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Life Cycle Cost Analysis of a Diesel/Photovoltaic Hybrid Power Generating System

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Abstract

This work is a Life Cycle Cost (LCC) analysis of a diesel/photovoltaic hybrid power generating system for an off-grid residential building in Enugu, Nigeria. It aims at optimizing different hybrid system configurations, and comparing the result obtained with the photovoltaic standalone (PVSA) system and conventional diesel standalone (DSA) system. The lifetime of the project is 25 years and a real interest rate of 9% per annum is assumed for the system analysis. The average hourly electrical load demand data for residential sector in Enugu were obtained from the power holding company of Nigeria (PHCN). The solar resource data for the location for the year 2010 were gotten from the NASA Langley Research Centre. The sizes of different components were determined to make sure their sizes suit the load demand. A PV standalone system is firstly sized, after which modules of the PV array are removed in sequence to get six different sizes, at the same time, introducing the diesel generator to make a hybrid system. The hours of operation of the diesel generator increases as modules are removed from the PV array. Optimization of the hybrid system is done to determine the system configuration that would satisfy the load demand at minimum cost. The result shows that the hybrid system with 20 modules and a 2.5 kVA diesel generator will serve the load at minimum cost. A life cycle cost analysis of the systems is done using the Net Present Value (NPV) and Internal Rate of Return (IRR). The result shows that the LCC of the hybrid system is N3,459,274.00 that of DSA system is N7,098,192.00 and N3,594,881.00 for the PV standalone system. The NPV of the hybrid system is N3,638,918.00 when compared with the DSA system and the internal rate of return is at 26.3%. The NPV of the PV standalone system when compared with the DSA system is N3,428,747.00 with its internal rate of return at 24.6%. The results obtained show that the diesel/photovoltaic hybrid system is economically the best option for power generation

1. Introduction

Procurement costs are widely used as the primary (and sometimes only) criteria for equipment or system selection based on a simple payback period. Life cycle cost (LCC) analysis is required to demonstrate that operational savings are sufficient to justify the investment costs (often the investment costs, for the lowest long term cost of ownership, are greater than for the simple payback period).

Electricity is one of the fundamental necessities for everyday life. However off grid regions in Nigeria still use diesel or other fossil fuelled generators as their major power source for short periods (5-7 hours/day). Most of these diesel generators are oversized. Initial cost of diesel generators may be comparatively low, but the long term cost can be high due to running cost (fuel consumption and maintenance requirements). In Nigeria the price of diesel fuel supplied from Nigeria National Petroleum Company is high since it amounts to N135/liter. Having said that the cost of power generation with diesel generator is high in a standalone mode, one can consider alternative energy sources. Considering the environmental effects of fossil fuelled generators, renewable energy generators like photovoltaic panels, wind turbines, are the best alternatives. Such renewable energy generators have high capital costs but low operation and maintenance costs as opposed by conventional diesel generators.

This design analysis investigates the method of choosing alternate generation capacity to supplement the output of the PV array when there is a large discrepancy between month-to-month system needs vs. month-to-month PV generation capacity. If installation of a PV array to meet minimum sun availability results in significant excess generation for a number of months, then much of the PV output is wasted. In such cases, it often makes better economic sense to use a generator to supplement the PV output during the months of low PV output and size the PV to meet most of the needs during months of higher peak sun.

2. Review of Literatures

Life cycle cost is the total cost of ownership of machinery and equipment, including its cost of acquisition, operation, maintenance, conversion, and/or decommission. LCC are summations of cost estimates from inception to disposal for both equipment and projects as determined by an analytical study and estimate of total costs experienced in annual time increments during the project life with consideration for the time value of money. The best balance among cost elements is achieved when the total LCC is minimized. As with most engineering tools, LCC provides best results when both engineering art and science are merged with good judgment to build a sound business case for action. Businesses must summarize LCC results in net present value (NPV) format considering depreciation, taxes and the time value of money [1]. Off grid renewable energy technologies satisfy energy demand directly and avoid the need for long distribution infrastructures. A combination of different but complementary energy generation systems based on renewable energies or mixed with a backup of Liquefied Petroleum Gas (LPG)/diesel/gasoline generating set), is known as a hybrid power system ("hybrid system"). Hybrid systems capture the best features of each energy resource and can provide "grid-quality" electricity, with a power range between 1 kilowatt (kW) to several hundreds of kilowatts [2].

