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Sizing and Economic Assessment of Photovoltaic and Diesel Generator for Rural Nigeria

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ABSTRACT
Sizing and economic assessment of solar photovoltaic (PV) and diesel power generators for Igu village in Bwari, FCT-Abuja was carried out. Load survey of the site was carried out in order to get the actual solar radiation (using full PV, HT ITALIA 2010 analyzer), village load requirement and other sundry data (using structured questionnaire). An off-grid solar PV design was done for the village. Life cycle cost analysis was used to assess the economic viability of the PV and diesel generating systems respectively using Music Macro Language (MML) to allow for the calculation and comparison of the levelised costs of electricity generation for the two systems. The total load of Igu village was estimated to be 140.24kW (Losses and tolerance inclusive). The system components computed include; 1194 PV modules of 235W, 351 batteries of 375Ah, 68 charge controllers of 60A and 14 inverters of 10kW each covering 3346.1m^2 area of installation. The PV system cost is ₦268, 000,000.00. Two diesel generators of 350KVA costing N39, 433,419.00, each operating at 12 hours and ten (10) years apart within an estimated period of twenty (20) years, were also sized to meet this load requirement. It was discovered, using the life cycle analysis method, that the PV system has a lower levelised cost of electricity production ranging from 26.52 ₦/kWh in the first year to about 35.82 ₦/kWh in the twentieth year compared to the 81.27 ₦/kWh and 143.34 ₦/kWh in the first and twentieth years respectively for the diesel generator. A comparison of the yearly total cost of electricity production showed that the cost of power generation by the PV system will equal that of the generator system in five years. It was concluded, therefore, that the PV system was the best option of power generation for Igu village.

Key Words: *Photovoltaic, diesel, assessment, economic, sizing.*

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I. Introduction

Energy has been a central concern to human development. The adequate provision of energy is a fundamental component of the conceptual strategy on sustainable development (Qoaider, L., andSteinbrecht, D. (2010). in Nigeria and indeed the rest of the world. Energy is dominant in the development of the country. However, Nigeria's fossil fuel led economy is under severe pressure. Nigeria is transiting from crude oil dependence to a less carbon intensive economy increasingly powered by gas and renewables.

Nigeria is a tropical Sub-Sahara West African country which lies between latitudes 4^o 1$'$and 13^{o}9$'$ North of the Equator and longitudes 2^o 2$'$ and 14^o 30$'$East. It transits to tropical rain forest further inland and progresses into a savannah region further north. (Adeoti,O. 2001)

Solar radiation intensity varies from an annual average of 3.5 kWh/m^2-day in the south to 7.0 kWh/m^2-day in the north while the annual average of daily sunshine hours has the same south-to-north trend from 4 to 9 hours/day. (Bala E. J. 2003). Among the technologies that may help to address climate change concerns is solar photovoltaic cell (PVs).

The current direct cost of solar PV power is widely acknowledged to be much greater than fossil fuel generation Agbemabiese, L. (2009). Proponents of solar PV panels argue, however, that standard analyses fail to capture the enhanced value of solar PV power that results from its temporal and vocational characteristics. On-site generation is argued to deliver economic advantage that is often overlooked in cost analyses. Most of the rural areas in Nigeria do not have access to the national grid as only less than 40% of the entire population is connected to the grid (World Bank, 2008). They therefore have to rely on other means to get electricity and some of them resort to using diesel and petrol for generating sets. This means of electricity generation has a lot of economic to environmental disadvantages. Igu village (studied site) depends on the use of petrol and diesel generator for electricity; therefore, there is need for a research into finding ways of enhancing an option for electricity access through a sustainable, environmentally friendly energy source.

Energy access is key to development and "no country has managed poverty alleviation without increasing energy access" (Rao*etal*., 2009). Urban electrification rates are significantly higher reaching 90% in developing countries (IEA, 2008). In 2008, the rural electrification rate in developing countries was only 58.4%, with the lowest rates in sub-Saharan Africa (11.9%) and South Asia (48.4%) according to a report by World Bank. The numbers show that rural communities especially suffer from energy poverty and are on the lowest rung of the energy ladder.

