Energy Optimization at GSM Base Station Sites Located in Rural Areas

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ABSTRACT

This paper explores the best energy options by which the choice of the most energy optimized solution for a given GSM Base Station Site and location in any rural area in Nigeria can be made. The patterns of load consumption by mobile base stations at various geographical locations in rural areas are studied and suitably modeled for optimization using HOMER software. Simulation results show the optimized energy options to be superior to conventional solutions whereby diesel generators are currently used to power GSM Base Station Sites around Nigeria. Total Net Present Cost (NPC) and total impact on the environment are used as indices for measuring the optimization level of each energy solution. The solution with the highest optimization value is considered to be the best energy option for that Base Station Site.

Keywords: *Diesel Generator, Economic Cost, Energy Optimization, Energy Simulation, Environmental Cost, Mathematical Model, Mobile Base Station, Renewable Energy*

INTRODUCTION

In Nigeria, over 80,000 villages remain un-electrified (Okoro & Chikuni, 2007). The energy situation in many parts of Nigeria poses a challenge to sustainable deployment of GSM base station sites. Like several other developing countries, Nigeria is characterized by severe energy deficit. In most of the remote and non-electrified sites, extension of utility grid lines experiences a number of problems, such as high capital investment, high lead time, low load factor, poor voltage regulation and frequent power supply interruptions (Miguel, 2008). The costs to install and service the distribution lines are considerably high for remote areas. This poor power quality substantially increases the capex and opex of telecom installations and also leads to unsatisfactory quality of services (Miguel, 2008).

One popular solution to this problem is the use of diesel generators. Unfortunately, these generators have been found to be very expensive and environmentally unfriendly. From environmental standpoint, diesel gensets exhaust harmful hydrocarbons into the atmosphere during their operation. Their operation and maintenance accounts for about 35 percent

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of the total cost of ownership (TCO) of base transceiver station (BTS) (Richard, 2007). These have made diesel generators a much less viable option for network operators in many developing countries of the world (Lipman, 1994; Schmid & Hoffman, 2004).

The irony of this situation is that Nigeria is endowed with very abundant renewable energy resources that remained unexplored and unexploited for alternative energy solutions for telecommunications particularly for the largely populated rural areas in the country. Nigeria lies along the Equator, with abundant sunshine all the year round. According to Bala, Ojosu, and Umar (2000), Nigeria is endowed with an annual average daily sunshine of 6.25 hours, ranging between about 3.5 hours at the coastal areas and 9.0 hours 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. Nigeria receives about $4.851x\ 10^{12}$ KWh of energy per day from the sun. This is equivalent to about 1.082 million tons of oil equivalent (mtoe) per day, and is about 4 thousand times the current daily crude oil production, and about 13 thousand times that of natural gas daily production based on energy unit. This huge energy resource from the sun is available for about 26% only of the day. Based on the land area of 924×10^3 km^2 for the country and an average of 5.535 $kWh/m^2/day$, Nigeria has an average of 1.804×10^{15} kWh of incident solar energy annually (Chendo, 2002).

There are lots of canals, several minor streams and rivulets that crisscross the entire Nigerian land mass, tributaries of main river Niger, Benue, as well as tiny waterfalls having potentials for setting up mini/micro hydropower units that can power GSM Base Station Site. These can be found mainly in coastal regions of the country. 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 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 the north-western winds in different parts 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 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. From meteorological centres in Nigeria and satellite-derived meteorology and solar energy parameters from National Aeronautics and Space Administration (NASA), the average daily wind speed across the country, at 50meter height above the earth, is within the range of 2.7m/s in the central western parts to 5.4 m/s in the North East.

There are now a number of energy conversion technologies, and applications that make renewable energy options either equal or better in price and services provided than the prevailing fossil-fuel technologies. For example, in a growing number of settings in industrialized nations, wind energy is now the least expensive option among all energy technologies—with the added benefit of being modular and quick to install and bring on-line (Mazza, 2000). Photovoltaic (solar) panels and wind turbine placed on a mast can help reduce energy costs, dramatically shave peak-power demands, produce a healthier living environment, and increase the overall energy supply.

There is therefore a great promise for alternative renewable energy for the telecommunications industry in Nigeria, if only the country could endeavour to explore and exploit these available resources. This study is part and perhaps the beginning of this endeavour. Its major goal is to explore best alternative renewable energy solutions to progressively increase the generation of renewable and clean energy so as to migrate network operators away from a dependence on fossil fuel energy.

AVAILABLE RENEWABLE ENERGY OPTIONS

The use of stand-alone wind electricity generation systems, stand-alone solar electricity generation systems, or stand-alone hydro electricity generation systems, is limited to remote areas as wind, solar or hydro resource is site dependent and depends on the season. Thus, stand-alone PV, stand-alone wind or stand-alone hydro energy systems do not produce usable energy for a considerable length of time during the year. A PV-based hybrid system (using wind and/or hydro and/or diesel generator) is an option to address this barrier and supply electricity to remote areas that are far from the grid (Elhadidy, 2002; Protogeropoulos, Brinkworth, & Marshall, 1997; Fortunato, Mummolo, & Cavallera, 1997; Raja & Abro, 1994; Lipman, 1994; Lundsager & Bindner, 1994; Woodell & Schupp, 1996). As the wind does not blow all the time nor does the sun shine all the time, solar and wind power alone are poor power sources. 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. 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, Pan, & Xiang, 2005). This makes the diesel 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.

One of the most promising applications of renewable energy technology in remote areas is the implementation of hybrid energy systems, where the cost of grid extension is prohibitive and the price for fuel increases drastically with the remoteness of the location (Wichert, 1997). A hybrid powered system can be described as an electricity production system which supply consists of a combination of two or more types of electricity generating sources (e.g., solar photovoltaic panels, wind turbine generators, Pico-hydro plants, and fuel gensets). Hybrid systems usually also include an energy storage.

Numerous hybrid energy systems have been installed in many countries over the last three decades, resulting in the development of systems that can compete with conventional fossil fuel based remote area power supplies in many applications. Hybrid energy systems are now becoming an integral part of the energy planning process to supply electricity to previously un-electrified remote areas and island communities in countries like India (White, 1996), Thailand (Kruangpradit & Tayati, 1996), Spain (Vallve & Serrasolses,1994), Greece (Manolakos, Papadakis, Papantonis, & Kyritsis, 2004), Italy (Scrivani, 2005) South Africa (Cowan, 1994; Hopkins, 1992), or Australia (Williams, 1994). In remote power applications, it is obviously very attractive to realise seasonal energy storage and to install a Hybrid energy system (PV/wind, PV/hydro, wind/hydro, or PV/wind/hydro). Excess energy is stored in the battery. The Battery function as an emergency, if the Hybrid system fails.

Renewable technologies are designed to run on a virtually inexhaustible or replenishable supply of natural "fuels." By definition, it is a strategy for sustainable growth, since operation of the facilities does not deplete the earth's finite resources. In reality, alternative energy means anything other than deriving energy via fossil fuel combustion (Motorola Reach, 2007). The introduction of renewable energy-based technologies to replace old systems is seen as playing an important role in reducing unsustainable fossil fuels consumption, and in addition greatly improves local environmental and health conditions. Renewable energy facilities enhance the value of the overall resource base of a country by using the country's indigenous resources for electricity generation to power base stations.

The choice of renewable power options is determined by the region in which the facility is located. Reliability, financial and environmental costs are often the deciding factors when choosing an alternative power system for GSM Base station. If we say that alternative energy comprises everything that is not based on fossil fuel consumption, the number of optional resources is impressive. There are, no doubt, many alternative energy sources not included here, either because they are not yet at anything beyond a theoretical stage or simply because no one has thought of using them to power base stations yet.

THE OPTIMIZATION PROBLEM

The energy situation in many parts of Nigeria poses a challenge to sustainable deployment of GSM base station sites. This challenge could be formulated as follows:

Given an electricity demand profile of a GSM Base Station for a certain location with estimated weather conditions, costs for components, labour, transport and maintenance, design an energy system made up of one or more electricity generating sources that covers the demand reliably and has lowest overall Net Present costs (economic & environmental costs).

Using total Net Present Cost (NPC) as a metric, the objective function to be minimized is the system's energy costs (Economic and Environmental costs), expressed as:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF\left(i, R_{proj}\right)} \quad (1)$$

Where $C_{ann,tot,c}$ is the total annualized cost and $CRF\left(i, R_{proj}\right)$ is the capital recovery factor over its lifetime. $C_{ann,tot,c}$ takes into account all the costs incurred over the system's component lifetime, which include annualized capital costs, the annualized replacement costs, the annual operation and maintenance (O&M) costs, the annual fuel and emissions costs (if applicable) of system's components.

