissions in tons of CO_2)

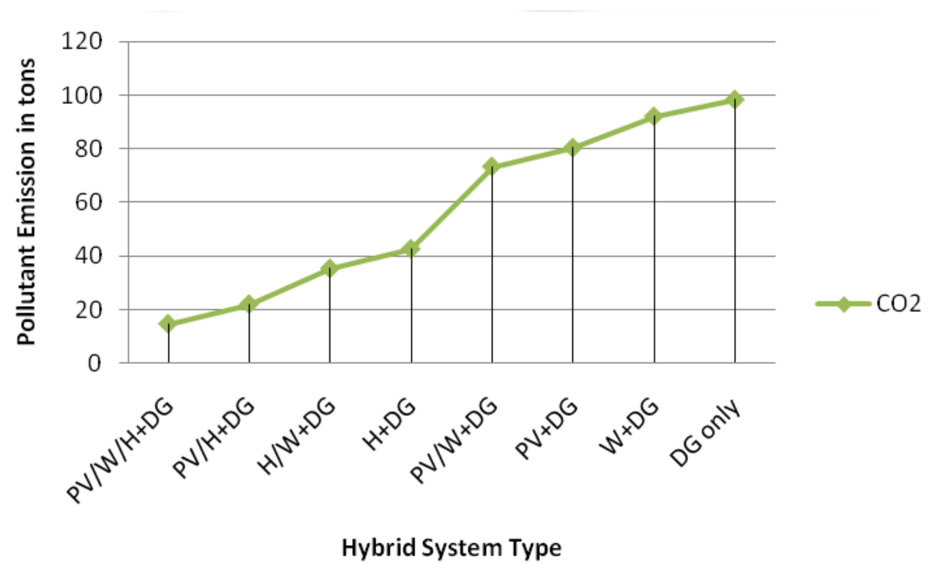


FIG. 6: Percentage energy generated by renewable energy components per each hybrid type

5.2 Analysis of the Results

Both Tables 11 and 12 and Figs. 4–6 described above reflect the eight hybrid energy types designed in this study. This design was intended to enable us investigate the potential of local applications of these various (eight) renewable energy hybrid configurations in the telecommunications industry. The detailed analysis of the results of this investigation is presented below.

5.3 Optimal Ranking of the Hybrid System Types

As stated above, a hybrid energy system may be considered as an optimal solution for any particular BTS site if it meets the required loads of the site at minimum total net present economic costs (NPC) and minimum adverse environmental impact. Thus, in one of the simulations, HOMER generated Table 14 illustrating this statement; where the hybrid system types are ranked both: 1) in a descending order of the highest percentage of energy generated (see Table 15 and Fig. 6), and 2) in an ascending order of (a) the least economic cost (NPC) (see Fig. 4), and (b) the least environmental impact (see Fig. 5), by the hybrid system types.

In other words, Table 14 tends to illustrate the superiority of the PV/wind/hydro/diesel hybrid system over any of the other seven configurations. That is, the solar/wind/hydro/DG hybrid energy system type could be considered as the most appropriate (optimal) hybrid renewable energy solution option for powering the BTS location sites studied. This option is followed by i) solar/hydro/DG hybrid energy system, ii) wind/hydro/DG hybrid energy system, iii) hydro/DG hybrid energy system, iv) so-

TABLE 14: Optimal ranking of the hybrid system types (as generated by HOMER)

S/N	HOMER optimization results
1	Hybrid (solar, wind & hydro) + DG
2	Hybrid (solar & hydro) + DG
3	Hybrid (wind & hydro) + DG
4	Hydro only + DG
5	Hybrid (solar & wind) + DG
6	Solar only + DG
7	Wind only + DG
8	DG

TABLE 15: Percentage of energy generated by renewable energy components of each hybrid system

Hybrid system type	PV/W/H + DG	PV/H + DG	H/W + DG	H + DG	PV/W + DG	PV + DG	W + DG
Percentage of energy generated	83	75	61	53	24	17	6

lar/wind/DG hybrid energy system, v) solar/DG hybrid energy system, vi) wind/DG hybrid energy system, and vii) DG alone, in that order.

