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Analysis of Environmental and Economic Prospects of Stand-By Solar Powered Systems in Nigeria

A. Offiong[1] and N. I. Okpura[2]

[1]Department of Mechanical Engineering, University of Uyo, Uyo, Akwa Ibom State, Nigeria.
[2]Department of Electrical/Electronic & Computer Engineering University of Uyo, Uyo, Akwa Ibom State, Nigeria.

Abstract

Photovoltaic power systems can be used as electrical power source for home to meet its daily energy requirement through direct conversion of solar irradiance into electricity. This paper presents environmental and economic analysis of two stand-by power supply options for a typical Nigerian household namely: diesel generator plant and solar powered systems. The analysis reveals that solar systems are more economically viable. The environmental benefits associated with substituting diesel powered stand-by plants with solar powered photovoltaic systems were also estimated. The amount of diesel saved was estimated and the reduction in air pollution calculated. With these two analyses, it is hoped that individual households in Nigeria, will be encouraged to go for solar stand-by systems while government will be encouraged to pursue further on energy-environmental friendly policy which will lead to the reduction in the production of air pollutants. This kind of policy is very essential, as the number of household installing stand-by power plants in Nigeria has been found to increase significantly over the past few years.

Keywords: Stand-by powered systems, Diesel generator plant, Inverter, Pollutants, Particulates, Nigeria.

1 Introduction

Energy plays a fundamental role in our daily activities. The degree of development and civilization of a country is determined by the amount of energy utilized by its human beings [1]. Crude oil, coal and gas are currently the main resources for the energetic world supply. The size of the reserves of these fossil resources is rapidly decreasing. The depletion of fossil fuels, the pollution and the climatic change impose the need of the energetic diversification by the rapid integration of renewable energies [2]. Renewable energy sources (solar, wind, etc.) are attracting more attention as alternative energy sources than conventional fossil fuel energy sources. This is not only due to the diminishing fuel sources, but also due to environmental pollution and global warming problems. Among these sources is the solar energy, which is the most promising, as the fabrication of less costly photovoltaic (PV) devices becomes a reality [3]. The socio-economic survey conducted by the National Bureau of Statistics [4] provides some information about the percentage distribution of households by states and various sources of electricity supply in Nigeria in 2009.

Data from the survey shows that an average of 35.3% of household lacked access to electricity that year. The survey also shows that the use of renewable energy (especially solar energy) for rural electrification is yet to be taken seriously, as there is near absence of solar electricity in Nigeria in the survey year as well as the low rural electrification rate provided [5].

Solar powered generating systems are well established and they have proved to be a reliable and problem free alternative to conventional power generating systems as stand-by in few Nigerian homes. Many manufacturers in America and Europe produce solar powered generating systems, which are becoming increasingly common in Nigeria. The technology is mature and the systems have proven that they can withstand the weather conditions. Their superiority to conventional systems lies not only in the economics but also in pollution abatement. The technical feasibility of solar power systems has been well established, while economic feasibility has been a major barrier restricting widespread use in Nigeria. Solar energy powered systems usually require a substantial initial investment as compared to conventional power system which makes them very sensitive and vulnerable to economic environment. However since solar powered systems usually have life span of about thirty years and the conventional system has a life span of only about ten years, there is room for comparison. The approach here is usually to compare the long run energy cost per annum of the solar system with that of the conventional system taking into account initial capital investment, running costs, maintenance cost, and fuel cost. The electrical power from Port Harcourt Electricity Distribution Company (PHED) is susceptible to frequent breakdowns usually resulting in long outage duration.

Several researchers have done economic and environmental analyses of solar thermal systems [8], [16], [15] and [11]. In economic analysis, a slight error in assumption of life of a capital-intensive system can produce misleading results. Also in a country like Nigeria where the energy resources are abundant there is needed to really assess the economic viability of this kind of project.

2 Review of Relevant Literatures

2.1 Solar Radiation in Nigeria

Nigeria lies within a high sunshine belt, that is, between latitude 4 – 14^0 North of the equator and thus has enormous solar energy potentials. The mean annual average of total solar radiation varies from about 3.5 KWh/m^2 per day in the costal latitudes of about 7 KWh/m^2 per day along the semi arid areas in the far north. On the average, the country receives $19.8MJ/m^2$ per day. Average sunshine hours are estimated at 6hrs per day. Given an average solar radiation level of about $5.5KWh/m^2$ per day and the prevailing efficiencies of commercial solar-electric generators, then if solar collectors or modules were used to cover 1% of Nigeria's land area of $923{,}773km^2$, it is possible to generate 1850 X 103GWh of solar electricity per year, which is over one hundred times the current grid electricity consumption level in the country [23,24].

