Feasibility Assessment of a PV-Diesel Hybrid Power System for an Isolated Off-Grid Catholic Church

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ABSTRACT Energy is essential for today's society and it is difficult to imagine life without electrical energy. This paper presents an analysis of the load requirements of the Catholic Parish Church, along with a technical and economical feasibility assessment of the option of incorporating solar Photo Voltaic (PV) generation to supplement the existing diesel power system that currently supplies power to the church. The proposed system would meet around 53% of the average annual parish church electrical load and result in 47% reduction in diesel use and CO_2 emissions compared to the diesel- only option. From the analyses, the solar PV- diesel system has less total net present cost and less emission as a result of less fuel consumption of the diesel generator when compared to the existing system (diesel only).

KEYWORDS Off-grid power supply, renewable energy, solar hybrid system.

Introduction

Many villages in Nigeria are in isolated areas far from the main utility grid. In Enugu state, especially in the small villages or communities in the remote and mountainous areas, access to electric energy is practically impossible due to the non-profitability of grid extension. In many rural communities in the state, extending electricity grids to meet their energy needs may prove more costly and take longer than harnessing new and alternative sources of energy already available in these communities - wind, solar, and hydro. The attraction of these sources lies primarily in their abundance and ready access. In Enugu State, many of the rural areas lying remotely from the grid have a high potential of renewable energy with solar energy being the most abundant.

Overview of the study area – problem statement

The parish church under study is a Catholic Mission, located in a remote setting of Ndiagu-Akpugo in Nkanu-West local government area of Enugu State, Nigeria. The church is not connected to the grid and currently utilizes a diesel power generating system to meet its energy needs. Here, they have a huge generator that provides continues power and operates according to power demand but lacks the capacity to run the generators for long periods of time, either due to the expense and difficulty of obtaining fuel or the lack of local mechanics to keep it running. Church activities cannot be held without starting the generator. So, there is a need to look for an appropriate source of reliable energy that is cost effective and sustainable for the church.

The objective of this study is to conduct the feasibility of installing solar PV generation to supply around 50% of the church's electrical energy needs, while ensuring the least cost of energy and maintaining reliability of supply. The aim of this study is to reduce the church's carbon footprint and reduce its dependence on diesel fuel.

Hybrid Power system

Hybrid PV systems are best suited to reduce dependence on fossil fuel by using available solar radiation. Hybrid PV system includes the PV generator, diesel generator and/or battery system. Battery storage increases the flexibility of system control and adds to overall system availability [Shaahid and El-Hadidy, 2003; Shaahid and El-Hadidy, 2004]. These energy systems have good prospects and many opportunities in Nigeria, and are termed as one of the cost-effective solutions to meet energy requirements of remote areas. A review of the hybrid PV/Diesel system can be found in [Ani and Emetu, 2013].

Simulation and Optimization Tool

The Hybrid Optimization Model for Electric Renewables (HOMER) optimizes energy systems. HOMER is a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone and distributed generation (DG) applications [NREL, 2005]. It is developed specifically to meet the needs of the renewable energy industry's system analysis and optimization [Lau et al, 2010].

The simulation process serves two purposes. First, it determines whether the system is feasible. HOMER considers the system to be feasible if it can adequately serve the electric and thermal loads and satisfies any other constraints imposed by the user. Second, it estimates the life-cycle cost of the system, which is the total cost of installing and operating the system over its lifetime. In the optimization process, HOMER performs simulation on different system configurations to come out with the optimal selection. In the sensitivity analysis process, HOMER performs multiple optimizations under a range of inputs to account for uncertainty in the model inputs.

There exist many references of using HOMER as a simulation tool including [Ani, 2013; Ani and Nzeako, 2012; Nfah et al, 2008; Rehman et al, 2007; Georgilakis, 2005; Khan and Iqbal, 2005; Shaahid et al, 2004; Lilienthal et al, 2004], among others. [Al-Karaghouli and Kazmerski, 2010] applied HOMER to study the life cycle cost of a renewable system for a rural health clinic in Iraq. Elhadidy and Shaahid [2004] and Nema et al. [2007] carried out system sizing using HOMER-optimization and simulation software tool. Borowy and Salameh [1996] reported an algorithm based on energy concept to optimally sized PV array in a PV/wind hybrid system. Kamaruzzaman et al [2008], Lambert [2009] and Ani [2013] used the annualized cost of a component to derive the calculation of the total Net Present Cost (NPC) of energy systems. Kamel and Dahl [2005] and Khan and Iqbal [2005] also used the HOMER software to find optimum sizing and minimizing cost for hybrid power system with specific load demand in stand-alone applications. Ashok [2007], developed a reliable system operation model based on HOMER to find an optimal hybrid system among different renewable energy combinations while minimizing the total life cycle cost. Protogeropoulos et al. [1998] carried out the optimization of PV–Wind– Battery systems, modifying the size of the batteries until a configuration that ensures sufficient autonomy is achieved. Koutroulis et al. [2006] presented a paper for economic optimization by means of Genetic Algorithms on PV–Wind–Battery systems. Yang et al. [2007] present a method for the optimization of hybrid PV–Wind–Battery systems which minimize the LCE. The optimization is carried out by trying component combinations: changing the number of PV modules, the orientation of PV modules, the rated power of the wind turbine, the tower height of the wind turbine, and the capacity of the battery bank. Diaf et al. [2008] present an application of hybrid PV–Wind–Battery systems in Corsica (France) which minimizes the LCE. In addition, simulations of the optimum system of hybrid PV–wind–battery was carried out by Berrill [2005], using HOMER and HYBRIDS and comparing the simulations obtained with each of the two programs. The HOMER model has been used for different household electrification feasibility studies [Ani, 2013; Ani and Nzeako, 2012; Farret and Simões, 2006; Iqbal, 2003; Manwell et al, 2003; Jubran et al, 2003; Fung et al, 2002; Debra et al, 1997].