ENERGY CONSUMPTION/LOAD PROFILE ESTIMATION

To estimate energy consumption at a GSM Base Station site we need to calculate the average daily electrical energy use in watt-hours as well as the total power demand in watts. Once the power consumption per appliance is known or estimated, we use equation (2) to calculate the kWh that type of load consumes in a day (Solar Energy International, 2007)

$$KWh/Day = n \cdot P_{LOAD} \cdot H_{DAY} \quad (2)$$

Where n represent the quantity of that type of load, P_{LOAD} is the power consumption of the type of load, H_{DAY} is the number of hours the load is consuming power. Total kWh/day of all the loads is obtained by adding individual load consumption as in equation (3).

$$Total\ KWh/Day = \sum_i KWh/Day_i \quad (3)$$

Where $Total\ KWh/Day$ is the sum of the individual i load consumption in KWh/Day. For calculating the yearly load, use the next formula (Miguel Rios Rivera, 2008).

$$YearlyLoad = \left(Total\ KWh/Day\right) \cdot 365 \quad (4)$$

For us to calculate the total wattage installed or, in other words, the maximum power wattage, we sum all the P_{LOAD} of all the loads i.

$$Maximum\ Power\ Wattage\ KW = \sum_i^n P_{LOAD_i} \quad (5)$$

From equation (2), the kWh/d for Primary A (Radio Base Station) being Critical Load is calculated as:

System kWh/Day =
(Quantity x Power Consumption
x Daily Load)
KWh/d = 1x7.860x24=188.64
approximately**189kWh/d**

Then, for Primary B (Climate & Auxiliary Equipment) being Not-critical Load is calculated as:

System kWh/Day =
(Quantity x Power Consumption
x Daily Load)
KWh/d = (1x2.590x24) + (1x0.200x14) =
64.96 approximately **65kWh/d**

From equation (3), the total kWh/d is calculated as:

Total System kWh/Day =
(Total Quantity x Power Consumption
x Daily Load)
Total kWh/d =189+65=**254kWh/d**

From equation (4), the yearly load is calculated as:

Total System kWh/Yearly
= (365 Days)*(Total System kWh/Day)
Yearly load = 365x254=**92710kWh/yr**

Load factor is a dimensionless number equal to the average load divided by the peak load.

In a **Radio Base Station,** the average load is 189kWh/d (or 7.86kW) and the peak load is 7.86kW, the load factor is 7.86kW/7.86kW=1.000.

In **Climate & Auxiliary Equipment,** the average load is 65kWh/d (or 2.71kW) and the peak load is 2.79kW, the load factor is 2.71kW/2.79kW=0.970. The typical RBS that was included in this study has a power consumption of about **10.7kW** at 24 V.

THE ENERGY OPTIMIZATION MODEL

Energy Optimization is a major issue in today's mobile communication provisioning (Willson, 2009). Energy Optimization at GSM base stations may be described as alternative options of power that are readily available and necessary to produce the desired power needs while minimizing the over dependence on diesel generators at the base stations. It is the provision of mobile communication services using a BTS energy solution which, against other solutions, allows the least financial expenditure on energy and has the least impact on the environment. The goal of energy optimization is being pursued here in two related broad ways: choosing the right energy solution for a BTS, and lowering both the financial cost and the environmental impact of the energy requirement at the BTS through modelling and design.

According to GSMA (2009), Ericsson (2007), Roy (2008), and Pierre (2006), the parameters useful for achieving the above goal are grouped into the following:

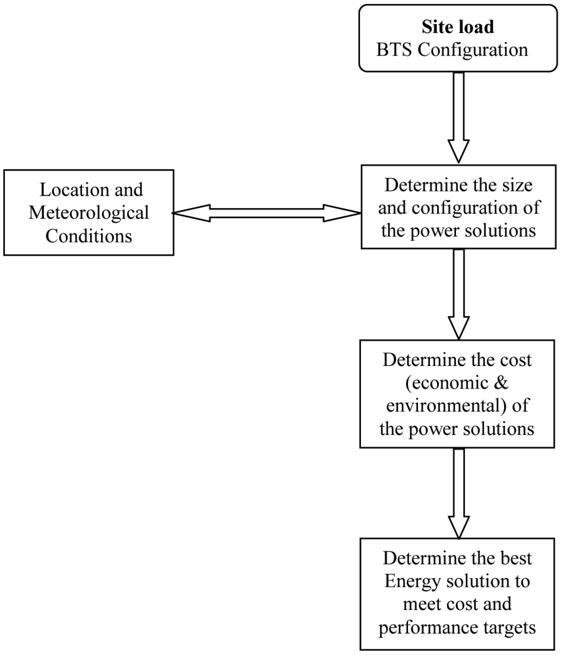
- Total Cost of Energy Generation, and
- Total Environmental Impact of each energy solution

These two summarize all the factors being proposed for evaluating the suitability of energy solution for any BTS and location. The model is presented in Figure 1.

ECONOMIC AND ENVIRONMENTAL COST MODEL

The application of renewable energy systems in telecoms has become an important alternative, as network operators need simple, efficient, cost-effective energy sources to power their base station sites (Pierre, 2006). However, the evaluation of the correct type of renewable energy system needs to be done so that the system can be optimized. Several studies have been

Figure 1. Model for choosing power solution for a BTS Site (adapted from Ani, 2011)



carried out to demonstrate the ability of some configurations of renewable energy systems to maximize performance while minimizing costs. The optimization of energy systems in the context of minimizing excess energy and cost of energy has been addressed by Razak, Sopian, and Ali (2007). Genetic algorithm have been used to find the optimum sizing as well as the suitable operation strategies to meet different load demand by, among others (Seeling-Hochmuth, 1998; Dufo-Lopez & Bernal-Augustin, 2005; Ashok, 2007). The high upfront cost of hybrid systems warrants the need to optimize unit sizing for reliable and cost-effective energy system (Kellog, Nehrir, Venkataramanan, & Gerez, 1996; Borowy & Salameh, 1994). Also, Kamaruzzaman, Azami, Yusoff, Zulkifli, Juhari, and Nor (2008) and Lambert (2009) used the annualized cost of a component to derive the calculation of the total Net Present Cost (NPC) of energy systems. Kamel and Dahl (2005) and Khan and Iqbal (2005), used the Hybrid Optimization Model for Electric Renewables (HOMER, 2005) software to find optimum sizing and minimizing cost for hybrid power system with specific load demand in stand-alone applications. Ashok (2007) developed a reliable system operation model based on Hybrid Optimization Model for Electric Renewable (HOMER) to find an optimal hybrid system among different renewable energy combinations while minimizing the total life cycle cost.

According to Lambert (2009), the annualized total cost of a component is calculated as follows:

$$C_{ann,tot,c} = \sum_{c=1}^{N_c} \left(C_{acap,c} + C_{arep,c} + C_{aop,c} + C_{emissions} \right) \tag{6}$$

Where:

$C_{acap,c}$ = Annualized capital cost of a component

$C_{arep,c}$ = Annualized replacement cost of a component

$C_{aop,c}$ = Annualized operating cost of a component

From equation (6), we derived the Economic and Environmental cost model through Annualized Total Cost of the Configurations of Power System as follows:

Economic and Environmental cost model of running **Hybrid (Hydro/ Solar/wind) + Diesel Generator** + **Batteries** is calculated as (Ani, 2011) shown in Box 1.

Where:

$C_{acap,h}$ = Annualized Capital Cost of Hydro Power

$C_{arep,h}$ = Annualized Replacement Cost of Hydro Power

$C_{aop,h}$ = Annualized Operating Cost of Hydro Power

$C_{emissions}$ = Cost of Emissions

$C_{acap,s}$ = Annualized Capital Cost of Solar Power

$C_{arep,s}$ = Annualized Replacement Cost of Solar Power

$C_{aop,s}$ = Annualized Operating Cost of Solar Power

$C_{acap,w}$ = Annualized Capital Cost of Wind Power

$C_{arep,w}$ = Annualized Replacement Cost of Wind Power

$C_{aop,w}$ = Annualized Operating Cost of Wind Power

$C_{acap,g}$ = Annualized Capital Cost of Diesel Generator

$C_{arep,g}$ = Annualized Replacement Cost of Diesel Generator

$C_{aop,g}$ = Annualized Operating Cost of Diesel Generator

$C_{af,g}$ = Annualized Fuel Cost for Diesel Generator

$C_{acap,b}$ = Annualized Capital Cost of Batteries Power

$C_{arep,b}$ = Annualized Replacement Cost of Batteries Power

$C_{aop,b}$ = Annualized Operating Cost of Batteries Power

METHODOLOGY

For this study, four technologies were considered. These are: solar PV, wind turbine, Micro hydro and Diesel Generator. Base Station Sites at rural locations in the following geographical areas in Nigeria were studied: Abaji (Abuja, FCT), Nkanu-West (Enugu State), Nembe (Bayelsa State), Mopa-Muro (Kogi State), Guzamala (Borno State), Kauru (Kaduna State), Ikwerre (Rivers State), and Tureta (Sokoto State). The data for solar and wind resources were obtained from the NASA Surface Meteorology and Solar

