Techno-economic modelling and simulation of cost-effective and reliable off-grid hybrid energy system for GSM transceiver station in Nigeria(July 2016)

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Abstract

Telecommunications industries sometimes fail to deliver 24 hours per day service due to inadequate power supply experienced in Nigeria. This study investigates the possibility of deploying a hybrid energy system as an alternative to a diesel-only generator system to supply reliable and cost effective electricity to Base Transceiver Station (BTS) equipment. The study focused on simulation, optimization, and sensitivity analysis of a PV/battery/generator hybrid energy system for a BTS station located in Lagos, Nigeria.

Air conditioning, used for cooling the equipment is the second highest energy consumer in BTS equipment and therefore makes significant demands on the power supply system. HUAWEI BTS3900 BTS equipment, which eliminates the use of air conditioning, was used in this study, hence reducing the amount of power consumption. The solar radiation data used for system design was obtained from the National Aeronautics and Space Administration (NASA) Surface Meteorology and Solar Energy database for a location at 6^{o}31.5'N latitude and 3^{o}22'E longitude, with the average annual radiation found to be 4.74kWh/m^2/day. Hybrid Optimization of Multiple Energy Resources (HOMER) Pro software was used for the proposed hybrid energy system design. A power dispatch strategy was developed to decide when electricity generated by the PV or generator or that stored in the batteries would serve the load and the savings associated with using hybrid energy system instead of diesel-only generator system were evaluated. The paper will discuss results derived from this study, which has been analysed in terms of power availability, total net present cost (NPC), energy yield, and CO_2 emissions, and draw conclusions about the contributions to knowledge made by the study and the method used.

***Index Terms*—Base Transceiver Station, GSM, HOMER,Hybrid energy system, Techno-economic.**

I. Introduction

Lack of reliable and affordable electricity supply has become a major challenge to the telecommunications industry in developing countries like Nigeria, where off-grid power systems are mostly used to supply electricity to telecommunication base transceiver stations (BTS). Conventionally, off-grid systems depend mainly on diesel generators, but climate change and unsteady price of oil have made diesel-based generator uneconomical(Gan et al., 2015).However, combining traditional diesel generator with renewable energy sources and energy storage systems may provide reliable and cost effective electricity supply.

Base transceiver stations (BTS) are known to be the main source of energy consumption in GSM networks, accounting for about 57% of the total energy used(Alsharif et al., 2015).Hybrid energy systems (HES) equipped with renewable energy sources such as photovoltaics (PV) panels will not only reduce environmental impact; they are also a reliable and cost effective means of powering base stations.

In 2002, the amount of CO_2 emission from Information and Communications Technology (ICT) industry was 151 $MtCO_2$ with 43% due to the mobile sector; this is estimated to increase to 349 $MtCO_2$ by 2020 with mobile sector contributing 51%(Suarez et al., 2012).This presents more challenge on operators to meet the demand of both cost reduction and environmental conservation.

Nigeria has abundant solar energy resource to tap into considering its geographical location around the equatorial sun-belt(Ndudu, 2015).Recent studies have shown the potential of renewable energy sources combined with conventional power generation systems to supply energy to telecommunications base station. Hybrid energy systems can significantly reduce the cost of energy if properly designed and implemented. It has been identified as one of the cost-saving renewable energy applications in the telecommunications industry, but no significant steps have been taken to take advantage of the system in Nigeria(Anayochukwu and Onyeka, 2014). This barrier may be attributed to high initial capital investment to adopt the system. In most cases, hybrid energy systems are studied from the perspective of standalone systems as they are often installed in remote areas with no access to the power grid as the extension of power supply to such areas may be difficult due to economic and geographical constraints.

The advent of Global System for Mobile Communication (GSM) in 2001 was embraced with great expectations by Nigerians, after waiting for years without GSM services(Okonji, 2012).Since its introduction in Nigeria, the telecommunication industry, which is the fastest growing telecommunications industry in Africa, has made positive contributions to the social and economic growth of Nigeria through its GSM services.This has given mobile phone users improved quality of life, improved access to information, enabling businesses to operate with an increase in productivity.Its penetration in the Nigerian market has given rise to job opportunities which contribute to the economic development. Despite its positive contributions to the economy and satisfactory return on telecommunication investment in Nigeria, existing and prospective investors still have theinfrastructure and inadequate power supply issues to deal with in their effort to provide quality service.

In addition to the lack of infrastructure to improve thequality of service,Eze (2012)found that one of the major challenges telecommunications service providers are facing is that of supplying power to the base stations, a situation which necessitates telecommunications operators to deploy at least one 20kVA capacity generating set to power a base station. Industry studies confirms that, due to poor public power supply in the country, telecommunications network operators spends an estimated cost of ₦22,440 per day on diesel to keep the generating set up and running for an average of 17 hours, ₦673,200 per month, and ₦8 million per annum to power a base station(Eze, 2012), which amounts to almost one-third of the total operating cost(Africa Telecom & IT, 2012). Studies carried out by other organizations concerned about the poor quality of service experienced by GSM subscribers reveals similar results(Onwuegbuchi, 2015, PeoplesDaily, 2015).

Having waited for more than a decade for improvements in the power sector since the inception of GSM industry in Nigeria, and considering the geographic location of Nigeria, its solar energy potential and the negative impact of inadequate power supply on the margins and profitability of the telecommunications industries, it has become necessary to seek alternative and cost effective means of powering base stations.