Barley et al. [1988] conducted a study using time-series computer simulation models to estimate the potential fuel and cost savings that may be achieved by retrofitting hybrid power systems to these existing diesel plants. The study found that wind retrofits to the existing diesel power plants in the Philippines are the most likely to be cost effective for wind speeds of approximately 5.5 m s^{-1} or more and fuel prices of US$0.20 to US$0.25 L^{-1}. [Manwell and McGowan, 2004] presented the feasibility study of potential hybrid energy developments on the islands of New England. The study showed that there is a great potential for hybrid system energy development in a number of New England Islands. Also, [Nfah et. al., 2007] studied a solar/diesel/battery hybrid power systems to meet the energy demands of a typical rural domestic in the range of 70–300 kWh yr^{-1} and found that a hybrid power system comprising a 1440Wp solar pv array and a 5kW generator could meet the required load.

System Design

In order to design a power system, it is necessary to provide some information from a particular remote location [Ani and Nzeako, 2012]. This information includes the load profile that should be met by the system, solar radiation for solar PV generation, initial cost of each component (renewable energy generators, diesel generator, battery, converter), annual interest rate, project lifetime, etc [Elliot et al, 2003; Renne et al, 2003]. After that, the simulation was performed to obtain the best power system configuration, which in this paper is done by utilizing HOMER software from NREL [Ani and Emetu, 2013].

Description of the energy load at the Catholic Mission

The parish house is a duplex building. It has four rooms, a kitchen and a sitting room at the ground floor, while it has three masters' rooms and a small sitting room upstairs. The building is furnished with electric power consumptions such as: washing machine, electric stove, electric pressing iron, DVD, Stereo Cassette, Television, Decoder/cable, water pumping machine, fans, electric bulbs, water bath, deep-freezer and microwave. Each room has fan, electric bulb and television. In the church building, there are two sections; the parish priest office and the church hall. In the parish priest office, the electric power consumptions are: air conditioner, computers (laptop and desktop), fridge, Television, Decoder, printer and bulbs. In the church hall where the congregation comes together to worship, the electric power consumptions are: fans and bulbs. The church has seven staff members (2 cookers/chefs, 2 seminarians, and 3 mass servants) with one parish priest.

The Pattern of Using Electric Power within the Church

The lights in the parish house and in the church are on from 5 am till 8 am. At this time, it goes off, once rays of light come in through the windows during day time (8 am-5 pm). The light comes on again at 5 pm until 10 pm. Once it is 10 pm, the light is turned off. The fans both in the parish house and at the church are all on from 5 am till 10 pm.

In the office, the fridge, television, decoder, computers and the printer all remain on from 8 am to 5 pm and the air conditioner is also on.

At the parish house, the deep-freezer remains on 24 hours. Between 3 am and 4 am, the occupants make use of the water for their morning bathing. The parish priest plays music from 4 am till 5 am, and conducts morning mass by 5 am and ending by 6 am.

Load Assessment

In order to establish the power needs of the church, an energy audit was carried out based on data provided by the parish priest and a site visit to evaluate the characteristics of the power system, power requirements, system management and operation. The daily power demands for the parish house are given in Table 1.

The table shows estimation of each appliance's rated power, its quantity and the hours of use by the church in a single day. The miscellaneous load is for unknown loads in the church.

The daily average load variation is shown in Fig. 1. It is assumed that it is identical for every day of the year. The annual peak load of 8.03 kW was observed between 18:00 h and 19:00 h with 117 KWh d^{-1} energy consumption.

Study area

The study area is located in a valley with poor wind but good solar resources. It is geographically located at 6°19'60.0" N latitude and 7°35'60.0" E longitude with annual average solar radiation of 4.92 kWh $m^{-2}d^{-1}$. The solar resource data was obtained from the NASA Surface Meteorology and Solar Energy web site [NASA, 2013]. Fig. 2 shows the solar resource profile of this location.

Solar Radiation Variation

February is the sunniest month of the year. In this month, solar energy resource is 5.7 kWh $m^{-2}d^{-1}$ while in August it is only 3.9 kWh $m^{-2}d^{-1}$ as shown in Fig. 2.

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. Whereas 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.