Several studies have been carried out by many investigators on the solar radiation pattern in Nigeria [6, 7]. As a tropical country, Nigeria receives on the average as high as $20MJ/m^2$ per day of solar insolation depending on the time of the year and the location considered. As can be seen in the work of [6, 7], the variations expected are quite small. The Nigerian Federal Ministry of Science and Technology estimates that the total annual energy consumption of about 21 x 10^9 kWh could be made by converting only 0.1% of the total solar radiation incident on the country at a conversion efficiency of 1% [9]. In order to be able to select the required size of the photovoltaic system required to sustain a typical household in Nigeria, a parameter called the Peak Sun Hours is employed. The peak sun hours gives the number of hours needed at peak sun ray condition to have an equal amount of solar energy for that day. Reference [7] gives the peak sun hours for various locations in Nigeria.

2.2 The Photovoltaic (PV) Power System

Direct conversion of sunlight into electricity can be achieved using photovoltaic cells. The technology involved in the fabrication of the cell is high and so are the initial costs of these cells. However, these systems are very attractive as they do not involve moving parts and hence are maintenance free. Photovoltaic cells were initially designed for use in space programmes, but recently the cost of these cells have come down and they are now widely used for non-space application such as the one we are considering now. Research has shown that the individual photovoltaic module can convert solar radiation into electricity with an efficiency of about 15% [12]. The life span of these cells is estimated at 30 years. Voltage by photovoltaic modules is almost constant with only very insignificant variation with changing solar radiation intensity. With these characteristics, the photovoltaic modules are very suitable for charging batteries so as to store part of the generated energy for later use after sunset. This is the basic principle behind the photovoltaic solar power plant.

The photovoltaic power plant is made of the following parts – the photovoltaic cell, battery bank, battery charger controller, inverter, protection devices and other accessories of the solar systems.

Photovoltaic cells: In photovoltaic cells the open voltage remains constant with changing solar radiation intensity. Variations are only found in current output. These variations have been found to be almost linear with respect to solar radiation intensity. Photovoltaic cells are usually connected together in what is known as module. They may be connected in series or in parallel or both. Series connections of the cells increases the voltage output of the module whereas parallel connection increases the current output of the module. In a photovoltaic power plant, several modules are connected in an array to achieve the desired electric power output. The electric power is given by $P = I \times V$: where P is in Watt, V is in Volts, and I is in Amperes. The photovoltaic power system is usually designed such that the solar cells operate at the point of maximum power, which can easily be achieved by using a maximum power point tracker in the system [9].

Battery Bank: These storage batteries are required because of the mismatch between supply and demand for power. Depending on the power requirement, the batteries can be arranged in series or in parallel. The power generated by the photovoltaic cells is direct current type, which is only good for few domestic operations like lighting.

Inverter: It is required because some of the loads that will be serviced by the power plant require alternating current like, the operation of television sets.

Battery Charger Controller: They are required to protect the batteries against excessive charging current.

Protection devices: They are required to protect the array of modules from consequences of failure in any of its modules. These devices are actually diodes placed along the bypass connection around the module. See Figures 1 – 3. A module may fail due to deterioration of electrical contacts or shading.

2.3 Diesel Engines Used In Most Homes Hold as Standby

A survey has shown that most Nigerian household seeking standby power supply for their houses usually go for the clone system, which is schematically illustrated in Figure 1. The system is usually made up of a diesel engine, a 10 kilowatts alternator, two water drums to act as cooling units and one diesel drum. The system is usually noisy and consumes a lot of fuel thereby generating a lot of smoke. Even though the systems live was being estimated at five years. This has to be sustained at very heavy maintenance cost. The most worrisome problems in the households using the system now are its economics, noise, maintenance cost, fuel cost and its environmental impact.