In recent years, significant attention has been given to the investigation of grid connected and standalone renewable energy based hybrid system.Anayochukwu and Onyeka (2014), in their work, used Homer simulation software to obtain optimal sizing of PV/diesel components for a base station located in Ikwerre Local Government Area of Rivers State of Nigeria. The result of their study showed that a PV/diesel hybrid system has a total net present cost (NPC) of \$19,451,848 and the amount of CO_2 emission of 75,859kg/yr, saving \$3,314,186 and 13,499kg/yr when compared with a diesel-only system with NPC of \$22,766,034 and amount of CO_2 of 89,358kg/yr.

Kazem et al. (2013), proposed a method for optimizing the size of a standalone PV system as well as tilt angle for remote areas in Sohar, Oman. The size of the system's energy source and the tilt angle of the PV array were designed for optimal performance and at a low cost of energy. The study implemented numerical methods using MATLAB, hourly meteorological data, and load demand profile for optimization of PV array size, PV module tilt angle, and battery storage capacity. The result showed that the PV array tilt angle would be adjusted twice a year, and the energy produced by the PV as a result of this adjustment practice increased by 20.6%, while the cost of energy generated was US\$0.196kWh (£0.136kWh).

In India, optimal sizing of wind turbine generators (WTG), solar photovoltaic (SPV) and diesel generator has been investigated for a GSM (2G) and Code Division Multiple Access (CDMA, 3G)(Nema et al., 2010, Rath et al., 2012).In this study, hourly wind speed and solar radiation meteorological data for Odisha, India was used for the optimal design of a PV/wind hybrid renewable energy system (HRES) for GSM/CDMA telecommunications base station using MATLAB software. The result of this study reveals that PV/wind HRES was more cost effective and more environmentally friendly than conventional diesel-only generator system.

Subodh et al. (2013), studied the optimisation of different hybrid systems for a remote telecommunications base station in Nepal. The study presented a technical and economic assessment of diesel generator only system, generator/battery hybrid energy system, and PV/generator/battery as a backup power supply to grid connected urban areas. PV/wind hybrid system with battery backup, PV only system with battery backup, and PV/fuel_cell/electrolyser/battery backup in the rural areas was also studied. The results of the analysis showed that the most feasible solution among the systems considered in the urban and rural areas was PV/generator/battery and PV/fuel_cell/electrolyser/battery backup respectively.

Kusakana and Vermaak (2013), investigated the possibility of supplying power to BTS sites in Republic of Congo using hybrid renewable energy system as the primary source of power. Three different locations not connected to the grid namely Kamina, Kabinda, and Mbuji-Mayi with available solar and wind resources were selected as pilot sites to implement this study. Four different power systems including PV/the wind, diesel generator, PV, and the wind were designed, and their technical and economic performance, and environmental impact evaluated and compared. The simulation was performed using HOMER to determine the initial capital cost, net present cost, the cost of energy, and a capacity shortage of different power supply option. The results of the simulation show that the hybrid system was the most economical and suitable solution than PV or wind or diesel generator system.

This current study investigates the technical and economic feasibility of using a PV/battery/diesel hybrid system to power base stations in terms of Net Present Cost, energy yield, and CO_2 emission using Hybrid Optimisation of Multiple Energy Resources (HOMER) Pro software.

The rest of the study is organised into seven sections. Section II discusses the state of Nigeria conventional energy and its renewable energy potential while Section III briefly describes the BTS subsystem. The methodology and system constraints were discussed in sections IV and V respectively, while the simulation configurations and HOMER Pro capabilities were discussed in section VI. The results obtained from the simulation are presented and discussed in section VII, while the concluding remarks are found in section VIII.

II. STATE OF NIGERIA CONVENTIONAL ENERGY AND ITS RENEWABLE ENERGY POTENTIAL

A. *Current state of conventional power in Nigeria*

Energy is an essential commodity which contributes significantly to the growth and development of a nation. It has been established that the rate of industrial growth is dependent on the amount of energy available and how it is utilized(Shaaban and Petinrin, 2014). Africa's electricity consumption grew on the average by 3.1% from 1980 to 2001. Its electricity demand per capita declined when compared with the Middle East and North America; making Africa the region with the least per capita consumption of electricity in the world(Nwulu and Agboola, 2011).

According to Okoro et al. (2008), Nigeria has a considerable amount of energy resources which includes over 187 trillion ft^3 of gas, 4 billion metric tons of coal and lignite and 36 billion barrel of oil. However, oil has remained the major source for electric energy production. Oil alone contributed 57% to Nigeria's electricity supply in 2005, followed by 36% of natural gas and hydroelectricity which contributed 7%(Oyedepo, 2012).Energy is a vital ingredient for economic growth, to keep existing industries running, to establish new ones, and to bring about a higher standard of living. Nigeria with its abundant energy resources generated only 2000MW of electricity in 2009, while South Africa with one-third the population of Nigeria generated 43,000MW in the same year(Muhammad, 2012). The current daily average power generated is about 3,809MW with a generation capacity of 5,988MW; which is about 30% of the peak electricity demand forecast of 12,390MW(Nigeria Power Reform, 2013). In Nigeria, access to grid-connected electric power has fallen due to variation in the availability and maintenance of production sources that regularly lead to a deficiency in supply. A recent survey carried out by the Manufacturers Association of Nigeria (MAN), reveals that the cost of electricity constitutes about 30% to 40% of production cost in Nigeria, unlike in most countries like China where the cost of electricity accounts for 5% to 10% of production cost. This high cost was attributed to the fact on the average, about 60% of the total energy required by the manufacturing industries was being generated using diesel generator(Adaramola et al., 2014).