Power System Description

The following system configurations have been considered in this study:

1) Diesel generator only

2) Diesel generator, PV array and inverter (no battery)

3) Diesel generator, PV array, control system, and battery bank

For option (3) of the above configurations, a control system is required, which is capable to control the diesel generator set and manage the battery charging

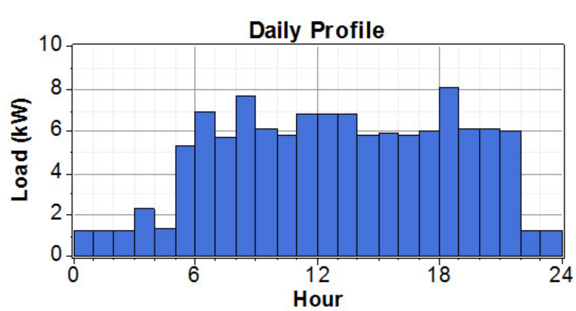


Figure 1 Daily average load variation for a Catholic Mission.

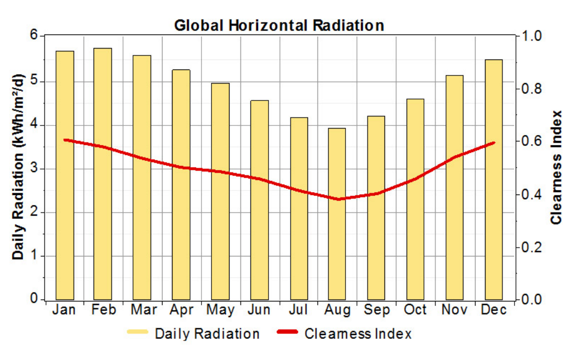


Figure 2 Solar daily radiation profile for Ndiagu-Akpugo in Nkanu-West (Enugu State).

Table 1 Daily Power Demands for the Catholic Mission

Components	Power Rating (Watts)		(Qty)		Hrs/ day		Watt Hrs/ day	Kilowatt Hrs/day	Time in use
Medium size deep freezer	130	x	1	x	24	=	3120	3.12	12 am – 12 am
Water pumping machine	1000	x	1	x	1	=	1000	1	1 pm – 2 pm
Washing Machine	280	x	1	x	1	=	280	0.28	9 am – 10 am
Electric stove	1000	x	1	x	2	=	2000	2	5 pm – 7 pm
Microwave Oven	1000	x	1	x	2	=	2000	2	6 am – 7 am; 11am – 12 noon
Electric pressing iron	1000	x	1	x	1	=	1000	1	12 noon – 1 pm
Air-Conditioner	1170	x	1	x	9	=	10530	10.53	8 am – 5 pm
Refrigerator	500	x	1	x	9	=	4500	4.5	8 am – 5 pm
Water bath	1000	x	1	x	2	=	2000	2	3 am – 4 am; 6 pm – 7 pm
Ceiling fan	100	x	29	x	17	=	49300	49.3	5 am – 10 pm
Incandescent Bulb	60	x	31	x	9	=	16740	16.74	5 am – 9am; 5 pm – 10 pm
Lighting-outdoor (security)	25	x	10	x	13	=	3250	3.25	6 pm – 7 am
21” TV with Decoder	150	x	1	x	9	=	1350	1.35	8 am – 5 pm
21” TV	100	x	1	x	11	=	1100	1.1	6 pm – 5 am
14” Television	80	x	8	x	22	=	14080	14.08	6 am – 5 pm; 6 pm – 5 am
Sony Music System	100	x	1	x	1	=	100	0.1	4 am – 5 am
DSTV Receiver	50	x	1	x	22	=	1100	1.1	6 am – 5 pm; 6 pm – 5 am
DVD Player	50	x	1	x	2	=	100	0.1	7 pm – 9 pm
Computer printer	100	x	1	x	1	=	100	0.1	3 pm – 4 pm
computer PC	115	x	1	x	9	=	1035	1.035	8 am – 5 pm
Computer Laptop	35	x	1	x	9	=	315	0.315	8 am – 5 pm
Miscellaneous	100	x	1	x	24	=	2400	2.4	12 am – 12 am
Total	8195						117400	117.4 kW	

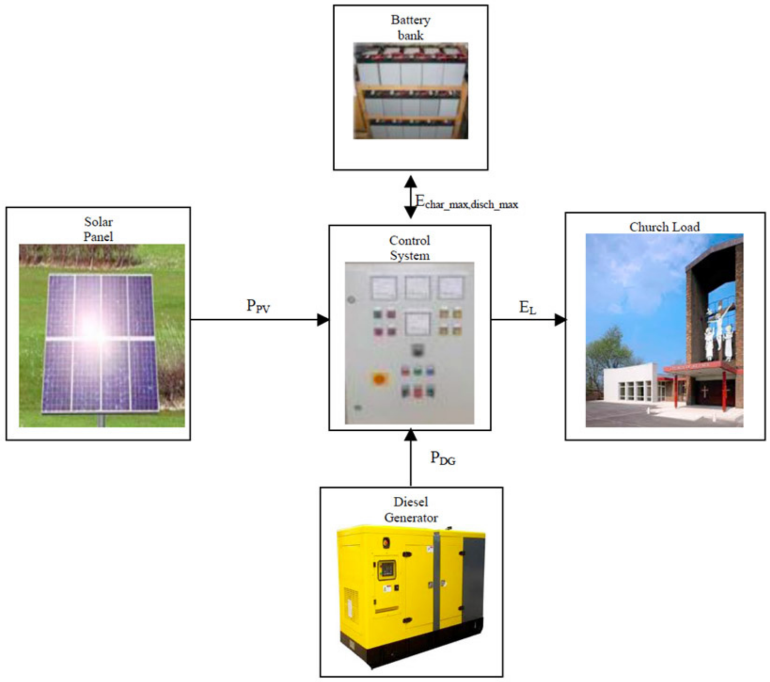


Figure 3 Diagram of the proposed PV/Diesel Hybrid System Configuration.

from both the PV and the generator. A control system for the hybrid PV - diesel energy system is shown in Fig. 4.1 and 4.2. Fig. 3 is a diagram of the proposed hybrid system configuration (option 3).