Energy not only has strong implications for the economic and social, but also for the environmental dimension of sustainable development (Munasinghe, 2009). When developing countries would climb up the same energy ladder as industrialized countries did, limited resources and a strong increase of carbon emissions would put major stresses on the environment (Hosier, 2004). According to Ugwuoke and Oparaku (2009), many homes in Nigeria are in remote locations where grid electricity supply cannot be extended. They attempted to present a concise life-cycle-cost comparison of diesel generator power supply system and photovoltaic power system for a remote rural application. In that comparative analysis, conceptual designs were developed for photovoltaic power and diesel powered systems to meet the base-load requirements. They concluded that the photovoltaic system would be more cost-effective at low-power ranges of electrical energy supply. Bala (2003) did appraisal based on economic consideration of grid extension, diesel generator and solar PV for use in an isolated population center which is characterized by power demand level. The results showed that the unit –energy-cost (UEC), for a given load, increases linearly with the distance away from the nearest tee-off from a high tension line for the grid extension, and from the nearest source of diesel fuel for the diesel generating set. The UEC, however, decreases with increase in the load, for each of the three sources. Comparison becomes meaningful only when the load to be served is specified. According to Mohanlal Kolhe*et al* (2002), terrestrial solar photovoltaic (PV) systems are presently economical for many remote applications where the costs of other alternatives such as extending utility power lines or transporting fuel are very high.

Economic analysis considers the costs and benefits associated with a project from the perspective of society, whereas financial analysis considers these factors from the perspective of the investor(s). The scope of economic analysis is much wider compared with financial analysis, since financial analysis considers only the direct monetary values associated with establishing and operating a project (OECD and IEA, 1991). As a result, a project is considered to be financially viable when a project's revenues exceed its costs (Lagman-Martin, 2004). The costs associated with energy projects are usually assessed using life-cycle analysis, which are also known as levelised costs. Lifecycle costs (LCC) are as shown in the equation below. (Sandia National Laboratories, 2002)

$$LCC = CC + OM + R + F \qquad (1)$$

Where the following apply; Initial capital costs (CC), Operation and maintenance costs (OM), Replacement costs (R) and Fuel costs (F). The life-cycle cost of a solar PV system consists of the initial capital investment (C_o) the present value of operation and maintenance costs (OM_{pv}) and the present value of battery replacement cost (R_{pv})

$$LCC = Co + OMpv + Rpv \qquad (2)$$

The initial capital investment C_0 is the sum of the investments of each part of the PV system. These investments depend on the peak power rating of the PV array. (*Kolhe, M. 2004)*. The O & M is generally specified as a percentage (say *m*) of the initial capital cost. All operating costs are escalated at a rate e_0 and discounted at rate *d*. The life-cycle maintenance for a lifetime of *N* years is: (*Kolhe, M. 2004*)

$$OMpv = OMo\left(\frac{1+e_o}{d-e_o}\right)\left[1-\left(\frac{1+e_o}{1+d}\right)^N\right] \text{ if } d \neq e_o \qquad (3)$$

$$OMpv = OMo * N \text{ If } d = e_o \qquad (4)$$

Where OM_0 is taken as:

$$OMo = m(Co) \qquad (5)$$

The battery replacement cost (R_{pv}), is mainly a function of the number of battery replacements (*v*), over the system lifetime, without taking the salvage value of replaced batteries. It is given by: (*Kolhe, M. 2004*)

$$Rpv = C_b B_e \sum_{j=1}^{v}\left(\frac{1+e_o}{1+d}\right)^{Nj/v+1} \qquad (6)$$

The battery life, i.e. N_R (cycles), in real operation is dominated by the daily depth of discharge (DOD_d) and the battery coefficient (B_c), which is given by Soras and Makios (1988) as 0.02-0.03 for flat-plate batteries and 0.01-0.02 for tubular batteries:

$$N_R = 0.5 N_A \exp\left(-B_c 100\left(DOD_d - DOD_o\right)\right) \quad (7)$$

Where $$DOD_d = \frac{1}{12}\sum_{m=1}^{12}\left(\frac{L - E_D}{B_r}\right) \quad (8)$$

