Optimal Operational Strategy for PV/Wind-Diesel Hybrid Power Generation System with Energy Storage

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ABSTRACT

Telecommunications industry requires efficient, reliable and cost-effective hybrid power system as alternative to the power supplied by diesel generator. This paper proposed an operational control algorithm that will be used to control and supervise the operations of PV/Wind-Diesel hybrid power generation system for GSM base station sites. The control algorithm was developed in such a way that it coordinates when power should be generated by renewable energy (PV panels and Wind turbine) and when it should be generated by diesel generator and is intended to maximize the use of renewable system while limiting the use of diesel generator. Diesel generator is allocated only when the demand cannot be met by the renewable energy sources including battery bank. The developed algorithm was used to study the operations of the hybrid PV/Wind-Diesel energy system. The control simulation shows that the developed algorithm reduces the operational hours of the diesel generator thereby reducing the running cost of the hybrid energy system as well as the pollutant emissions. With the data collected from the site, a detailed economic and environmental analysis was carried out using micro power optimization software homer. The study evaluates savings associated with conversion of the diesel powered system to a PV/Wind-Diesel hybrid power system.

Keywords: *Base Station Site, Control Strategy, HOMER, Hybrid System, Optimization Algorithm, Pollutant Emission, Power Supply, Renewable Energy, University of Nigeria*

INTRODUCTION

Power supply is one of the critical challenges the telecom operators confront in deploying their networks. At present the problem of poor electricity supply experienced at the telecom installations in Nigeria is being tackled by using diesel generators. These generators, however, are associated with many problems. These include, among other things, noise pollution emanating from the generators and environmental pollution. Diesel generators exhaust harmful hydrocarbons in the atmosphere during operations. The operation and maintenance is relatively costly which typically accounts for 35 percent of the Total Cost of Ownership (TCO)

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(ALCATEL-LUCENT, 2009) of a Base Transceiver Station (BTS). Mobile Telecommunication of Nigeria (MTN), one of the four mobile telecoms operators in Nigeria with 4,798 base stations spends a whooping $82.8 million on generator acquisition almost every three years and $3.5 million monthly on diesel oil and generator maintenance (IT News Africa, 2010). This puts the Operating Expenditure (OPEX) of generators and diesel at about $69 million annually. Engr. Eyo Ita advanced that global system for mobile communication (GSM) operators had spend over $3,086.42 (N500, 000) on diesel generators in each of their base stations - roughly 520 - with costs being transferred to subscribers in terms of billing (Melford, 2003). Taking into consideration the excess cost of normal operation that the utilization of diesel generating sets brings to the operators, it is inevitable that consumers pay more for mobile service (Ani, & Emetu, 2013a). Apart from high-call-cost that is blamed on high running cost, even poor services is also linked with use of diesel generating set and this could be true if no mischief is intended because generating sets have to be periodically maintained besides, even though seldom, breakdown maintenance. Thus, it has become increasingly evident that diesel generator powered stations are becoming a much less viable option for network operators.

Renewable energy sources system is an option which would have been the best for network operators, but it cannot provide a continuous source of energy due to the low availability during different seasons. Hybridizing diesel with renewable energy sources (solar and/or wind power) will be one method of reducing call-cost and improving the services of the wireless telephony from the angle of powering the base station sites. This will allow telecom companies to circumvent rising energy costs and realize an excellent Return on Investment (ROI) and make communications more accessible and again reduce the environmental impact. Hybrid power system is therefore proposed to solve the aforementioned problems.

Problem Statement

From the above overview, it is evident that lack of grid power supply in rural Nigeria poses great challenges to all stakeholders in the telecommunications industry. Regrettably, available solutions can best be described as begging the issues, with much emphasis on conventional energy supplies (diesel generators). Little or no attention has been paid to the exploitation of all other available energy (renewable) resources in rural areas and the latest technologies in the field. It has been established that the main cost of telecommunication accrues from energy consumption. Renewable energy is believed to contribute significantly to the reduction of this energy cost, if properly integrated into the BTS energy sources. Hybrid Power Systems (HPSs) have been described as among the popular cost-saving renewable energy applications in the telecommunications industry. But till date these systems (HPSs) have found little or no applications in Nigeria. This may be attributed to the lack of information on the necessary site and system parameters required to design suitable HPSs to meet given loads of BTS sites.

Hybrid Power Systems (HPS)

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/or fuel generators). The useful components of hybrid systems considered in this study are the diesel generator, the solar photovoltaic panels and wind turbine generator. A diesel generator can provide energy at any time, whereas energy from PV and wind is greatly dependent on the availability of solar radiation and wind speed, respectively (Wichert, 1997; Yu, Pan, & Xiang, 2005). This makes the system (generator) more reliable, and can be used to operate when PV and/or wind fail to satisfy the load and when the battery storage is depleted.

The major concern in the design of an electric power system that utilizes renewable energy source is the accurate selection of system components that can economically satisfy the load demand. Optimally sizing of the components is not enough to get the maximum performance of the hybrid as the problems getting complicated when power supplied by the renewable unable to meet the load demand. The use of battery for storage and power supply and the question of when to start the back-up generator require proper algorithms for operation strategy. In the above optimization problem, an operational strategy for power generation was developed that coordinates when power should be generated by renewable energy (PV panels and Wind turbine) and when it should be generated by diesel generator and is intended to maximize the use of renewable system while limiting the use of diesel generator.

The purpose of this study is to develop an operational control algorithm that will be used to control and supervise the operations of PV/Wind-Diesel hybrid power generation system with energy storage for GSM base station site. The aim of the operational control strategy design is to minimize the high running cost and the poor services experienced in our network; through utilizing the renewable energy sources to the maximum extent while limiting the use of diesel generator.

Energy Consumptions

In identifying the energy consumption at GSM Base Station sites and assessing the impact of various operational strategies, a macro Base Transceiver Station (BTS) was used as a model. A BTS is a tower or mast mounted with telecommunication equipment (e.g. antenna, radio receiver and transmitters at the top of the mast) that enables the transmission of mobile signals (voice and data). At the bottom of each tower, there is a shelter with additional transmission equipment, air conditioning, battery racks and – for those that are off-grid or with unreliable electricity supply – in a separate room, the diesel generator (Ani & Emetu, 2013a). A BTS site load profile depends on multiple parameters including Radio Equipment, Antenna, Power Conversion Equipment, Transmission Equipment, etc. Therefore, it is important to outline an accurate power profile in order to select the energy components and their sizing. The energy consumption of the various components at a typical RBS site has been categorized by Pierre (2006), Roy (2008), Willson (2009), GSMA (2009) as follows:

1. Radio Equipment:
    - Radio Unit [Radio Frequency (RF) Conversion and Power Amplification] = 4160W;
    - Base Band [Signal Processing and Control] = 2190W;
2. Power Conversion Equipment:
    - Power Supply & Rectifier = 1170W;
3. Antenna Equipment:
    - RF feeder = 120W;
    - Remote Monitoring and Safety (aircraft warning light) = 100W;
4. Transmission Equipment:
    - Signal Transmitting = 120W;
5. Auxiliary Equipment:
    - Security and Lighting = 200W;
6. Climate Equipment:
    - Air Conditioning = 2590W.