Box 1. Equation 7

$$C_{ann,tot,h+s+w+g+b} = \sum_{h=1}^{N_h}\left(C_{acap,h} + C_{arep,h} + C_{aop,h} + C_{emissions}\right) + \sum_{s=1}^{N_s}\left(C_{acap,s} + C_{arep,s} + C_{aop,s} + C_{emissions}\right) +$$
$$\sum_{w=1}^{N_w}\left(C_{acap,w} + C_{arep,w} + C_{aop,w} + C_{emissions}\right) +$$
$$\sum_{g=1}^{N_g}\left(C_{acap,g} + C_{arep,g} + C_{aop,g} + C_{emissions} + C_{af,g}\right) + \sum_{b=1}^{N_b}\left(C_{acap,b} + C_{arep,b} + C_{aop,b} + C_{emmisions}\right) \tag{7}$$

Energy web site (NASA, 2010), while HOMER Import Time Series Data Files were the source for the hydro resource. The specific geographical locations based on solar and wind resources are as follows:

- Abaji (Abuja, FCT) at a location of 9° 00' N latitude and 7° 00' E longitude with annual average solar (clearness index and daily radiation) of 5.45 kWh/m²/d whereas its annual average wind is 2.4m/s. Figures 2 and 3 show the solar and wind resource profile of the location tabulated in Table 1.
- Nkanu-West (Enugu State) at a location of 6° 00' N latitude and 7° 00' E longitude with annual average solar (clearness index and daily radiation) of 4.92kWh/m²/d whereas its annual average wind is 2.1m/s. Figures 4 and 5 shows the solar resource profile and wind resource profile in Nkanu-West tabulated in Table 2.
- Ikwerre (River State) at a location of 4° 00' N latitude and 7° 00' E longitude with annual average solar (clearness index and daily radiation) of 4.21kWh/m²/d whereas its annual average wind is 2.8m/s. Figures 6 and 7 show the solar and wind resource profile of this location tabulated in Table 3.
- Nembe (Bayelsa State) at a location of 4° 917' N latitude and 6° 25' E longitude with annual average solar (clearness index and daily radiation) of 4.12kWh/m²/d whereas its annual average wind is 3.0m/s. Figures 8 and 9 show the solar and wind resource profile of this area tabulated in Table 4.
- Mopa-Muro (Kogi State) at a location of 7° 00' N latitude and 6° 00' E longitude with annual average solar (clearness index and daily radiation) of 5.09kWh/m²/d whereas its annual average wind is 2.3m/s. Figures 10 and 11 show the solar and wind resource profile of this location tabulated in Table 5.
- Kauru (Kaduna State) at a location of 10° 00' N latitude and 7° 00' E longitude with annual average solar (clearness index and daily radiation) of 5.64kWh/m²/d whereas its annual average wind is 2.5m/s. Figures 12 and 13 shows the solar and wind resource profile of this area tabulated in Table 6.
- Guzamala (Borno State) at a location of 11° 05' N latitude and 13° 00' E longitude with annual average solar (clearness index and daily radiation) of 5.89 kWh/m²/d whereas its annual average wind is 2.1m/s. Figures 14 and 15 show the solar and wind resource profile of the location tabulated in Table 7.
- Tureta (Sokoto State) at a location of 13° 00' N latitude and 5° 00' E longitude with annual average solar (clearness index and daily radiation) of 6.24kWh/m²/d whereas its annual average wind is 2.5m/s. Figures 16 and 17 show the solar and wind resource profile of the location tabulated in Table 8.

The energy system proposed for each of the GSM Base Station Sites consists of wind, solar, hydro and diesel power as depicted in Figure 18. A typical Base Station Site energy consumption is 254kWh/day with a 10.67kW peak demand load, and the energy system consists of Generic 10kW wind Turbine Generator, 10.3 kW Hydro Turbine Generator, 16 kW diesel generator, 10.7 kW solar PV array, Surrette 6CS25P Battery Cycle Charging, and a 25 kW AC/DC converter. The lifetime of the project is estimated at 20 years with a fixed annual interest rate of 6%.

In this paper the system sizing (Elhadidy & Shaahid, 2004; Nema, Nema, & Rangnekar, 2007) is carried out using HOMER-optimization and simulation software tool. 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, 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 and;
- PV/wind/hydro-diesel system.

From the outlined design, we were able to compare the cost-effectiveness of adding renewable energy components to the existing energy (Diesel):

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.

OPTIMIZATION PROCESS

HOMER is an optimization program based on energy cost (Economic and Environmental) calculations. The basic idea is to design an approximately optimal system and have a general idea of the optimal system amongst the feasible systems considered by HOMER. The total net present cost of the system, which includes the investment costs and all future costs during the lifetime of the system, is the parameter to minimize in the optimisation process. It is therefore necessary to simulate the system throughout its lifetime. As a basic control rule, the energy produced by renewables must be preferentially used to feed the loads. For every hour, if the renewable sources produce more energy than is demanded, the surplus power (Pcharge) can be used to charge the batteries. This is the charge process. The decision to use the spare energy to charge the batteries depends on the value of Pcharge. If, on the contrary, the renewable sources produce less energy than demanded, the deficit power (Pdischarge) should be produced by the battery. This process is called discharge. To produce the cheapest energy, the costs of providing the required energy using each technology must be evaluated.

OPTIMAL SYSTEM

To obtain this optimal system, a few assumptions and restrictions have been made. Firstly, the Generic 10kW wind turbine has not been modified, and the number of wind turbines in the system has been fixed at 1. Moreover, willing to keep all the different components within the system, the minimum power of each component is limited to 10kW. Finally, in order to favour the use of renewables over the use of the Diesel Generator, the Generator size has been limited to 16kW to match its energy production.

It is also important to note that this optimal system has been obtained with particular capital, replacement, operation and maintenance costs for each component. HOMER basing its optimization process on costs calculations, 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 in accordance with the prices of the market.

This optimal sizing has been obtained step by step by modifying gradually the size of the different elements with the objectives to minimize their size for cost interests and to reduce as far as possible the use of the diesel generators for environmental interests.

OPTIMIZATION RESULTS

The different types of possible single-source systems and hybrid system combinations were simulated with their costing and sizing compared with a PV/wind/hydro/diesel/battery system. It can be seen from the simulation results Tables 25 through 32 that no renewable only system, PV/battery, wind/PV/battery or wind/battery, can meet the demand requirements cost effectively. For the high demand level of 254kWh/day, a diesel generator only system is more reasonable in cost than a renewable only system.

Applying the energy optimization model of Figure 1, the best energy solution is determined for any BTS and location. In our work

Figure 2. HOMER output graphic for Solar (clearness index and daily radiation) profile for Abaji

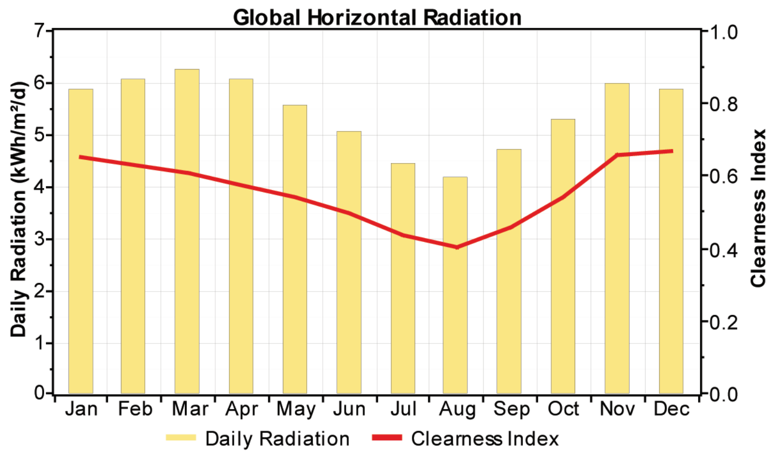


Figure 3. HOMER output graphic for wind speed profile for Abaji

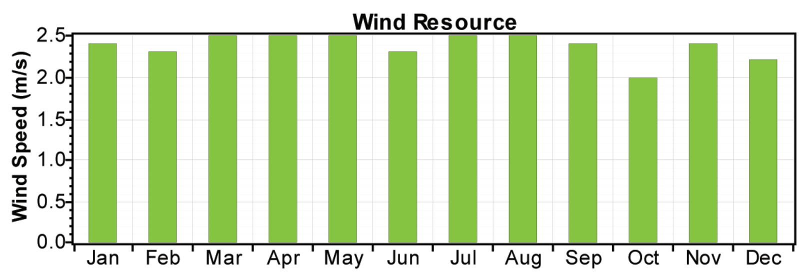


Figure 4. HOMER output graphic for solar (clearness index and daily radiation) profile for Nkanu-West