The number of battery replacements (v) is computed as:

$$v = INT \frac{N}{N_R / 365} \quad \text{Soras and Makios (1988)} \quad (9)$$

The cost annuity method aims to convert all the net cash-flow life-cycle costs (LCC) with an investment project into a series of annual payment of equal amounts. The conversion takes place by multiplying LCC by CRF (i.e. capital recovery factor). The levelised energy cost (LEC) from the PV system is given by:*(Kolhe, M. 2004)*

$$LEC = \frac{LCC * CRF}{\sum_{m=1}^{12} N_d L_m} \quad (10)$$

Where; N_d is the number of days per month, $L_m$is monthly daily energy supplied by the PV system CRF is given by:

$$CRF = \frac{d}{1-(1+d)^{-N}} \quad \text{(Kolhe, M. 2004)} \quad (11)$$

System sizing has a critical role to play in the economic system analysis.
The required size of a diesel generator set capacity can be given by:

$$Diesel\ Gen\ Size = \frac{Max\ Energy\ Demand}{(Max\ Operating\ Hours/Day) * Max\ Load\ Factor} \quad \text{(Eskenaziet al. (1986))} \quad (12)$$

The generator set must also be capable of meeting the maximum peak demand (MPD). Thus, the larger value of the two (the calculated generator set size or MPD) has been used. The fuel consumption is given by:

$$Fuel\ Consumption = AOH * FCR * 365 \quad (13)$$

Where; AOH (h/day) is the average generator-set operating hours per day, FCR (l/h) is the fuel consumption rate, which is a function of diesel generator-set size and load factor.
The lifetime of the diesel generator set has been assumed to be 10 years. (Eskenazi*et al*. (1986))
The life-cycle cost of recurring fuel can be calculated as:

$$LCC(fuel) = Annual\ fuel\ Cost * \left[\left(\frac{1+FE}{d-FE}\right) * \left(1 - \left(\frac{1+FE}{1+d}\right)^N\right)\right] d \neq FE \quad (14)$$

Where FE represents fuel escalation.
The life-cycle cost of recurring maintenance is given by:

$$LCC\ (Maintenance) = Annual\ Maitenance\ Cost * \left[\left(\frac{1+e_0}{d-e_0}\right) * \left(1 - \left(\frac{1+e_0}{d-e_0}\right)^N\right)\right] \quad (15)$$

Joshi, J.C.(2004).

Where annual maintenance cost is the annual non-fuel expenditure and e_0 represents general escalation.
The non-recurring life-cycle costs of diesel system include replacements of engines/generator and replacement of system batteries, and are given by

$$LCC(Replacement) = \sum_{j=1}^{v}\left[item\ cost * \left(\frac{1+e_0}{1+d}\right)^{Nj/v+1}\right] \quad (16)$$

Where item cost is the non-recurring expenditure in the present day and v is the total number of replacements over a life period of N years. The levelised cost of electricity generation (LCG) is defined as the ratio of the net present value of total capital and operating costs of a particular plant to the net present value of the net electricity generated by that plant over its operating life, **(**ADB.2001**).**

$$LCG = TOTC / NPVG \quad (17)$$

Where; LCG is the Levelised cost of generation (₦/kWh), TOTC is the Net present value (NPV) of total costs (capital and operating), NPVG = NPV of net electricity generation kWh

$$TOTC = \sum (TC_n /(1+r)^n) \quad \text{(ADB.2001).} \qquad (18)$$

TC_n = Total costs for power in operating year n (capital and operating)

$$NPVG = \sum G_n /(1+r)^n) \quad \text{(ADB.2001).} \qquad (19)$$

G_n = Net generation in operating year n, n = Operating year, r = Annual discount rate (10%), l = Operating life of plant

2.0 Studied System

Igu Village is a community located in Bwari, local Government Area, F.C.T, in Nigeria. The community has 7 districts. The population of Igu Village is one thousand seven hundred and twenty eight people (1,728), with about 300 households. 80% of the residents are farmers. The community is about 10km from the urban city which is Bwari, and 8km from the nearest national grid, the community is about 35km from Abuja city. The growth rate of Igu village is 7% (1999 Census). The systems design is for 20 years. The community has establishment and institutions as follows: One Health center / clinic, One Market, One Primary school, One Secondary school and One Adult training center.

Materials used in the study included**:** PV Module (Sharp, 235W, 29.3V_{max}, Polycrystalline Silicon type, 18% efficiency), Solar I-V meter (Full PV System Analyzer, HT ITALIA,2010, Version ES 1.00), Questionnaire, Sizing Equations, MML and Excel Spreadsheet.