Load Variation of the GSM Base Station Site

The slight changes as well as the flat lines for extended periods of time in Figures 1 and 2 are realistic of daily electricity consumption of the GSM base station site on study. These facilities (Radio Equipment, Power Conversion Equipment, Antenna Equipment and Transmission Equipment) were modeled as Radio Base Station Equipment, while climate and auxiliary equipment are modeled as Climate & Auxiliary Equipment, as shown in Figures 1 and 2, respectively. All the facilities (Radio Equipment, Power Conversion Equipment, Antenna Equipment, Transmission Equipment, and climate equipment) at the base station site are all on for 24hrs (00:00h – 23:00h) except the Auxiliary Equipment (security light) that comes on only for 13hrs (18:00h – 7:00h). It is assumed that it is identical for every day of the year. The annual peak load of 10.67kW was observed between 18:00h and 07:00h, with 254Wh/day energy consumption. The daily average load variation for the base station site is shown in Figures 1 and 2 and Table 1.

Study Area

The study area was University of Nigeria, Nsukka (UNN) located in a valley on a plateau at an average elevation of approximately 500 metres above sea level in the town of Nsukka, about eighty kilometers North of Enugu (Post-graduate Studies Prospectus, 2010) at a specific geographical location of 6°51'56"N latitude and 7°24'22"E longitude (UNN geographical Location, 2012) with annual average solar daily radiation of 4.95kWh/m^2/d whereas its annual average wind is 2.1m/s. The data for solar and wind resources were obtained from the NASA Surface Meteorology and Solar Energy web site (NASA, 2010). The campus is located on 871 hectares of hilly savannah, and that is where this base station site is located. For this study, PV and Wind technology were considered in terms of renewable energy. Figures 3 and 4 shows the solar and wind resources profile of this location tabulated in Table 2.

Figure 1. Daily profile of electricity consumption of radio base station equipment

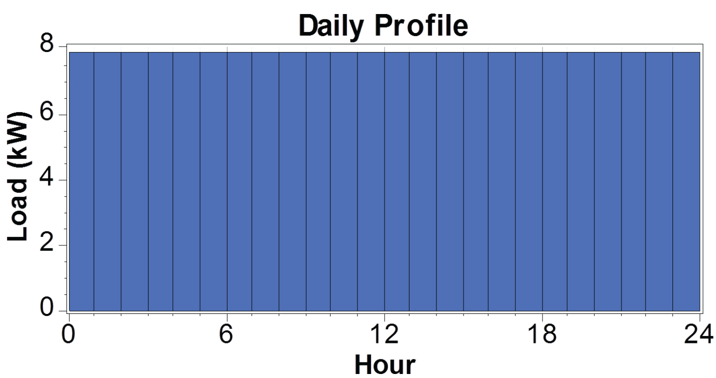


Figure 2. Daily profile of electricity consumption of climate and auxiliary equipment

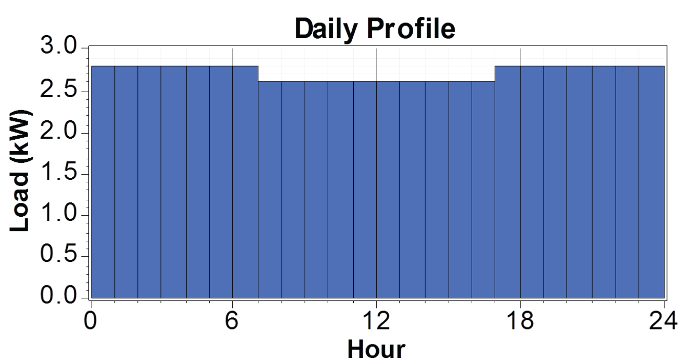


Table 1. The electrical load (daily load demands) data for the base station site

Time	Daily Load Demands								Total/Hr
	Radio Unit	Base Band	Power Supply and Rectifier	RF Feeder	Remote Monitoring and Safety	Signal Transmitting	Security and Lighting	Air Conditioning	
00-01	4160	2190	1170	120	100	120	200	2590	10650
01-02	4160	2190	1170	120	100	120	200	2590	10650
02-03	4160	2190	1170	120	100	120	200	2590	10650
03-04	4160	2190	1170	120	100	120	200	2590	10650
04-05	4160	2190	1170	120	100	120	200	2590	10650
05-06	4160	2190	1170	120	100	120	200	2590	10650
06-07	4160	2190	1170	120	100	120	200	2590	10650
07-08	4160	2190	1170	120	100	120		2590	10450
08-09	4160	2190	1170	120	100	120		2590	10450
09-10	4160	2190	1170	120	100	120		2590	10450
10-11	4160	2190	1170	120	100	120		2590	10450
11-12	4160	2190	1170	120	100	120		2590	10450
12-13	4160	2190	1170	120	100	120		2590	10450
13-14	4160	2190	1170	120	100	120		2590	10450
14-15	4160	2190	1170	120	100	120		2590	10450
15-16	4160	2190	1170	120	100	120		2590	10450
16-17	4160	2190	1170	120	100	120		2590	10450
17-18	4160	2190	1170	120	100	120		2590	10450
18-19	4160	2190	1170	120	100	120	200	2590	10650
19-20	4160	2190	1170	120	100	120	200	2590	10650
20-21	4160	2190	1170	120	100	120	200	2590	10650
21-22	4160	2190	1170	120	100	120	200	2590	10650
22-23	4160	2190	1170	120	100	120	200	2590	10650
23-00	4160	2190	1170	120	100	120	200	2590	10650
Total	99840	52560	28080	2880	2400	2880	2600	62160	253400

Solar Radiation Variation

In the months of September, October, November, December, January, and February, the solar radiation increases with differences from month to month as (0.28), (0.38), (0.54), (0.35), (0.22), and (0.06) respectively. While in the months of March, April, May, June, July, and August, the solar radiation decreases with differences from month to month as (0.17), (0.32), (0.31), (0.4), (0.4), and (0.23) respectively.