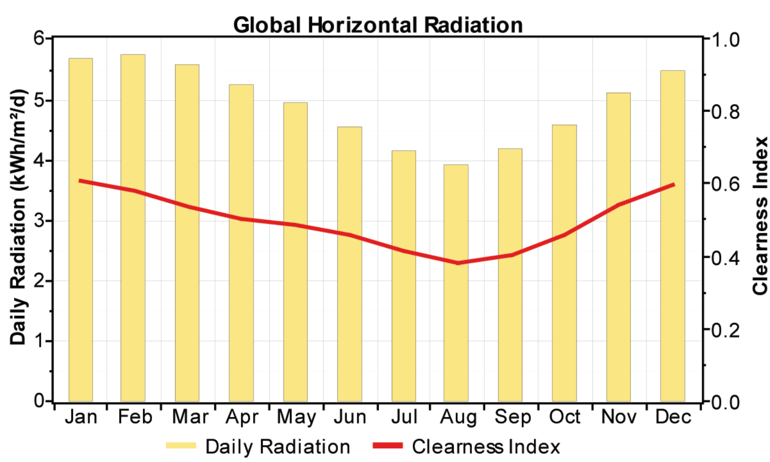


Figure 5. HOMER output graphic for wind speed profile for Nkanu-West

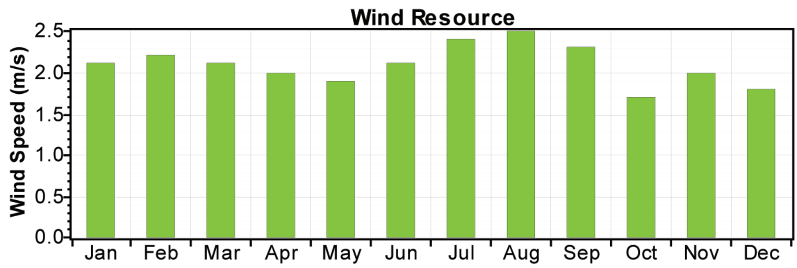


Figure 6. HOMER output graphic for solar (clearness index and daily radiation) profile for Ikwerre

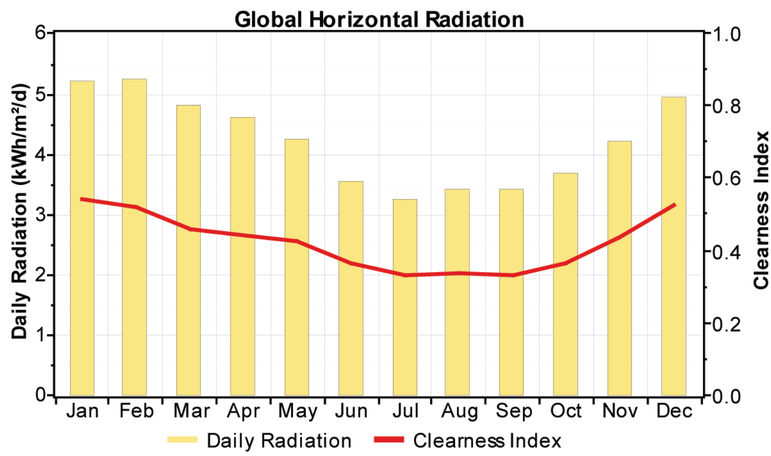


Figure 7. HOMER output graphic for wind speed profile for Ikwerre

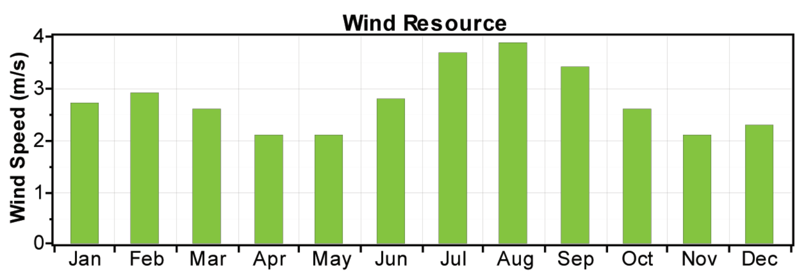


Figure 8. HOMER output graphic for solar (clearness index and daily radiation) profile for Nembe

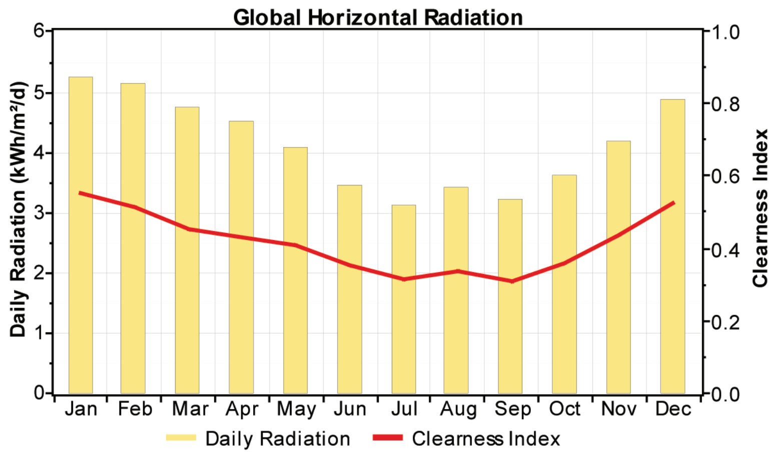


Figure 9. HOMER output graphic for wind speed profile for Nembe

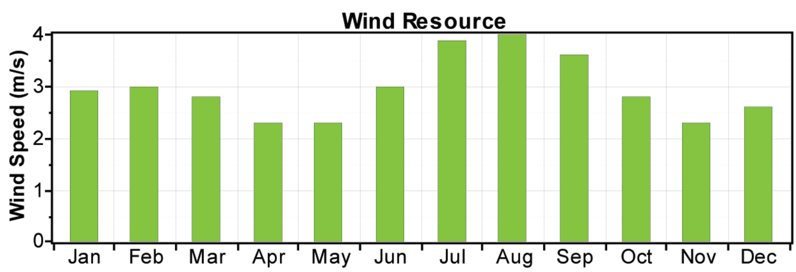


Figure 10. HOMER output graphic for solar (clearness index and daily radiation) profile for Mopa-Muro

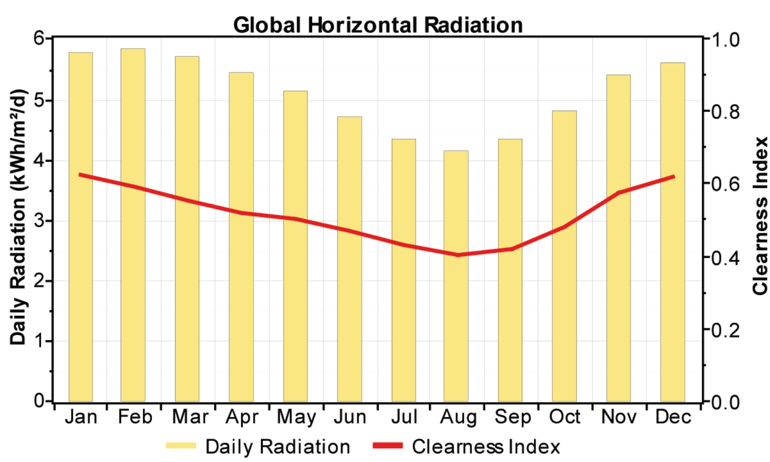


Figure 11. HOMER output graphic for wind speed profile for Mopa-Muro

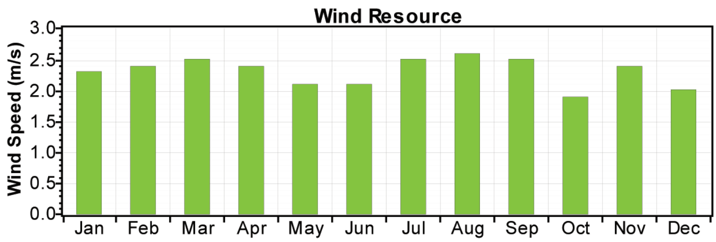


Figure 12. HOMER output graphic for solar (clearness index and daily radiation) profile for Kauru

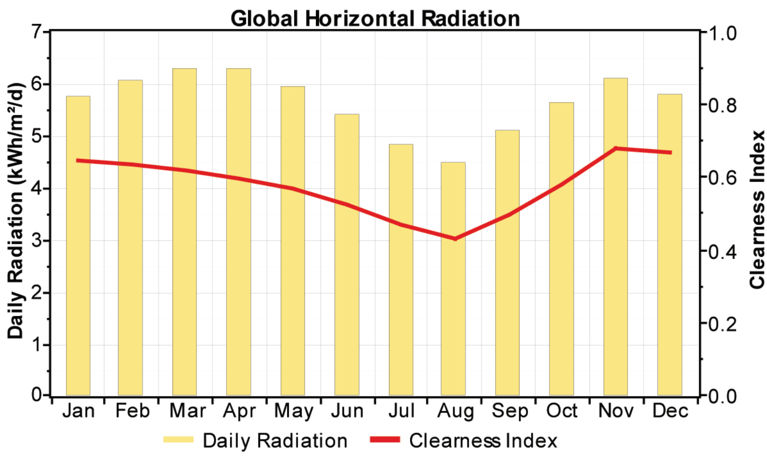
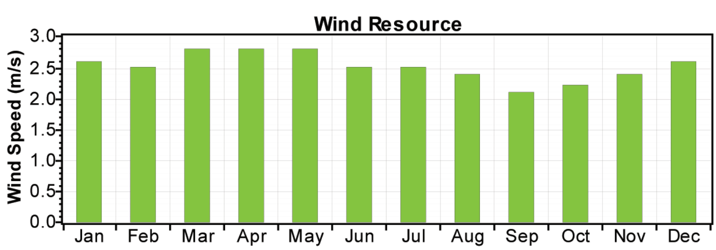