The expansion in hybrid literature was driven by the need to increase grid stability and reliability as large quantities of wind power were being added to small autonomous grids [3]. Schmid et al, examined the economic feasibility of converting stationary diesel plants in rural Brazil into Diesel/Battery/Photovoltaic (PV) plants and found that conversions were economically favorable for smaller (<50 kW) diesel-based systems [4]. Park et al, modeled the cost savings of converting a ferry's propulsion from diesel into PV/Battery/Diesel [5]. Chedid and Rahman, created software that predicted the operational cost of a hypothetical autonomous PV/Wind/Diesel system. He concluded that the inclusion of renewable energy into a diesel power plant would significantly reduce the operational cost of the plant [6]. Nehrir et al, used a Matlab model to examine the performance of a Wind/PV system and concluded that the use of an electric hot-water heater as a dump load made the renewable-only system more economically feasible [7].

Ashok used a Quasi-Newtonian method to find the system that provided the lowest cost electricity to a rural Indian village. He finds that a PV/Wind/Diesel/Microhydro system would provide 24 hour coverage at the cost of only US$0.14/kWh [8]. Nfah and Ngundam examined picohydro/biogas/PV systems for use in rural Cameroon and reasoned that the inclusion of biogas would decrease the generation cost of hybrid systems [9]. Ruther et al converted a diesel-only mini-grid into a hybrid system in rural Brazil. They then used diesel consumption data to show that similar PV/diesel systems with no battery storage can reduce diesel fuel consumption in Northern Brazilian plant. Ruther dismissed the inclusion of battery banks into a hybrid because the losses introduced by the batteries increases diesel fuel consumption [10]. Phuangpornpitak and Kumar examined the economic benefit (or lack thereof) of 10 solar/wind/diesel hybrid systems installed in Thailand between 1990 and 2004 [11]. This was the only paper found that described the financial cost of actual systems and even stated that some systems were more costly than the baseline diesel-only system due to overdesign. Nayar et al. built, installed, and tested a PV/diesel/battery/grid Uninterruptible Power Supply (UPS) in two locations in India [12]. They reported roughly 24 hours of data on the system performance including plots of the battery bank's voltage, inverter power output, utility voltage, and system frequency, but omitted any information on system cost. However, they did not discuss system design and optimization.

3. Materials and Method

3.1 Power Plant Economics

Fixed costs consist of annual costs for interest and depreciation. Interest rates i depend on the general financial conditions at the time of installation. Depreciation rates are determined by the life expectancy of the equipment and the method used for calculating the depreciation. The power generating unit and its components will have a certain period of useful life. After years of use, the equipment loses its efficiency or becomes obsolete and needs replacement. To enable this to be done when necessary, some money is put aside annually, and is known as the depreciation fund or sinking fund [13].

3.2 Present worth concept

The present worth concept is the value of a sum of money at the present time that, with compound interest, will have a specified value at a certain time in the future. Compound interest payment at the interest rate *i* will increase the value of a fund by $(1+i)^N$ within N years. The present worth (PW) of a payment C to be made after N years is therefore

$$PW = \frac{C}{(1+i)^N} \quad (1)$$

On many occasions, equal amounts of annual expenses are required. Then the present worth of a uniform annual series of payments P after N years is calculated from equations (2) and (3).

$$PW = P\frac{(1+i)^N - 1}{i} \times \frac{1}{(1+i)^N} \quad (2)$$

$$= \frac{P}{i(1+i)^N}[(1+i)^N - 1] \quad (3)$$

Here, the term $\frac{i(1+i)^N}{(1+i)^N - 1}$ is called the capacity recovery factor or present worth factor.

4. Data Collection

4.1 System load

Serving loads is the reason for the existence of power generation systems, so analysis of power systems begins with the analysis of the load or loads that the system must serve. Hourly average load data for residential sector in Enugu was collected from the Power Holding Company of Nigeria (PHCN).

Table 1: Daily average electricity demand for month of March (2010)

Hour	Load(kWh)
00:00-01:00	0.68
01:00-02:00	0.58
02:00-03:00	0.59
03:00-04:00	0.65
04:00-05:00	0.75
05:00-06:00	0.79
06:00-07:00	1.08
07:00-08:00	0.84
08:00-09:00	0.75
09:00-10:00	0.82
10:00-11:00	0.80
11:00-12:00	0.94
12:00-13:00	0.95
13:00-14:00	0.98
14:00-15:00	1.01
15:00-16:00	1.09
16:00-17:00	1.05
17:00-18:00	1.15
18:00-19:00	1.31
19:00-20:00	1.50
20:00-21:00	1.48
21:00-22:00	1.44
22:00-23:00	0.98
23:00-24:00	0.72
Total	22.93

Since the demand for electricity varies with season, we show the monthly average load demand in table 2.

