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Techno-Economic Analysis of the Usage of Solar Photovoltaic (SPV) System Compared to Premium Motor Spirit (PMS) for Power Generation in Nigeria

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Abstract: Issues concerning increasing population on the global scale have greatly increased the overall demand of energy in different forms but mainly as electrical power for industrial and domestic needs. With a population of over 231,400,000 people as stated by World Bank, between (60-70)% of this population have little or no access to electricity. As a result, fossil fuels have since been employed but its effects on health, environment, and climate have been detrimental. Restorative measures to the environment against further impact have precipitated the need for renewable energy (R. E) sources that are better alternatives. This study looks into solar photovoltaic (PV) as a R. E source, limiting its scope to self-generation in Calabar and attempts to draw comparison with the conventional method for self-generation (petrol generator) of equal capacity and equivalent working conditions. Experiment was carried out on test-bed quantitatively and qualitatively to determine unit values like fuel consumption rate and emissions respectively for the test-bed. Values obtained were simulated using HOMER PRO alongside generated irradiance value for solar PV. Other values obtained were simulated with actual parameters like capital cost, operational & maintenance cost, etc., to determine the Levelized Cost of Energy (LCOE) and emissions rate for individual systems over a period of 10yrs. Results yielded a Net LCOE of #1.924/kWh and Net Zero emission for PV system; a Net LCOE of #16.401/kWh and a Net emission (Carbon content only) of 365,240 kg/yr for engine test-bed curing the two basic issues of cost and emission on the long-term.

Keywords: Photovoltaic, Homer Pro, Solar, Irradiation, Emissions, Renewable Energy

1. Background of the Study

Power being the prime-mover of any economy in the world today has long been attributed to fossil fuel for its generation. It is no news that over 63% of global electricity generations comes from burning fossil fuel, while the remaining 37% goes to low-carbon sources [1]. Emissions resulting from the 63%-fossil fuel accounts for a plethora of air pollutants (particulate matter and green-house gases), of which our major concern CO_2 takes a better percentage composition [2]. On a global scale, CO_2 emissions from fossil fuel have experienced a sharp rise in the past 70yrs, reaching up to 35bn metric tons emitted in the 2020 as opposed to the merely 5bn metric tons in the year 1950 [3]. Accordingly, these pollutants have been known to be bringers of diseases like allergies, heat-related illnesses, cardiovascular diseases, dermatologic diseases, etc., alongside the gross environmental degradation they cause.

Away from health and environment, there are economic crisis too associated with burning fuels: Olowosejeje [4], in their study on the economic implication of unreliable energy, tied Nigeria's socioeconomic development rate to energy unavailability and unreliability as established that the Nigerian economy is weakened by the lack of energy (electricity) availability and reliability [5]. Both views looked to validate the fact of energy being the prime mover of any and every economy.

Furthermore, the basic objective for employing renewables in India is to improve and advance economic growth and evolution, improve energy access, limit rate of environmental degradation, and improve energy security [6]. The need to transit from non-renewables to renewable sources is mainly due to a known fact that the available petroleum and its derivatives in use today is limited, hence, will run out eventually, leaving us with the decision to either be proactive about the future by beginning the gradual switch to sustainable sources now we still have time, or come face to face with reality when we eventually run out of options [7].

According to research by Ajayi, O. O., et al [8] on the wind and solar potentials in the Northern region of Nigeria, they concluded that solar PV technology is a feasible option to facilitate sustainable development goals; [9]. evaluated the renewables potentials of the country and concluded that the nation can run a 100% renewable energy supply because she has the raw materials and also because it has been already achieved in some other regions of the world, however, they added that it is a capital intensive project to achieve. Capital estimates sits high between #(40 and 200)bn for energy production between (30 and 175)GW generation capacity [10]. Hence, it is apparent that the potentials for energy transition/mix for Nigeria from fossil fuels to renewables exists, however, the capital requirement and enabling governmental policies remains the basic limitations for progress.