B. *Nigeria renewable energy potential*

Renewable energy sources are energy sources that are replenished by the natural process at a rate comparable or faster than its rate of consumption by humans. Nigeria geographical location within the equatorial region, between latitudes 4.321^0N and 141^0N and longitude 2.721^0E and 14.641^0E(Shaaban and Petinrin, 2014), has abundant renewable energy resources like hydropower, biomass, wind and solar to tap into(Adaramola and Oyewola, 2011). Hydropower has the highest renewable energy potential with about 734MW for small hydropower and 10,000 MW for large hydropower. In Nigeria, it is the major source of electricity because the country is enriched with large rivers, waterfalls, and dams. Hydropower is the only known commercial renewable energy technology in the electric power mix in the country. Wind energy with an average generated wind speed of 2.0 – 4.0 m/s has a potential $4.2\text{x}10^7$MW per year, biomass at $1.7\text{x}10^8$MW per year, and solar energy radiation estimated at 3.5–7.0 kWh/m^2(Akuru and Okoro, 2010). Nigeria has more than enough renewable energy resources to meets its present and future energy needs and at the same time contribute to its economy which currently depends on oil (Shaaban and Petinrin, 2014).

C. *Solar energy in Nigeria*

Solar energy is the most promising renewable energy resource in Nigeria due to its abundance(Ilenikhena and Ezemonye, 2010). It is the energy contained in sunlight and can be converted into heat, chemical energy, and electricity. About 3.8 x 10^{23}kW of energy is radiated from the sun, which is equivalent to 1.082 million ton of oil per day(Sambo, 2005). This is about 4,000 and 13,000 times the current daily crude oil and natural gas production in Nigeria respectively, based on standard energy unit(Idigbe and Onohaebi, 2009). The direct conversion of solar energy into electricity using semiconductor based devices is known as photovoltaics.Ohunakin et al. (2014), suggests that the yearly daily average of total solar radiation ranges from about 12.6MJ/m^2/day (3.5 kWh/m^2/day) in the coastal region to about 25.2MJ/m^2/day (7.0 kWh/m^2/day) in the far north, making it the region with the highest amount of solar radiation throughout the year. The total amount of solar energy radiation falling on its 923,768 km^2 land area is estimated at 17 million MJ/day (17.439 TJ/day). The total energy demand of Nigeria could be met if only 0.1% of the total energy radiant on its land mass is converted at an efficiency of 1%(Bugaje, 2006). Provided there is an estimated average of 18.9 MJ/m^2/day (5.3 kWh/m^2/day) over a period of one year, an average of $1.8\text{x}10^6$TWh/year of solar energy radiation is estimated to fall on the entire land area(Ohunakin et al., 2014). The average solar radiation is about 6.5 h/day; the country's yearly solar energy value is about 27 times its total fossil fuel resources in energy units and is over 115,000 times the electricity produced(Augustine and Nnabuchi, 2009). This implies that about 3.7% of the country's land mass would be required to receive the amount of solar energy that is equivalent to the Nigeria's conventional energy reserves(Shaaban and Petinrin, 2014).

III. BASE TRANSCEIVER STATION SUBSYSTEM

A base station is a set of equipment centrally located to communicate with mobile units and the backhaul network. It consists of multiple transceivers (TRXs), each serving one transmit antenna element. A transceiver is made up of a power amplifier (PA), a radio frequency (RF) feeder, a DC – DC power supply, a baseband (BB), a cooling system, and an AC – DC unit for connection to the generator/electrical power grid(Alsharif et al., 2015).

Several solutions have been suggested to improve the power efficiency of the internal components of a BTS(Faruk et al., 2012). The power amplifier has attracted more attention in previous studies since it consumes more energy than the other components(Alsharif et al., 2014). However, this work employed Huawei BTS3900A system which eliminates the use of air conditioner, the second largest energy consumer in a base station. BTS3900A is an outdoor macro base station, and it is applicable to the outdoor centralized installation scenario. Detailed information about the system components can be found at(Alibaba.com, 2015, Huawei Technologies, 2012). A BTS3900A (Ver.C) cabinet which consists of an RF cabinet and a power cabinet, or of an RF cabinet and a transmission cabinet houses the equipment outdoors since it uses a direct ventilation system(Huawei Technologies, 2012).

IV. POWER AND ECONOMIC MODELLINGOF SYSTEM COMPONENTS

The proposed hybrid energy system consists of the PV array, battery, converter and diesel generator. The battery, charge controller, converter, distribution panels and the wiring make up the balance of system (BOS).The main purpose of a good HRES system design is to ensure that the load demand is satisfied by providing a well-designed, cost effective, and durable system with a life expectancy of about 25 years. This is possible with sound design, specification and procurement of quality components, good engineering and installation practices, and an appropriate preventive maintenance program.

The design/sizing of off-grid hybrid energy system takes all the components that the system is made of into consideration. The system considered in this study has the following important component, PV panels, diesel generator, battery, and converter. The key factors to be determined in sizing a stand-alone PV/battery/generator hybrid power system are: (i) the load demand profile, (ii) solar resource, (iii) the size and type of generator, and (iii) the battery size.

A. Site location

The solar resource used for this study was for a site in Lagos Nigeria at the location of latitude 6º 31.5’ N and longitude 3º 22.8’ E, with average annual solar radiation and average annual temperature of 4.74 kWh/m^2/day and 25.75ºC respectively. Solar radiation and temperature data for this region was obtained from the NASA Surface meteorology and Solar Energy database

B. Load profile

The model uses a realistic demand load profile that the system needs to meet, and also a measured environmental data to ascertain the contribution of the solar PV towards the total power supply.The size of the load and the insolation variability of the seasons at the site are the two major indicators that work together to enable the designer to decide thepossible hybrid application. The power consumption of a BTS depends on whether it is in operational or non-operational mode, with more power consumed in the operational mode. The maximum power consumption of Huawei BTS3900 considered in this study is 1.037 kW while the climate and auxiliary equipment together consume 300W of electricity. It is important to note that the BTS, climate, and auxiliary equipment will not be loaded to full capacity at all time due to the variability in operating hour of the equipment which often dependson the level of usage by the mobile subscribers.