Table 2: Average daily load demand for each month of the year (2010)

Month	Load(kWh/day)
January	21.08
February	22.00
March	22.93
April	22.54
May	19.39
June	17.34
July	17.43
August	17.01
September	18.33
October	19.57
November	19.95
December	21.08
Total	240.20
Annual average	20.02

The monthly mean daily global solar radiation data for Enugu were obtained from [14] as shown in table 3

Table 3: Meteorological data and global solar radiation for Enugu (Lat: $6^0$26'24"N and Long: $7^0$30'36"E)

Month	psh (hours)	G (kWh/m²/day)	Clearness index	Temperature (?)
January	6.35	6.35	0.65	25.84
February	6.55	6.55	0.62	26.27
March	5.99	5.99	0.56	25.81
April	6.45	6.45	0.52	25.54
May	6.49	6.49	0.50	25.40
June	5.35	5.35	0.48	24.39
July	3.86	3.86	0.43	23.62
August	3.78	3.78	0.40	23.61
September	4.45	4.45	0.43	23.80
October	5.94	5.94	0.47	24.09
November	7.50	7.50	0.56	24.10
December	6.93	6.93	0.63	24.78

psh = peak sunshine hours a day; G = measured monthly mean daily global radiation

Figure 1 shows the block diagram of the hybrid dwelling electrical system. It is assumed that the batteries will be placed in a reasonably well-insulated location.

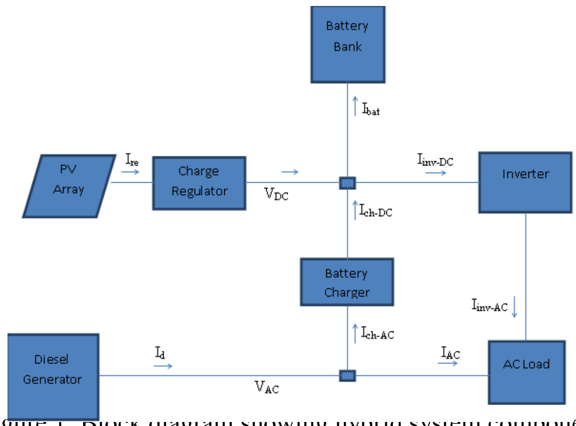

Figure 1: Block diagram showing hybrid system components and configuration

4.2 Photovoltaic Array

A Photovoltaic (PV) array is a device that produces DC electricity in direct proportion to the global solar radiation incident upon it. The power output of the PV array depends strongly on the amount of solar radiation striking the surface of the PV array and also on the PV cell temperature. The power output [15] of the PV array at any given time is simulated by using the expression;

$$P_{PV} = P_R f_{PV} \left(\frac{G}{G_{STC}}\right) \tag{4}$$

Where: P_R is the rated capacity of the PV array, i.e. its power output under standard test condition; f_{PV} is the PV derating factor (%); G is the solar radiation incident on the PV array in the current time step (kW/m^2); G_{STC} is the incident radiation at STC (1kW/m^2).

4.2.1 Sizing the PV Array

Sizing the array for a hybrid system is generally an iterative process. The first step is to size the array for a system with no generator and then to gradually reduce the number of modules in the array while simultaneously computing the percentage of the annual energy needs provided by the PV array. The daily required energy, E'_{PV}, in Ah from the PV array is;

$$E'_{PV} = \frac{E_{PV}}{V_S} \tag{5}$$

Where: E_{PV} is the required energy (kWh), and V_S is the system voltage on the DC side (V).
Taking into consideration the converter losses and the meteorological data, the required design current I_d in Amperes of the PV array is;

$$I_d = \frac{E'_{PV}}{psh\,\eta_{conv}\,f_{PV}} \tag{6}$$

Where: psh is the peak-sunshine hours of the considered month for the design (hours); η_{conv} is the converter efficiency.
Then the number of modules m_p connected in parallel is;

$$m_p = \frac{I_d}{I_m} \tag{7}$$

Where: I_m (A) is the PV module current in STC.
Similarly, the number of modules m_s connected in series is:

$$m_s = \frac{V_s}{V_m} \tag{8}$$

Where: V_m is the module voltage (V)
The total number of modules in the array is therefore, number of modules in parallel times number of modules in series, i.e.
Total number of modules = $m_p \times m_s$ (9)

For our design analysis, we used BP4175 Photovoltaic model [16]
Since the system voltage is equal to the module voltage, there will be no series connection. The total number of modules needed to serve the load demand was obtained from the combination of equations (5) to (9) and data from Table 2 to be 23. To form a hybrid system, we remove some modules from the array and make up the shortcomings by the remaining modules in the array by introducing a diesel generator. We repeat this for different array sizes to find the hybrid system that would serve the load at minimum LCC for the period considered.

