Cost Analysis of Building Integrated Photovoltaic (BIPV) System for Urban Home in Bayelsa State, Nigeria

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Abstract. Building integrated photovoltaic (BIPV) based system is gaining popularity in Nigeria due to the incessant blackout and cost of fueling petrol generators. However, one of the reasons for slow installation of the BIPV is the cost of the entire system which include PV modules, storage battery, inverters, etc. This paper analyses the factors that determine the cost of the BIPV system such as building load, and the autonomy of the storage battery. Some electrical appliances were used to develop different load profile for an urban building. The different load profile and the battery depth of discharge (DoD) and autonomy of the battery bank were used to analyse a sustainable and cost effective BIPV system. The paper reveals that a sustainable cost effective BIPV system for urban homes in Nigeria is determined by the type of electrical appliances used, and the appliances usage pattern. Also, the cost of the system is also affected by the depth of discharge (DoD) and autonomy of the battery bank as revealed in the paper.

Keyword: Photovoltaic, BIPV system, Standalone inverter, Load profile, Depth of discharge

1. Introduction
Electrical energy is very important to economic growth and it is fundamental to fulfilling basic social needs [1]. The unreliable trend of electricity supply in Nigeria has influenced an increasing number of people; to rely on PV based renewable energy sources to meet their energy needs. Electricity demand is increasing rapidly in Nigeria and utility companies are unable to meet power demand due to limited power generating stations. Therefore, to solve the raising demand, standalone BIPV system can be applied to reduce the unreliable energy scenario in Nigeria. Today, Nigerians are beginning to embrace small-scale micro-grid such as standalone BIPV systems. Solar energy is the driving force of standalone BIPV system. Standalone BIPV systems are not synchronized with the frequency and amplitude of the utility grid and therefore must always be installed in a separated electrical circuit that is anti-islanding. Standalone BIPV system consists of a PV array, standalone inverter, and battery for
storage. Small standalone systems are used for boating, cottage and street lighting and are usually operated in DC coupling. The PV panels, load, controllers, and accumulators run on 12V, 24V or 48V and many hundreds of amperes, and sometimes-higher system voltage.

BIPV system requires some sort of energy storage system to store excess solar energy from the Photovoltaic (PV) array during the day (Solar hour period). There are different types of energy storage systems such as Lead-acid batteries, Lithium ion batteries, Sodium-Sulphur, Redox flow batteries and Nickel-cadmium batteries. Lead accumulators are still the first choice for solar PV system application because they are reliable when properly maintained. According to reference [2], battery storage market has experience significant growth and the cost of batteries has reduced. However, the falling price of batteries cannot be said to be cost effective comparatively in some countries like Nigeria, Ghana, etc. as of yet.

Solar BIPV system hold potential in providing electrical energy for rural and low-income earners and it is cost effective when compared with diesel and petrol powered generators due to the cost of fuelling these generators in the end. BIPV system does not only guarantee electrical energy sustainability but also helps to promote renewable energy systems as a reliable alternative to diesel and petrol powered generators. This paper discusses and evaluates the parameters that determine the cost of the BIPV system.

2. Material and Method
BIPV system consists of PV array, standalone inverter, battery bank and building load as shown in figure 1. The PV array generates electricity from solar radiation, which is then used to charge the batteries, and the current from the battery now goes through the standalone inverter to meet the load requirements [3]. Charge controller is also important because it regulates and control the output of the PV array to prevent the battery from been over-charged or over-discharged. Although the charge controller is optional but good due to safety reasons. Section 2.1 – 2.3 describe the components in the system and the methodology used for the evaluation of the parameters that determines a cost of BIPV system such as load, inverter size and battery autonomy.

![Figure 1: Schematic diagram of a standalone BIPV system](image)

2.1. Building Electrical Load Profile
Presently, there is no historical information of household electricity consumption pattern (load profile) in Nigeria. No detailed load profile is available in Nigeria because the utility companies do not supply 24 hours’ electrical power to consumers but only monthly bills or estimated bill in some cases are gathered. Because there is no historical record of household
load profile in Nigeria, an electrical household load profile generated using a bottom-up model. The bottom-up model for estimating a building load profile based on [4];

- The types of appliances
- Each appliance electricity demand during usage
- Each appliance usage pattern

Urban building electrical energy needs are restricted to TV, lighting, washing machine (optional), ceiling fan, fridge/freezer, water pump, Desktop computer (optional), home air conditioner (optional), etc. With the power rating and usage pattern of these appliances, the household load profile and behavior is developed. The bottom-up model is used to develop the building load profile in this paper.