C.Photovoltaic system model

The photovoltaic system model is made up of conversion of solar radiation on a tilted PV array and a PV array energy model(Al-Shamma'a and Addoweesh, 2014). PV array is made up of interconnection of PV modules which supplies the photo-generated power required by the system. The power rating of the PV array was determined based on the load requirements.The power (in kW) generated from the PV array with respect to solar radiation is given by the following equation

$$\boldsymbol{P_{PV} = f_{PV} Y_{PV} \frac{G_{G,tilted}}{I_{S,tilted}}} \tag{1}$$

where $\boldsymbol{f_{PV}}$ is the derating factor of PV, $\boldsymbol{Y_{PV}}$is the PV array rated capacity (kW), and $\boldsymbol{I_{S,tilted}}$ (1 kW/m^2) is the standard amount of radiation used to rate the PV array capacity(Lambert et al., 2006). The rated or peak capacity is the amount of power a PV array is capable of producing under standard conditions of 1 kW/m^2 irradiance and a panel temperature of 25ºC. HOMER specifies the size of PV array in terms of rated capacity, which accounts for both efficiency and area of the PV module. Hence those parameters do not appear explicitly in HOMER. HOMER uses the Hay-Davies-Klucher-Reindl (HDKR) model(Duffie and Beckman, 2013)to calculate the global solar radiation incident on the PV array. The derating factor accounts for effects of wire losses, dust on the panel, elevated temperature, and other factors that may cause the PV array output to deviate from that expected under ideal conditions(Lambert et al., 2006).

C. Battery model

The modelling of the battery is based on the state of charge (SOC) condition. The state of charge and discharge of the battery can be calculated using Eq. (2) and Eq. (3) respectively(Subodh et al., 2013).$\boldsymbol{\eta_{bat}}$ is the round-trip efficiency of the battery in the charging process, $\boldsymbol{P_S}$ is the total power supplied to the site, $\boldsymbol{P_L}$ is the power consumption of BTS load, $\boldsymbol{V_{bat}}$is the nominal voltage of individual battery, and $\boldsymbol{\Delta t}$is the hourly time interval.

$$SOC(t+1) = SOC(t) + \eta_{bat}\left(\frac{P_S(t) - P_L(t)}{V_{bat}}\right)\Delta t \quad (2)$$

$$SOC(t+1) = SOC(t) - \eta_{bat}\left(\frac{P_S(t) - P_L(t)}{V_{bat}}\right)\Delta t \quad (3)$$

The relationship between the minimum state of charge (SOC_{min}), maximum state of charge (SOC_{max}), and the depth of discharge of the battery (DOD) is expressed in Eq. (4)(Subodh et al., 2013).

$$SOC_{min} = (1 - DOD)SOC_{max} \quad (4)$$

The battery bank is sized to meet the load demand when energy from renewable resources cannot satisfy the load. Days of autonomy represents the number of the day a fully charged battery can supply energy to the load without the contribution of the auxiliary power source.HOMER calculates the battery bank autonomy (A_{bat}) by using Eq. (5)(Lambert et al., 2006), where $L_{avg}$is the average daily load (kWh) of the BTS site.

$$A_{bat} = \frac{N_{bat} * V_{bat} * C_N\left(1 - \frac{SOC_{min}}{100}\right)(24h/day)}{L_{avg}(1000Wh/kWh)} \quad (5)$$

The battery float life (the maximum life regardless of throughput) and lifetime throughput are two separate factors that may limit the lifetime of the battery bank, which has a direct impact on replacement cost. HOMER estimates the life of the battery bank based on these two factors as given in Eq. (6)(Lambert et al., 2006).

$$R_{bat} = min\left(\frac{N_{bat} * Q_{lifetime}}{Q_{thrpt}}, R_{bat,f}\right) \quad (6)$$

where $Q_{lifetime}$, Q_{thrpt} and $R_{bat,f}$are the lifetime throughput of a single battery (kWh), annual battery throughput (kWh/year) and the battery float life (year) respectively.

D. Power converter

The power converter is a power conditioning unit essential in the proposed hybrid energy system since it comprises of both AC and DC systems. The size of the converter is a decision variable, which refers to the inverter capacity. Inverter capacity is the maximum AC power that the device can produce by inverting DC power, while the rectifier capacity refers to the maximum DC power that the device can generate by rectifying AC power, as a percentage of the inverter capacity. HOMER assumes that the device can withstand inverter and rectifier capacities for as long as necessary(Lambert et al., 2006).

E. Diesel generator model

A hybrid power system consists of more than one type of generator, usually a diesel or gasoline powered engine generator and a renewable energy source such as wind, PV, or hydro-power system. A hybrid system is mostly used for a larger application such as residential systems where generators already exist, village power, and in telecommunication applications where power availability requirements are near 100 percent(Sandia National Laboratories, 1995). A diesel generator (DG) is required to supply the load demand when energy generated from PV and that stored in battery bank is not enough to meet the load. The DG is used only for the backup purpose during worst-case conditions, typically in the raining season months. When the DG size is estimated, the main consideration is operating efficiency. DGs operate most efficiently when running close to their rated output power. When operating at low loads, their efficiency can drop by 50% or more, which may result in increased maintenance costs and a shorter lifetime of DG(Sandia National Laboratories, 1995).Hence, the generator is sized to provide the power needed to meet the demand load. The cost of fuel consumption of the DG can be estimated using

$$C_{DG} = C_F \sum_{t=1}^{8760} F(t) \quad (7)$$

where $F(t)$ (in l/h if the fuel is denominated in litre) is the hourly fuel consumption and can be estimated as

$$F(t) = A * P_{DG} + B * P_{DG,rated} \quad (8)$$

where C_F is the cost of fuel per litre, $P_{DG}$is the power generated by the DG, $P_{DG,rated}$is the rated power of the DG, A and $B$are the fuel curve coefficients in l/kWh (Lambert et al., 2006). The fuel consumption of the DG is influenced by the rated and generated power as shown in Eq. (8) above. HOMER assumes that all the fuel energy isconverted into either electricity or waste heat by the generator.