Table 4: Monthly excess kWh capability of PV array for six different array sizes.

Month	kWh needed	23 modules	20 modules	16 modules	12 modules	8 modules	4 modules
January	651.9	56.8	-31.8	-155.8	-279.8	-403.9	-527.9
February	616.0	44.2	-38.3	-153.9	-269.4	-384.9	-500.5
March	710.8	-42.3	-125.9	-242.9	-359.8	-476.8	-593.8
April	676.2	20.4	-66.7	-188.6	-310.5	-432.4	-554.3
May	616.6	107.7	17.1	-109.6	-236.3	-363.1	-489.8
June	535.2	42.6	-29.6	-130.7	-231.9	-333.0	-434.1
July	540.3	-109.5	-163.4	-238.7	-314.1	-389.5	-464.9
August	527.3	-105.5	-158.2	-232.0	-305.9	-379.7	-453.5
September	566.4	-85.8	-145.9	-230.0	-314.1	-398.2	-482.3
October	609.8	53.1	-29.8	-145.8	-261.8	-377.8	-493.8
November	598.5	211.5	110.3	-31.5	-173.3	-315.0	-456.8
December	651.9	121.5	24.8	-110.5	-245.9	-381.2	-516.6
Total	7300.9						
Useful PV Generation		6,957.8	6,511.3	5,330.9	3,998.1	2,665.4	1,332.6
Useful DieselGen Generation		_	789.6	1,970	3,302.8	4,635.5	5,968.3
% of Generation by PV		95.3%	89.2%	73%	54.8%	36.5%	18.3%

4.3 Battery Bank

Storage batteries are indispensable in all PV power systems operating in standalone mode to act either as a power buffer or for energy storage. When designing a hybrid diesel-photovoltaic system, the selection of the battery is a significant factor, since its capacity determines not only the energy it can supply but also the peak load that can be served by the battery-inverter subsystem.

4.3.1 Sizing the Battery Bank

In general the capacity of battery is calculated as follows:

$$E_{BAT} = \frac{E_L \times d}{\eta_{conv} \times V_s \times \eta_{BAT} \times DOD} \tag{10}$$

Where: E_L is the required daily load (kWh); d is the number of days the battery can supply the load; V_s is the system voltage on the DC side (V); DOD is the used depth of discharge (%); η_{BAT} is the efficiency of the battery.

The batteries are connected in series and parallel. The number of batteries connected in parallel is:

$$b_p = \frac{battery\ bank\ capacity\ (Ah)}{nominal\ capacity\ of\ a\ single\ battery\ (Ah)} \quad (11)$$

The number of batteries connected in series is:

$$b_s = \frac{system\ voltage\ on\ the\ DC\ side}{nominal\ voltage\ of\ a\ single\ battery} \quad (12)$$

Therefore, the total number of batteries in the battery bank is given by:

$$N_{BAT} = b_p \times b_s \quad (13)$$

4.3.2 Battery bank life

The life of a battery bank is calculated using the following equation (14); [11]

$$R_{BAT} = \frac{N_{BAT} Q_{lifetime}}{Q_{thrpt}} \quad (14)$$

Where: N_{BAT} is the number of batteries in the battery bank; $Q_{lifetime}$ is the lifetime throughput of a single battery (kWh); Q_{thrpt} is annual battery throughput (kWh/yr) given as;

$$Q_{thrpt} = P_{tot,pv} - P_{pv,used} + \left(P'_{gen,bat} \times N_{gen}\right) \quad (15)$$

Where: $P_{tot,pv}$ is the total annual power generated by the PV array (kWh/yr); $P_{pv,used}$ is the annual power supply to the load from PV array that does not pass through the battery bank (kWh/yr); $P'_{gen,bat}$ is the electrical output of the generator that goes to the battery bank (kW); N_{gen} is the number of hours the generator operates in a year (hr/yr).

To size the battery bank, we consider the month of March which has the highest load demand. Then, from equation (10), and combination of data from Tables 1 and 3, the battery bank capacity was obtained as 1047.6Ah.