5.4 Energy Rating of the Hybrid Systems and Components

As illustrated in Table 15 and Fig. 6, the percentage energy generated by the renewable energy components (solar, wind, hydro) of each hybrid system type depends on the number and combination of these components; the more the number, the higher the percentage. The latter (generated energy) also depends on the combination, with PV/W/H and PV/H combinations generating higher percentages than the other two combinations (PV/W, H/W), and this is by far higher than that of the individual components alone (except diesel). These results agree with the results of many other works (Deepak et al., 2011; Kellogg et al., 1998; Ashok, 2007). For example, in (Deepar et al., 2011), the 3 type renewable energy combination (PV/W/H) generate higher percentage of energy than 2 type renewable energy combinations (PV/H, H/W, and PV/W) and far higher than that of the individual renewable components alone (PV, W, and H).

5.5 Economic Rating of the Hybrid System Types and Components

The second most important criterion for assessing an optimal solution (renewable energy hybrid system) for any particular BTS site is the economic cost of the system. The cost ratings here are discussed in terms of two major cost components: 1) the initial capital cost (ICC), and 2) the total net present cost (NPC), the former being completely exclusive (i.e., ICC excludes other costs), while the latter is inclusive (i.e., includes the present value of all the costs that it incurs over its lifetime).

5.6 Initial Capital Costs (ICC)

The initial capital cost of a component is the total installed cost of that component at the beginning of the project. The results illustrated in Fig. 7 shows that the more the renewable energy components in a hybrid system, the higher the initial capital cost (ICC). On the other hand, a diesel only system has a lower initial capital cost (ICC) as shown in Fig. 7, but a higher (NPC) as illustrated in Fig. 4.

5.7 Total Net Present Cost (NPC)

The total net present cost (NPC) of a system has been described as the present value of all the costs that it incurs over its lifetime, minus the present value of all the revenue that it earns over its lifetime. Costs include capital costs, replacement costs, operation and maintenance costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Revenues include salvage value and grid sales revenue. However, the analysis presented here considers neither the costs of buying power from the grid nor any revenues (either salvage value or grid sales revenue), since the focus

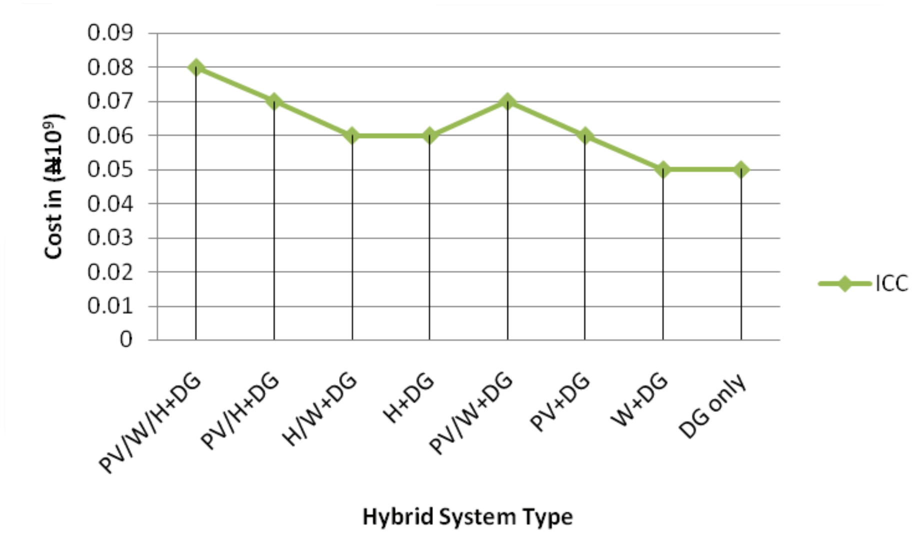
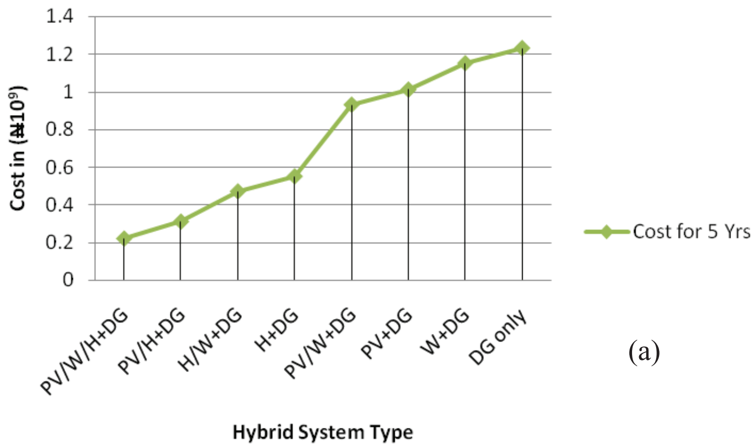