Wind Speed Variation

In the months of June, July, and August, the wind speed increases with differences from month to month as (0.2), (0.3), and (0.1) respectively. In the months of September and October, the wind speed decreases with differences from month to month as (0.2) and (0.6) respectively. In the month of November, the wind speed increases with differences from month to month as (0.3), and decreases in the month of December as

Figure 3. Solar daily radiation profile for University of Nigeria, Nsukka

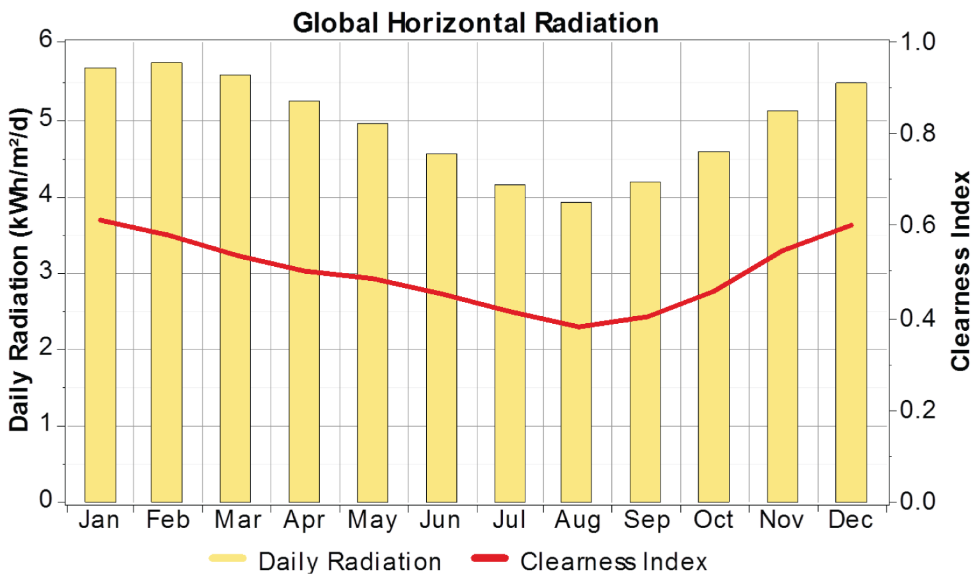
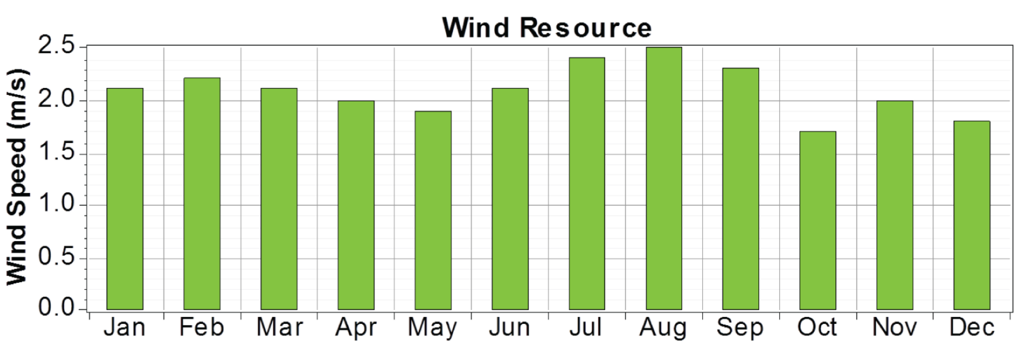


Figure 4. Wind speed profile for University of Nigeria, Nsukka



(0.2). In the months of January and February, the wind speed increases with differences from month to month as (0.3) and (0.1) respectively. In the months of March, April, and May, the wind speed increases with differences from month to month as (0.1), (0.1), and (0.1) respectively. The difference in months falls in the range of 0.1 - 0.3 except in the month of October which is 0.6.

These differences are due to earth's movement (rotation of the earth).

As can be seen from the previous figures, the wind speed is highest in the rainy season, particularly in the months of July, August and September, and thus compensates for the short fall in solar radiation in this season (rainy season), when the sun shine is quite low. Also, during the day when the sun shine is plenty, the excess energy from the sun is stored by the storage components (batteries) of the system and

Table 2. Solar and wind resources for University of Nigeria, Nsukka (Ani, to be published)

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

eventually used together with wind to provide power at nights when the sun shine is low.

METHODOLOGY

Hybrid Energy System Configuration

The proposed hybrid renewable is consists of solar photovoltaic (PV) panels, and wind turbine. Conventional Energy (CE) source such as diesel generator with battery and rectifier (battery charger) are added as part of back-up and storage system. This proposed system is shown in Figure 5. The study involves a theoretical load demands as shown in Table 1 and Figures 1 and 2. The load is assumed constant all year.

To serve the load, electrical energy can be produced either directly from PV (I_{PV}), wind turbine (I_{WT}), diesel generator (I_{ch_AC}), or indirectly from the battery (I_{bat}). A Hybrid Controller is used to coordinates when power should be generated by renewable energy (PV panels and Wind turbine) and when it should be generated by diesel generator and to control the charge and discharge current from the battery. A battery charger is used to convert AC (I_{ch_AC}) current from diesel generator to DC (I_{ch_DC}) current to charge the battery and serve the load.

Model Development

The following equations, used in the algorithms, are based on equations used by HOMER (2012), Kamaruzzaman, et al. (2008), and Lambert (2009) to derive the power supplied by renewable, battery charging and discharging.

The PV Power:

$$P_{PV} = \eta_{PV} \cdot N_{PVP} \cdot N_{PVS} \cdot V_{PV} \cdot I_{PV} \tag{1}$$

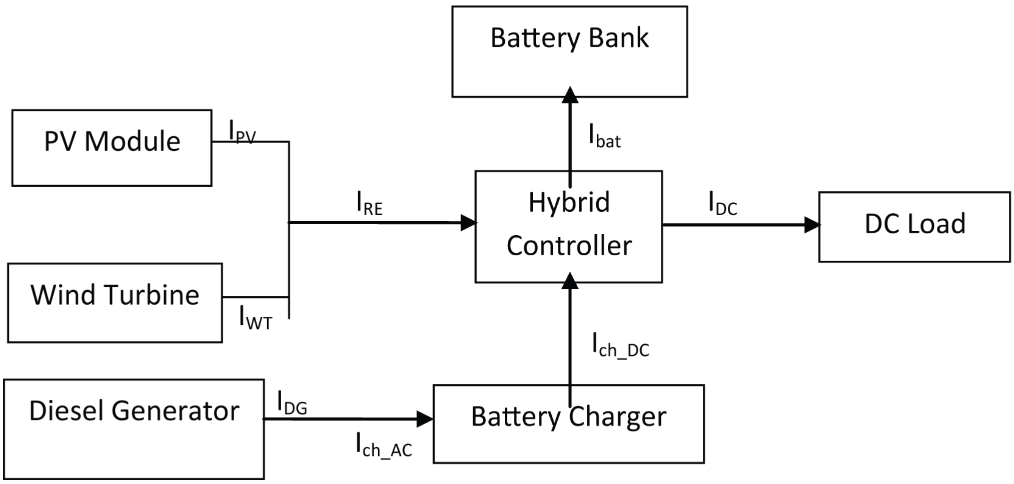
The Wind Power:

$$P_{WT} = \eta_{WT} \cdot \eta_g \cdot 0.5 \cdot \rho_a \cdot C_P \cdot A \cdot V_r^3 \tag{2}$$

Total Renewable Power:

$$P\left(t\right) = \sum_{PV=1}^{n_{PV}} P_{PV} + \sum_{WT=1}^{n_{WT}} P_{WT} \tag{3}$$

Figure 5. Proposed PV/wind-diesel hybrid energy system model



Battery Discharging:

$$P_B(t) = P_B(t-1)\cdot(1-\sigma) - \left[\frac{P_{BR}(t)}{P_{BL}(t)}\right] \quad (4)$$