Table 5: Annual amount of energy stored and lifetime of battery bank for different array sizes

	20 modules	16 modules	12 modules	8 modules	4 modules
Annual throughput (kWh)	4,674.04	3,877.27	2,977.63	2,078.09	1939.73
Lifetime (years)	7.89	9.52	12.39	17.76	19.02

For the hybrid system, the energy that passes through the battery bank is partly supplied by the PV array, while the rest is supplied by the diesel generator. About 0.65kW of power generated by the diesel generator is supplied to the battery bank each it operates.

4.4 Diesel Generator

Diesel generators are widely used as alternative energy sources mainly due to their low capital costs. In a hybrid system, it is mainly included to supply power during extended periods of low solar radiation and supply peak power in order to reduce the array size as well as the battery bank. The rating/size of the generator is determined by the load. It must cover the maximum demand of the residence.

4.4.1 Fuel Curve

The fuel curve (Fig. 2) describes the amount of fuel the generator consumes to produce electricity. The following equation gives the generator's fuel consumption in L/hr as a function of its electrical output; [10]

$$F = F_o . P_{gen} + F_1 . P'_{gen} \quad (16)$$

Where: F_o is the fuel curve intercept coefficient (L/kWh); F_1 is the fuel curve slope (L/kWh); P_{gen} is the rated capacity of the generator (kW); P'_{gen} is the electrical output of the generator (kW).

4.4.2 Generator Operational Life

The generator operating lifetime is given as;

$$\mathrm{R_{gen}} = \frac{\mathrm{R_{gen,h}}}{\mathrm{N_{gen}}} \quad (17)$$

Where: $R_{gen,h}$ is generator lifetime (hours); N_{gen} is the number of hours the generator operates in a year (hr/yr) and

$$N_{gen}(\text{hrs/yr}) = \frac{\text{total annual power generated by the DG } \left(\frac{\text{kWh}}{\text{yr}}\right)}{2 \text{ kW}} \quad (18)$$

A 2.5kVA generator with a lifetime of 9000 operating hours was used for the analysis.

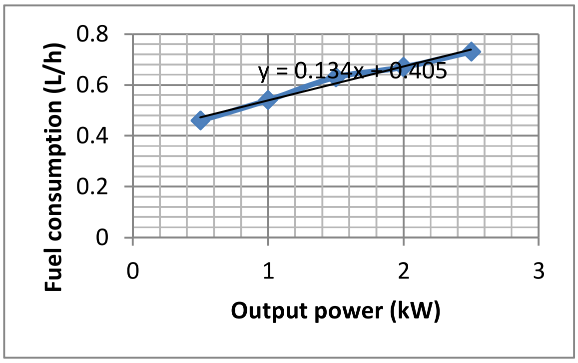

Figure 2: Fuel curve for the diesel generator

Table 6: Diesel generator operational characteristics for five array sizes.

Parameter	20 modules	16 modules	12 modules	8 modules	4 modules
Operation time (hrs/yr)	394.8	985	1,651.4	2,317.8	2,984.2
Fuel consumption (L/yr)	264.5	656	1106.4	1553	1999.4
Lifetime (yrs)	22.8	9.1	5.4	3.9	3.0
Annual fuel cost	25,127	93,575	156,883	220,191	283,499

For the diesel stand alone system, the generator runs continuously and will run well below its maximum efficiency most of the time, thus significantly increasing annual fuel and maintenance costs.

5. Economic Analysis

Hybrid system economic analysis used in this work is based on the use of life cycle cost (LCC). Project with the lowest LCC will be selected. The lifetime of the power systems considered is 25 years. This is chosen because out of all components, PV panel has the highest lifetime of 25 years.

The annual real interest rate is related to the nominal interest rate by the equation given below:[17]

$$i = \frac{i' - f}{1 + f} \quad (19)$$

Where: i' is the nominal interest rate; f is the annual inflation rate.

For the purpose of this study, the annual real interest rate is assumed to be 9% over all costs considered.

5.1 Life Cycle Cost

We calculate the total LCC of a power system using the following equation: [17]

$$LCC = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \quad (20)$$

Where: $C_{ann,tot}$ is total annualized cost (N/yr); CRF is capital recovery factor; R_{proj} is the project lifetime (years)

We rank all systems according to their total LCC. The capacity recovery factor is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows). The equation for capital recovery factor is:[17]

$$CRF(i, R) = \frac{i(1+i)^R}{(1+i)^R - 1} \quad (21)$$

Where: R is number of years considered.