FIG. 7: Initial capital costs (ICC)

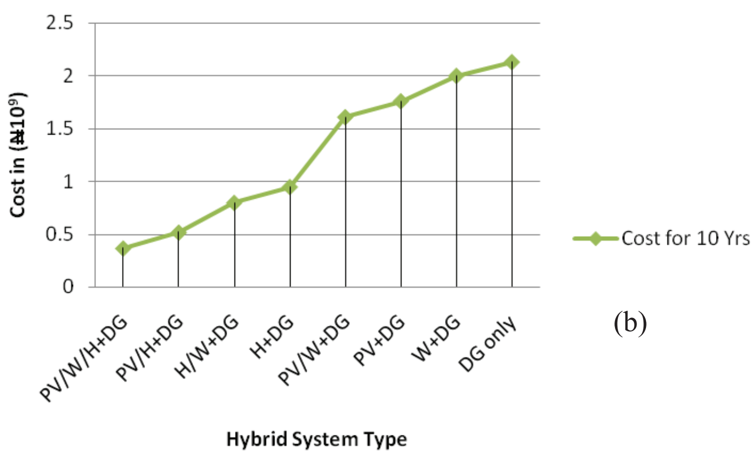
of this study is on BTS site in rural area without grid connections. To appreciate the significance of the life cycle cost (NPC) in the choice of optimal combination of renewable energy components and the ranking of optimized renewable energy hybrid systems (as illustrated in Table 15) for a typical rural BTS site, further simulation runs were conducted at 5 years intervals (for a period of 25 years) for each of the 8 design configurations [eight renewable energy component combinations (hybrid types)]. The results of these simulations are illustrated in Figs. 8a–e and 9. The following general observations were made from these results:

1) The total net present cost (NPC) increases with the decrease of renewable energy components in the hybrid systems (from 3 to 1) (see Fig. 8a,b). This observation agrees with the work of Bagul et al. (1996). According to their paper, single source renewable energy usually leads to component over-sizing, which increases the operating and life cycle cost. However, there are two exceptions to the above observation, and these are: (a) type 4 (hydro only + DG) and (b) type 5 (PV + W + DG) hybrid systems, respectively, where the NPC of the former (a) is significantly lower than that of the latter (b), and this difference is consistent in all the five interval periods investigated (see Figs. 8a–10e). There are two possible explanations to these two exceptions:

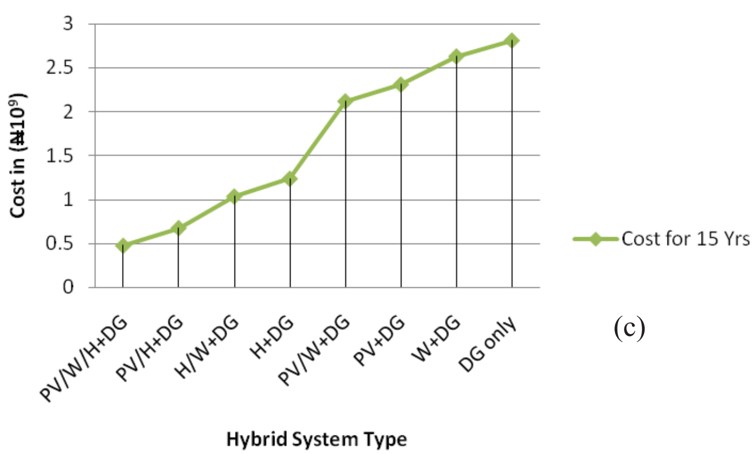
   i) the highest percentage of energy generated by type 5 (PV/W + DG) hybrid system is by far lower (24%) than that (53%) by type 4 (H + DG) hybrid system (see Table 16). This means more operational hours (5286 h. vs. 3067 h) and more fuel consumption (27,906 vs. 16,194) by the diesel generator (DG)