2. Descriptive Overview

The solar energy prospects in Nigerian cities were investigated with strategic locations (Kano, Lagos and Onitsha) by Okoye, O. C., et al [11]. The survey discovered, first and foremost, that access to the national grid is restricted, and that power delivered to URBAN regions with grid connections is extremely intermittent. The cities selected were based on the grounds of their large commercial activities and also because they all have access to the national grid but unfortunately, experiencing frequent power interruptions, which impedes commercial and socioeconomic development. Over the course of a year, the solar resources for these cities were determined using synthetic hourly meteorological data in a standard meteorological format. Kano has the highest approximate average-global-horizontal resources of (6.08 kWh), with Lagos (4.42 kWh m^{-2}) and Onitsha (4.43kWhm^{-2}). On the basis of logical and computational simulation sizing techniques, a stand-alone solar PV system is estimated to fulfill a realistic household demand. These parameters are generic and can be used in any situation. The analysis indicate that the proposed standalone PV systems have a lower unit cost of electricity than current systems. The projected PV capacity and accompanying unit cost of energy for the selected cities ranged from 1.26kW p at 0.206 USD $kWh^{-1}$to 2.92kW p at 0.502 USD kWh^{-1}. The results demonstrated that the suggested standalone PV systems have a lower unit cost of electricity than the frequently used diesel generators. In light of Nigeria's current infrastructure and energy policy, it was determined that standalone PV electricity is technically and economically viable for urban residential applications.

The emissions of greenhouse gases (GHGs) in Nigeria from the year 1980-2014 was analyzed by Giwa, S. O., et al [12]. For the time period studied, the fuel usage figures was acquired from NNPC reports and used to predict GHGs emissions using default emission factor [69300kg/TJ (CO_2; $gasoline$), 74100kg/TJ ($CO_2; diesel$), 18kg/TJ ($CH_4; gasoline$), 3.85kg/TJ (($CH_4; diesel$) , 9kg/TJ($N_2O; gasoline$) and 2.25kg/TJ$N_2O\ diesel$). Using the fuel consumption statistics with Tier-1 technique recommended for National GHGs estimation and $Analytica^{TM}$ software, the total amount of GHGs estimated for the period under consideration was $7.30 \times 10^8 tCO_{2e}$ [$gasoline$; $5.20 \times 10^8 tCO_{2e}$ and $2.10 \times 10^8 tCO_{2e}$ $diesel$] from 2.13×10^{11} and 7.45×10^{10} liters of gasoline and diesel respectively. As a result, it's noteworthy that gasoline use accounted for 71.23 percent of total GHG emissions with CO_2 making up 98.72% [$CH_4 = 1.39\%$ and $N_2O = 0.61\%$]. The viability of solar as a parameter which is reliant on governmental policies and interventions was viewed by Abdulkarim, H. T., [13]. He discovered that, as with any new product, solar power-related research and development costs make for a considerable portion of the overall cost of manufacturing solar panels, driving up the unit cost. Citing India as an example, he explained that solar-favored governmental policies and subsidies saw a drive from 2650MW of solar power generations to over 20GW, an achievement that many west doubters thought impossible.

The opportunity of photovoltaic systems in Nigeria was compared with the already existent household energy generation by using AGO-driven generators [14]. Juxtaposing the duo against parameters like environmental impacts, economic benefits, reliability, total costs, availability and utility. The result showed greater environmental depletion from diesel, unreliability in quantity per unit price of diesel, lower initial costs but higher expenses incurred for operation and maintenance, etc. For PV it showed, no environmental depletion, relative reliability due to ever present insolation in Nigeria, even though at varying intensities, higher initial cost, but negligible operational/maintenance costs, relatively low availability. Furthermore, as compared to the usual operation of generators, financial analysis of home PV reveals savings of 60-65 percent throughout the PV lifecycle.