5.1.1 Total Annualized Cost

The total annualized cost is the sum of the annualized costs of each system component.

$$C_{ann,tot} = C_{ann,pv} + C_{ann,bat} + C_{ann,con} + C_{ann,dg} \tag{22}$$

$$C_{ann,comp} = C_{acap} + C_{arep} + C_{ann,O\&M} + C_{ann,fuel} \tag{23}$$

Where: C_{acap} is annualized capital cost; C_{arep} is annualized replacement cost; $C_{ann,O\&M}$ is annual operation and maintenance cost; $C_{ann,fuel}$ is annual fuel cost (if applicable).

5.1.2 Annualized Capital Cost (Amortization)

To calculate the annualized capital cost of each component, we use the following equation:

$$C_{acap} = C_{cap} \times CRF(i, R_{proj}) \tag{24}$$

Where: C_{cap} is initial capital cost of the component

5.1.3 Annualized Replacement Cost (Depreciation Fund)

The annualized replacement cost of a system component is given by equation (25);

$$C_{arep} = [C_{rep} \times f_{rep} \times SFF(i, R_{comp})] - [S \times SFF(i, R_{proj})] \tag{25}$$

f_{rep} is a factor arising because the component lifetime can be different from the project lifetime, and is given by:

$$f_{rep} = \begin{cases} CRF(i, R_{proj})/CRF(i, R_{rep}), & R_{rep} > 0 \\ 0 \quad , & R_{rep} = 0 \end{cases} \tag{26}$$

R_{rep} is the replacement cost duration for the entire project lifetime, and is given by:

$$R_{rep} = R_{comp}.INT\left(\frac{R_{proj}}{R_{comp}}\right) \tag{27}$$

INT is the integer function, returning the integer portion or a real value.
We assume that the salvage value of the component at the end of the project lifetime is proportional to its remaining life. Therefore the salvage value S is given by:

$$S = C_{rep} \times \frac{R_{rem}}{R_{comp}} \tag{28}$$

Where: R_{rem}, the remaining life of the component at the end of the project lifetime, and is given by:

$$R_{rem} = R_{comp} - (R_{proj} - R_{rep}) \tag{29}$$

Note: C_{rep} is replacement cost of the component; R_{comp} is lifetime of the component; SFF is sinking fund factor.
The equation for SFF is:

$$SFF(i, R) = \frac{i}{(1+i)^R - 1} \tag{30}$$

5.2 Cost of Energy (COE)

The equation for the COE is given as follows:

$$COE = \frac{C_{ann,tot}}{E_{prim}} \tag{31}$$

Where: E_{prim} is the primary load served

5.3 Net Present Value (NPV)

The net present value of the proposed system is the difference between the LCC of the base case (diesel stand-alone) and the proposed system. A positive value indicates that the proposed system saves money over the project lifetime compared to the base case system.

$$NPV_{hybrid} = LCC_{diesel} - LCC_{hybrid} \tag{32}$$

Or

$$NPV_{PVSA} = LCC_{diesel} - LCC_{PVSA} \tag{33}$$

The relevant cost data for the economic assessment are shown in Table 7.

Table 7: Cost of major components considered for the analysis

System component	Capital cost (N)	Replacement cost (N)	O&M cost (N)	Fuel cost (N/Litre)
Diesel Generator	90,000	90,000	7.42 per hour	95
PV Array	95,000 per module	95,000 per module	3,500 per year	0
Converter	110,000	110,000	13,000 per year	0
Battery bank	456,000	456,000	4,000 per year	0

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6. Hybrid System

The LCC for systems with six different array sizes: 4, 8, 12, 16, 20, 23 was calculated, with the system having 23 modules used as PV stand-alone power generating system (Fig. 3a and 3b).