Figure 13. HOMER output graphic for wind speed profile for Kauru



the categorized list displays eight different configurations, ordered by the most effective NPC as follows:

1. Hybrid (Solar, Wind & Hydro) + DG + Batteries + Converter
2. Hybrid (Solar & Hydro) + DG + Batteries + Converter
3. Hybrid (Wind & Hydro) + DG + Batteries + Converter
4. Hydro only + DG + Batteries + Converter
5. Hybrid (Solar & Wind) + DG + Batteries + Converter
6. Solar only + DG + Batteries + Converter
7. Wind only + DG + Batteries + Converter
8. DG + Converter

Figure 14. HOMER output graphic for solar (clearness index and daily radiation) profile in Guzamala

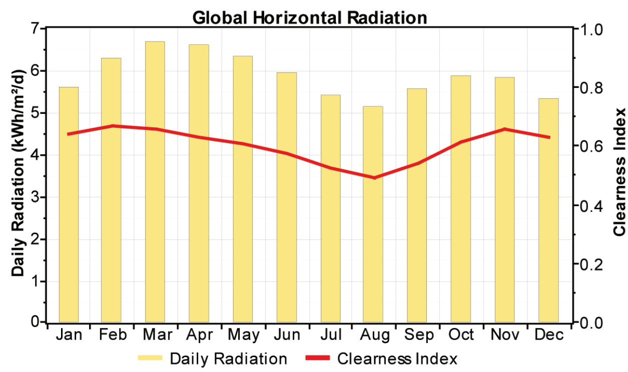


Figure 15. HOMER output graphic for wind speed profile in Guzamala

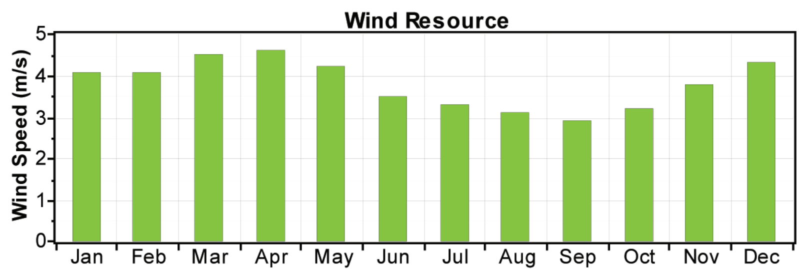


Figure 16. HOMER output graphic for solar (clearness index and daily radiation) profile for Tureta

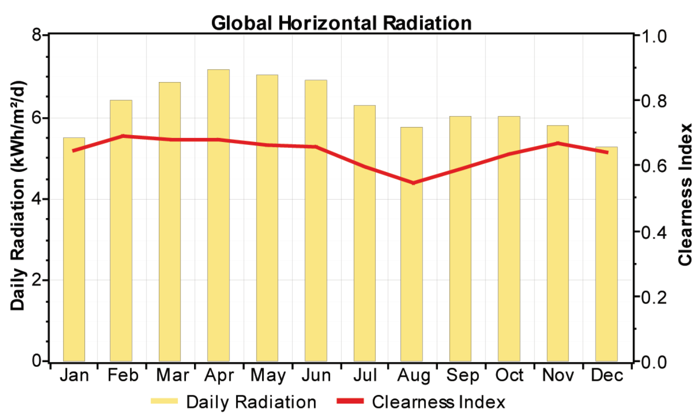


Figure 17. HOMER output graphic for wind speed profile for Tureta

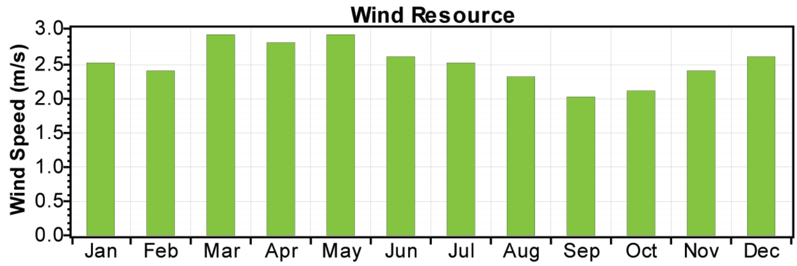


Table 1. Wind and solar resource for Abaji (Abuja, FCT)

Month	Clearness Index	Average Radiation	Wind Speed	Stream Flow
		(kWh/m²/day)	(m/s)	(L/s)
Jan	0.652	5.880	2.4	19.5
Feb	0.630	6.090	2.3	20.0
Mar	0.610	6.270	2.5	20.0
Apr	0.577	6.060	2.5	20.0
May	0.539	5.580	2.5	19.0
Jun	0.497	5.060	2.3	18.0
Jul	0.434	4.440	2.5	16.0
Aug	0.404	4.190	2.5	13.0
Sep	0.460	4.730	2.4	13.5
Oct	0.542	5.310	2.0	14.5
Nov	0.655	5.980	2.4	16.0
Dec	0.668	5.860	2.2	18.5
Scaled annual average		**5.450**	**2.4**	**17.3**

However, the life cycle costing of a diesel generator only system can be improved by adding a battery, and can be further improved by also adding other renewable sources, as in Diesel/PV/wind/hydro/battery system. From the optimization results the best optimal combination of energy system components are 10.7kW PV-Array, Generic 10kW, 10.3kW Hydro, 16 kW Diesel Generator, Surrette 6CS25P and 25kW Rectifier.

SIMULATION RESULTS

System located in Abaji (Abuja, FCT), Nkanu-West (Enugu), Ikwerre (Rivers), Nembe (Bayelsa), Mopa-Muro (Kogi), Kauru (Kaduna), Guzamala (Borno), and Tureta (Sokoto), are found to be optimized.

The Simulations provide information concerning the electricity production, economic costs and environmental characteristics of each system, such as the CO_2 emissions. The obtained results are presented in Tables 9 through 32.

Table 2. Wind and solar resource for Nkanu-West (Enugu State)

Month	Clearness Index	Average Radiation	Wind Speed	Stream Flow
		(kWh/m²/day)	(m/s)	(L/s)
Jan	0.605	5.680	2.100	19.5
Feb	0.578	5.740	2.200	20.0
Mar	0.537	5.570	2.100	20.0
Apr	0.503	5.250	2.000	20.0
May	0.487	4.940	1.900	19.0
Jun	0.458	4.540	2.100	18.0
Jul	0.415	4.140	2.400	16.0
Aug	0.382	3.910	2.500	13.0
Sep	0.406	4.190	2.300	13.5
Oct	0.457	4.570	1.700	14.5
Nov	0.539	5.110	2.000	16.0
Dec	0.595	5.460	1.800	18.5
Scaled annual average		**4.950**	**2.1**	**17.3**

Table 3. Wind and solar resource for Ikwerre (Rivers State)

Month	Clearness Index	Average Radiation	Wind Speed	Stream Flow
		(kWh/m²/day)	(m/s)	(L/s)
Jan	0.540	5.200	2.700	19.5
Feb	0.519	5.240	2.900	20.0
Mar	0.460	4.800	2.600	20.0
Apr	0.444	4.600	2.100	20.0
May	0.423	4.230	2.100	19.0
Jun	0.364	3.540	2.800	18.0
Jul	0.330	3.240	3.700	16.0
Aug	0.337	3.420	3.900	13.0
Sep	0.332	3.430	3.400	13.5
Oct	0.363	3.680	2.600	14.5
Nov	0.435	4.210	2.100	16.0
Dec	0.525	4.950	2.300	18.5
Scaled annual average		**4.21**	**2.12**	**17.3**

Table 4. Wind and solar resource for Nembe (Bayelsa State)

Month	Clearness Index	Average Radiation	Wind Speed	Stream Flow
		(kWh/m²/day)	(m/s)	(L/s)
Jan	0.551	5.240	2.900	19.5
Feb	0.512	5.130	3.000	20.0
Mar	0.454	4.730	2.800	20.0
Apr	0.433	4.500	2.300	20.0
May	0.406	4.090	2.300	19.0
Jun	0.351	3.450	3.000	18.0
Jul	0.314	3.110	3.900	16.0
Aug	0.335	3.420	4.000	13.0
Sep	0.311	3.220	3.600	13.5
Oct	0.357	3.600	2.800	14.5
Nov	0.436	4.180	2.300	16.0
Dec	0.525	4.880	2.600	18.5
Scaled annual average		**4.12**	**2.12**	**17.3**