HOMER calculates the generator's fixed cost of energy using the following equation

$$c_{DG,fixed} = c_{om,DG} + \frac{C_{rep,DG}}{R_{DG}} + B * P_{DG,rated}c_{fuel,eff} \quad (9)$$

where $c_{om,DG}$, $C_{rep,DG}$, R_{DG} and $c_{fuel,eff}$are the operation and maintenance (O&M) cost, the replacement cost, the generator lifetime in hours, and the effective price of fuel respectively(Lambert et al., 2006).

V. SYSTEM CONSTRAINTS MODEL

A. System reliability model

The issue of dispatch strategy arises when one or more renewable resources are supplemented with both diesel generator and hour-to-hour energy storage (batteries). Of particular interest and controversy is the possibility of charging the batteries using energy generated from the diesel generator (cycle-charging).The advantages of cycle-charging include (i) maximizing efficiency of diesel generator by operating it at full rated capacity, and (ii) minimizing the frequency of diesel starts. Disadvantages include (i) battery wear (shortening of battery life), (ii) lost opportunity for storing energy from renewable source in the battery, and (iii) electrical losses in power conversion and in the battery (depending on the arrangement of the AC/DC bus)(Barley et al., 1995). The inclusion of a diesel generator to the system serves as a backup solution, which provides redundancy and possibly increases overall reliability if the hybrid system is properly controlled and maintained.

This study expressed power system reliability in terms of loss of power supply probability (LPSP), which is defined as the probability that energy deficiency occurs when the HRES cannot supply the loadand can be calculated using Eq. (10) (Yang et al., 2007).

$$\boldsymbol{LPSP} = \frac{\sum_{t=0}^{T} \boldsymbol{power\ failure\ time\ (PFT)}}{\boldsymbol{T}} \qquad (10)$$

The power failure time (PFT) is defined as the time that the load demand is not met when the energy sources cannot generate sufficient energy and the battery is exhausted.

The method can be summarized as follows:

1) If demand load $(\boldsymbol{P_L}(t))$ is less than the energy generated by PV $(\boldsymbol{P_{PV}}(t))$, then excess energy is used to charge battery via AC/DC and charge controller. Excess energy is dissipated when the battery capacity $(\boldsymbol{C_{bat}})$ attains $(\boldsymbol{SOC_{max}})$ level.
2) If P_L (t) is greater than P_{PV} (t), the battery will supply the deficient energy if the state of charge of the battery (SOC (t)) is higher that SOC_{min}
3) If P_L (t) is greater than the total PV generated energy, and if the SOC(t) is equal to $\boldsymbol{SOC}_{min}$, DG will supply the load as follows: (i) If the energy deficit is less than the minimum operating point of DG $(\boldsymbol{P_{DG,min}})$, the DG will be operated at its minimum capacity and the excess will be dumped. (ii) However, if the energy deficit is greater than the $\boldsymbol{P_{DG,min}}$ and less than the rated power of DG $(\boldsymbol{P_{DG,rated}})$, the DG will supply the energy deficit. DG only operates at its rated capacity $(\boldsymbol{P_{DG,rated}})$ to meet maximum load demand (when all the electrical appliances are in use), when PV generated energy and that stored in the battery bank cannot meet the demand.

B. Renewable fraction model

Renewable energy fraction (REF) is the fraction of the energy supplied to the load that comes from renewable sources, and it can be estimated using(Al-Shamma'a and Addoweesh, 2014)

$$\boldsymbol{REF} = \left(\boldsymbol{1} - \frac{\boldsymbol{E_{L,DG}}}{\boldsymbol{E_{L,served}}}\right) * \boldsymbol{100} \qquad (11)$$

where $\boldsymbol{E_{L,DG}}$ is the load satisfied by the DG. REF of 100% and 0% corresponds to a pure renewable system and a pure diesel system respectively. Hence, values within these boundaries correspond to HRES.

C. System economics model

Economics play an important role both in the simulation process of HOMER; wherein the system is operated so as to reduce total net present cost, and in its optimization process, wherein it looks for the system composition with the lowest total net present cost (NPC) (Lambert et al., 2006). HOMER utilizes total net present cost $(\boldsymbol{C_{NPC}})$ as the economic figure of merit, and can be calculated using the following Eq. (12)

$$\boldsymbol{C_{NPC}} = \frac{\boldsymbol{C_{ann.tot}}}{\boldsymbol{CRF(i, R_{proj})}} \qquad (12)$$

where $\boldsymbol{C_{ann,tot}}$, $\boldsymbol{i}$and $\boldsymbol{R_{proj}}$are the total annualized cost, annual real interest rate (the discount rate) and project lifetime respectively, and $\boldsymbol{CRF}$is the capital recovery factor, which is given by Eq. (13) (Lambert et al., 2006), where $\boldsymbol{N}$is the number of years.

$$\boldsymbol{CRF(i, N)} = \frac{\boldsymbol{i(1+i)^N}}{\boldsymbol{(1+i)^N - 1}} \qquad (13)$$

HOMER uses total NPC as its main economic figure of merit rather than the levelized cost of energy (LCE) which is often a convenient metric, because the definition of LCE is arguable in a way that the definition of total NPC is not. HOMER uses the amount of load that the system really satisfies in developing the formula for LCE instead of the total electrical demand, which may be different if some unmet load is allowed by the user. This makes the definition of levelized cost of energy somewhat arbitrary. Since NPC does not suffer from such ambiguity definition, it is used as the primary economic figure of merit (Lambert et al., 2006).