Hybrid PV - Diesel Energy System Controller (Supervisory Controller)

It 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, and consume the smaller possible quantity of fossil fuel [Ani, in press; Ani and Emetu, 2013; Seeling-Hochmuth, 1997]. In this study, a supervisory controller was developed to regulate the power of the power generating system (PV/Diesel Hybrid system). The PV power (P_{PV}) generation is the primary source of energy, the battery ($E_{char\_max,disch\_max}$) acts as the supplement and the diesel generator power (P_{DG}) as the back-up source of energy. Fig. 4 outlines the flow between the different modes. The system uses solely the energy generated by the PV panels to supply the load (E_L). When the PV panels produce excess energy, it is used to charge the battery (E_{char_max}). During the charging of the battery, if the excess energy from the PV is less than the battery charging (E_{char_max}), then there will be no excess energy (E.E), but if the excess energy from the PV is greater than the battery charging (E_{char_max}), then the excess energy will be calculated by the system. The Loss of power supply (LPS) is equal to zero; meaning that the load will always be satisfied.

Conversely, if the energy supplied by the PV panels is not sufficient to supply the load, then the system goes to the decision mode (SOC<or≥thanSOC%) where the program determines what element (batteries or diesel generator) has priority to supply energy using decision rules, based on two conditions:

- If the SOC of the battery is greater than the minimum amount and therefore the battery is able to supply power to the load, then the battery will be used.
- If the load cannot be supplied by the energy source i.e. the power of the PV panels is not suffi-

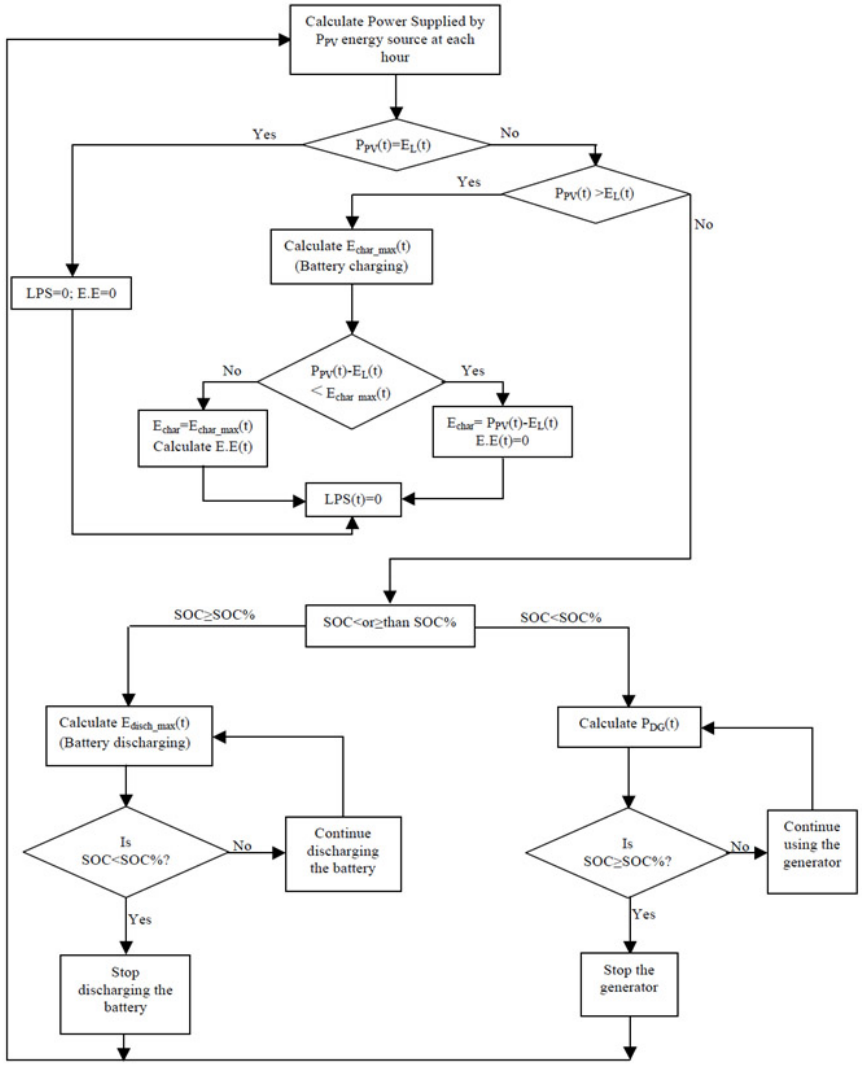


Figure 4.1 Supervisory Controller for the Hybrid PV - Diesel Energy System.

cient to supply the load and the battery is at its minimum SOC and therefore cannot be used to supply the deficit of power required, then the diesel generator will be used to supply the load and charge the battery.