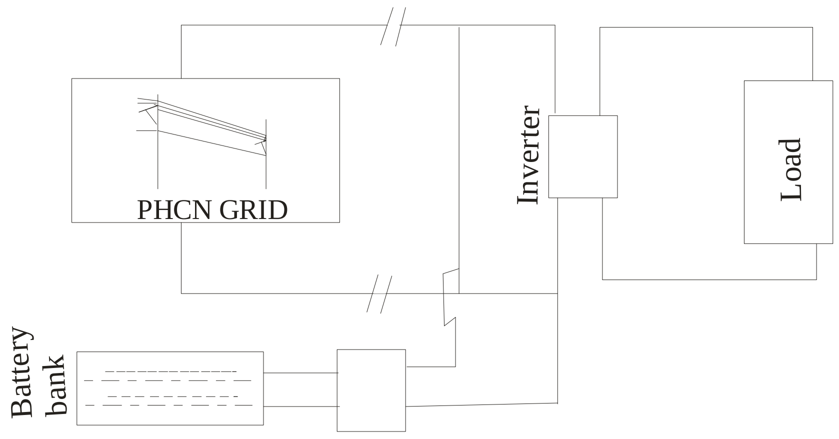

Figure 1: Schematic diagram of the Battery back-up system in use in most household in Nigeria.

2.4 The Photovoltaic Systems Used In Few Nigerian Households

In the Nigerian solar market, there are three kinds of systems in use namely: the Battery back – up system; the stand-alone photovoltaic solar system; and the hybrid Photovoltaic system.

The Battery back-up system is schematically shown in Figure 1. Basically the battery back up system is a combination of the PHED system, battery bank, inverter and all the necessary solar installation accessories without the photovoltaic modules. Domestic consumers usually use them where PHED supply is fairly stable for example in Government reserved areas. Specifically they are usually recommended where PHED outage hours are not more than I hour per day. The batteries are charge by the PHED system when it is on and the electricity stored is sufficient to last till the PHED comes on again

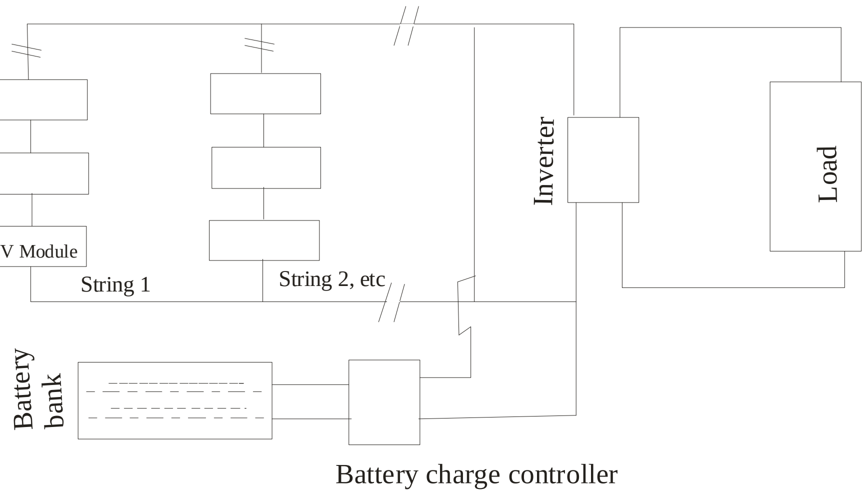

Figure 2: Schematic diagram of a stand-alone photovoltaic power plant for use in Nigeria household

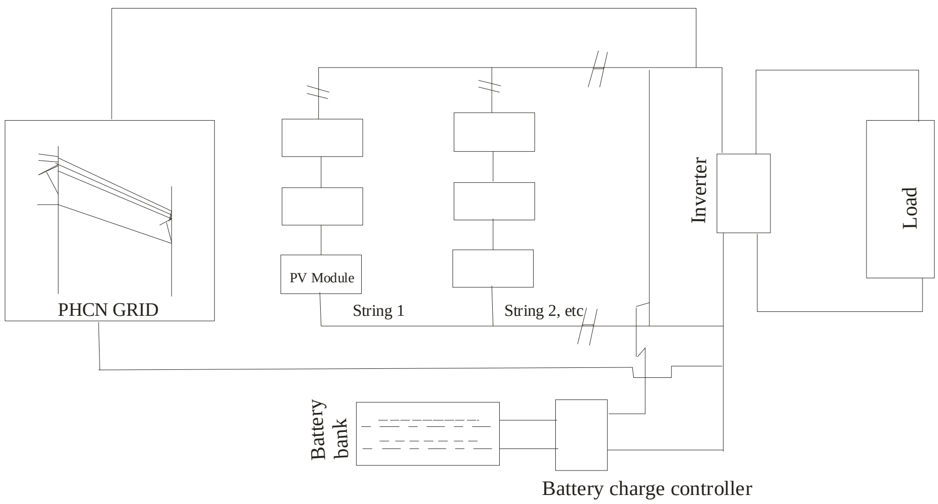

Figure 3: Schematic diagram of a hybrid photovoltaic power plant for use in Nigeria House hold