1.4
1.2
1
0.8
0.6
0.4
0.2
0
Cost in (₦10^9)
Cost for 5 Yrs
PV/W/H+DG
PV/H+DG
H/W+DG
H+DG
PV/W+DG
PV+DG
W+DG
DG only
Hybrid System Type

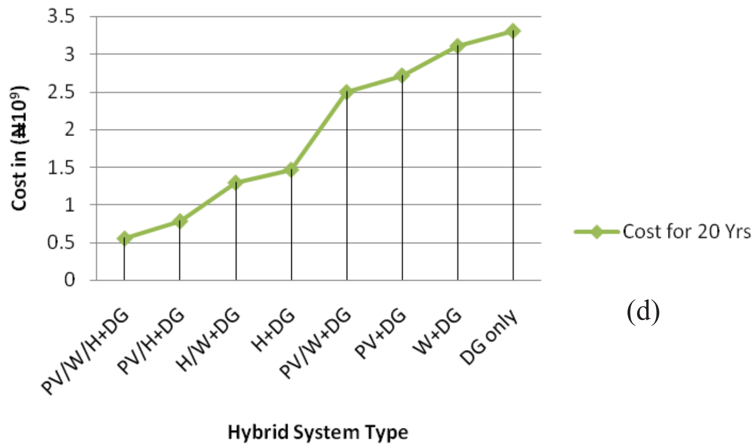
(a)


2.5
2
1.5
1
0.5
0
Cost in (₦10^9)
Cost for 10 Yrs
PV/W/H+DG
PV/H+DG
H/W+DG
H+DG
PV/W+DG
PV+DG
W+DG
DG only
Hybrid System Type

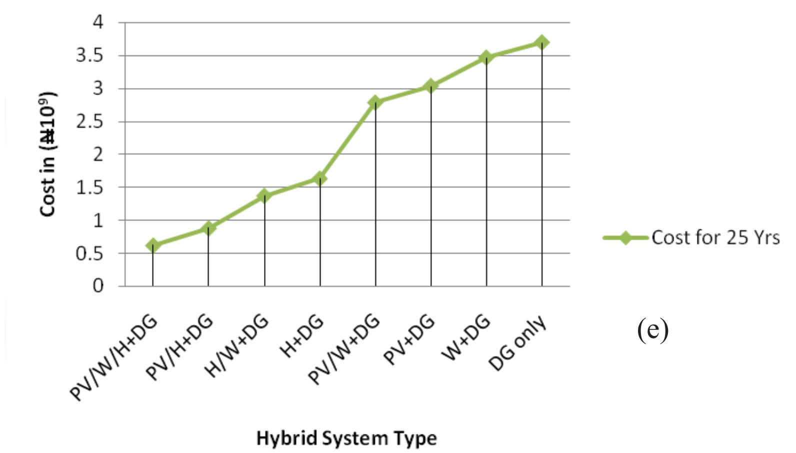
(b)


3
2.5
2
1.5
1
0.5
0
Cost in (₦10^9)
Cost for 15 Yrs
PV/W/H+DG
PV/H+DG
H/W+DG
H+DG
PV/W+DG
PV+DG
W+DG
DG only
Hybrid System Type

(c)



(d)



(e)

FIG. 8: Economic costs in: a) 5, b) 10, c) 15, d) 20, e) 25 years

(as shown in Table 16 and Fig. 10), and consequently higher NPC, in type 5 (PV/W + DG) than in type 4 (H + DG) hybrid systems, respectively. This result is supported by Laidi et al. (2012) with the comparison of operational hour and fuel consumption of diesel with renewable energy and without renewable energy. Their results are as follows: PV/wind/diesel (4220; 3068), wind/diesel (3819; 2798), PV/diesel (8116; 5465), and diesel only (8618; 5939);

ii) components replacement costs for type 5 (PV/W + DG) hybrid system could apparently be higher than that of type 4 (H only + DG) system. These observations are supported by Deepak et al. (2011) in which the replacement of a PV/W + DG hybrid system cost about $17,946, whereas H only + DG cost $9977.