2.1 Methods and Data

The availability of data is prerequisite for sizing and economic analysis. Sources of data for this research were grouped into two; primary and secondary data sources. The survey was conducted for the whole village considered in this research work which includes; households, schools, hospitals and shops and the survey questionnaires was administered by the enumerators to capture the required data. A total of 300 questionnaires were administered with 289 valid responses representing a 96% response rate. The methods applied and the content of the design of the questionnaire made it easily to understand and apply on the respondents. The survey took about one month period to complete.

2.2 System Sizing Method

Based on the survey carried out in the village the total load was found to be140, 240W (140.24kW) with a 12 hours usage per day

$$Total\ energy\ Demand = Total\ load * total\ hours\ usage \qquad (20)$$

Using above equation (Eq. 20) the total energy demand was calculated to be 1.68288MWh. The Load Factor chosen is 0.75; therefore, the peak energy demand was calculated using the equation below (Eq. 21) to be 1.26216MWh

$$Peak\ Energy\ Demand = \frac{total\ Energy\ Demand}{total\ hours} * Load\ Factor \qquad (21)$$

2.3 System Components Design

The sizing of the solar module was calculated thus;

$$AER = MPR * PSH \qquad (22)$$

Where: AER is the amount of energy required per module in a day, PSH is Peak Sunshine Hours (6 hr/d), MPR is the Module power Rating (24V, 235W), AER which is the amount of energy required from 235WModule in a day is by;

$$Number\ of\ modules = {Total\ Energy\ Demand\ per\ day}/{AER} \qquad (23)$$

Total energy demand per day is equal to 140.24kW *12 =1682.88kWh, AER = 1.410kWh/day

$$Number\ of\ modules = {Total\ Energy\ Demand\ per\ day}/{AER}$$

Therefore,

System Voltage = 48V, Days of autonomy=3

$$Energy\ Stored\ in\ Batteries = \left(\frac{Energy\ Demand\ per\ Day}{System\ Voltage}\right) * DOA \qquad (24)$$

Where; DOA is the day of autonomy = 3

Total current from Modules = Total Energy/systems voltage × Sunshine hours

Inverter Choice is based on power (See appendix for economic parameters and cost of components).

Land area requirement may be calculated using solar-to electricity ratio, Modules efficiency is equivalent to 10% (Solar-to-Electricity).

3.0 Results and Discussion

The solar irradiation taken hourly for five days between 10 -14th of February 2014, and the ambient temperature recorded between the hours of 7.00am to 6.00pm are as ploted in figure 1. The temperature ranges from 26.3^{O}C (degree centigrade) in the morning to 48.6^{O}C (degree centigrade) after mid-day. The same pattern of temperature and irradiation were observed for the rest of the days. The highest radiation of over 800W/m^2 was observed by 12.00 noon for all the five day period of survey, however, only sun intensity between 10.00 am and 4.00 pm was used in the study, this give 6 hours of sun intensity with average value of 700W/m^2 at 10.00am and 400W/m^{2}at 4.00pm.

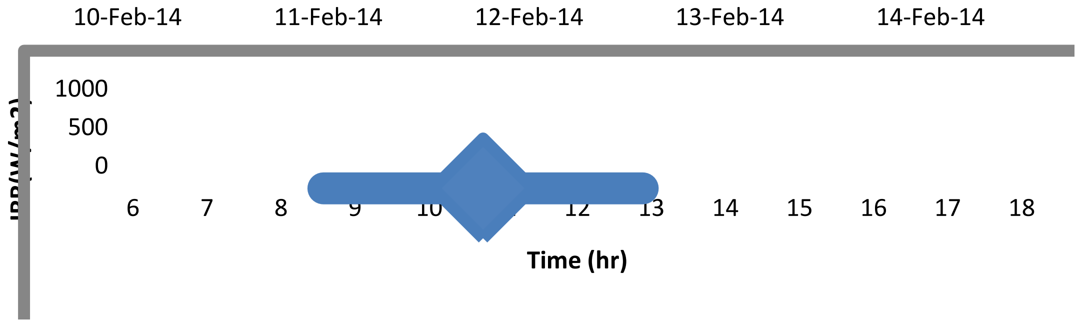


Figure 1: Solar irradiation of the study area.