This is done by monitoring the power needed by the load and the capacity 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, and track which modes the system spends the most time in, the power supplied by each of the energy sources over the year, and the power required by the load over the year.

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 set point 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 Fig. 4.2.

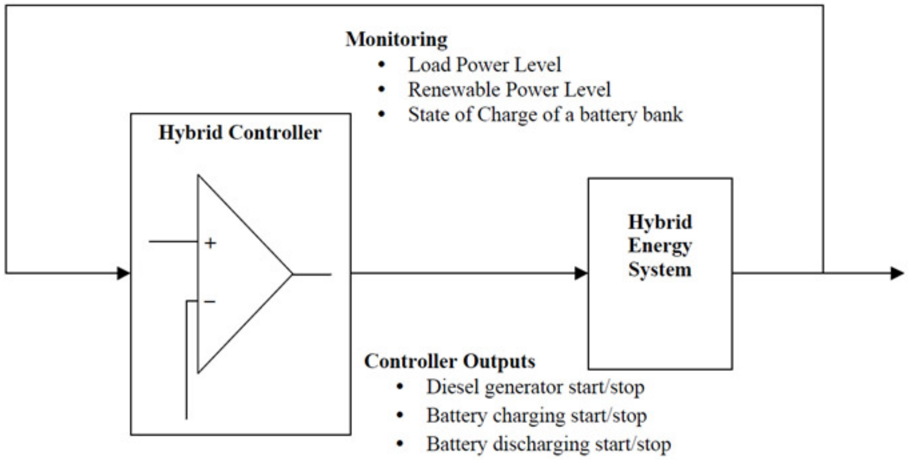


Figure 4.2 Hybrid System Controller Block Diagram [Ani and Emetu, 2013].

Assumptions

A number of constraints and assumptions were made in order to develop the input information required for the simulation model used to optimize size and life cycle economics. These assumptions are described below.

1) there is no capacity shortage for the system and operating reserve is 10% of hourly load. The operating reserve as a percentage of hourly load was 10%. Meanwhile, the operating reserve as a percentage of solar power output was 25%.

2) the cost analysis is based on a system lifetime of 20 years. The lifetime of PV Modules is taken as 20 years. The lifetime of the inverter is estimated as 20 years. The diesel generator operational life is assumed as 20,000 hours. The battery life is assumed to be 9,390 cycles at 23.3% depth of discharge. A real interest rate of 6 % was used for the analysis. The capital costs for all system components including the PV module, diesel generator, inverter, battery and balance of system prices are based on quotes from PV system suppliers in Nigeria [Solarshopnigeria, 2013; Ani and Emetu, 2013]. The replacement costs of equipment are estimated to be 20% – 30% lower than the initial costs. All initial costs including installation and commissioning, replacement costs and operating and maintenance costs are summarized in Table 2.

Configuration of the Stand-Alone 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 and Nzeako, 2012; Ani, 2013]. A typical stand-alone hybrid diesel-solar PV system has an electricity generation device equipped with the wiring setup and supporting structures, as well as necessary BOS components (i.e., the battery bank, the charging controller and the DC/AC inverter) [Kamaruzzaman et al, 2009]. The diagram of a proposed stand-alone hybrid Diesel-solar PV system is shown in Fig. 5 below.

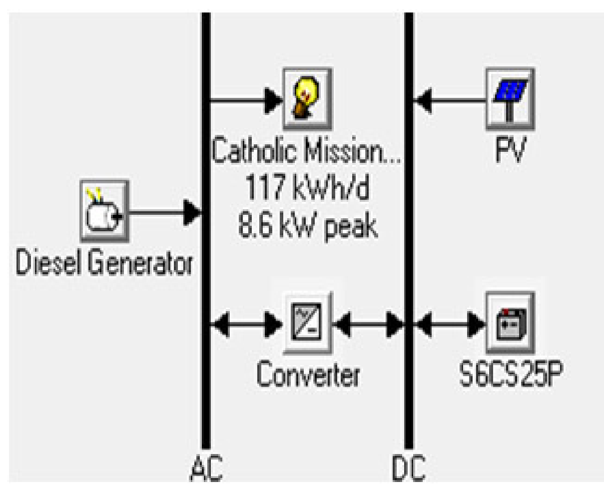


Figure 5 The network architecture for the HOMER simulator (Proposed stand-alone hybrid Diesel-solar PV system).

Table 2 Summary of initial system costs, Replacement costs and Operating & Maintenance costs [Solarshopnigeria, 2013; Ani and Emetu, 2013]

Item	Initial System Costs	Replacement Costs	Operating & Maintenance Costs
PV modules	₦ 324/W ($2)	₦ 291.6/W ($1.8)	₦ 16,200/kW/yr ($100)
20kVA Diesel Generator	₦ 2,106,000 ($13,000)	₦ 2,106,000 ($13,000)	₦ 405/hr ($2.5)
Surrete 6CS25P battery	₦ 185,490 ($1,145)	₦ 162,000 ($1,000)	₦ 16,200 ($100)
Converter	₦ 324/W ($2)	₦ 324/W ($2)	₦ 16,200/kW/yr ($100)

Optimization analysis of the HOMER shows that the most least lowest cost and the optimal combination of energy system components is the combination of the 16 kW diesel generator, 20 kW solar PV array, 96 Surrette 6CS25P Battery Cycle Charging, and a control system. Fig. 6 shows a complete list of HOMER solutions.