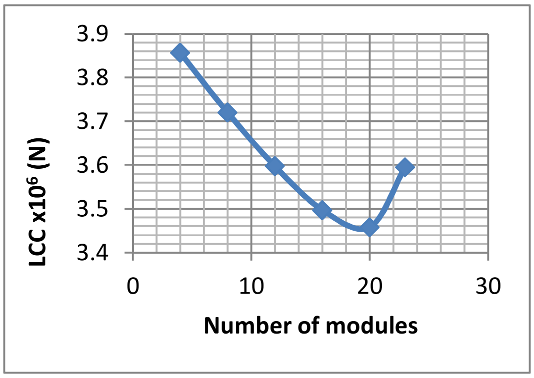

Figure 3a: Hybrid system LCC vs. Number of modules

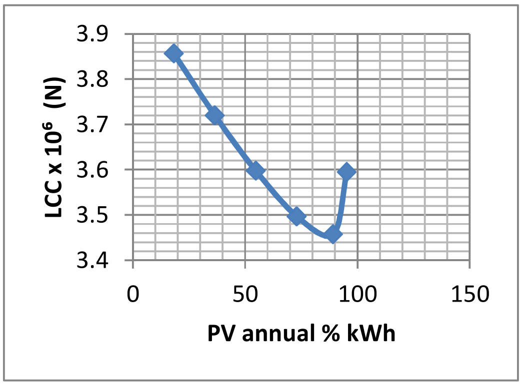

Figure 3b: Hybrid system LCC vs. Percentage of annual power supplied by PV array

Based on the life-cycle cost figures, the system with 20 modules is chosen. The PV array of this system supplies 89.2% of the annual energy needs and, as indicated by Figure 3b, appears just at the point where system cost vs. PV availability begins to increase sharply. In this system, the PV array will provide most of the system energy needs over the period from February to October. From November to January, the generator will provide somewhere between 10.8 and 32.2 kWh/month with an annual fuel consumption of 264.5 litres with approximately 295 hours of operation. The generator operates only if the batteries have discharged to 20% of their capacity and then charges the batteries throughout its hours of operation.

Table 8: Life cycle cost result of the optimal hybrid system (20 modules)

Component	Capital (N)	Replacement (N)	O&M (N)	Fuel (N)	Salvage (N)	Total (N)
PV	1,900,000	0	34380	0	0	1,934,380
Diesel Gen	90,000	12,616	28,776	246,817	9,430	387,639
Battery Bank	456,000	407,385	39,292	0	43,967	946,644
Converter	110,000	66,092	127,691	0	6,378	310,161
System	2,556,000	486,093	230,139	24,817	59,775	3,459,274

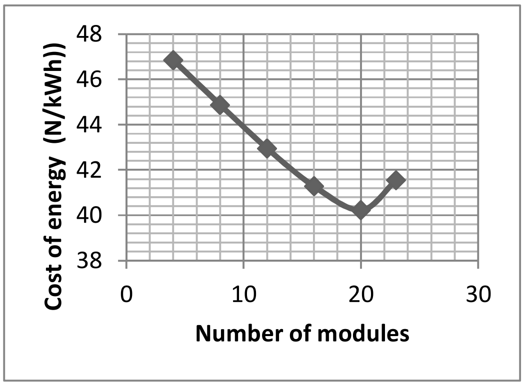

Figure 4: Cost of energy of different system sizes

The annual cost of generating power for the hybrid configuration was calculated, and the results are as shown in figure 4. The 20 module hybrid power system has the least COE per annum at N40.23 per kWh. While for the PV standalone system (23 modules) the cost of energy is N41.55 per kWh.

7 Diesel Stand Alone System

Table 9 shows the costs involved in the system's lifetime. The costs shown are the present worth.

Table 9: System cost for DSA

Capital (N)	Replacement (N)	O&M (N)	Fuel (N)	Salvage (N)	Total (N)
180,000	819,712	638,468	5,476,813	-16,801	7,098,192

The DSA system result is as shown below. The values gotten will be used to compare the proposed hybrid system.

Table 10: DSA system result

Initial Capital (N)	Total NPC (N)	COE (N/kWh)	Fuel Consumption (L/yr)	Operating Hours (hrs/yr)
180,000	7,098,192	98.42	5,869.2	8,760