Battery Charging:

$$P_B(t) = P_B(t-1)\cdot(1-\sigma) + \left[P_{BR}(t) - P_{BL}(t)\right]\cdot\eta_{BB} \quad (5)$$

where:

- V_{PV} - Operating voltage of PV panels;
- N_{PVS} - Numbers of PV panels in series;
- η_g - Efficiency of the gravitational acceleration;
- P_{WT} - Wind turbine power output;
- η_{WT} - Efficiency of wind turbine;
- ρ_a - Density of air;
- C_P - Power coefficient of wind turbine;
- A - Wind turbine swept area;
- V_r^3 - wind velocity;
- P_{PV} - PV power output;
- η_{PV} - Conversion efficiency of PV;
- N_{PVP} - Number of PV panels in parallel;
- N_{PVS} - Number of PV panels in series;
- I_{PV} - Operating current of PV panels;
- P_B - Battery energy at time interval;
- P_{BR} - Total energy generated;
- σ - Self discharge factor;
- P_{BL} - Load demand at time interval;
- η_{BB} - Battery charging efficiency.

In the optimization procedure, the sizes of system components are decision variables, and their costs and the pollutant emissions are objective function.

Objective Function

The objective functions to be minimized are the total costs ($) and the pollutant emissions.

Costs

The costs objective function is the total Net Present Cost (*NPC*) of the system, which includes the cost of the initial investment plus the discounted present values of all future costs throughout the total life of the installation. In the following paragraph, the costs taken into account are indicated. A more detailed description of its calculation can be found in Ani & Nzeako (2012), and Ani (2013).

The annualized cost of the components of PV panels, the wind turbine, the batteries, the inverter, the charge regulator, and the diesel generator are:

- Annualized capital cost of the components;
- Annualized replacement cost of the components;
- Annual O and M cost of the components;
- Annual fuel cost (generator).

Annualized Capital Cost

The annualized capital cost of a system component is equal to the total initial capital cost multiply by the capital recovery factor.

Annualized Replacement Cost

The annualized replacement cost of a system component is the annualized value of all the replacement costs occurring throughout the lifetime of the project, minus the salvage value at the end of the project lifetime. The salvage value of the component at the end of the project lifetime is proportional to its remaining life.

Annual Operating and Maintenance Cost

The operating and maintenance cost is the annualized value of all cost and revenues other than initial capital costs.

Annual Fuel Cost

Annual fuel cost (generator) is the cost of the fuel consumed throughout the life of the system.

Pollutant Emissions

In order to measure the pollutant emissions, the total amount of kg of all the pollutant emissions (CO_2, CO, UHC, PM, SO_2, and NO_x) produced by the hybrid system throughout one year is the correct measure of the pollutant emissions and, therefore, it can be used as the objective to be minimized. This value depends upon the characteristics of the diesel generator and of the characteristics of the fuel, and it usually falls in the 2.4-2.8 kg/l range (Sonntag, Borgnakke & Wylen, 2002; José, Rodolfo & David, 2005).

Measuring the Pollutant Emissions

The equation shown in Box 1, used by Lambert & Gilman (2004) was used to calculate the Pollutant emissions.

Power Reliability

The objective of the proposed Optimization Algorithm is to optimize the availability of energy source to the loads according to their priority. It is also proposed to maintain a fair level of energy storage in battery to meet peak load demand (together with the PV array and wind); during low or no radiation periods and when wind speed is very less. Restrictions are usually included that are applied to reliability. Because of the intermittent of renewable resources (solar radiation and wind speed characteristics), which highly influence the resulting energy production, power reliability analysis has been considered as an important step in any system design process. Several approaches are used to achieve the optimal configurations of hybrid systems in terms of technical analysis. Among these methods, we find the least square method applied by Kellogg et al. (1996), Borowy & Salameh (1994), the trade-off method (Elhadidy & Shaahid, 1999; Gavanidou & Bakirtzis, 1993) and the technical approach also called loss of power supply probability (LPSP) (Abouzahr & Ramakumar, 1990, 1991; Hongxing, Lu, & Burnett, 2002; Yang & Burnett, 2002).

A reliable electrical power system means a system has sufficient power to feed the load demand during a certain period or, in other words, has a small loss of power supply probability (LPSP). LPSP is defined as the probability

Box 1.

$$E_{ann} = \frac{M_{CO_2} + M_{CO} + M_{UHC} + M_{PM} + M_{SO_2} + M_{NO_X}}{1000} \quad (6)$$

where:

M_{CO_2} =annual emissions of CO_2 [kg/yr];

M_{CO} =annual emissions of CO [kg/yr];

M_{UHC} =annual emissions of unburned hydrocarbons (UHC) [kg/yr];

M_{PM} =annual emissions of particulate matter (PM) [kg/yr];

M_{SO_2} =annual emissions of SO_2 [kg/yr];

M_{NO_x} =annual emissions of NO_x [kg/yr].

that an insufficient power supply results when the hybrid system (PV array, wind turbine and battery storage) is unable to satisfy the load demand (Yang, Burnett & Lu, 2003). It is a feasible measure of the system performance for an assumed or known load distribution. A LPSP of 0 means the load will always be satisfied; and an LPSP of 1 means that the load will never be satisfied. In this study, the system reliability model is developed according to the concept of LPSP and was imbedded in the system operation strategy; during bad renewable resource period the diesel generator compensates.

Configuration of the Stand-Alone Hybrid Energy System

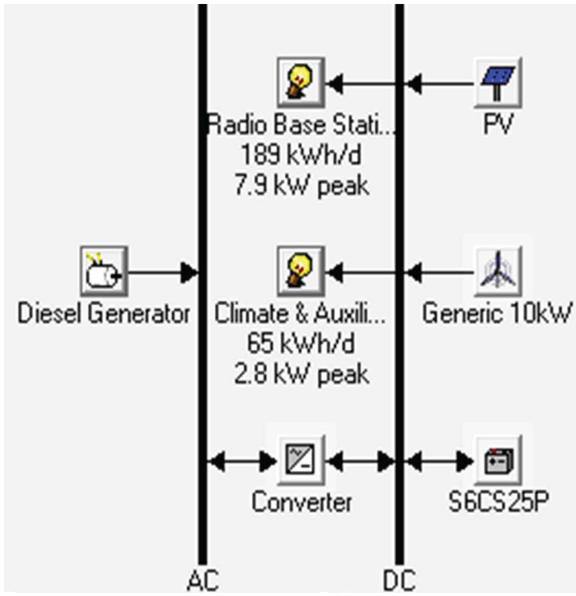
The design of a stand-alone hybrid system is site specific and depends on both the resources available and the load demand (Ani & Nzeako, 2002). A typical stand-alone hybrid PV/Wind-Diesel system has an electricity generation device equipped with the battery bank, the charging controller and the AC/DC converter (Kamaruzzaman et al., 2009). The energy system proposed for the GSM base station site consists of solar PV, Wind turbine and diesel power as depicted in Figure 6. The base station site in study has 254Wh/day energy consumption with 10.67kW peak demand load. The energy system proposed consists of 10.7kW solar PV array, 10kW Generic wind turbine, 16kW diesel generator, 96 Surrette 6CS25P Battery Cycle Charging, and a 25 kW AC/DC converter.