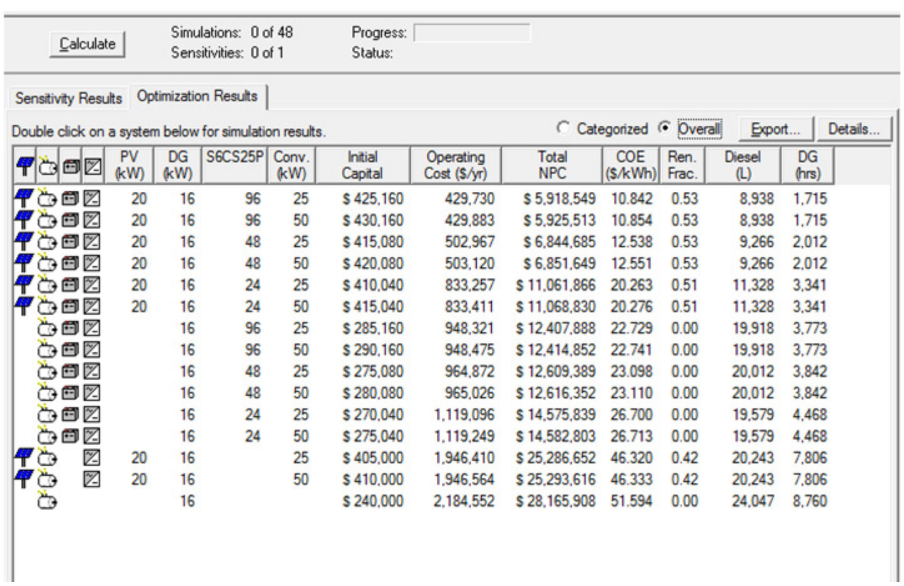
Discussion of Results

The simulations provide information concerning the electricity production, economic costs and environmental characteristics of each system, such as the CO_2 emissions. The obtained results are presented in Tables 3, 4, 5, and 6. The detailed analyses obtained at the end of the simulations are described below:

Proposed Hybrid System: Solar PV-Diesel System with Battery Bank

In this hybrid system, the PV system supplies 29,884 kWh yr^{-1} (53%) of the annual electricity production, while the Diesel generator contributes 26,973 kWh yr^{-1} (47%) of the total electricity with a capacity factor of 19.2%, as shown in Table 6. The PV-diesel system gives an opportunity for renewable energy to supply 53%, as shown in Table 3. It has total NPC of $5,918,549, operating cost of $429,730, and initial cost of $425,160 as shown in and Table 4. This system saves $22,247,359 for the church when compared with the diesel only.

In a hybrid PV-diesel system, the diesel generator operates for 1,715 h $annum^{-1}$; has a fuel consumption



PV (kW)	DG (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs)
20	16	96	25	$ 425,160	429,730	$ 5,918,549	10.842	0.53	8,938	1,715
20	16	96	50	$ 430,160	429,883	$ 5,925,513	10.854	0.53	8,938	1,715
20	16	48	25	$ 415,080	502,967	$ 6,844,685	12.538	0.53	9,266	2,012
20	16	48	50	$ 420,080	503,120	$ 6,851,649	12.551	0.53	9,266	2,012
20	16	24	25	$ 410,040	833,257	$ 11,061,866	20.263	0.51	11,328	3,341
20	16	24	50	$ 415,040	833,411	$ 11,068,830	20.276	0.51	11,328	3,341
	16	96	25	$ 285,160	948,321	$ 12,407,888	22.729	0.00	19,918	3,773
	16	96	50	$ 290,160	948,475	$ 12,414,852	22.741	0.00	19,918	3,773
	16	48	25	$ 275,080	964,872	$ 12,609,389	23.098	0.00	20,012	3,842
	16	48	50	$ 280,080	965,026	$ 12,616,352	23.110	0.00	20,012	3,842
	16	24	25	$ 270,040	1,119,096	$ 14,575,839	26.700	0.00	19,579	4,468
	16	24	50	$ 275,040	1,119,249	$ 14,582,803	26.713	0.00	19,579	4,468
20	16		25	$ 405,000	1,946,410	$ 25,286,652	46.320	0.42	20,243	7,806
20	16		50	$ 410,000	1,946,564	$ 25,293,616	46.333	0.42	20,243	7,806
	16			$ 240,000	2,184,552	$ 28,165,908	51.594	0.00	24,047	8,760

Figure 6 Overall Optimization results of HOMER selected solutions.