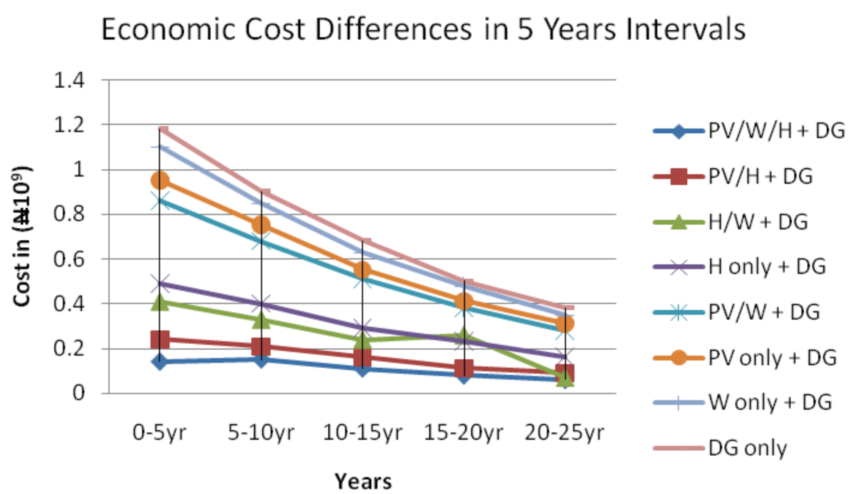


FIG. 9: Economic cost differences in 5 yr intervals

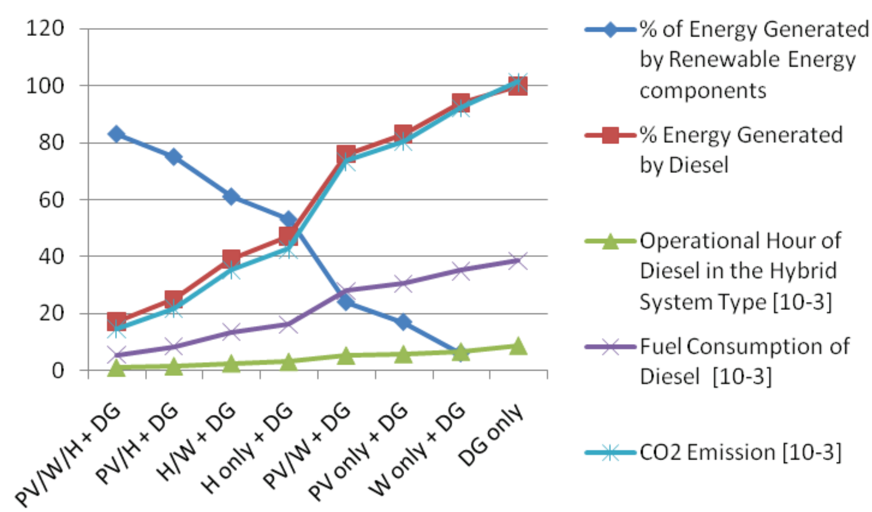


FIG. 10: Environmental impact analysis

2) As shown in Fig. 9, the differences in costs (NPC) between the intervals, and also the NPC decreases as the lifetime of the hybrid systems increases, and these differences vary significantly from one hybrid system type to another; with those of (PV/H/W + DG) and (H only + DG) hybrid types being lower than those of (DG alone) and (W only + DG) hybrid types. This observation highlights the differences in the total net present costs (NPC) among the various hybrid system types, as observed above. It also makes a lot of difference

TABLE 16: Environmental impact analysis

Hybrid system type	Percentage of energy generated by renewable energy components	Percentage of energy generated by diesel	Operational hour of diesel in the hybrid system type (10^{-3})	Fuel consumption of diesel (10^{-3})	CO_2 emission (10^{-3})
PV/W/H + DG	83	17	1.06	5.56	14.63
PV/H + DG	75	25	1.58	8.35	21.99
H/W + DG	61	39	2.54	13.42	35.33
H only + DG	53	47	3.07	16.19	42.64
PV/W + DG	24	76	5.29	27.91	73.49
PV only + DG	17	83	5.79	30.57	80.49
W only + DG	6	94	6.64	35.03	92.24
DG only		100	7.09	37.41	98.50

not only in the choice of the renewable energy components, but also in their combinations and sizing, for particular BTS sites.