Tables 1, 2 and 3 Summarize the solar photovoltaic components and diesel generator used respectively for the study with respect to their investments. Operation and maintenance cost was calculated from the cost of services of the generator, salaries of staff, decarbonisation and overhaul of generator after 5 years. Total operation and maintenance cost is seventy eight million eight hundred and sixty six thousand, eight hundred and thirty eight Naira (₦78, 866,838).

Table 1: Summary of PV components

S/N	Input	Descriptive Characteristics	Result for required quantity
1	Module	235W, 24V	1,194
2	Battery	375Ah, 12V	351
3	Charge Controller	60AMPS, 48V	68
4	Inverter	10kW, 24V/230Vac, 50Hz	14
5	Land Area	m^2	3346.1 m^2

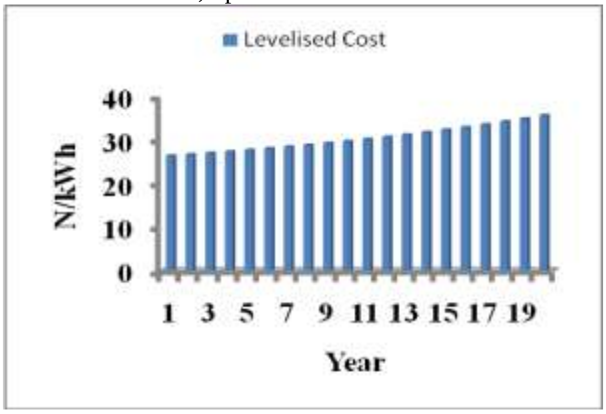
Table 2: Investment Cost of the Solar PV system

S/N	Item Description	Qty	Unit Price (₦)	Amount (₦)
1	235W, 24V polycrystalline Module	1,194	47,000	56,118,000
2	375Ah, 12V Trodjan Deep Cycle Battery	351	60,000	21,060,000
3	60AMPS, 48V Charge Controller	68	55,000	3,740,000
4	10kW, 24V/230Vac, 50Hz pure sine wave Inverter	14	550,000	7,700,000
5	Cable and other accessories	------		82,556,000
6	Contigencies/Workmanship	------		96,826,000
	Total			**268,000,000**

Table 3: Investment Cost of the Generators

S/N	Item Description	Investment Cost (₦)
1	First Generator	15,000,000
2	Second Generator after 10 years at 5% inflation rate	24,433,419
	Total	**39,433,419**

Fuel cost of the generator for the study period was calculated from the rate of diesel consumption per hour, total operation hours and the price of diesel per litre. 350KVA pekin diesel generator consumption is 66 liters per hour at less than 60% load, total operation hours was 87,600 hours and total diesel cost for the period at initial price of ₦180 and at escalation rate of 3% is one billion four hundred and forty million, one hundred and twenty nine thousand three hundred and twenty eight Naira seventy four Kobo (₦1, 440,129,328.74). Total cost is the cost of investment, operation and maintenance cost. The fuel cost for the study period is ₦1, 445,064,949.74



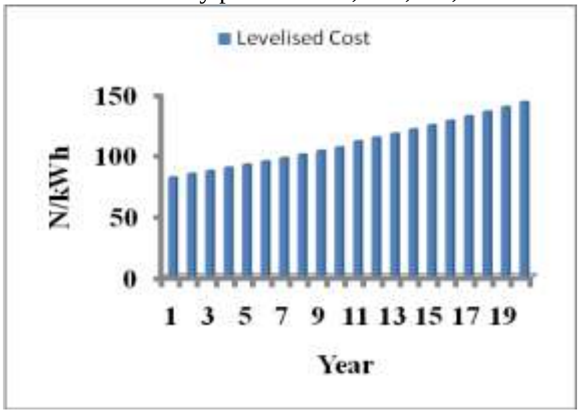


Figure 2: Levelised Cost of Solar PV **Figure 3**: Levelised Cost of Electricity Using Diesel Generator

The levelised cost is the cost of producing 1kilowatt hour of energy for the study period. The figures 2 and 3 show levelised costs for each year of the study period for both solar and diesel generators. The investment cost was divided over the life span of the module and the operation and maintenance cost at 5% escalation rate per year while the generation per year is constant at 657,000kWh. The levelised cost was calculated by yearly production cost by generation per year. Figure 4 depicts the average levelised cost of electricity generation.