Operational Control Strategies

In hybrid systems with batteries and without diesel generators, the dispatch strategy is very simple: the battery charges if the renewable energy is in excess after meeting the demand, and the battery discharges if the load exceeds the renewable energy. However, the control strategies of a hybrid system can become very complex if the system includes a diesel generator and batteries (Bernal-Agustín & Dufo-Lo´pez, 2009). Therefore, it is necessary to determine how the batteries are charged and what element (batteries or diesel generator) has priority to supply energy when the load exceeds the energy generated from renewable sources.

Barley et al. (1995) proposed various strategies for the operation of hybrid PV–diesel–battery systems. One-hour intervals are considered, in which the system parameters remain constant. They also consider ideal batteries, without taking into account losses or the

Figure 6. Proposed stand-alone hybrid PV/wind-diesel system with energy storage for GSM base station site



influence of the cycles in their lifespan. Three basic control strategies proposed:

- **Zero-charge strategy (Load Following Diesel):** the batteries are never charged using the diesel generator. Therefore, the Setpoint of the State of Charge (SOC_Setpoint) is 0%;
- **Full cycle-charge strategy:** The batteries are charged to 100% of their capacity every time the diesel generator is on (SOC_Setpoint = 100%);
- **Predictive control strategy:** The charging of the batteries depends on the prediction of the demand and the energy expected to be generated by means of renewable sources, resulting in a certain degree of uncertainty. With this strategy, the energy loss from the renewable energies tends to decrease.

An optimum point for the SOC_Setpoint between 0 and 100% was used for this study in such a way that the total operation cost of the system was minimal.

In other words, the strategy lies between zero-charge and full cycle-charge. Barley & Winn (1996) improved the control strategies model of Barley et al. (1995), introducing new parameters that have become of great importance in the control strategies of the HOMER software tool. The critical discharge power (Ld) is the value from which the net energy (energy demanded by the charges minus energy supplied by the renewable sources) is more profitable when supplied by means of the diesel generator than when supplied by means of the batteries (having previously been charged by the diesel generator). The authors propose four control strategies:

- **Frugal dispatch strategy:** If the net demand is higher than Ld, the diesel generator is used. If it is lower, the batteries are used;
- **Load following strategy:** The diesel generator never charges the batteries;
- **SOC_Setpoint strategy:** The diesel generator is on at full power, attempting to

charge the batteries until the SOC_Setpoint is reached;

- **Diesel operation strategy:** At maximum power for a minimum time (charging the batteries).

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.

In this study, the control strategies used are based on the strategies described by Barley & Winn (1996) and used by the HOMER program (HOMER, 2012).

CONTROL ALGORITHM FOR POWER MANAGEMENT OF HYBRID SYSTEM

Hybrid System Operating Strategy for the Hybrid PV/Wind-Diesel System

When the renewable sources produce less energy than demanded (wind speed and the solar radiation are low), the deficit power should be supplied by the battery bank. When the state of charge of battery bank reaches its minimal level (40%), then the diesel generator functions. The surplus of energy produced by the diesel generator and the renewable energy sources (variation of the climatic data) is stored in the battery bank.

Optimization of Operational Strategy

As is well-known, a good operation of a hybrid system can be achieved only by a suitable control of the interaction in the operation of the different devices. An exhaustive knowledge of the management strategies to be chosen in the preliminary stage is therefore fundamental to optimize the use of the renewable sources, minimize the wear of batteries, consume the smaller possible quantity of fossil fuel (Seeling-Hochmuth, 1997; Seeling, 1995).

The method of operational strategy used here is sliding control, using a hybrid controller. Taking PV energy generation as the primary source of energy, wind energy generation as the secondary source, battery as the supplement and diesel generator as the back-up. The system moves between different modes dependant on the power needed by the load and the power able to be supplied by each of the sources. Figure 7 outlines the flow between the different modes.

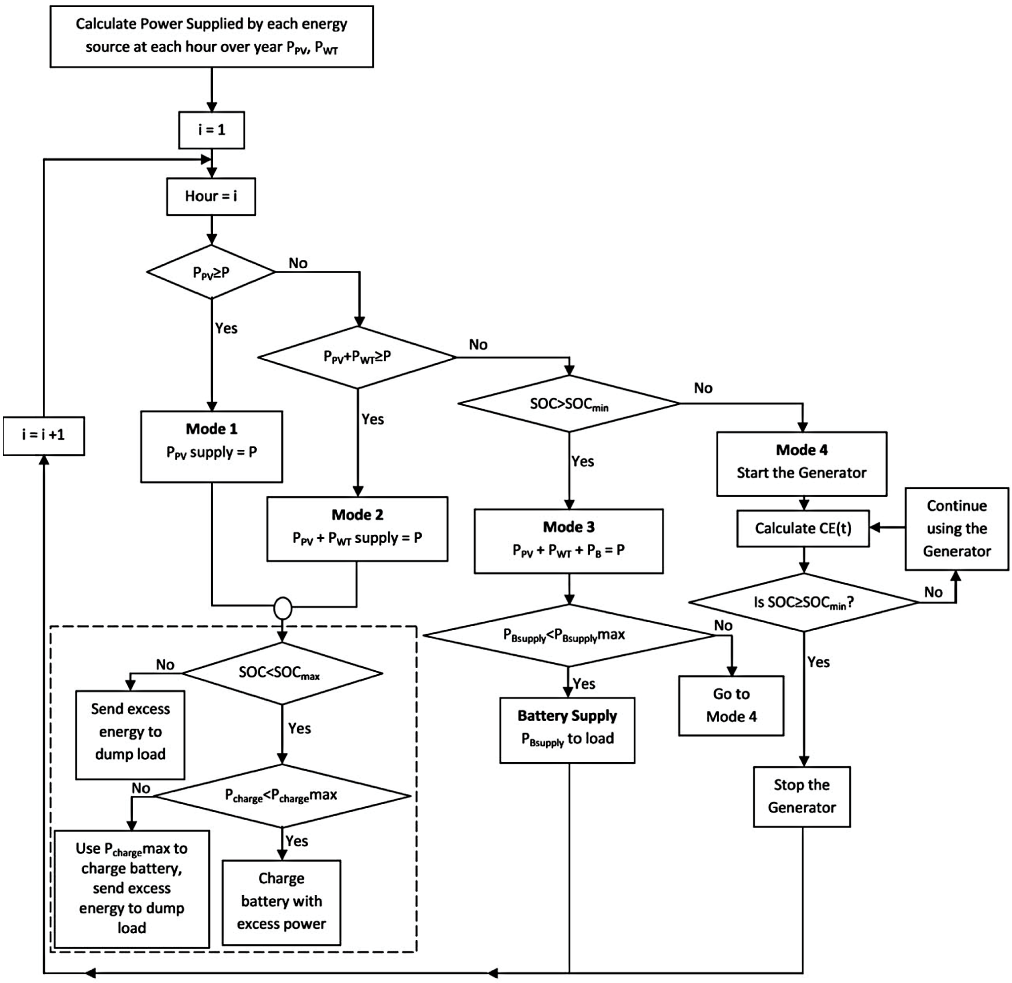
Initially, the power supplied by the PV panels and the wind turbines is calculated for each hour over the year and stored in matrices, so that power availability in each hour can be accessed easily. The control process then begins at hour 1. The first decision loop looks at the power that can be supplied by the PV panel in this hour and the power required by the load. If the power generated by the PV panel is sufficient to match the load, the system enters Mode 1. If the PV panel cannot provide sufficient energy for the load, the control looks at the total amount of energy that can be provided by the PV panel and the wind turbine together. If these together are sufficient to provide power for the load, the system enters Mode 2. If the combined energy supplied by the PV panels and the wind turbine is not sufficient to supply the load, the state of charge of the battery is considered. If the battery SOC is not at its minimum value, the system enters Mode 3. If the SOC of the battery is already at its minimum, then the system enters Mode 4.