Table 5. Wind and solar resource for Mopa-Muro (Kogi State)

Month	Clearness Index	Average Radiation	Wind Speed	Stream Flow
		(kWh/m²/day)	(m/s)	(L/s)
Jan	0.623	5.770	2.300	19.5
Feb	0.593	5.840	2.400	20.0
Mar	0.552	5.710	2.500	20.0
Apr	0.518	5.420	2.400	20.0
May	0.502	5.130	2.100	19.0
Jun	0.470	4.700	2.100	18.0
Jul	0.431	4.340	2.500	16.0
Aug	0.401	4.130	2.600	13.0
Sep	0.420	4.330	2.500	13.5
Oct	0.483	4.800	1.900	14.5
Nov	0.577	5.400	2.400	16.0
Dec	0.618	5.590	2.000	18.5
Scaled annual average		**5.06**	**2.12**	**17.3**

Table 6. Wind and solar resource for Kauru (Kaduna State)

Month	Clearness Index	Average Radiation	Wind Speed	Stream Flow
		(kWh/m²/day)	(m/s)	(L/s)
Jan	0.648	5.760	2.600	19.5
Feb	0.634	6.060	2.500	20.0
Mar	0.618	6.320	2.800	20.0
Apr	0.599	6.300	2.800	20.0
May	0.570	5.940	2.800	19.0
Jun	0.526	5.400	2.500	18.0
Jul	0.471	4.850	2.500	16.0
Aug	0.429	4.470	2.400	13.0
Sep	0.498	5.110	2.100	13.5
Oct	0.579	5.630	2.200	14.5
Nov	0.678	6.110	2.400	16.0
Dec	0.671	5.790	2.600	18.5
Scaled annual average		5.641	2.518	17.3

Table 7. Wind and solar resource for Guzamala (Borno State)

Month	Clearness Index	Average Radiation	Wind Speed	Stream Flow
		(kWh/m²/day)	(m/s)	(L/s)
Jan	0.642	5.610	4.100	19.5
Feb	0.666	6.300	4.100	20.0
Mar	0.658	6.700	4.500	20.0
Apr	0.628	6.620	4.600	20.0
May	0.606	6.360	4.200	19.0
Jun	0.576	5.970	3.500	18.0
Jul	0.523	5.430	3.300	16.0
Aug	0.492	5.140	3.100	13.0
Sep	0.544	5.570	2.900	13.5
Oct	0.612	5.890	3.200	14.5
Nov	0.658	5.840	3.800	16.0
Dec	0.631	5.350	4.300	18.5
Scaled annual average		5.89	2.12	17.3

Table 8. Wind and solar resource for Tureta (Sokoto State)

Month	**Clearness Index**	**Average Radiation**	**Wind Speed**	**Stream Flow**
		(kWh/m²/day)	(m/s)	(L/s)
Jan	0.644	5.470	2.500	19.5
Feb	0.692	6.410	2.400	20.0
Mar	0.681	6.870	2.900	20.0
Apr	0.678	7.150	2.800	20.0
May	0.663	7.030	2.900	19.0
Jun	0.657	6.910	2.600	18.0
Jul	0.595	6.260	2.500	16.0
Aug	0.546	5.730	2.300	13.0
Sep	0.590	6.010	2.000	13.5
Oct	0.637	6.030	2.100	14.5
Nov	0.671	5.790	2.400	16.0
Dec	0.640	5.250	2.600	18.5
Scaled annual average		6.24	2.12	17.3

Figure 18. The proposed energy system for GSM Base Station Site

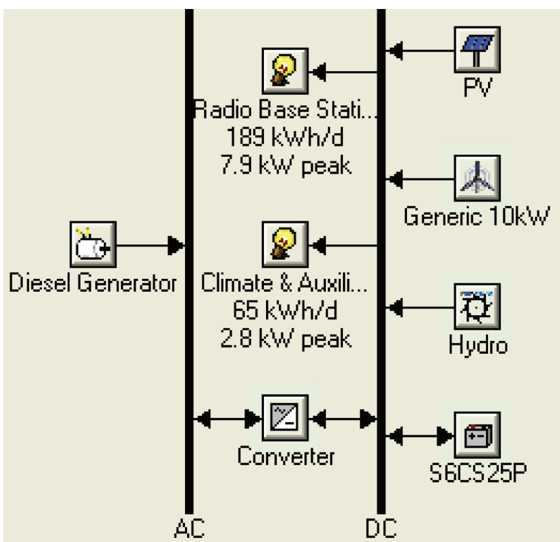


Table 9. Comparison of simulation results of economic cost in Abaji (Abuja, FCT)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/ Wind-Diesel	Hydro-Diesel	Wind/ Hydro-Diesel	PV/ Hydro-Diesel	PV/Wind/ Hydro-Diesel
Initial Cost	$265,000	$334,320	$360,060	$389,060	$335,160	$384,320	$430,220	$439,060
Operating Cost	$2,168,571	$1,741,614	$1,458,235	$1,442,250	$769,343	$747,389	$417,644	$402,188
Levelized Cost($/ kWh)	$23.613	$19.067	$16.032	$15.884	$8.581	$8.385	$4.868	$4.708
Total NPC	$27,986,610	$22,597,986	$19,001,202	$18,825,856	$10,169,943	$9,938,459	$5,769,107	$5,580,376

Table 10. Comparison of simulation results of economic cost in Nkanu-West (Enugu)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hy-dro-Diesel	PV/Hydro-Diesel	PV/Wind/ Hydro-Diesel
Initial Cost	$310,360	$344,400	$390,300	$409,220	$360,360	$384,320	$410,060	$464,260
Operating Cost	$1,756,634	$1,748,908	$1,490,073	$1,484,188	$759,911	$753,837	$460,242	$443,242
Levelized Cost($/ kWh)	$19.208	$19.154	$16.401	$16.353	$8.500	$8.455	$5.310	$5.172
Total NPC	$22,766,034	$22,701,310	$19,438,430	$19,382,120	$10,074,569	$10,020,884	$6,293,492	$6,130,377

Table 11. Comparison of simulation results of economic cost in Ikwerre (Rivers)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hy-dro-Diesel	PV/Hydro-Diesel	PV/Wind/ Hydro-Diesel
Initial Cost	$310,360	$334,320	$380,220	$419,300	$360,360	$389,360	$435,260	$464,260
Operating Cost	$1,756,634	$1,723,238	$1,532,202	$1,494,715	$759,911	$722,379	$493,226	$461,143
Levelized Cost($/ kWh)	$19.208	$18.868	$16.847	$16.475	$8.500	$8.120	$5.741	$5.365
Total NPC	$22,766,034	$22,363,088	$19,966,900	$19,526,780	$10,074,569	$9,623,793	$6,804,257	$6,359,211

Table 12. Comparison of simulation results of economic cost in Nembe (Bayelsa)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Initial Cost	$310,360	$344,400	$380,220	$419,300	$360,360	$384,320	$435,260	$464,260
Operating Cost	$1,756,634	$1,712,404	$1,534,685	$1,487,759	$759,911	$712,405	$500,211	$450,453
Levelized Cost($/kWh)	$19.208	$18.760	$16.873	$16.400	$8.500	$8.008	$5.762	$5.250
Total NPC	$22,766,034	$22,234,664	$19,998,642	$19,437,860	$10,074,569	$9,491,244	$6,829,639	$6,222,566

Table 13. Comparison of simulation results of economic cost in Mopa-Muro (Kogi)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Initial Cost	$310,360	$334,320	$380,220	$409,220	$360,360	$384,320	$435,260	$459,220
Operating Cost	$1,756,634	$1,742,607	$1,480,041	$1,468,534	$759,911	$745,653	$441,828	$426,775
Levelized Cost($/kWh)	$19.208	$19.077	$16.284	$16.184	$8.500	$8.367	$5.133	$4.991
Total NPC	$22,766,034	$22,610,684	$19,300,116	$19,182,008	$10,074,569	$9,916,266	$6,083,299	$5,914,837

Table 14. Comparison of simulation results of economic cost in Kauru (Kaduna)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Initial Cost	$320,440	$344,400	$390,300	$424,340	$365,400	$394,400	$445,340	$469,300
Operating Cost	$1,756,231	$1,732,272	$1,441,613	$1,420,448	$761,941	$734,337	$395,378	$373,774
Levelized Cost($/kWh)	$19.213	$18.974	$15.878	$15.679	$8.526	$8.253	$4.640	$4.427
Total NPC	$22,770,968	$22,488,644	$18,818,948	$18,582,432	$10,105,568	$9,781,685	$5,499,597	$5,247,390