2.2. Standalone Inverter sizing

The PV system produces direct current (DC) and the inverter convert the DC into alternating current. The AC appliances are design for the public utility connection can be used in the BIPV system because of the standalone inverter. The larger voltage level of the inverter also facilitates the energy distribution for larger building complexes. Standalone inverters are used for off grid systems, and they are not synchronized with the utility grid. For standalone BIPV system, the inverter is sized with the maximum hourly load. The inverter size and rating for a building can be determined with eqn 1.

\[
\text{Inverter Size for a building} = \text{Max. hourly load} + 25\% \text{ of Max. hourly load} \quad (1)
\]

2.3. Battery Bank sizing

Battery storage system plays a very significant role in standalone BIPV system. There various types of batteries, and they come in different capacities and voltage which enable them to be connected in series and parallel for power storage requirement in a specific system with no loss of impedance. Paralleling batteries provide higher battery bank capacity while voltage remains the same. For BIPV system, only deep cycle batteries are required and used. The state of charge (SoC) and depth of discharge (DoD) of a battery are also very important because they determine the lifetime of the battery. The operating temperature and the discharging pattern of the battery can significantly reduce the lifetime of the battery by more than half [2]. Although, the DoD of the battery is determined by the customer. However, customers are advised not to allow the DoD to fall above 50%. The authors in reference [6], reveals that a higher SoC level plays a significant impact on ageing of the battery while a lower SoC level generate less ageing.

The following equations (2) to (6) are used to calculate the required amount of batteries for a building load, [5];

\[
\text{Ampere Hour (Ah) to power load} = \frac{T_b (Wh)}{S_b} \quad (2)
\]

where \(T_b\) is the total building load in Wh, while \(S_b\) is the battery system voltage.

The battery storage (\(B_s\)) is the product of the Ah power for the load and the system autonomy. The system autonomy is the time or day you want the battery bank to operate during a bad weather.

\[
B_s = \text{Autonomy of system} \times \text{Ah power for load} \quad (3)
\]
4

Battery Capacity \( (B_c) = \frac{B_s \cdot S_f}{D_oD} \) \quad (4)

where \( B_s \) is the battery storage, \( S_f \) is safety factor and DoD is the depth of discharge.

Number of batteries in parallel \( = \frac{B_c}{\text{Chosen battery capacity}} \) \quad (5)

Number of batteries in series \( = \frac{\text{Battery System voltage}}{\text{Chosen battery voltage}} \) \quad (6)

2.4. PV system sizing

Solar PV system technology is one of the most important area of renewable energy system because its resources are readily available and abundant globally \[7\]. PV systems converts the solar energy into useful electrical power. Solar PV system module is a combination of PV cells and when these cells are exposed to sunlight, negatively charged electrons now absorbed the light quantum. Due to this phenomenon, the opposite end of the PV cell now creates a positive charge. The separation of the positive and negative charges creates a potential difference or electric tension, and current will begin to flow when load is connected. A combination of the PV cell in series and parallel forms the PV module while the connection of the PV module in series and parallel forms the PV array. PV module or array can be installed on a sloppy building rooftop. The slop (tilt) of the PV array determines the amount of solar energy that will be captured by the PV array. In the standalone building system, the number of PV modules are determined by the hourly load of the building. The PV array can be sized from two main factors (1) by using the module minimum temperature; and (ii) by using the module maximum temperature depending on the location.

Equation (7) to (10), helps us determine the number of PV modules for the standalone system.

\[ V_{\text{adj,max}} = (T_{\text{min}} - T_{\text{STC}}) \times \text{Temp. coeff}(V/\text{C}) + V_{\text{oc}} \] \quad (7)

Where \( V_{\text{adj,max}} \) is maximum PV module voltage, \( T_{\text{min}} \)is the minimum temperature of the PV module, \( T_{\text{STC}} \) is the standard test temperature, \( V_{\text{oc}} \) is the open circuit voltage of the PV module, Temp. coeff(V/C) is the temperature coefficient of the PV module.

\[ PV_n = \frac{S_i}{V_{\text{adj,max}}} \] \quad (8)

where \( PV_n \) is the number of PV modules, and \( S_i \) is inverter rated system voltage

Now, the maximum voltage of the array string is given as;

\[ \text{Maximum string voltage} = PV_n \times V_{\text{adj,max}} \] \quad (9)

The maximum string power is now given as;

\[ \text{Maximum string power} = PV_n \times P_{\text{max}} \] \quad (10)

where \( P_{\text{max}} \) is the power of the selected PV modules.
3. Discussion and Result Analysis

The cost of the BIPV system for urban household is evaluated by considering the impact of the building load, appliances type, appliances usage pattern, DoD and autonomy of the battery bank. The cost analysis of the system is evaluated using different building load pattern.