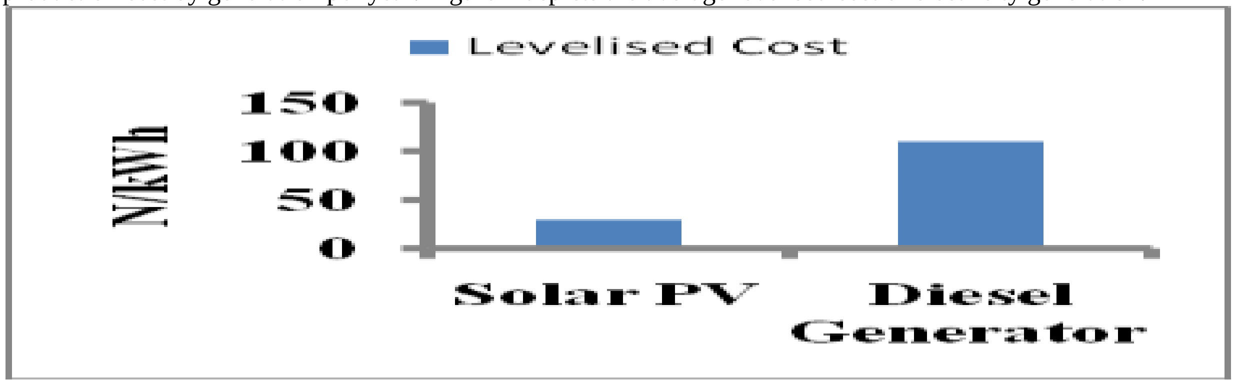
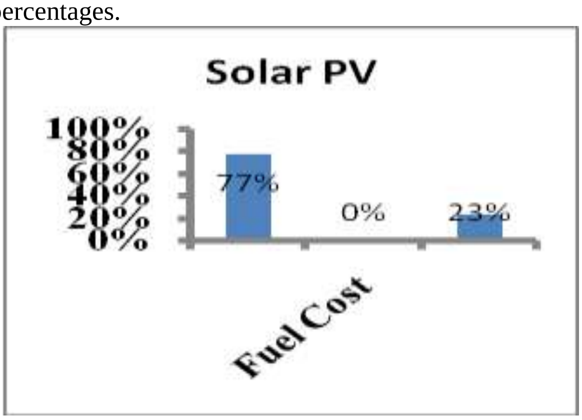


Figure 4: Average Levelised cost of Electricity Generation.

Figure 5 and figure 6 show the contributions of cost components of solar PV and diesel generator respectively in percentages.



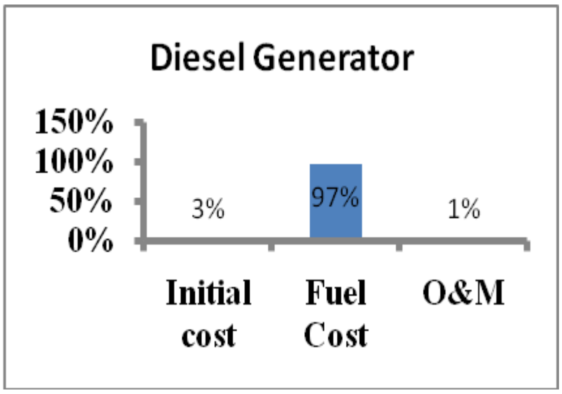


Figure 5: Contribution of Cost Components of Solar PV in %. **Figure 6**: Contribution of Cost Components of Diesel Generator in %

System Components: One thousand one hundred and ninety one panels is required to generate 1,680kWh of energy per day for Igu village. Which also requires about 3,346.1m^2 (0.335 hectares), 350 batteries to store energy for a period of 3 days, 68 charge controllers of 60A and 14 inverters of 10kW capacity.

Cost of Solar PV System A one hundred and forty–Kilowatt (kW) solar energy system was designed and costed about ₦268,500,000 and uses 12 hours of a typical village household's energy needs. The yearly cost of power production ranges from ₦272, 500,000.00 in the first year to about ₦400, 763,816.00.

Cost of Diesel Generator Power System: In comparison to conventional hydrocarbon fuels. A liter of diesel on the average produces approximately 10 kWh of electricity at a cost of about ₦180 per liter at a generator load factor of 65%.