3) Judging from the two cost components, the initial capital cost (ICC) and the total net present costs (NPC), as well as the amount (%) of energy generated, the hydro system appears to be the most cost effective renewable energy component that could be deployed for BTS sites in the rural areas of Nigeria. This observation agrees with many other works in the literature (Paish, 2002; Kamaruzzaman et al., 2008). For example, Paish (2002) and Kamaruzzaman et al. (2008) pointed out in their papers that the price of the hydro turbine is much less compared to other renewables (such as wind turbine and PV panels).

5.8 Environmental Impact Rating of the Hybrid System Types and Components

One of the major attractions of renewable energy systems is their environmental friendliness, and this informs their preferences in hybrid systems for various applications. In this study, for instance, one of the objectives is to investigate alternative energy solutions that are not only feasible, but also optimal for powering BTS sites in nongrid-serviced rural areas in Nigeria. As stated above, a hybrid energy system is considered as an optimal solution for any particular BTS site if it meets the required loads of the site not only at minimum economic costs (NPC), but also at minimum adverse environmental impact, more specifically, if there is minimum CO_2 emission to the environment by the diesel generator component of the hybrid system. As illustrated in Table 16 and Fig. 10, this condition obtains only when any combination of the renewable energy components (PV, H, W) in the hybrid system generates as much (maximum) energy as would reduce to a minimum: i) the operational hour, ii) the fuel consumption, and iii) the percentage energy generated by a diesel generator. It could be seen in both Table 16 and Fig. 10 that this is achieved only by the PV/H/W + DG hybrid configuration. It is also shown that, as the energy (%) generated by the other combinations (PV/H + DG, H/W + DG, H only + DG, PV/W + DG, PV only + DG and W only + DG] decreases, the CO_2 generated by the generator increases proportionally, so also is each of the other two related parameters, as mentioned above. In summary, it could therefore be stated that the more the number of the renewable energy components (in combination with a diesel generator (DG)) in any renewable energy hybrid system, the lower the CO_2 generated by the generator and hence the less (minimum) is the adverse environmental impact of the hybrid system, and consequently the optimum is the renewable energy solution at any given BTS site. However, the point (at H only + DG) where the energy generated by the combinations of the three renewable energy components (PV, H, W) and that generated by DG only intersect indicates a significant exception to the above phenomenon. This again points to the overriding superiority of the hydro system over the other components (PV and W) in any renewable energy hybrid configurations. Evidently, H generates more than twice the energy generated by either PV or W only, or a combination of the two, in all the hybrid types studied. These were supported by Kamaruzzaman et al. (2008) in which they show in their paper that the use of hydro turbine in the renewable energy setup is an important sizing determination. Their reason been that the turbine can operate 24 hours provide enough flowing water into the gathering chamber.

6. CONCLUSIONS

The significance of this study has been reflected by the results and this can be concluded as follows. The study has not only highlighted some of the basic concepts and attractions of renewable energy systems and their applications, it has also demonstrated that these systems and applications could also be deployed very effectively in Nigeria. Specifically, they can contribute significantly to the reduction of energy costs, believed to be the most costly items in the delivery of telecommunications services particularly to the rural off-grid communities of this country. Pollution reduction is another attraction of renewable energy applications in the telecommunications industry that has been highlighted and demonstrated in this study. Finally, the study has also provided useful information (such as component sizing tools, solar radiation, wind speed, water head and flow rate, climate conditions, geographical location, etc.) on the choice of systems as well as necessary parameters required to design suitable hybrid power systems (HPSs) to meet given loads of BTS sites in any geographical region of Nigeria. This information could not only lead to the development of (renewable) energy optimization maps of Nigeria, but also serve as useful tools for policy formulation on BTS sites by the Nigerian telecommunications regulation authority (the NCC). One such policy could be a requirement for green energy prefeasibility studies of any intended location for BTS sites, particularly in the rural off-grid areas. Such green policies are already in existence in many countries of the developed world, particularly in US where it is a prerequisite for the approval of any proposal for a physical project. This study has also demonstrated that the telecommunications industry is one of the areas where renewable energy systems could be deployed to maximum national economic and environmental benefits, as obtains in many developed and developing countries, including a number of countries in Africa.

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