The detailed mode of operational control (sliding) is given below.

Mode 1

Mode 1 uses solely the energy generated by the PV panel to supply the load. When the system is in mode 1, sometimes the energy available from the PV panel might be in excess of what is needed by the load and therefore the amount of energy supplied to the load must be matched to the load demand. This is called sliding control.

Figure 7. Flowchart of modes of control for Hybrid PV/wind-diesel energy system with energy storage



As the wind turbine are connected to the system, but not used to supply the load in this mode, the energy generated by the wind turbine as well as any excess energy from the PV panels can be used to charge the battery.

If the SOC of the battery is at its maximum possible SOC value, the excess power is sent to a dump load [*Dump load* is a device to which power flows when the system batteries are too full to accept more power], which can be defined according to the base station site's need, charging of phones, etc., or interfaces the hybrid energy system with the utility grid to feed power. The flowchart inside the dotted line shown in Figure 7 is the charging control circuit.

If the SOC of the battery is less than the maximum SOC, the amount of excess power is checked. (Battery-Experts, 2011) advise not using a charging current of more than 60A. The power is then checked to make sure that the current used to charge the battery will be less than 60A. If the excess power is less than this maximum charging power, the battery is charged with the full excess power. If the power is above that of maximum charging for the battery, the maximum battery charge power is used to charge the battery and the excess is used for the dump load.

Mode 2

Mode 2 uses the power of the PV panels plus the power of the wind turbine to supply the load. In mode 2, if the energy available from the PV panel and the wind turbine combined is in excess of what is needed by the load, then the full power available from the PV panels is used to supply the load and the power from the wind turbine is supplied using sliding control to match the power required by the load. The excess energy from the PV panels and the wind turbine can be used to charge the battery, as in mode 1.

Mode 3

The system enters mode 3 when the power generated by the PV panels and wind turbine is not sufficient to supply the load, but the SOC of the battery is greater than the minimum amount and therefore the battery is able to supply power to the load. The full power generated by the PV panels and wind turbine is supplied to the load. There is however a possibility that the amount of power required by the load is not able to be supplied by the battery. Manufacturers specify that the batteries should not supply more than 80A current, and therefore the amount of power needed to be supplied by the batteries must be checked before it can supply that amount. If the load power needed to be supplied by the batteries is below this maximum, the battery then supplies the load power. Otherwise, load cannot be supplied and it enters mode 4.

Mode 4

When the system is in mode 4, the load cannot be supplied by the renewable energy sources. The combined power of the wind turbine and the PV panels is not sufficient to supply the load and the battery is at its minimum SOC and therefore cannot be used to supply the deficit of power required, and the hybrid controller connects (starts the generator) to the diesel generator to enable the necessary load to be met.

In Modes 1, 2, and 3 sliding mode control is used to ensure that the supply meets the load. This is done by monitoring the power needed by the load and the power of the power generating mechanism.

From this control simulation we are able to see the performance of the system over the course of the year; to see which modes the system spends most time in, the power supplied by each of the energy sources and the power required by the load. This is a very useful manner to check how the system is being supplied and which source of energy is the most proficient in supplying the load.

Hybrid System Controller

An operational control strategy is a Hybrid system controller that consists of certain predetermined control settings [time ($i = i + 1; i = 1 - 23$) and state of charge of battery] that are set when installing the system. Such settings concern the setpoint of when to switch on the diesel or not, based on certain values representing the system state, such as the battery state of charge and demand placed on the system. The time-independent controller setting in the developed design algorithm is shown in Figure 8.

RESULTS AND DISCUSSION

Tables 3 through 5 show how the demand is met by the hybrid energy system (PV, Wind and diesel generator) for three consecutive days. It shows how the sources were allocated according to the load demand and availability. The entire operations of the hybrid controller can be seen from Figure 7. It shows that the power from PV is fully utilized to supply the load demand as well as charging the battery during day times (mid-days). The charging and discharging of the battery bank is also shown.

Figure 8. Hybrid system controller block diagram (Ani & Emetu, 2013b)

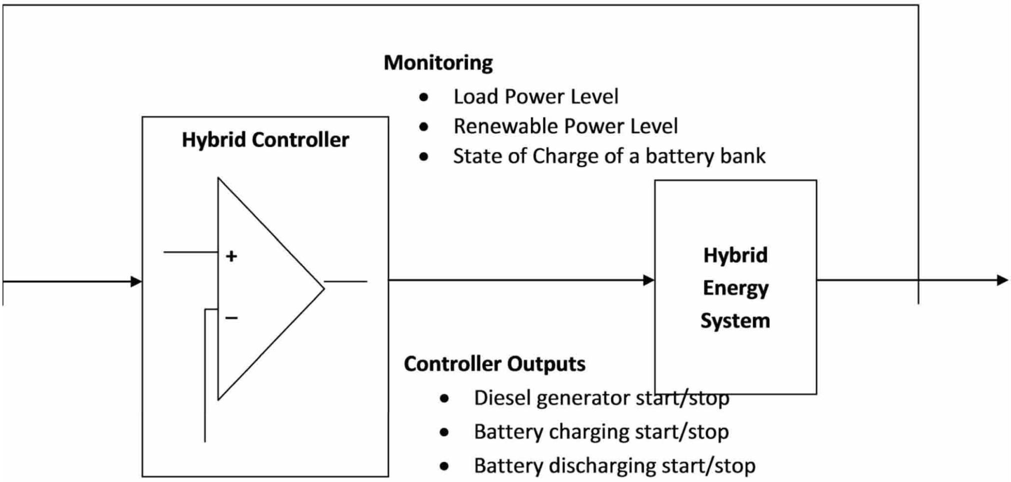


Table 3. Power demand met by the hybrid energy system (PV, Wind and diesel generator) in day one