3.1. Modelling of the building load profile, Inverter sizing

Due to the fact that there are no historical data for electrical load profile in Nigeria, a bottom-up approach is used to estimate the load profile for a low income home. The commonly used equipment in a low income homes are ceiling fan, fridge/freezer, TV, Dstv decoder, Home air conditioner (optional), washing machine (optional), desktop computer (optional), water pump etc. these appliances and their usage pattern was used to develop the building electrical load profile. The appliance and their usage pattern are given in Table 1.

Table 1: Appliances power rating and usage pattern for a low middle class home

| S/n | Appliances         | Qty | Watt (W) | Usage pattern         |
|-----|--------------------|-----|----------|-----------------------|
| 1   | Ceiling Fan        | 2   | 70       | 1am to 12am (24hrs)   |
| 2   | Colour TV          | 2   | 150      | 6am to 11pm (18hrs)   |
| 3   | Washing Machine    | 1   | 500      | 6pm to 9pm (4hrs)     |
| 4   | Fridge Freezer     | 1   | 400      | 1am to 12am (24hrs)   |
| 5   | Dstv Decoder       | 1   | 18       | 6am to 11pm (18hrs)   |
| 6   | Desktop Computer   | 1   | 450      | 6pm to 11pm (6hrs)    |
| 7   | Water Pump         | 1   | 400      | 12pm to 5pm (6hrs)    |
| 8   | Home Air conditioner | 1 | 1000    | 5pm to 11pm (7hrs)    |
| 9   | Security Bulbs     | 8   | 18       | 7pm to 7am (12hrs)    |
| 10  | Room Bulbs         | 6   | 18       | 5am to 7am, 7pm to 11pm (7hrs) |

The building hourly electrical load and total daily building energy demand is very important because it enable us to determine the inverter and battery bank size respectively. Therefore, to analyse the cost of the inverter and the battery for the building, three different case scenarios and load profiles were developed as shown Table 2 and figure 2, figure 3 and figure 4. Table 3 shows the maximum hourly electrical load for each scenario as shown in figure 2, figure 3 and figure 4.

Table 2: Electrical appliance in each scenario

| s/n | Scenarios     | Available electrical appliances in each case                                                                 |
|-----|---------------|----------------------------------------------------------------------------------------------------------|
| 1   | Case scenario 1 | All the electrical appliances usage pattern as indicated in Table 2                                        |
| 2   | Case scenario 2 | Home Air Conditioner and desktop computer were excluded from building home appliances and load profile    |
| 3   | Case scenario 3 | Washing machine, water pump, desktop computer and home air conditioner were excluded from the building load |
Table 3: Maximum hourly load and daily energy consumed for each scenario

| s/n | Scenarios         | Maximum hourly load for each case scenario in Watts/h | Total daily energy consumed by building (Wh)/day |
|-----|-------------------|-------------------------------------------------------|--------------------------------------------------|
| 1   | Case scenario 1   | 3060                                                  | 35628                                            |
| 2   | Case scenario 2   | 1610                                                  | 26216                                            |
| 3   | Case scenario 3   | 1110                                                  | 21816                                            |

Fig 2: Load Profile for case scenario 1

Fig 3: Load profile for case Scenario 2

Fig 4: Load Profile for case scenario 3

The inverter sizes of each load profile scenarios were calculated using eqn (1) and the maximum hourly load of each scenario as depicted in Table 3. Table 4 shows the rated inverter sizes and the cost of the estimated inverter against the different electrical load scenarios. Table 4 reveals that the smaller the hourly electrical load the lower the inverter price. With this information, customers can now regulate their building electrical loads to arrive at sustainable inverter size and cost for the developed load.