For the development of PV systems in Nigeria, Abdulkarim and King [15] conducted a statistical and economic analysis of sun radiation and climate. The data/study was limited to three places, one from each of Nigeria's radiation areas (Maiduguri, Minna, and Port Harcourt). The data was analyzed using Minitab17, which revealed that Maiduguri was more feasible for solar energy conversion systems than the other two locations, with the peak watt (Wp) of solar array considered necessary for the same energy demand of 1.1MWh being 619419.27Wp, 821142.52Wp, and 1219489.32Wp for Maiduguri, Minna and Port Harcourt respectively. This study concluded that the project cost of solar systems increased with reduction in average solar irradiance and sunshine hours with Maiduguri having the lowest cost of #3,223,971.60 and irradiance of

$266W/m^2$, while PH #4,595,270.99 and at $218W/m^2$ rate of radiation. Eliaban O., et al and Ahmad H. M., [16, 17] in their study described solar power as a fast expanding power source with an average growth rate of 50% a year over the last decade. Showing that annual installations of PV panels increased from a capacity below 0.3GW in 2005 to 45GW in 2014-enough to power more than 7.4 million homes in America. They described the momentum to be a result of innovations in regulations, industry, technology and financing.

3. Research Methodology

In determining the techno-economic analyses of solar PV system as alternative source of power in Calabar, a qualitative comparison between the proposed PV system and a main player in self-generation (petrol generator) was carried out. Comparison was possible after the systems were made to run independently but subjected to equal loading and weather conditions. The materials employed in the running processes were:

1. For petrol generator: 6.1kVA petrol engine test-bed; 1 liter of petrol; An exhaust gas analyzer; Timer/stop clock.
2. For solar PV system: A 6.1kVA solar PV system (Panels, inverter, charge controller, batteries).
3. For Both systems: Load of 955W and a daily energy requirement of 6500kWh.

To get the 6.1kVA petrol engine test bed running, petrol had to be gotten from CHRIEZIK fuel station, EkpoAbasi at the rate of ₦220/liter. This was used to crank up the test-bed after routine oil check had been carried out to forestall engine knock during the experiment. The test-bed was used to power a bungalow with a daily energy requirement of 6.5kWh.

Through the powering process, the gas-analyzer was rigged to the exhaust of the test-bed to account for the amount of gases expelled during the experiment. The procedure required that the test-bed which is connected to load, be run with a liter of petrol until dryness. This allowed for the accurate measurement of the fuel consumption rate using three (3) different stopwatches to reduce error. Three readings were recorded:

1. 33.47 minutes for 1-litre of fuel;
2. 34.08 minutes for 1-litre, and;
3. 34.55 minutes for same amount of fuel.

An average specific fuel consumption rate of 34.03mins to 1-ltr (0.3ltr/min and 15,731ltrs/yr) was obtained and thus, used for analysis.

Furthermore, operation costs for petrol generator were calculated, and they included

1. Routine oil change (Castrol engine oil)— 10ltrs per year;
2. SumecFirman spark plug— 3pcs;
3. Quarterly carburetor servicing;
4. Workmanship for technician.

All summing up to ₦194,181/year is recorded alongside the Capital cost of the test-bed obtained from Jumia. com. ng at ₦455,000. Fuel price stood at ₦3,460,747/year for 8,712 annual running hours, assuming 48-hrs downtime lost to routine maintenance.

On the other hand, the Capital cost for a complete 6.1kVA solar PV system is gotten from AliXpress. com and recorded as ₦3.42m. Operation cost stands at ₦5,000/year with an estimated working time of 8712hrs, assuming 48-hrs downtime to routine maintenance.

4. Results and Discussion

The experiment in this research was conducted under certain conditions and with certain assumptions. These assumptions were set to ensure equal working conditions for solar and for petrol generator, and allow for a fair comparison between both so that short term and long-term costs can be deduced and analyzed. These assumptions are:

1. Both system (Petrol generator and solar PV system) have equal electrical ratings;
2. Both systems power equal loads throughout their operation time;
3. That both systems are stand-alone, i. e., the power the given load solely without the grid;
4. They work 24hrs a day and 7 days a week for a period of one year, except for downtimes allowed for servicing and routine maintenance.