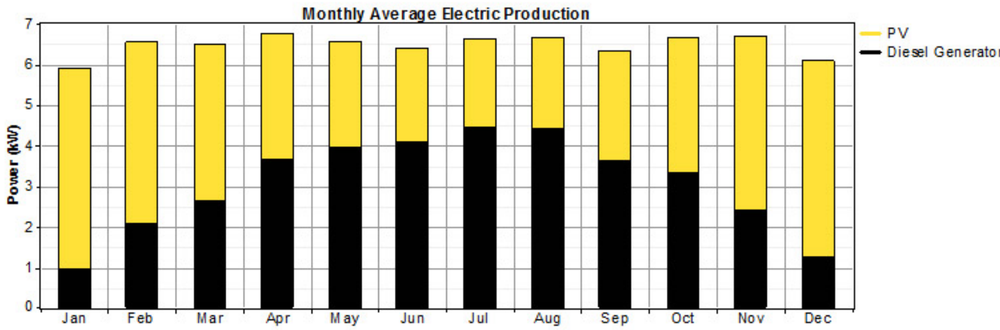


Figure 7 Electrical production of hybrid Diesel-solar PV energy system with storage.

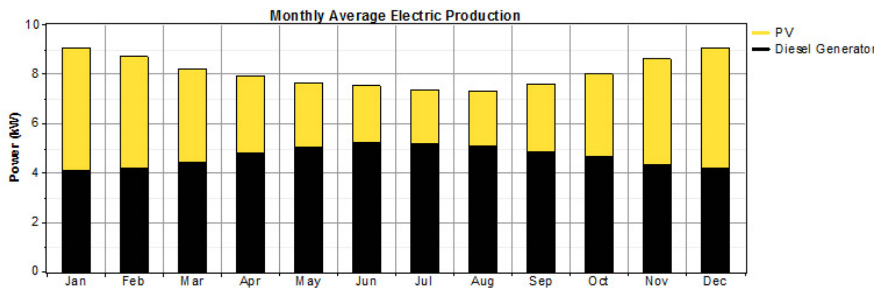


Figure 8 Electrical production of hybrid Diesel-solar PV energy system without storage.

of 8,938 L annum^{-1} and an operational life of 11.7 yr, as shown in Table 6. This system emits 23.538 tones of CO_2, 0.0581 tones of CO, 0.00644 tones of UHC, 0.00438 tones of PM, 0.0473 tones of SO_2, and 0.518 tones of NO_x annually into the atmosphere as shown in Table 5. A 53% decrease in each pollutant is noticed for a 53% renewable penetration into the existing diesel only power system. The reduction in the quantity of different air pollutants for 53% renewable penetration compared to that diesel only are thus: 39.785 tones of CO_2, 0.0979 tones of CO, 0.01086 tones of UHC, 0.00742 tones of PM, 0.0797 tones of SO_2, and 0.877 tones of NO_x.

Solar PV-Diesel System without Battery Bank

In this hybrid system, the PV system supplies 29,884 kWh yr^{-1} (42%) of the annual electricity production, while the Diesel generator contributes 41,003 kWh yr^{-1} (58%) of the total electricity with a capacity factor of 29.3%, as shown in Fig. 8 and Table 6. The PV-diesel system gives an opportunity for renewable energy to supply 42%, as shown in Table 3. A Solar PV-diesel system without battery has total NPC of $28,165,908, operating cost of $2,184,552, and initial cost of $240,000 as shown in Table 4.

In this hybrid system, the diesel system operated for 7,806 h annum^{-1}; had a fuel consumption of 20,243 L annum^{-1} and operational life of 2.56 yr, as shown in Table 6. It generated 53.307 tones of CO_2, 0.132 tones of CO, 0.0146 tones of UHC, 0.00992 tones of PM, 0.107 tones of SO_2, and 1.174 tones of NO_x as shown in Table 5. A 42% decrease in each pollutant was noticed for a 42% renewable penetration into the existing diesel only power system. The reduction in the quantity of different air pollutants for 42% renewable penetration compared to that diesel only are thus: 10.016 tones of CO_2, 0.024 tones of CO, 0.0027 tones of UHC, 0.00188 tones of PM, 0.02 tones of SO_2, and 0.221 tones of NO_x.

Existing System: Diesel Only

The Diesel-only system contributes 100% of the total electricity with a capacity factor of 36.6% as shown in Table 3, and Table 6 respectively. It has total NPC

Table 3 Comparison of Simulation results of Electricity Production (kWh yr^{-1})

Quantity	Diesel only		Diesel in Hybrid System (Diesel-solar PV) without batteries		Diesel in Hybrid System (Diesel-solar PV) with batteries	
	kWh yr^{-1}	**%**	**kWh yr^{-1}**	**%**	**kWh yr^{-1}**	**%**
Load						
AC primary load	42,705	100	42,705	100	42,705	100
Production						
PV array	None	None	29,884	42	29,884	53
Diesel Generator	51,334	100	41,003	58	26,973	47
Total energy	51,334	100	70,887	100	56,858	100

Table 4 Comparison of Simulation results of Economic Cost.

Parameter	Existing System Diesel only	Proposed Project Hybrid Diesel-solar PV System without battery	Proposed Project Hybrid Diesel-solar PV System with battery
Initial Cost	$240,000	$405,000	$425,160
Operating Cost ($/yr)	$2,184,552	$1,946,410	$429,730
Levelized Cost($/kWh)	$51.594	$46.320	$10.842
Total NPC	$28,165,908	$25,286,652	$5,918,549

of $28,165,908, operating cost of $2,184,552, and initial cost of $240,000 as shown in Table 4. Diesel only system operates for 8,760 h $annum^{-1}$; has a fuel consumption of 24,047 L $annum^{-1}$ and operational life of 2.28 yr, as shown in Table 6. It generates 63.323 tones of CO_2, 0.156 tones of CO, 0.0173 tones of UHC, 0.0118 tones of PM, 0.127 tones of SO_2, and 1.395 tones of NO_x as shown in Table 5.