Table 11: Cash flow for hybrid and PV stand-alone systems

Year	Cash flow for hybrid	Cash flow for PVSA	Cash flow for DSA	Net cash flow for PVSA	Net cash flow for hybrid	Cum net cash flow for hybrid	Cum net cash flow for PVSA
0	-2556000	-2751000	-180000	-2571000	-2376000	-2376000	-2571000
1	-44549	-18808	-571169	552361	526620	-1849380	-2018639
2	-40870	-17255	-524008	506753	483138	-1366242	-1511886
3	-37495	-15830	-631592	615762	594097	-772145	-896124
4	-34398	-14522	-441047	426525	406649	-365496	-469599
5	-31559	-13324	-531053	517729	499494	133998	48130
6	-28953	-290762	-371220	80458	342267	476265	128588
7	-26562	-11214	-446519	435305	419957	896222	563893
8	-255400	-10288	-312449	302161	57049	953271	866054
9	-22357	-9439	-375443	366004	353086	1306357	1232058
10	-66975	-55124	-262982	207858	196007	1502364	1439916
11	-18817	-7944	-315681	307737	296864	1799228	1747653
12	-17264	-177428	-221347	43919	204083	2003311	1791572
13	-15839	-6687	-265434	258747	249595	2252906	2050319
14	-14530	-6134	-186303	180169	171773	2424679	2230488
15	-13330	-5628	-223184	217556	209854	2634533	2448044
16	-129281	-5163	-156808	151645	27527	2662060	2599689
17	-11220	-4737	-187659	182922	176439	2838499	2782611
18	-10294	-108272	-131982	23710	121688	2960187	2806321
19	-9444	-3987	-157790	153803	148346	3108533	2960124
20	-28293	-23286	-111086	87800	82793	3191326	3047924
21	-7948	-3356	-132677	129321	124729	3316055	3177245
22	-7293	-3079	-93499	90420	86206	3402261	3267665
23	-19306	-66305	-111560	45255	92254	3494515	3312920
24	-65440	-2591	-78696	76105	13256	3507771	3389025
25	54143	37282	-77004	39722	131147	3638918	3428747

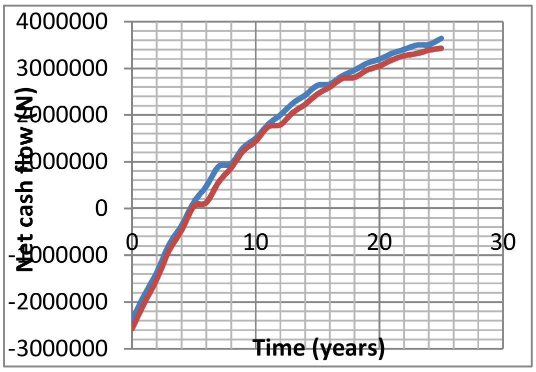

Figure 5: Net cash flow for hybrid and PVSA

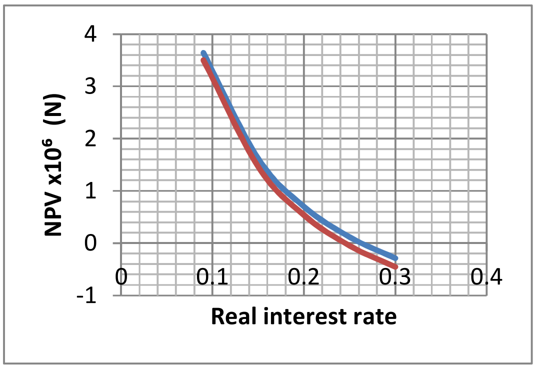

Figure 6: Internal rate of return for the hybrid system and PVSA system.

From Figure 5, graph in red shows the net cash flow for PV stand-alone while graph in blue shows the net cash flow for hybrid system. The curves show that the net present value of the hybrid system is N3,638,918, while that of DSA is N3,428,747. However, from Figure 6, graph in red shows rate of return for PVSA while graph in blue shows rate of return for hybrid system. Hybrid system therefore has an IRR of 26.3%, PV stand-alone an IRR of 24.6%. We can now say that, other things being equal, and using IRR as the decision criterion, the hybrid system (with higher IRR) is the better choice.

8. Conclusion

The obtained computational results showed clearly that hybridizing PV array and diesel generator makes an economically efficient power generating system for residential consumption. This hybrid system reduces the high capital cost associated with PV panels and also reduces the high fuel cost, operation and maintenance costs associated with diesel generator. The use of diesel generator reduces the number of modules needed for the PV array, while at the same time the operation hours of the diesel generator is drastically reduced as a result of high contribution of the PV array to power generation. From the optimization done, it is clearly seen that system with 20 modules supplies the power needs at minimum cost, with the PV array generating 89.2% of the total power demand and the diesel generator producing 10.8% of the electricity demand.

The economic analysis shows that the hybrid system has the least life cycle cost and cost of energy out of the three power systems considered. When the net present value of the hybrid system is compared with that of PV stand alone system, with the diesel stand alone system as the base case, it is also shown that the hybrid system has a higher NPV of N3,638,918 than PV stand-alone system with N3,428,747. The hybrid system has an internal rate of return of 26.3% while the PV stand alone system has an internal rate of return of 24.6%. Apart from the economic gains made, the hybrid system is also environmentally friendly because of the reduced emission of greenhouse gasses and other pollutants associated with diesel. It is also important to state here that the hybrid system will help in extending the lifetime of the non-renewable energy sources.

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