Time (h)	Global Solar (kW/m²)	Incident Solar (kW/m²)	Wind Speed (m/s)	DC Load (kW)	PV Power (kW)	Generic 10kW (kW)	Diesel Generator (kW)	Rectifier Input (kW)	Rectifier Output (kW)	Battery Power (kWh)	Battery State of Charge (%)
0:00	0.000	0.000	2.068	10.667	0.000	0.000	16.000	16.000	13.600	2.933	75.604
1:00	0.000	0.000	1.935	10.667	0.000	0.000	16.000	16.000	13.600	2.933	75.801
2:00	0.000	0.000	2.606	10.667	0.000	0.000	16.000	16.000	13.600	2.933	75.999
3:00	0.000	0.000	2.211	10.667	0.000	0.000	16.000	16.000	13.600	2.933	76.196
4:00	0.000	0.000	2.790	10.667	0.000	0.030	16.000	16.000	13.600	2.963	76.395
5:00	0.000	0.000	3.049	10.667	0.000	0.086	16.000	16.000	13.600	3.019	76.598
6:00	0.000	0.000	1.710	10.667	0.000	0.000	16.000	16.000	13.600	2.933	76.795
7:00	0.001	0.000	1.590	10.667	0.000	0.000	16.000	16.000	13.600	2.933	76.992
8:00	0.100	0.136	2.188	10.467	1.307	0.000	16.000	16.000	13.600	4.439	77.291
9:00	0.299	0.350	2.159	10.467	3.369	0.000	16.000	16.000	13.600	6.502	77.728
10:00	0.443	0.470	3.337	10.467	4.522	0.148	16.000	16.000	13.600	7.803	78.253
11:00	0.492	0.486	2.767	10.467	4.685	0.025	16.000	16.000	13.600	7.843	78.780
12:00	0.900	0.957	2.651	10.467	9.215	0.001	16.000	16.000	13.600	12.348	79.611
13:00	0.963	1.014	3.038	10.467	9.769	0.084	16.000	16.000	13.600	12.985	80.484
14:00	0.505	0.481	2.639	10.467	4.630	0.000	0.000	0.000	0.000	-5.837	79.993
15:00	0.575	0.575	3.239	10.467	5.533	0.127	0.000	0.000	0.000	-4.808	79.589
16:00	0.606	0.659	3.243	10.467	6.345	0.128	0.000	0.000	0.000	-3.994	79.253
17:00	0.453	0.533	2.206	10.467	5.137	0.000	0.000	0.000	0.000	-5.330	78.805
18:00	0.246	0.346	1.767	10.667	3.328	0.000	0.000	0.000	0.000	-7.339	78.188
19:00	0.026	0.041	1.599	10.667	0.398	0.000	0.000	0.000	0.000	-10.270	77.325
20:00	0.000	0.000	2.197	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	76.428
21:00	0.000	0.000	2.756	10.667	0.000	0.023	0.000	0.000	0.000	-10.644	75.534
22:00	0.000	0.000	3.184	10.667	0.000	0.115	0.000	0.000	0.000	-10.552	74.647
23:00	0.000	0.000	2.945	10.667	0.000	0.064	0.000	0.000	0.000	-10.604	73.756

Battery power indicates the operating strategy of the hybrid system: charging (power positive) or discharging (power negative).

Hybrid controller switches the batteries into charging mode whenever excess power is available from the sources, and switch to discharging mode whenever there was a shortage of power from sources. It shows that the hybrid controller utilizes the battery bank effectively.

In day three shown in Table 6, it was observed that the demand of 10.467kW that occurred at 12:00hr was met by all the energy sources along with the battery bank. During that time excess power was available from the renewable energy sources (PV/Wind) and can be used to charge the battery.

It was mentioned in the Figure 8, that the hybrid controller turns off the diesel generator

Table 4. Power demand met by the hybrid energy system (PV, Wind and diesel generator) in day two

Time (h)	Global Solar (kW/m²)	Incident Solar (kW/m²)	Wind Speed (m/s)	DC Load (kW)	PV Power (kW)	Generic 10kW (kW)	Diesel Generator (kW)	Rectifier Input (kW)	Rectifier Output (kW)	Battery Power (kWh)	Battery State of Charge (%)
0:00	0.000	0.000	1.844	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	72.859
1:00	0.000	0.000	3.040	10.667	0.000	0.084	0.000	0.000	0.000	-10.583	71.969
2:00	0.000	0.000	3.459	10.667	0.000	0.174	0.000	0.000	0.000	-10.493	71.087
3:00	0.000	0.000	2.988	10.667	0.000	0.073	0.000	0.000	0.000	-10.594	70.197
4:00	0.000	0.000	2.342	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	69.300
5:00	0.000	0.000	1.146	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	68.404
6:00	0.000	0.000	0.840	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	67.507
7:00	0.001	0.000	1.118	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	66.610
8:00	0.059	0.057	1.719	10.467	0.554	0.000	0.000	0.000	0.000	-9.914	65.777
9:00	0.256	0.277	2.918	10.467	2.664	0.058	0.000	0.000	0.000	-7.745	65.126
10:00	0.276	0.260	3.242	10.467	2.503	0.128	0.000	0.000	0.000	-7.836	64.467
11:00	0.399	0.379	2.492	10.467	3.648	0.000	0.000	0.000	0.000	-6.819	63.894
12:00	0.779	0.811	3.585	10.467	7.813	0.201	0.000	0.000	0.000	-2.454	63.688
13:00	0.905	0.946	3.327	10.467	9.109	0.146	0.000	0.000	0.000	-1.212	63.586
14:00	0.709	0.717	4.743	10.467	6.903	0.578	0.000	0.000	0.000	-2.986	63.335
15:00	0.327	0.302	4.263	10.467	2.906	0.339	0.000	0.000	0.000	-7.222	62.728
16:00	0.267	0.246	4.253	10.467	2.372	0.337	0.000	0.000	0.000	-7.759	62.076
17:00	0.201	0.187	3.865	10.467	1.803	0.258	0.000	0.000	0.000	-8.407	61.369
18:00	0.038	0.034	3.766	10.667	0.332	0.238	0.000	0.000	0.000	-10.098	60.520
19:00	0.022	0.026	3.267	10.667	0.252	0.133	0.000	0.000	0.000	-10.282	59.656
20:00	0.000	0.000	3.418	10.667	0.000	0.166	0.000	0.000	0.000	-10.502	58.773
21:00	0.000	0.000	2.576	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	57.877
22:00	0.000	0.000	1.894	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	56.980
23:00	0.000	0.000	0.732	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	56.083

Table 5. Power demand met by the hybrid energy system (PV, Wind and diesel generator) in day three