4.1. Energy Audit

Table 1. *Energy audit of appliances for a 3-bedroom apartment.*

Appliances	Unit	Power rating/unit (W)	Total power (W)	Hours/day	Daily Energy Requirement (Wh)
Table Top Freezer	1	60	60	10	600
Energy saving bulb	5	15	75	10	750
Computer (laptop)	1	120	120	5	600
150-inch TV	1	490	490	5	2450
Ceiling Fan	3	70	210	10	2100
Total			955		6500

From the energy audit carried out in the table above, the Daily Energy Requirement is obtained for the apartment to be 6.5kwh. The Daily Energy is required for the selection and sizing of petrol generator and solar PV components. It can be seen in table 1, that column one is the electrical items whose loads were measured during the experiment, the corresponding units, that is, the amount of each of the same items are as shown in column two, whereas column three shows the power ratings for each items of the units, as column fours indicates power rating for all the items. The hourly usage is as could be seen in column five, and finally daily consumption in Watt-hour (Wh) is as shown in column six. This will help to determine the total daily energy required, and the befitting engine to carry out the experiment.

4.2. Input Parameters

Other useful parameters as costs, operational hours, fuel consumption rate, etc., are shown in table 2 below.

Table 2. *Input parameters for HOMER simulation.*

Costs	Solar PV (6.1kVA)	Petrol Generator (6.1kVA)
Capital/Installation cost (NGN)	₦3.42m	₦455,000
Operation Hours per year	8712hrs	8712hrs
Operation and Maintenance Cost per year	₦5,000	₦193,581
Fuel consumed in one year	NIL	15,731 L/yr
Cost of fuel per liter as at time of research (NGN)	____	₦220

The data displayed in the tables 1&2 above are real time experimental data obtained from running individual systems (Petrol generator and solar PV system) independently under same working and loading conditions. Data for solar insolation was generated from the HOMER software for the location: Yellow Duke street, Calabar, Nigeria existing between (4°56.2'N & 8°19.6'E). the table 2 shows the capital cost for the Solar PV installation, and the cost of purchase for the engine test bed, the operational cost and number of operational hours per annum.

4.3. Solar Radiation

Data for solar radiation for the location was generated online from the site, courtesy of the NASA data base. Figure 1 below shows the solar resource for the location under consideration.