The stand-alone photovoltaic solar system is schematically shown in Figure 3. The stand-alone system is a complete solar system made up of photovoltaic modules, battery bank, inverter and all the necessary solar installation accessories without the advantage of being also connected to PHED. Consumers in remote areas where PHED grid has not been connected usually use them. These remote areas include islands, isolated telecommunication stations, remote villages, river – data region and isolated desert locations. The photovoltaic storage battery involved here are usually many so that they can sufficiently charge/store power in the system in the day times such that there will be power all night.

The hybrid photovoltaic Solar system is schematically shown in Figure 4. The hybrid system is a complete solar system made up of photovoltaic solar installation accessories with the additional advantage of being also connected to PHED.

The hybrid systems are the most commonly used stand – by systems in most Nigerian households. The hybrid system is usually cheaper than the stand alone system because it requires less number of photovoltaic cells and batteries. Hence we are going to compare the hybrid system with the diesel plant in our analysis.

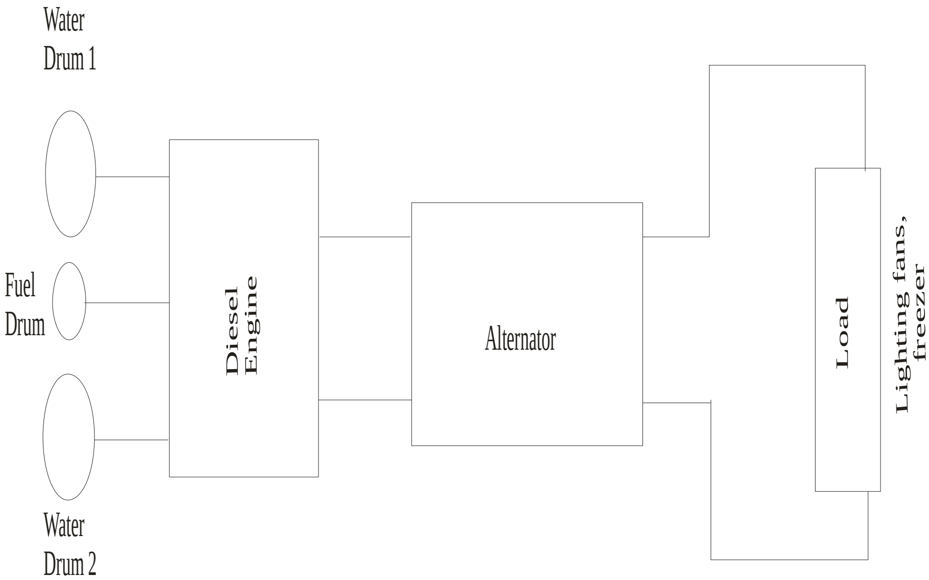

Figure 4: Schematic diagram of the conventional diesel power plant used in most Nigerian households.

3 Methodology

3.1 The Photovoltaic Power System Sizing

The following data are needed to adequately size the photovoltaic power system: accurate data on the solar radiation of the location concerned, accurate data on the characteristics of the solar cells employed in the design of the plant, the peak load of the system to be powered together with variation of this demand on daily/seasonal basis.

The above data are then used to estimate the following parameters, which gives the size of the plant.

(1) The required number of the photovoltaic modules; this for stand-by systems can be given by the equation:

$$P_{PV} = \frac{E_{L+(E_L D\ X\ BE)\ X\ 100}}{KC_R} \quad (1)$$

Where P_{PV} is the photovoltaic module array size in peak watt, E_L is the daily energy requirement (Wh/day); D is the number of storage days; C_R is charge recovery of the battery efficiency (days); BE is watt – hour efficiency of the battery; and k is the annual average equivalent peak hours per day (sunshine period).

(2) The required number and size of the storage batteries. This for stand-alone systems can be given by the equation:

$$C_t = \frac{E_L X\ D}{C_D} \quad (2)$$

where C_t is the storage capacity of battery (Ah) and C_D is maximum permissible depth of discharge (DOD) and E_L and D as previously defined.