Table 15. Comparison of simulation results of economic cost in Guzamala (Borno)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Initial Cost	$325,480	$354,480	$400,380	$414,260	$360,360	$404,480	$410,060	$464,260
Operating Cost	$1,750,568	$1,637,952	$1,428,032	$1,311,820	$759,911	$618,892	$393,065	$263,303
Levelized Cost($/kWh)	$19.156	$17.966	$15.740	$14.498	$8.500	$7.016	$4.585	$3.232
Total NPC	$22,703,616	$21,293,008	$18,655,420	$17,183,726	$10,074,569	$8,315,998	$5,434,744	$3,830,156

Table 16. Comparison of simulation results of economic cost in Tureta (Sokoto)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Initial Cost	$305,320	$334,320	$360,060	$409,220	$335,160	$364,160	$410,060	$439,060
Operating Cost	$1,761,552	$1,742,359	$1,415,227	$1,392,950	$769,343	$744,224	$372,075	$351,243
Levelized Cost($/kWh)	$19.257	$19.075	$15.568	$15.369	$8.581	$8.334	$4.359	$4.159
Total NPC	$22,823,866	$22,607,510	$18,451,416	$18,215,800	$10,169,943	$9,877,843	$5,166,431	$4,929,130

Table 17. Comparison of simulation results of environmental cost in Abaji (Abuja, FCT)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Carbon dioxide (kg/yr)	20268.4	19527.6	16368.2	16181.8	8651.2	8384.2	4691.2	4524.2
Carbon monoxide (kg/yr)	50	48.2	40.4	40	21.4	20.6	11.58	11.16
Unburned hydrocarbon (kg/yr)	5.54	5.34	4.48	4.42	2.36	2.3	1.282	1.238
Particulate matter (kg/yr)	3.78	3.64	3.04	3.02	1.61	1.56	0.872	0.842
Sulphur dioxide (kg/yr)	40.8	39.2	32.8	32.4	17.38	16.84	9.42	9.08
Nitrogen oxides (kg/yr)	446.4	430.2	360.6	356.4	190.6	184.6	103.4	99.6

Table 18. Comparison of simulation results of environmental cost in Nkanu-West (Enugu)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Carbon dioxide (kg/yr)	98,500	98,014	83,523	83,189	42,644	42,283	25,903	24,832
Carbon monoxide (kg/yr)	243	242	206	205	105	104	63.9	61.3
Unburned hydrocarbon (kg/yr)	26.9	26.8	22.8	22.7	11.7	11.6	7.08	6.79
Particulate matter (kg/yr)	18.3	18.2	15.5	15.5	7.94	7.87	4.82	4.62
Sulphur dioxide (kg/yr)	198	197	168	167	85.6	84.9	52	49.9
Nitrogen oxides (kg/yr)	2,170	2,159	1,840	1,832	939	931	571	547

Table 19. Comparison of simulation results of environmental cost in Ikwerre (Rivers)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Carbon dioxide (kg/yr)	98,500	96,613	85,914	83,746	42,644	40,503	27,947	25,833
Carbon monoxide (kg/yr)	243	238	212	207	105	100	69	63.8
Unburned hydrocarbon (kg/yr)	26.9	26.4	23.5	22.9	11.7	11.1	7.64	7.06
Particulate matter (kg/yr)	18.3	18	16	15.6	7.94	7.54	5.2	4.81
Sulphur dioxide (kg/yr)	198	194	173	168	85.6	81.3	56.1	51.9
Nitrogen oxides (kg/yr)	2,170	2,128	1,892	1,845	939	892	616	569

Table 20. Comparison of simulation results of environmental cost in Nembe (Bayelsa)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Carbon dioxide (kg/yr)	98,500	95,970	86,053	83,358	42,644	39,961	28,058	25,236
Carbon monoxide (kg/yr)	243	237	212	206	105	98.6	69.3	62.3
Unburned hydrocarbon (kg/yr)	26.9	26.2	23.5	22.8	11.7	10.9	7.67	6.9
Particulate matter (kg/yr)	18.3	17.9	16	15.5	7.94	7.44	5.22	4.7
Sulphur dioxide (kg/yr)	198	193	173	167	85.6	80.2	56.3	50.7
Nitrogen oxides (kg/yr)	2,170	2,114	1,895	1,836	939	880	618	556

Table 21. Comparison of simulation results of environmental cost in Mopa-Muro (Kogi)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Carbon dioxide (kg/yr)	98,500	97,694	82,997	82,314	42,644	41,824	24,791	23,928
Carbon monoxide (kg/yr)	243	241	205	203	105	103	61.2	59.1
Unburned hydrocarbon (kg/yr)	26.9	26.7	22.7	22.5	11.7	11.4	6.78	6.54
Particulate matter (kg/yr)	18.3	18.2	15.4	15.3	7.94	7.78	4.61	4.45
Sulphur dioxide (kg/yr)	198	196	167	165	85.6	84	49.8	48.1
Nitrogen oxides (kg/yr)	2,170	2,152	1,828	1,813	939	921	546	527

Table 22. Comparison of simulation results of environmental cost in Kauru (Kaduna)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Carbon dioxide (kg/yr)	98,445	97,083	80,813	79,576	42,742	41,156	22,163	20,910
Carbon monoxide (kg/yr)	243	240	199	196	106	102	54.7	51.6
Unburned hydrocarbon (kg/yr)	26.9	26.5	22.1	21.8	11.7	11.3	6.06	5.72
Particulate matter (kg/yr)	18.3	18.1	15	14.8	7.95	7.66	4.12	3.89
Sulphur dioxide (kg/yr)	198	195	162	160	85.8	82.6	44.5	42
Nitrogen oxides (kg/yr)	2,168	2,138	1,780	1,753	941	906	488	461

Table 23. Comparison of simulation results of environmental cost in Guzamala (Borno)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Carbon dioxide (kg/yr)	98,115	91,769	80,020	73,527	42,644	34,663	22,141	14,657
Carbon monoxide (kg/yr)	242	227	198	181	105	85.6	54.7	36.2
Unburned hydrocarbon (kg/yr)	26.8	25.1	21.9	20.1	11.7	9.48	6.05	4.01
Particulate matter (kg/yr)	18.3	17.1	14.9	13.7	7.94	6.45	4.12	2.73
Sulphur dioxide (kg/yr)	197	184	161	148	85.6	69.6	44.5	29.4
Nitrogen oxides (kg/yr)	2,161	2,021	1,762	1,619	939	763	488	323

Table 24. Comparison of simulation results of environmental cost in Tureta (Sokoto)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Carbon dioxide (kg/yr)	98,793	97,680	79,438	78,088	43,256	41,810	20,937	19,698
Carbon monoxide (kg/yr)	244	241	196	193	107	103	51.7	48.6
Unburned hydrocarbon (kg/yr)	27	26.7	21.7	21.4	11.8	11.4	5.72	5.39
Particulate matter (kg/yr)	18.4	18.2	14.8	14.5	8.05	7.78	3.9	3.67
Sulphur dioxide (kg/yr)	198	196	160	157	86.9	84	42	39.6
Nitrogen oxides (kg/yr)	2,176	2,151	1,750	1,720	953	921	461	434

Table 25. Comparison of simulation results of electricity production in Abaji (Abuja, FCT)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Diesel	(113,687) 100%	(112,357) 99%	(94,181) 84%	(93,109) 83%	(49,776) 47%	(48,240) 46%	(26,992) 27%	(26,032) 26%
PV	0%	0%	(18,175) 16%	(18,175) 16%	0%	0%	(18,175) 18%	(18,175) 18%
Wind	0%	(980) 1%	0%	(980) 1%	0%	(980) 1%	0%	(980) 1%
Hydro	0%	0%	0%	0%	(55,885) 53%	(55,885) 53%	(55,885) 55%	(55,885) 55%
Total	(113,687) 100%	(113,337) 100%	(112,356) 100%	(112,264) 100%	(105,661) 100%	(105,105) 100%	(101,052) 100%	(101,072) 100%

Table 26. Comparison of simulation results of electricity production in Nkanu-West (Enugu)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Diesel	(113,349) 100%	(112,790) 100%	(96,117) 86%	(95,733) 85%	(49,072) 47%	(48,656) 46%	(29,808) 29%	(28,576) 28%
PV	0%	0%	(15,930) 14%	(15,930) 14%	0%	0%	(15,930) 16%	(15,930) 16%
Wind	0%	(504) 0%	0%	(504) 0%	0%	(504) 0%	0%	(504) 0%
Hydro	0%	0%	0%	0%	(55,885) 53%	(55,885) 53%	(55,885) 55%	(55,885) 55%
Total	(113,349) 100%	(113,294) 100%	(112,047) 100%	(112,167) 100%	(104,957) 100%	(105,045) 100%	(101,623) 100%	(100,895) 100%