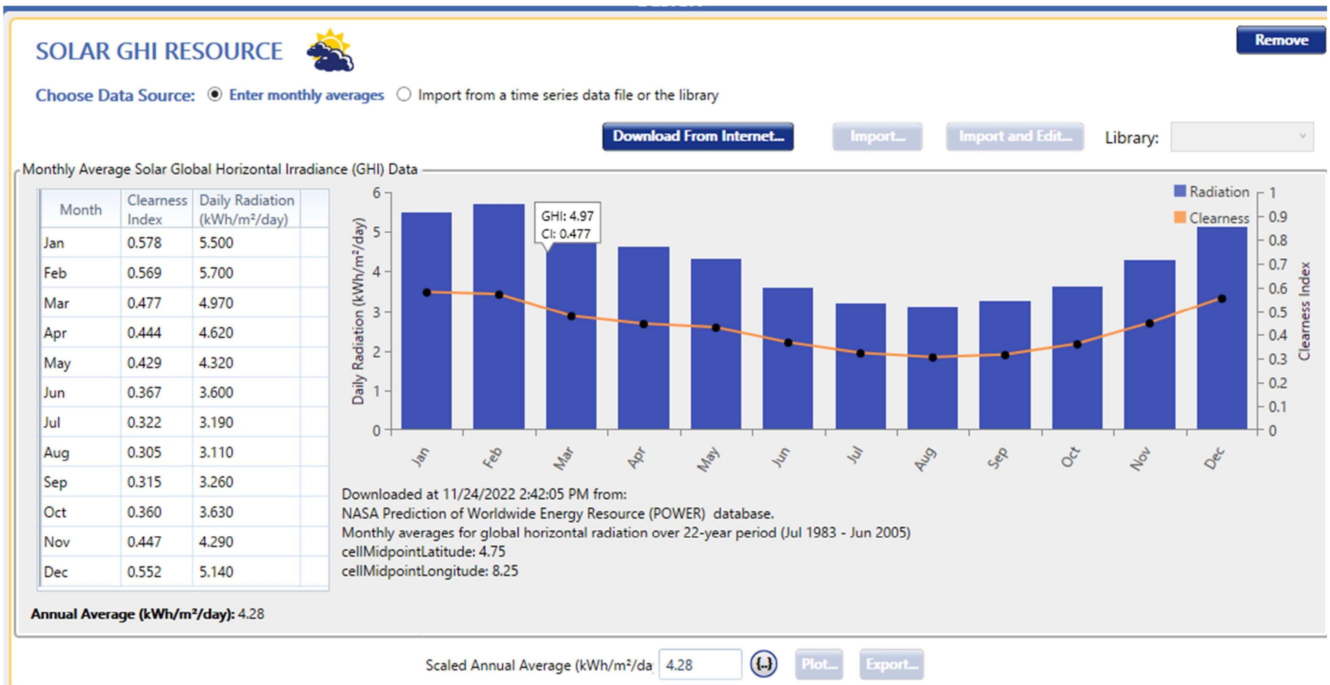

Figure 1. *Annual Solar radiation for Yellow Duke Str., Calabar (NASA).*

The simulation covered a-ten-year period of operation: assuming equal working conditions for both systems (petrol generator and solar PV system). The yearly results reveal such comparative quantities as Levelized Cost of Energy (LCOE), Emissions, etc.

Emissions describes the amount of gaseous particulate discharge from the individual systems to the environment. The tables 3 below show the yearly emission rate for both the petrol generator and the solar PV system. The emission gas analyzer displayed the values of each gas as could be seen in table 3 below.

Table 3. *Yearly emission breakdown for petrol generator.*

QUANTITY	VALUE	UNITS
Carbon Dioxide	36,267	kg/yr
Carbon Monoxide	257	kg/yr
Unburned hydrocarbons	11.3	kg/yr
Particulate Matter	1.54	kg/yr
Sulphur Dioxide	7.96	kg/yr
Nitrogen Oxide	242	kg/yr

On the other hand, the emission rate per year for the solar

PV system is displayed in the table below.

Table 4. *Yearly Emission rate for solar PV system.*

QUANTITY	VALUE	UNITS
Carbon Dioxide	0	kg/yr
Carbon Monoxide	0	kg/yr
Unburned hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulphur Dioxide	0	kg/yr
Nitrogen Oxide	0	kg/yr

4.4. Levelized Cost of Energy (Lcoe)

The LCOE of any energy system is the measure of the cost of energy generated per kilowatt from the system. The LCOE for individual systems is simulated by HOMERPRO using the mathematical relationship:

$$COE = \frac{C_{ann,tot} - C_{boiler} H_{served}}{E_{served}} \quad (1)$$

Where $C_{ann,\ tot}$ = total annualized cost of the system [$/kWh]

C_{boiler} = boiler marginal cost [#/kWh]

H_{served} = total thermal load served [kWh/yr]

E_{served} = total electrical load served [kWh/yr]

C_{boiler} H_{served} as seen in the numerator of the equation is the part of C_{ann} that results from serving the thermal load. In systems such as wind or PV that do not serve a thermal load, ($H_{thermal}$ = 0). The tables below show the LCOE over a ten-year period for individual systems.

Table 5. *Yearly LCOE for solar PV and test-bed over a period of ten years.*

Year	Solar LCOE (#/kWh) for PV	Solar LCOE (#/kWh) for test-bed
1	204.83	1783
2	201.91	1681
3	199.06	1648
4	196.26	1631
5	193.52	1621
6	190.83	1615
7	188.20	1610
8	185.63	1606
9	183.11	1604
10	180.65	1602

The table above shows the annual cost of energy per kilowatt-hour for both systems working independently but under equal working conditions.

The tables 3 and 4 above shows the emission rate for petrol generator and solar PV system (of the same size and under the same loading conditions) respectively simulated over the same period of time. The results show that running a petrol generator for a period of one year leaves a carbon footprint of over 36500kg per year in the atmosphere as opposed to a net zero carbon emission per year from the solar PV system. This gives a whopping 365,240kg/yr of emitted carbon from a single generator over the ten years of operation as simulated, and a net zero for the comparative solar PV system.