(3) The capacity of inverter, Battery charger controller and other accessories: This depends on the electrical parameter (voltage to current) that is expected to go through the equipments. Several sizes are usually available in the market.

For the hybrid system the above equations are still applicable but only that the values obtained from the equations has to be multiplied by the demand factor, which can be determined by using the average outage duration of the conventional system.

3.2 Economic Evaluation

The capacity of the system depends on the fuel consumption of the system, which is necessary for economic-environmental evaluation of the diesel powered system against photovoltaic solar powered system. The first step in doing this is to estimate the plant size and average load requirement for a typical household in a case study location in Nigeria. From Table 1, the size of the generator required is a 1.75 kW engine since the total load is 0.775kW and the average power requirement is 2.325kWh/day (Table 1) assuming each equipment is operated for 3h/day.

Table 1: Load Data

Load Type	**Total load**	**Power Requirement (Load x 3h/day)**
10 lamps 40W	400W	1200Wh/day
2 lamps 25W	100W	300/day
1 refrigerator 25W (1/6 Hp)	125W	375Wh/day
2 television set 40W	80W	240Wh/day
1 video set 40W	40W	120Wh/day
2 radio set 15W	30W	90Wh/day
Total	**0.775kW**	**2.325kWh**

The cost of the diesel engine is estimated at ₦200,000.00 and maintenance cost are estimated at 25% of capital cost per annum. Empirical studies have shown that 7 litres of diesel per day (i.e. 2555 litres per annum) will be required to deliver the estimated 2.325kWh. With diesel cost at ₦120 per litre, the total cost of fuel can be put at ₦306,600.00 per annum. The life expectancy of this diesel engine from empirical studies can be put at 10 years.

In order to determine the cost of a solar photovoltaic system, the photovoltaic module size must be estimated. Using Eq. 1, the load data, insolation data, and market survey of battery data. The size of the PV module was estimated at 200-peak watt. Thus, a total of 2 square meter PV modules of 100-peak watt per square meter are to be used. Also in order to determine the cost of solar photovoltaic systems, its battery storage capacity must be estimated. Using equation 2, the load data and market survey of battery data the battery storage capacity was estimated at 2.5kWh. The total costs of the required modules and inverters (output 230V, 50Hz) are ₦1,100,000.00 from market studies. Installation costs and spares including battery replacement twice during the photovoltaic life span is estimated at ₦600,000.00. The total comes to ₦1.7 million.

With any photovoltaic system there is no fuel cost and no maintenance cost for the system in 30 years.

The annual cost of energy supply for the systems can be determined from the equation below:

$$E = \frac{C_C}{L_E} + M_C + F_C \qquad (3)$$

Where Cc is capital cost; L_E is the life expectancy; Mc is the maintenance cost; and F_C is the fuel cost. Table 2 compares the annual cost of energy supply for the diesel generator system with the photovoltaic system.

Table 2: Annual costs of energy supply for the diesel generator and photovoltaic systems.

Economic parameter	**Diesel Generator System**	**Photovoltaic System**
Life expectancy(L_E)	10 years	30 years
Capital cost (C_C)	₦200,000.00	₦1,700,000.00
Maintenance cost per annum (M_C)	₦50,000.00	-
Fuel cost per annum (F_C)	₦219,000.00	-
Annual cost of energy (E)	₦289,000.00	₦56,666.67

From Table 2 it can be seen that the diesel generator system is a costlier option. The high cost of the diesel generator system arises mainly from the high running costs in terms of fueling and maintenance. The hybrid solar photovoltaic system is therefore a more viable power supply system as stand-by for house hold usage.

3.3 Environmental Impact Evaluation

The environmental benefits associated with the substitution of the diesel powered system with the solar powered system can easily be estimated by determining the reduction in the production of air pollutants associated with these substitutions. Reference [11] gives the pollutant emission factors necessary for the calculation of the emissions from the electricity producing thermal plants using diesel oil as shown in row 1 of Table 3. From the load estimation, the system requires 2.325kWh, dividing this value by 1000 and multiplying the result with the emission factors for diesel oil gives the value in row 2 of Table 3 which gives the emission per day of the pollutants for one household plant. Row 3 of Table 3 gives the emission per year of the pollutants of one household plant. Note that the value in row 3 of Table 3 can be obtained by multiplying the values in row 2 of table 3 with 365 the number of days in a year.