Table 27. Comparison of simulation results of electricity production in Ikwerre (Rivers)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Diesel	(113,349) 100%	(111,179) 98%	(98,869) 88%	(96,373) 86%	(49,072) 47%	(46,608) 45%	(32,160) 32%	(29,728) 29%
PV	0%	0%	(13,527) 12%	(13,527) 12%	0%	0%	(13,527) 13%	(13,527) 13%
Wind	0%	(2,036) 2%	0%	(2,036) 2%	0%	(2,036) 2%	0%	(2,036) 2%
Hydro	0%	0%	0%	0%	(55,885) 53%	(55,885) 53%	(55,885) 55%	(55,885) 55%
Total	(113,349) 100%	(113,214) 100%	(112,396) 100%	(111,935) 100%	(104,957) 100%	(104,529) 100%	(101,572) 100%	(101,175) 100%

Table 28. Comparison of simulation results of electricity production in Nembe (Bayelsa)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Diesel	(113,349) 100%	(110,439) 98%	(99,029) 88%	(95,927) 86%	(49,072) 47%	(45,984) 44%	(32,288) 32%	(29,040) 29%
PV	0%	0%	(13,396) 12%	(13,396) 12%	0%	0%	(13,396) 13%	(13,396) 13%
Wind	0%	(2,676) 2%	0%	(2,676) 2%	0%	(2,676) 3%	0%	(2,676) 3%
Hydro	0%	0%	0%	0%	(55,885) 53%	(55,885) 53%	(55,885) 55%	(55,885) 55%
Total	(113,349) 100%	(113,115) 100%	(112,424) 100%	(111,999) 100%	(104,957) 100%	(104,545) 100%	(101,569) 100%	(100,997) 100%

Table 29. Comparison of simulation results of electricity production in Mopa-Muro (Kogi)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Diesel	(113,349) 100%	(112,422) 99%	(95,512) 85%	(94,725) 84%	(49,072) 47%	(48,128) 46%	(28,528) 28%	(27,536) 27%
PV	0%	0%	(16,620) 15%	(16,620) 15%	0%	0%	(16,620) 16%	(16,620) 16%
Wind	0%	(879) 1%	0%	(879) 1%	0%	(879) 1%	0%	(879) 1%
Hydro	0%	0%	0%	0%	(55,885) 53%	(55,885) 53%	(55,885) 55%	(55,885) 55%
Total	(113,349) 100%	(113,301) 100%	(112,131) 100%	(112,223) 100%	(104,957) 100%	(104,892) 100%	(101,032) 100%	(100,919) 100%

Table 30. Comparison of simulation results of electricity production in Kauru (Kaduna)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Diesel	(113,285) 100%	(111,719) 99%	(92,998) 83%	(91,575) 82%	(49,184) 47%	(47,360) 45%	(25,504) 25%	(24,058) 24%
PV	0%	0%	(18,835) 17%	(18,835) 17%	0%	0%	(18,835) 19%	(18,835) 19%
Wind	0%	(1,302) 1%	0%	(1,302) 1%	0%	(1,302) 1%	0%	(1,302) 1%
Hydro	0%	0%	0%	0%	(55,885) 53%	(55,885) 53%	(55,885) 56%	(55,885) 56%
Total	(113,285) 100%	(113,021) 100%	(111,832) 100%	(111,712) 100%	(105,069) 100%	(104,547) 100%	(100,224) 100%	(100,079) 100%

Table 31. Comparison of simulation results of electricity production in Guzamala (Borno)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Diesel	(112,907) 100%	(105,605) 94%	(92,085) 82%	(84,613) 76%	(49,072) 47%	(39,888) 39%	(25,477) 25%	(16,837) 17%
PV	0%	0%	(19,554) 18%	(19,554) 18%	0%	0%	(19,554) 19%	(19,554) 20%
Wind	0%	(6,962) 6%	0%	(6,962) 6%	0%	(6,962) 7%	0%	(6,962) 7%
Hydro	0%	0%	0%	0%	(55,885) 53%	(55,885) 54%	(55,885) 55%	(55,885) 56%
Total	(112,907) 100%	(112,567) 100%	(111,639) 100%	(111,130) 100%	(104,957) 100%	(102,735) 100%	(100,916) 100%	(99,239) 100%

Table 32. Comparison of simulation results of electricity production in Tureta (Sokoto)

Parameter	Diesel	Wind-Diesel	PV-Diesel	PV/Wind-Diesel	Hydro-Diesel	Wind/Hydro-Diesel	PV/Hydro-Diesel	PV/Wind/Hydro-Diesel
Diesel	(113,687) 100%	(112,406) 99%	(91,416) 82%	(89,861) 80%	(49,776) 47%	(48,112) 46%	(24,083) 24%	(22,646) 23%
PV	0%	0%	(20,703) 18%	(20,703) 19%	0%	0%	(20,703) 21%	(20,703) 21%
Wind	0%	(1,183) 1%	0%	(1,183) 1%	0%	(1,183) 1%	0%	(1,183) 1%
Hydro	0%	0%	0%	0%	(55,885) 53%	(55,885) 53%	(55,885) 56%	(55,885) 56%
Total	(113,687) 100%	(113,588) 100%	(112,119) 100%	(111,747) 100%	(105,661) 100%	(105,180) 100%	(100,671) 100%	(100,417) 100%

The detailed analyses obtained at the end of the simulations are described.

FOR DIESEL ONLY

Diesel only system has the least initial capital cost but in the end has the highest total net present cost for the whole project as shown in Tables 9 through 16. Furthermore, this system emits more CO_2, particulate matter (PM) and NOx as a result of burning a lot of fossil fuel with a low efficiency operation, as shown in Tables 17 through 24.

FOR ONE RENEWABLE-DIESEL HYBRID

Wind-diesel system, Solar-diesel system, and Hydro-diesel system give an opportunity for renewable energy to supply 1%, 16%, and 53%, respectively, of the energy demand in Abaji (Abuja, FCT); 0%, 14%, and 53% respectively, for Nkanu-West (Enugu State); 2%, 12%, and 53%, respectively, for Ikwerre (Rivers State); 2%, 12%, and 53%, respectively, Nembe (Bayelsa State); 1%, 15%, and 53%, respectively, for Mopa-Muro (Kogi State); 1%, 17%, and 53%, respectively, for Kauru (Kaduna State); 6%, 18%, and 53%, respectively, for Guzamala (Borno State); and 1%, 18%, and 53%, respectively, for Tureta (Sokoto State), as shown in Tables 25 through 32, respectively.

FOR TWO RENEWABLES-DIESEL HYBRID

PV/hydro-diesel system, PV/wind-diesel system and wind/hydro-diesel system have the ability for reducing the proportion of energy supplied by diesel generator to 27%, 83%, and 46%, respectively, in Abaji (Abuja, FCT); 29%, 85%, and 46%, respectively, in Nkanu-West (Enugu State); 32%, 86%, and 45%, respectively, in Ikwerre (Rivers State); 32%, 86%, and 44%, respectively, in Nembe (Bayelsa State); 28%, 84%, and 46%, respectively, in Mopa-Muro (Kogi State); 25%, 82%, and 45%, respectively, in Kauru (Kaduna State); 25%, 76%, and 39%, respectively, in Guzamala (Borno State); and 24%, 80%, and 46%, respectively, in Tureta (Sokoto State), as shown in Tables 25 through 32, respectively.

FOR THREE RENEWABLES-DIESEL HYBRID

And finally the PV/wind/hydro-diesel system has the highest renewable energy penetration by supplying 74% of the energy demand in Abaji (Abuja), 71% of the energy in Nkanu-West (Enugu), 70% of the energy in Ikwerre (Rivers), 71% of the energy demand in Nembe (Bayelsa), 72% of the energy demand in Mopa-Muro (Kogi), 76% of the energy demand in Kauru (Kaduna), 83% of the energy demand in Guzamala (Borno), and 78% of the energy demand in Tureta (Sokoto) as shown in Tables 25 through 32 respectively. These hybrid system topologies need higher initial capital cost, but in the end they have less total net present cost as a result of less fuel consumption and higher efficiency operation of the diesel generator as shown in Tables 9 through 16. Reducing fuel consumption also means less emission from the system as shown by the PV/wind/hydro-diesel system which has the lowest emission of CO_2, PM and NOx as shown in Tables 17 through 24.

The differences are due to geographical locations.

CONCLUSION

In general, the hybrid power system offers a better performance to provide power supply than the diesel only system. The simulation results demonstrate that utilizing renewable generators such as a hybrid (PV/hydro/ wind) generator reduces the operating costs and the greenhouse gases (CO_2 and NOx) and particulate matter emitted to the environment, as an impact of improving diesel efficiency operation and also less fuel consumption. The results also demonstrate that renewable energy technologies, including solar PV, wind and micro hydro systems, have the potential of supplying electricity to base station sites in a cost effective manner.

However, it is important to note that there is no general least-cost option for powering GSM base station sites at different locations. It all depends on climatic conditions and available renewable energy resources. A major contribution of this study is that it demonstrates that it is possible to develop an optimized energy map for appropriate locations of GSM Base Station sites in the country, both as a design guide for network operators and for the formulation of energy use policies by the national telecommunications regulatory authority (the NCC). One of such policies could be the requirement that any network operator intending to site a base station in any location should first produce an optimized energy feasibility study of the location before an approval would be granted.

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