VI. Simulation Configuration and Features of HOMER Pro Hybrid Power System Modelling Software

The project's lifetime is 25 years, which corresponds to the lifetime of the PV panel(SolarShop, 2012). In terms of capital cost, the solar cells are the most expensive(Alsharif et al., 2015). Hence, the hybrid system will be used to supply energy to another BTS in the future.A SolarWorld SW255 model monocrystalline module was considered in this study and the PV sizes were added in 5 kW increments in the HOMER Pro software search space window. 0 kW was also added as a size in the search space window to compare the economics of system with and without PV. An FG Wilson Perkins generator set, Trojan IND17-6V Industrial Line Flooded Lead AcidBattery, and Sukam converter were used in system design. All the components used in the system are available in Nigerian market (Jumia, 2016, konga.com, 2016, SolarShop, 2015). XE currency converter was used in the conversion of currency from Nigerian Naira (₦) to US dollar ($) (Xe, 2016). In this study, the Central bank discount rate of Nigeria used was 4.25% (Macro Economy Meter, 2016). More technical and economic parameters of the hybrid system are shown in table 1 below. Sensitivity analysis, also known as whatifanalysis was carried out on the diesel price to understand how changes in the price of diesel would affect the choice of least cost system.

The system was designed such that the PV would supply power to both the load and backup power system each hour. Based on the constraint from the chosen dispatch strategy in the simulation and a set-point of 80%, HOMER makes a decision in each time step to satisfy the power needs at the lowest cost. HOMER uses load-following and cycle-charging dispatch strategies. In load-following, the diesel generator does not charge the battery bank but produces enough energy to meet the load. While in cycle charging, the generator operates at maximum rated capacity to serve the load and charges the battery bank with the excess energy(Lambert et al., 2006).

HOMER Pro is a rapid assessment tool for least cost solutions for clean and reliable power. It compares thousands of possible combinations of solar, the wind, storage, load management and conventional generators, including combined heat and power systems as either stand-alone or grid-connected systems in basically only a few minutes.

The main capability of HOMER is the simulating operation of a micro-power system over a long period of time. Optimization and sensitivity analysis, which are the higher capabilities depend on the simulation capabilities. The simulation process determines how the configuration of a particular system, a combination of specific sizes of system components, and an operating condition that controls how those components work together, would perform in a defined setting over a long period of time (Lambert et al., 2006).

HOMER does not consider changes over time, such as declining of battery performance with aging, changes in the interest rate or increase in demand load. Instead, it simulates the yearly operation of a system and assumes that the main simulation outcome for the year (such as excess power production, battery throughput, and changes fuel prices) represents every other year in the lifetime of the project. However, these assumptions do not represent real life situation. For instance, the price of oil has been falling in recent time, but there has been no significant change in the price of other system components.

HOMER allows users to sort feasible system from a range of variables, and HOMER optimization can consider interest rates, tariffs, sell back rates, emission goals, renewable resources goals, fuel prices, equipment prices and performance (HOMER Energy, 2015b).

The HOMER software has a unique paradigm which embedded a production cost simulation engine within an optimization algorithm and packaged in the decision analytic framework to identify sensitivities and robust solutions. From a programming perspective, it is a set of nested for loops. The innermost loop dispatches generation and manages storage to meet the load in every simulation time steps. These time steps are typically hours, but can be as short as one minute. It does that for a period of one year to calculate fuel consumption, runtimes, maintenance requirements and operating costs. It then optimizes the design by simulating hundreds or thousands of different design configurations, ranking them by net present costs or other criteria, and identifying what is best for a particular scenario. In HOMER, these scenarios are known as sensitivity cases, which represents the results of individual optimizations. Sensitivity analysis is sets of optimizations that HOMER will perform in a single run during the calculations (HOMER Energy, 2015a).

VII. RESULTS AND DISCUSSION

HOMER performed an hourly chronological simulation of all the systems described by the search space for one year, ranking them by net present cost (NPC).During simulation, HOMER searches for the optimum system configuration that satisfies the load demand at the lowest NPC. HOMER switches from the design view to the result view at the end of the simulation. In the result view, the optimization cases table presents the results of all the system considered for each sensitivity case. The simulation analysis produces five optimization cases (energy systems) for each discount rate and diesel price considered in the sensitivity cases. The energy system configurations which makes up the five optimization cases are (i) generator only, (ii) PV/generator, (iii) generator/battery, (iv) PV/battery system, and (v) PV/generator/battery system. The average annual solar radiation for Odenike Street, Lagos Nigeria, the chosen location for this study is 4.74 kWh/m^2/day. Results of optimized energy system for adiscount rate of 4.25% and diesel price of $0.50 (₦180) is shown in Table 2. It shows that system (v) which comprises of PV/battery/generator is economically the most suitable solution while system (i) with only diesel generator is the least feasible solution. Discount rate of 4.25% and diesel price of $0.50 (180) has been chosen because they represent the current discount rate and diesel price in Nigeria

The results of the optimum configuration are discussed in the subsections below.

The optimal hybrid energy system comprises of 10kW PV, 5kW generator, 15 batteries and 5kW converter. The net present cost (NPC) of the system is $47,014, with an initial capital cost of $31,678, annual operation cost of £805, and levelized cost of energy of $0.217/kWh.