Time (h)	Global Solar (kW/m²)	Incident Solar (kW/m²)	Wind Speed (m/s)	DC Load (kW)	PV Power (kW)	Generic 10kW (kW)	Diesel Generator (kW)	Rectifier Input (kW)	Rectifier Output (kW)	Battery Power (kWh)	Battery State of Charge (%)
0:00	0.000	0.000	0.821	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	55.187
1:00	0.000	0.000	1.665	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	54.290
2:00	0.000	0.000	0.998	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	53.394
3:00	0.000	0.000	0.956	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	52.497
4:00	0.000	0.000	2.549	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	51.600
5:00	0.000	0.000	2.558	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	50.704
6:00	0.000	0.000	2.775	10.667	0.000	0.027	0.000	0.000	0.000	-10.640	49.809
7:00	0.002	0.000	3.754	10.667	0.000	0.235	0.000	0.000	0.000	-10.432	48.932
8:00	0.141	0.260	2.948	10.467	2.506	0.064	0.000	0.000	0.000	-7.897	48.269
9:00	0.417	0.543	2.828	10.467	5.227	0.038	0.000	0.000	0.000	-5.202	47.831
10:00	0.687	0.791	2.870	10.467	7.616	0.048	0.000	0.000	0.000	-2.804	47.596
11:00	0.940	1.025	2.522	10.467	9.866	0.000	0.000	0.000	0.000	-0.601	47.545
12:00	1.062	1.126	1.766	10.467	10.843	0.000	0.000	0.000	0.000	0.376	47.570
13:00	1.061	1.113	2.576	10.467	10.714	0.000	0.000	0.000	0.000	0.247	47.587
14:00	0.978	1.028	2.017	10.467	9.895	0.000	0.000	0.000	0.000	-0.572	47.539
15:00	0.846	0.901	2.282	10.467	8.679	0.000	0.000	0.000	0.000	-1.788	47.389
16:00	0.679	0.748	3.116	10.467	7.204	0.101	0.000	0.000	0.000	-3.162	47.123
17:00	0.464	0.544	2.626	10.467	5.234	0.000	0.000	0.000	0.000	-5.233	46.683
18:00	0.208	0.257	3.427	10.667	2.479	0.168	0.000	0.000	0.000	-8.021	46.009
19:00	0.043	0.165	2.972	10.667	1.591	0.070	0.000	0.000	0.000	-9.007	45.252
20:00	0.000	0.000	2.543	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	44.355
21:00	0.000	0.000	2.336	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	43.459
22:00	0.000	0.000	1.863	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	42.562
23:00	0.000	0.000	1.231	10.667	0.000	0.000	0.000	0.000	0.000	-10.667	41.665

when the load demand can be met together by the PV, wind and battery bank. For example on the typical day (day one), at 13:00 hours when the battery state of charge is 80%, the hybrid controller turns off the diesel generator and at 14:00 hours the hybrid controller allocates PV, wind and battery bank to supply the energy to the load without allocating the diesel generator.

During the day one, the hybrid controller allocated the diesel generator for 14 hours

Table 6. Comparison of simulation results of economic cost

Parameter	Existing System Diesel Only		Proposed Hybrid PV/Wind-Diesel System	
	Dollars($)	Naira(N)	Dollars($)	Naira(N)
Initial Cost	280,570	45,452,340	384,470	62,284,140
Operating Cost	1,759,724	285,075,288	1,478,858	239,574,996
Total NPC	20,464,460	3,315,242,520	17,346,854	2,810,190,348

(0:00hr – 13:00hr). The demand of the other remaining hours was met by the renewable energy sources (PV + wind) along with the battery bank. It reduces the operational hours of the diesel generator thereby reducing the running cost of the hybrid energy system as well as the pollutant emissions. It is observed that the hybrid controller allocates the sources optimally according to the demand and availability.

Tables 3 through 5 also show the contributions of the different renewable sources (PV and Wind) and the diesel generator and it was observed that the variation is not only in the demand but also the availability of sources. The diesel generator compensates the shortage.

ECONOMIC AND ENVIRONMENTAL ANALYSIS

With the data collected from the site, a detailed economic and environmental analysis has been carried out using micro power optimization software homer. The cost of all the components of the hybrid system used in this research work is presented in the previous work of the author (Ani & Nzeako, 2012). The results of the simulation are presented in Tables 6 and 7.

Economic Cost

PV/wind-diesel has total NPC of $17,346,854, operating cost of $1,478,858, and initial cost of $384,470, while diesel only has total NPC of $20,464,460, operating cost of $1,759,724, and initial cost of $280,570 as shown in Table 6. This system saves $3,117,606 to the network operator when compared with the diesel only.

Environmental Impact

In the PV/wind-diesel system, diesel generator operates for 5,974h/annum with fuel consumption of 31,538L/annum. This system emits 83.05 tonnes of CO_2, 0.205 tonnes of CO, 0.0227 tonnes of UHC, 0.0155 tonnes of PM, 0.167

Table 7. Comparison of simulation results of Emissions from diesel only and proposed system

Parameter	Diesel	PV/Wind-Diesel	Reduction in Pollutant
Carbon dioxide (t/yr)	101.342	83.05	18.292
Carbon monoxide (t/yr)	0.250	0.205	0.045
Unburned hydrocarbon (t/yr)	0.0277	0.0227	0.005
Particulate matter (t/yr)	0.0189	0.0155	0.0034
Sulphur dioxide (t/yr)	0.204	0.167	0.037
Nitrogen oxides (t/yr)	2.232	1.829	0.403

tonnes of SO_2, and 1.829 tonnes of NO_x annually into the atmosphere of the location under consideration as shown in Table 7. Whereas diesel only system operates for 8,760h/annum has a fuel consumption of 38,485L/annum and generates 101.342 tonnes of CO_2, 0.250 tonnes of CO, 0.0277 tonnes of UHC, 0.0189 tonnes of PM, 0.204 tonnes of SO_2, and 2.232 tonnes of NO_x annually into the atmosphere as shown in Table 7. The reduction in the quantity of different air pollutants for renewable penetration compared to that diesel only are thus: 18.292 tonnes of CO_2, 0.045 tonnes of CO, 0.005 tonnes of UHC, 0.0034 tonnes of PM, 0.037 tonnes of SO_2, and 0.403 tonnes of NO_x.

CONCLUSION

In this study, an operational control algorithm was developed to satisfy the load demand by optimally allocate the renewable energy sources to the maximum extent while limiting the use of diesel generator. From the control simulation, the hybrid controller reduces the operational hours of the diesel generator thereby reducing the running cost of the hybrid energy system as well as the pollutant emissions. It was observed that the hybrid controller allocates the sources optimally according to the demand and availability.

The study also determines the suitability of hybrid PV/wind-diesel system with battery in telecommunication industry, in the perspective of economic and environmental analysis. From the homer simulation results, this system (PV/wind-diesel system) saves $3,117,606 and has reduction in the quantity of different air pollutant (18.292 tonnes of CO_2, 0.045 tonnes of CO, 0.005 tonnes of UHC, 0.0034 tonnes of PM, 0.037 tonnes of SO_2, and 0.403 tonnes of NO_x) to the network operator when compared with the diesel only.

As a conclusion, the high running cost were minimized thereby minimizing high-call-cost charged to the subscribers, and the poor services experienced in the network improved (no power failure) which shows that the developed algorithm is an optimal operational strategy for power generation with energy storage at GSM Base Station Site.

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