LCOE

Going away from the emissions, we consider the LCOEs for both systems using the figures below:

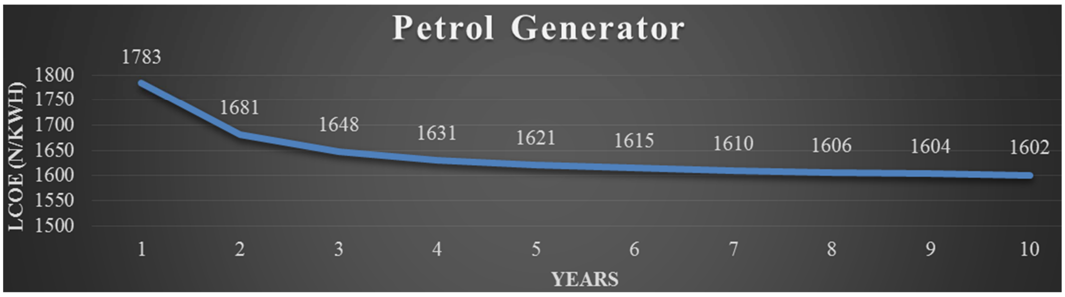

Figure 2. *LCOE-Time graph for Petrol generator.*

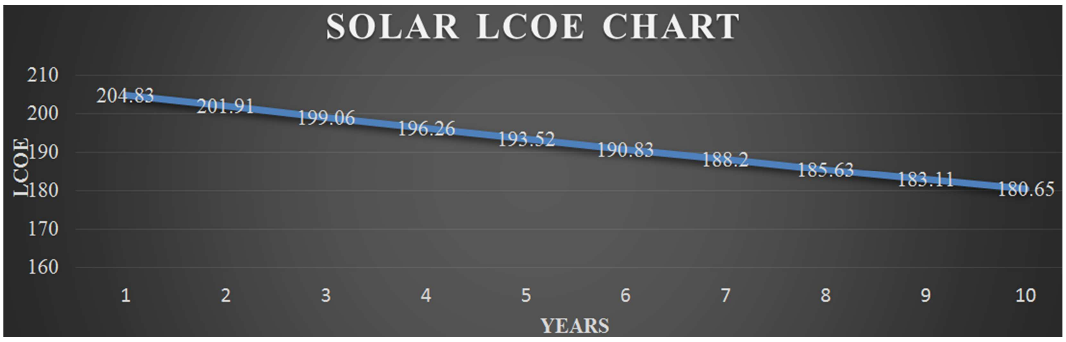

Figure 3. *LCOE-Time graph for Solar PV system.*

Figure 2 shows the graphical representation of the LCOE for the petrol generator already displayed in table 5 above. An approximate 5.72% of depreciation was noticed on the second year; a smaller margin of approximately 1.9% between year 2 and year 3; a further depreciation to the value of percentage change from previous 1.9% to an approximate 1.03% between year 3 and year 4; etc. however, the overall depreciation between year 1 and year 10 shows a 10% drop in the price of energy per kilowatt.

Similarly, Figure 3 presents the LCOE-Time chart for the solar PV system. Like Figure 2, the pattern shows a depreciation in the price of energy per kilowatt over operation time. An approximate 1.43% depreciation occurred between year 1 and year 2; between year 2 and year 3, year 3 and year 4, year 4 and year 5, year 5 and year 6, year 6 and year 7, year 7 and year 8. Year 8 and year 9, year 9 and year 10, a uniform approximate depreciation of 1.3% occurred between respective year pairs. However, the overall depreciation between year 1 and year 10 is calculated to be 11.8% approximately.

5. Conclusion

The following conclusions were drawn from the research and results presented herein shows the economic viability of solar as alternative source of power for a 3-bedroom bungalow in Calabar. Under equal working conditions;

1. The all-time-high LCOE for solar-PV system was 204.83N/kWh, while that of petrol generator was 1783N/kWh (difference of 1578.17N/kWh between systems; greater than the net LCOE for solar-PV for the first 8yrs).
2. The all-time-low LCOE for PV-system after 10yrs was 180.65N/kWh (about 11.8% decrement in 10yrs), while the all-time-low LCOE for petrol test-bed over a period of 10yrs read 1602N/kWh (about 10.15% decrement in 10yrs).
3. Gasoline test-bed produced a whopping 36,267kg/yr of CO_2 (emissions like CO, SO_2, not accounted for) annually, and 362,670kg/yr of CO_2 in 10yrs, whereas, PV-system had a Net-zero carbon emission for 10yrs.

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