A. Power and Energy yield analysis

The details of electricity generated by energy systems considered are presented in Table 3. The result shows that theelectricity generated by each of the system combination satisfies the load requirement. From **Error! Reference source not found.**, the total electricity production of the PV/battery/generator hybrid energy system is 15,215kWh/yr, with PV contributing 13,980kW (89.2%) while the generator contributed 1,235kW (10.80%) per year.**Error! Reference source not found.** also reveals that the system generated more electricity than that required to meet the load demand.Deferrable load or any other unexpected increase in demand load can be taken care of by the excess electricity.

Renewable energy conversion system produces about 75 to 99% of the total electricity generated by hybrid energy systems (Alliance for Rural Electrification, 2011). However, this high contribution from renewable energy sometimes makes it difficult to control the hybrid system, and at the same time maintaining a stable voltage and frequency (Shaahid et al., 2007).

Infield suggests that the contribution from a renewable source in hybrid energy systems may sometimes be limited to about 25% of the total electricity generated (Infield, 1999). On the other hand, high electricity contribution from renewable sources can minimize the dependence of hybrid energy systems on the price of diesel and reduces operation and maintenance cost as well as fuel costs, since the generator will be run for a short period of time. Hence, 85.35% contribution from the PV to the total electricity generated by the PV/battery/diesel hybrid energy system is a good trade-off from an economic point of view. The generator only system will not be a suitable solution both from the economic and environmental point of view due to the operation and maintenance costs, the cost of diesel, and greenhouse gas emission (GHG). The generator/battery system may be a suitable solution due to the inclusion of battery to the system.The generator operates at full rated capacity to satisfy the load and charges the battery to its maximum state of charge. The generator stops running to enable the battery to carry out the responsibility of supplying electricity to meet the demand load. This reduces operation and maintenance costs, fuel consumption, and environmental impact. The PV/generator hybrid energy system produced the largest amount of electricity. However, only about 50% of the total electricitygenerated is being used to meet the load demand. This is due to the absence of a storage system (battery) to store the excess energy generated.

Table 1. Technical and economic setup of components of the hybrid system

System components	Parameters	Value
Control parameters	Discount rate	4.25%
	Project lifetime	25 years
	Dispatch strategy	Cycle charging
	Apply set-point state of charge	80%
PV	Sizes considered	0, 5, 10, 15, 20, 25, 30kW
	Operational lifetime	25 years
	Derating factor	80%
	Ground reflectance	20%
	Capital cost	£0.9/w
	O&M cost per year	£0.01/w
Battery	Number of batteries considered	0, 5, 10, 15, 20 and 25
	Roundtrip efficiency	81%
	Nominal voltage	6V
	Maximum capacity	1231 Ah/100 hour rate
	Float time	20 years
	Lifetime throughput	9300 kWh
	Maximum charge current	155 A
	Maximum charge rate	1.0 A/Ah
	Maximum discharge current	208 A
	Capital cost	$1206
	Replacement cost	$1206
	O&M cost per year	$10
	Min. state of charge	20%
Converter	Sizes considered	0, 5, 10, 15, 20, 25 kW
	Operational lifetime	15 years
	Efficiency	90%
	Capital cost	0.2/W
	Replacement cost	0.2/W
	O&M cost per year	0.004/W
Diesel generator	Sizes considered	0, 5, 10, 15, 20, 25 kW
	Rating	16 kVA (12.8 kW)
	Speed	1500 rpm
	Fuel tank capacity	65 litre
	Cost of fuel	0.5, 0.6, 0.7 $

Table 2. Energy system optimization cases for an interest rate of 4.25% and diesel price of $0.50. (i) generator only (ii) PV/generator (iii) generator/battery (iv) PV/battery (v) PV/battery/generator

Sys	PV (kW)	Gen (kW)	Bat (unit)	**Conv**	Op ($)	NPC ($)	Ini capt

				(kW)			($)
i		5		5	3,408	69,100	4,137
ii	10	5		5	2,531	61,822	13,588
iii		5	5	5	3,523	77,322	10,167
iv	20		15	5	818	54,018	38,433
v	10	5	15	5	805	47,014	31,677

Table 3. Energy yield analysis for (i) generator only (ii) PV/generator (iii) generator/battery (iv) PV/battery (v) PV/battery/generator system

Sys	Production (kWh/year)		Consumption (kWh/year)		Quantity	
	PV	Gen	AC	DC	Excess kWh/yr	Ren. Frac
i		12,986	2,300	9,084	0	0
ii	13,980	8,900	2,300	9,084	10,540	21.8
iii		12,994	2,300	9,084	0	0
iv	27,960		2,299	9,082	14,825	100
v	13,980	1,235	2,300	9,084	1,872	89.2

Table 4. Economic analysis of PV/battery/generator hybrid energy system with discount rate of 4.25% and diesel price of $0.50

Comp.	Capital ($)	Replace ($)	O&M ($)	Fuel ($)	Salvage ($)	NPC ($)
PV	9,451	0.00	3,738	0.00	0.00	13,189
Gen	2,695	0.00	25	4,064	1,297	5,487
Bat	18,090	12,028	2,860	0.00	6,957	26,021
Conv	1,441	1,039	120	0.00	278	2,322
Sys	**31,677**	**13,067**	**6,743**	**4,064**	**8,532**	**47,019**

Table 5. Comparison of greenhouse gas emissions for the energy systems considered in this study for discount rate of 4.25% and diesel price of $0.50