Investment costs: The investment costs of the generator set include the actual cost of the generator, transport and installation costs. Investment Cost of 350KVA generator was fifteen million naira (₦15, 000,000.00). Number of generators equals study period divided by the life span of generator, two generators were proposed for the study period. The total investment cost was equal to thirty nine million four hundred and thirty three thousand four hundred and nineteen Naira (₦39, 433,419).

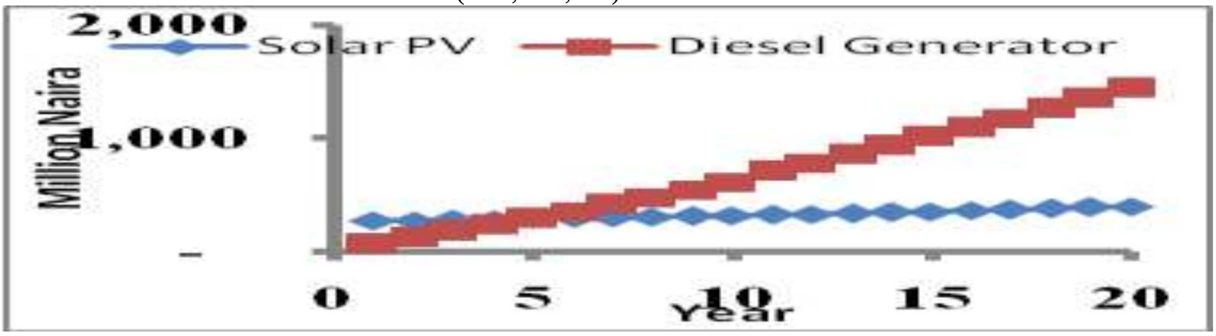


Figure 7: Comparison of Cost of Production for the Solar PV System and Diesel Generator System

4.0 Conclusion

Generators running on diesel have a lower capital cost but higher levelised cost than the solar PV generation alternatives. Given the projected increase in diesel prices, the following conclusions were drawn from this research:

The one hundred and forty kilowatt (140 kilowatt) solar PV will adequately supply the power needs of Igu village but without future projections. The initial cost of the PV system of ₦268,500,000.00 is much higher than ₦15,000,000.00 initial investment on a diesel generator that provides the same amount of power. The levelised cost of power production for the solar PV system is significantly below that for diesel generator, at 26.52₦/kWh against 81.27₦/kWh for the project start. In the medium to long term, inflation rate and escalating diesel prices increase the levelised cost further to 35.82 ₦/kWh and 143.34₦/kWh for solar PV and diesel generator after twenty years respectively.

A comparison of the total yearly costs shows that the solar PV system cost will equal the diesel generator cost in the fifth (5^{th}) year (see figure 7); with no fuel costs and very little maintenance cost, the solar PV system is, therefore, a better option than the diesel generator for Igu village.

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Appendix

The Economic Parameters and Cost of Components for the Base Case

Economic Parameters	**Cost of Components**
PV array cost per watt (C_P)	**₦200**
Battery375Ah, 12V cost (C_b)	**₦60.000**
Battery DOD_0	**0.8**
Battery average life (N_A cycles)	**1200**
Battery coefficient (B_c)	**0.02**
Cost of each Inverter unit	**₦550,000**
Cost of 60A charge controller	**N55,000**
Miscellaneous cost (wiring, panels, etc) (C_m)	**5% of Capital Cost**
Packing, transportation, etc. costs (C_s)	**5% of Capital Cost**
Economic evaluation period (*N*)	**20 Years**
General inflation rate (*i*)	**5%**
Discount rate (*d*)	**10%**
Escalation rate (e_0)	**7.5%**
Annual fixed charge rate of expenses (*m*)	**1%**
Diesel cost	**₦180 per litre**
Fuel escalation rate (FE)	**3%**
Life period of diesel set	**10 Years**
O & M costs of diesel engine	
Oil & filter change	**10% of cost generator**
Frequency of oil & filter change	**300 hours of operation**
Decarbonisation	**5% of cost of generator**
Frequency of decarbonisation	**1,500 hours of operation**
Engine overhaul	**50% of cost generator**
Frequency of engine overhaul	**6,000 hours of operation**