In summary, the diesel only system had the least initial capital cost, but in the end had the highest total net present cost for the whole project. The hybrid system topologies needed higher initial capital cost, but in the end they had less total net present cost as a result of less fuel consumption.

Comparison of System Design Scenarios

The results of the analysis of three possible system configuration scenarios considered in this study are summarized in Tables 3, 4, 5, and 6. These scenarios are also compared with the existing diesel only option.

- The first scenario is a PV-diesel-battery hybrid system configuration a battery bank and a control system.
- The second scenario is a PV-diesel hybrid system configuration with NO battery storage.
- The third and final scenario is a diesel only system which is currently in place at the parish church.
- Economic indices determined the life cycle economics of the system. Of particular interest are

Table 5 Comparison of simulation results of Pollutant Emissions.

Pollutant (t yr^{-1})	Emissions (kg yr^{-1})		
	Existing system Diesel only	Diesel-solar PV system without Batteries	Diesel-solar PV system with Batteries
Carbon dioxide	63.323	53.307	23.538
Carbon monoxide	0.156	0.132	0.0581
Unburned hydrocarbons	0.0173	0.0146	0.00644
Particulate matter	0.0118	0.00992	0.00438
Sulfur dioxide	0.127	0.107	0.0473
Nitrogen oxides	1.395	1.174	0.518

Table 6 Comparison of diesel characteristics in diesel only and diesel in hybrid system.

Quantity	Diesel only		Diesel in Hybrid System (Diesel-solar PV) without batteries		Diesel in Hybrid System (Diesel-solar PV) with batteries	
	Value	Units	Value	Units	Value	Units
Hours of operation	8,760	h yr^{-1}	7,806	h yr^{-1}	1,715	h yr^{-1}
Operational life	2.28	yr	2.56	yr	11.7	yr
Capacity factor	36.6	%	29.3	%	19.2	%
Fuel consumption	24,047	L yr^{-1}	20,243	L yr^{-1}	8,938	L yr^{-1}

the levelized cost of energy (LCOE) and total net present cost (NPC). This information, in turn, enables the optimum renewable energy component sizes that would be required to meet the specified fraction of the load at the least cost. The most important environmental indices are fuel consumption and CO_2 emissions. The best LCOE is given by the PV-diesel-battery hybrid power systems.

System Recommendation

The church will be able to choose the system that is most suitable for its requirements based on project evaluation criteria, such as initial capital cost, cost of energy, diesel use, etc. All of the results are tabulated in Tables 3, 4, 5, and 6 allowing a comparison of the various options.

- PV - battery-diesel with storage
- PV - diesel with no storage
- Diesel only system

As indicated in Table 4, the cost of energy supplied from a PV-diesel system with 20 kW PV array, and 96 Surrette 6CS25P batteries would be approximately $40.752 kWh^{-1} lower than the cost of electricity supplied from the diesel only option. If future interest rates are lower than the 6% that has been assumed, the cost of energy supplied from the PV diesel battery hybrid system would be reduced greatly, whereas the cost of electricity supplied using the diesel only option would not change significantly. Also, if the future cost of diesel is higher than the cost used in this calculation, the cost of supplying electricity using the diesel only option would increase more than would all of the other options discussed.

In the PV-Diesel configuration without battery storage, the PV array size is constrained by the minimum base load of the church. If the PV array is too large, the energy from the PV array would have to be wasted, which leads to poor utilization of the PV and the solar resource. One would not recommend a stand-alone system that did not include battery storage as such a configuration would require the diesel generator to operate continuously and would force the diesel generator to operate at very low load conditions for extended periods of time, reducing significantly the fuel efficiency and the diesel engine lifetime. This would in turn significantly offset the CO_2 emissions reduction as seen in Table 5. In addition, even though this configuration is technically feasible, no known, off-the-shelf inverters are available that can perform the control task for this configuration.

Conclusions

This paper is an initial assessment based on limited load data, but can be used as the basis for a detailed hybrid power system design for an isolated off-grid parish church. A hybrid system (PV/diesel energy system without batteries) was analyzed but it yielded poor life cycle economics, high CO_2 emissions and high diesel usage compared to the other system (PV/diesel energy system with battery). The proposed system (PV/diesel energy system with battery and supervisory controller) would meet around 53% of the average annual parish church electrical load and result in 47% reduction on diesel use and CO_2 emissions compared to the diesel only option. Based on the comparisons of the different systems modeled, the hybrid PV/diesel system with battery bank and supervisory controller was the best. It had the lowest NPC, and the power drawn from the diesel is minimal, amounting to a considerable reduction in the amount of CO_2 emitted from the system. The developed supervisory controller was used in the proposed hybrid system configuration (option 3) to regulate the power of the power generating system (PV/Diesel Hybrid system with battery). This is done by monitoring the power needed by the load and the capacity of the power generating mechanism as shown in Fig. 4.2.

This study shows that developing a stand-alone hybrid power system is more cost effective, reliable and suitable for rural applications than running stand-alone diesel generators.

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