Sys	**Quantity (kg/year)**					
	CO_2	CO	SO_2	NO	Un. hydr	Part. mat
Gen	15,316	37.81	30.76	337.35	4.19	2.85
Gen/Bat	15,312	37.79	30.75	337.24	4.19	2.85
PV/Gen	10,558	26.06	21.20	232.54	2.89	1.96
PV/Bat	0	0.00	0.00	0.00	0.00	0.00
PV/Bat/Gen	1,123	2.77	2.26	24.73	0.31	0.21

From the environmental perspective, PV/battery hybrid energy system would be a suitable solution since the electricity generated completely comes from a renewable source (PV).However, designing a PV/battery system to be available all the time would be expensive as large PV and battery bank size would be required to meet demand load as days of autonomy increases due to unpredictable weather condition.If the size of PV/battery system is increased to lower the downtime in raining season, more energy would be wasted during the sunny, dry season when the PV array will produce more than is required by the load. This increases the system cost while energy efficiency utilization is decreased.

System reliability is measured by the availability of the hybrid energy system to meet the demand load. System availability is the percentage of time that a power system is able to meet the load requirement(Sandia National Laboratories, 1995). Failures and maintenance time are the major contributors to decreasing system availability for any energy system. However, availability takes on added uncertainty for PV systems due to the variability of the system's fuel source. An estimate of the average amount of solar radiation available is required for the design of PV system. Using the average solar radiation value implies that in a year with above average solar radiation, the system may not experience downtime.

B. *Economic analysis*

The cost breakdown of PV/battery/diesel hybrid energy system based on thediscount rate of 4.25% and a fuel price of $0.50 as a case study, and within the project lifetime is presented in Table 4. The bulk of the total net present cost (NPC) comes from thebattery for PV/battery/generator hybrid energy system. The total initial capital cost which is paid at the beginning of the project is $31,677 (₦8.9m), as telecommunications operators in Nigeria have the capacity to make this initial investment. The cost of PV accounts for 29.84% of the initial capital cost of the system, while generator, battery, and converter account for 8.5%, 57%, and 4.55% respectively. The cost of the charge controller and cost of wiring was not considered in this study. The bulk of the replacement cost goes to the system component with short operational lifetime (the batteries). The replacement cost of the batteries after 12 years of operation accounts for 92% while that of the converter accounts for only 8%. Each system component has a salvage value at the end of the project lifetime.

The operation and maintenance cost of each system component occur each year of the project lifetime. The annual operation and maintenance cost of the system during the projects lifetime is $6,743(₦1.9m)as shown in Table 4, with the O&M of the PV and battery accounting for 55.44% and 42.41% respectively. The O&M of the generator accounts for only 0.37 % because 89.2% of the total electricity generated comes from the PV. Hence, the generator runs for a short period of time (305 hours/year).

The NPC of the system is the difference between the present value of all the costs that it incurs and the present value of all the revenue that it earns over its lifetime(Alsharif et al., 2015). Costs include initial capital cost, replacement cost, and operation and maintenance cost while revenue includes salvage value. The sum of the discounted cash flows in each year of the project life is equal to NPC. The battery accounts for 55.34% of the total NPC. This is as a result of the replacement cost of the battery after 12 years, which adds to the NPC. PV, generator, and converter account for 28.1%, 11.67%, and 4.94% respectively.

C. *Greenhouse gas (GHG) emission analysis*

The carbon dioxide and other pollutant emissions released by different hybrid energy systems are compared and presented in Table 5. It is observed from this table, that the carbon dioxide and other pollutants emitted significantly dropped by using PV/battery/generator hybrid energy system.PV/battery/generator system contributed 1,123kg, 2.77kg, 2.26kg and 24.73kg of carbon dioxide, carbon monoxide, sulphur dioxide and nitrogen dioxide of GHG emission per year respectively. On the other hand, the diesel generator only system emitted 15,316kg, 37.81kg, 30.76kg and 337.35kg of carbon dioxide, carbon monoxide, sulphur dioxide and nitrogen oxide of GHG per year. Table 5 also shows that the amount of unburn hydrocarbon and particulate matter emitted from diesel generator only and generator/battery system is more are more than the amount emitted from the PV/battery/generator system.

In addition, the emitted pollutants from hybrid energy systems with battery storage are observed to be lower than those without battery storage. Therefore, the PV/battery/generator hybrid energy system emitted the least greenhouse gases and other pollutants in addition to being the most economically viable solution to supply electricity to telecommunications BTS site.

VIII. Conclusion

This study carried out a technical and economic investigation of a standalone photovoltaic/battery/diesel hybrid energy system for GSM base station located in Lagos Nigeria using HOMER pro software. The results reveal that the PV/battery/generator hybrid energy system is the most suitable option at the current interest rate and diesel price in Nigeria. The cost of producing electricity with the hybrid energy system is considerably cheaper than using the conventional diesel generator only system with or without batteries. Even if the current power situation improves in Nigeria, the cost of national grid extension may make it difficult for telecommunications industries to have access to grid-connected electricity.

The reliable supply of cost-effective electricity through the use of PV/battery/generator hybrid energy system can improve the quality of service, by providing 24hour daily service to subscribers. The costs saved can also be used for equipment upgrade to improve the quality of service. Furthermore, greenhouse gas emissions can also be reduced by using hybrid energy systems, which is not only good for the environment but also could minimize health hazards from diesel generator only based systems. The method used and the finding of this study can also be implemented to other geopolitical zones in Nigeria and neighbouring countries with global solar radiation similar to the one considered in this work using sensitivity analysis. The knowledge gained from this study and the method used may be valuable to advice telecommunications operators on more reliable and cost effective way of supplying electricity to BTS sites using PV/battery/generator hybrid energy system instead of diesel generator only system.

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