Table 4: Estimated Inverter size and cost for each max. hourly load case

| Load Case | Max. hourly load (W) | Inverter Size (kVA) | Cost of Inverter (₦) |
|-----------|----------------------|---------------------|----------------------|
| Case 1    | 3825                 | 4.5                 | 258,000              |
| Case 2    | 1832.5               | 2.5                 | 151,000              |
| Case 3    | 1387.5               | 2                   | 117,700              |

Source of inverter price: www.solaroidenergy.com
3.2. Battery bank sizing and cost with DoD and battery autonomy
Allowing the batteries to drain completely is detrimental to the life cycle of the batteries. Therefore, the DoD and SoC plays an important role in battery ageing and it also determine the number of batteries to be configured in the battery bank. Battery autonomy is the time in which the batteries would power the load during bad weather and at night. The battery autonomy also determines the number of batteries in the bank and cost of the battery bank. The DoD and battery autonomy are used to estimate the most cost effective battery bank for the building using equation (2) to (5). Table 5 reveals that the autonomy of the battery determines the number of battery to be used in the BIPV system. The higher the autonomy, the higher the number of batteries and the cost of the battery bank as shown in Table 5. In this paper, the battery used in this analysis is a 200AH with a system voltage of 24V. The 200AH battery is estimated to cost about ninety-five thousand (₦95,000) in Nigeria. Although the cost of batteries, most time are dependent on the manufacturer and marketer. The Table 5 also reveal that the higher the DoD, the smaller the number of batteries and the lesser the cost of the battery bank.

Table 5: The DoD against the battery autonomy, and the number of batteries in the bank

| Load Cases | DoD  | Autonomy 2 day | Autonomy 1 day | Autonomy 12 hrs |
|------------|------|----------------|----------------|-----------------|
|            |      | No of battery  | Cost of bank (₦) | No of battery  | Cost of bank (₦) | No of battery | Cost of bank (₦) |
| CASE 1     | 30%  | 59             | 5.61 Million    | 30             | 2.85 Million    | 15            | 1.43 Million     |
|            | 40%  | 44             | 4.18 Million    | 22             | 2.09 Million    | 11            | 1.05 Million     |
|            | 50%  | 35             | 3.33 Million    | 18             | 1.71 Million    | 9             | 855,000          |
|            | 60%  | 30             | 2.85 Million    | 15             | 1.43 Million    | 7             | 665,000          |
| CASE 2     | 30%  | 43             | 4.1 Million     | 22             | 2.09 Million    | 11            | 1.05 Million     |
|            | 40%  | 33             | 3.14 Million    | 16             | 1.52 Million    | 8             | 755,000          |
|            | 50%  | 26             | 2.47 Million    | 13             | 1.24 Million    | 7             | 665,000          |
|            | 60%  | 22             | 2.09 Million    | 11             | 1.05 Million    | 6             | 570,000          |
| CASE 3     | 30%  | 30             | 3.42 Million    | 18             | 1.71 Million    | 9             | 855,000          |
|            | 40%  | 27             | 2.57 Million    | 14             | 1.33 Million    | 7             | 665,000          |
|            | 50%  | 22             | 2.09 Million    | 11             | 1.05 Million    | 6             | 570,000          |
|            | 60%  | 18             | 1.71 Million    | 9              | 855,000        | 5             | 475,000          |

3.3. PV Array Sizing
In this paper, a 100Wp PV module with a maximum temperature of 38˚C, a minimum temperature of 6˚C, an open circuit voltage (Voc) of 24V and temperature coefficient of -0.12V/˚C was selected design the PV array for the different load cases using equation (6) to (9). Table 6, shows the cost the PV array with an inverter input voltage (DC) of 550 V. The 100Wp module used for the cost analysis, is about eighteen thousand naira (₦18,000.00). The Table reveals that the smaller the load the lesser the cost of the array. Although, case 3 PV module were increased to accommodate more appliances due to the input voltage of the inverter.
Table 6. Number of PV module and cost

| Load case | Case 1 | Case 2 | Case 3 |
|-----------|--------|--------|--------|
| Number of PV module | 20 | 10 | 10 |
| Cost of PV Array (₦) | 360,000 | 180,000 | 180,000 |

Source of PV module price: www.solaroidenergy.com

4. Conclusion

The bottom-up model was used to model the estimated building load profile and the maximum PV module temperature technique, DoD and autonomy of the battery bank were used to analyze a sustainable and cost effective standalone BIPV system. The investigation and analyses of a sustainable standalone BIPV system for an urban household indicated that to have a sustainable system, a proper selection of important appliances and a well-structured usage pattern must be developed and followed. The findings also indicate that the cost of the overall BIPV system can be reduced significantly if the DoD and the autonomy of the battery bank can be increased to about 60% maximum and reduced to a day or 12 hours respectively. Reduction in the overall cost of the BIPV system can increase the application of renewable energy technologies like PV systems; this can lead to reduction in CO₂ emission from diesel and petrol fuel generator.

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