Table 4 shows the annual emission of the various pollutants into the Nigeria atmosphere should the given percentage of household in Nigerian install a diesel generator set. Row 1 in Table 4 is gotten by multiplying row 3 of Table 3 by 22.44 million the number of households in Nigeria. Multiplying row 1 in Table 4 by 0.9 gets Row 2 in Table 4. Row 3 in Table 4 is got by multiplying row 1 in table 4 by 0.8 and so on. For now it is reasonable to assume that only about 12% of a household in Nigeria are using stand-by diesel plants.

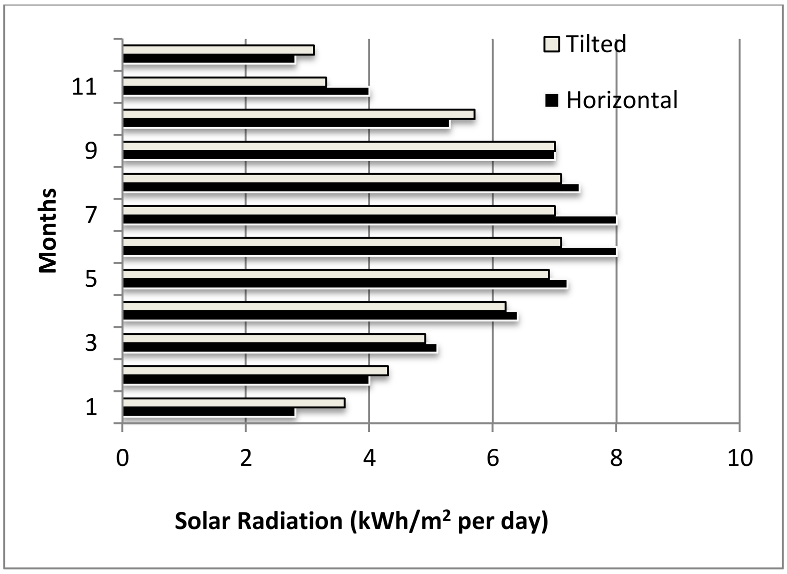

Figure 5: Monthly Average Daily Global Radiation (total irradiance) on a horizontal surface and on a 29^0 tilted plane.

Table 3: The emission of pollutants by one household diesel plant

Emission	**Pollutants in Kilograms**			
	NO_X	CO_2	SO_2	Particulates
Emission factors for diesel (kg/100kWh)	1.5	1062.5	19.4	1.0
Emission per day of the pollutants by a diesel plant	0.0035	2.4703	0.0451	0.0023
Emission per annum of the pollutants by a diesel plant	1.2729	901.6641	16.4633	0.8486

Table 4: Annual emission of pollutants into the Nigerian atmosphere

% of household in Nigeria using the diesel plant as stand-by	**Emission per annum of pollutants in million kilogrammes**			
	NO_X	CO_2	SO_2	Particulates
100	28.5647	20233.3416	369.4364	19.0426
95	27.1365	19221.6745	350.9646	18.0905
85	24.2800	17198.3404	314.0209	16.1862
75	21.4235	15175.0062	277.0773	14.2820
65	18.5671	13151.6720	240.1337	12.3777
55	15.7106	11128.3379	203.1900	10.4734
45	12.8541	9105.0037	166.2464	8.5692
35	9.9976	7081.6696	29.3027	6.6649
25	7.1412	5058.3354	92.3591	4.7606
15	4.2847	3035.0012	55.4155	2.8564
12	3.4278	2428.0010	44.3324	2.2851
10	2.8565	2023.3342	36.9436	1.9043
5	1.4282	1011.6671	18.4718	0.9521

4 Conclusion

From the financial analysis, it is clear that after considering the life expectancy of both the diesel generator system and photovoltaic system, the maintenance cost per annum and the fuel cost per system, the annual cost of running the diesel generator system is ₦376,600.00 while the annual cost of using photovoltaic system is ₦56,666.67. Hence the amount of pollutant that will be avoided in the Nigerian environment should each household consider the more economical option, that is, the photovoltaic system – is given as 3,427,800kg for NOx, 2,428,001,000kg for CO_2 44,332,400kg for SO_2 and 2,285,100kg for the particulates. It is therefore recommended that stand-by solar powered systems be installed in homes in Nigeria in order to make Nigeria free from these deadly pollutants.

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