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Techno-Economic Analysis of Building Rooftop Photovoltaic Power System for Lecture Hall at Imo State University, Owerri

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Abstract: Numerous published literatures have given diverse ways of designing photovoltaic (PV) systems including the rooftop mounted PV systems. In this paper, ideas extracted from such studies are employed in a single building rooftop PV power system. Particularly, in this paper, PVSyst simulation software is used for the techno-economic analysis of Building Rooftop Photovoltaic (BRFPV) power system for the Lecture hall at the Faculty of Engineering of Imo State University, Owerri Nigeria was carried out. First, the dimensions of the selected roof were measured and the effective area of the roof for PV installation was determined. PVSyst software was used for the determination of the PV energy generation potential of the BRFPV system along with its other techno-economic performance parameters. The meteorological data used for the simulation was obtained from NASA website. According to the simulation results, the BRFPV system at the Faculty of Engineering of Imo State University had yearly energy output of 2804 KWh/year while the performance ratio was 86% and the unit cost of energy was 69.5 Naira per KWh. Essentially, the BRFPV can satisfy a yearly load demand of 2804 KWh or equivalent daily load demand of 7.69KWh. Finally, the nominal efficiency of the PV module was 5.59%as against the manufacturer's quoted efficiency of 12.6% at standard test condition. Compared to the exiting literatures, this paper has presented a step by step approach for designing BRFPV using PVSyst software and empirically determined dimensions of the roof of the building. Equally, there are several mathematical and logical approaches that can be used to realize the same results obtained in this paper, however, this paper has presented one of such approaches. Particularly, the paper presented an approach that can be used to determine the effective or operating efficiency of the PV modules based on the energy yield and the PV area.

Keywords: Rooftop Photovoltaic, Photovoltaic, Load Demand, Optimal Tilt Angle, Techno-Economic Analysis, Performance Ratio, Unit Cost of Energy, Nominal Efficiency

1. Introduction

In Nigeria, the national grid power is grossly inadequate for the national load demand. As such, the power outage is excessive and detrimental to socio-economic activities in the country. However, despite the high level of solar energy availability across Nigeria, the installed PV systems are still very small and many individuals and organizations are still depending on diesel generator sets as alternative power supply. Diesel generators emit gasses that are not good for the environment. Also, diesel is not renewable, it depletes with use. Also, with proper design, at the long run, the solar power system can serve as better alternative electric energy supply instead of diesel generators.

On the other hand, in the city and other densely populated areas there are few or limited open land spaces for elaborate PV panel installation. As such, the adoption of PV as the alternative energy may be hampered by such challenge. However, the solution to such problem is the installation of rooftop PV power system where the PV modules are installed on top of the roof. In practice, the solar energy potential of such rooftops are required for effective planning of the rooftop

PV power deployment.

Consequently, in this paper, the rooftop energy potential of a lecture hall in the faculty of engineering of Imo State University is conducted. PVSyst simulation software is used to conduct the techno-economic analysis of the rooftop PV power system. Solar radiation data from NASA website is used for the analysis.

2. Review of Relevant Studies

A rooftop photovoltaic power station, or rooftop PV system, is a photovoltaic system that has its electricity-generating solar panels mounted on the rooftop of a residential or commercial building or structure [1-2]. This is particularly useful in the cities where there are limited open lands for the installation of elaborate PV panels. Besides, the rooftop PV power system can provide the energy needs of the residential building of particular set of offices in a commercial building. According to experts, low-slope roofs are ideal locations for PV systems because PV panels can be effectively exposure for substantial solar radiation capture; power is generated in close proximity to loads; and the location is easy to secure and is unobtrusive [3-4].

There are many ways to install PV systems in a building. For existing buildings, the most common manner without drastically affecting its appearance is to mount the PV modules on a frame on the roof top [5]. Typically, they are mounted above and parallel to the roof surface with a standoff of several centimeters to reduce module temperature through air circulation. Ideally, they should also be installed facing north-south orientation to maximize the amount of solar energy received [5] In a new development, besides mounting on the roof top, the PV modules or panels could in a creative, aesthetically-pleasing manner be integrated into the building facade (this form of PV is commonly known as Building Integrated Photovoltaic or BIPV in short). Building integrated photovoltaic (BIPV) systems, is a PV power system where the solar cells are integrated within the climate envelopes of buildings and utilizing solar radiation to produce electricity [6]. BIPV could be mounted on any part of the roof or external walls that is well-exposed to sunlight e.g. skylights, claddings, windows, external shading devices. It could also be integrated into external structures such as canopies, car park shelters and railings [5]. Building integrated photovoltaic (BIPV) systems replace parts of the conventional building materials and systems in the climate envelope of buildings, such as the roofs and facades. BIPV systems are considered as a functional part of the building structure, or they are architecturally integrated into the building's design [6].

Depending on the system configuration, there are three main types of PV systems: stand-alone, grid-connected, and hybrid. In either case, basic PV system principles and elements remain the same. Stand-alone or off grid systems rely on PV power only [7, 8, 9, 10]. These systems can comprise of only PV modules and a load or can include batteries for energy storage. On the other hand, grid-connected PV systems are connected to the grid through inverters, and do not require batteries because the grid can accept all of the electricity that a PV generator can supply [7, 11-13]. Increasingly, grid-connected PV systems have become increasingly popular as building integrated application. Alternatively they are used as power stations. Hybrid systems consist of combination of PV modules and a complementary means of electricity generation such as a diesel, gas or wind generator [14 - 16].

In [17] Nordahl presented the design of a PV system for a flat roof in Oslo, Norway. The energy yield of the PV system and the effect of shading are determined using PVsyst. In [18] the authors presented the design of grid-connected rooftop photovoltaic (PV) systems for two buildings in Juhannuslehto Business Park in Pori, Finland. The key design factors are the available solar radiation, module orientation (azimuth and inclination) and the inter-row shading effect. Also, the life cycle cost analysis was carried out. In [19] the authors presented the design of a 50 kW solar PV rooftop system. The focus of the paper was on the rooftop PV system component sizing and the economic analysis using RETSCREEN software. In this paper a step by step approach for designing BRFPV using PVSyst software and empirically determined dimensions of the roof of the building is presented. Particularly, the paper presented an approach that can be used to determine the effective or operating efficiency of the PV modules based on the PV area and the daily input/output graph provided in the PVSyst result.

3. Methodology

In this project, simulation approach is used for techno-economic analysis of the Building Rooftop PV (BRFPV) power system for the lecture hall at the Faculty of Engineering of Imo State University. The procedure used in the BRFPV energy potential is as follows:

Step 1: Determine the effective rooftop area that can accommodate PV installations for the selected facility.

Step 2: Get the coordinates (Latitude and Longitude) of the PV installation site (Lecture Hallat the Faculty of Engineering of Imo State University)

Step 3: Download the Solar Radiation data for the site.

Step 4: Select the Optimal Tilt angle and PV Azimuth angle for the site.

Step 6: Select and size the PV system's components

Step 7: Simulate for the technical analysis of the system.

Step 8: Simulate for the economic analysis of the system

Step 9 Discuss results

2.1. Step 1: Determine the Effective Rooftop Area That can Accommodate PV Installations for the Selected Facility

The calculation for the rooftop area of the selected facility (lecture hall) at the Faculty of Engineering of Imo State University is conducted with respect to the schematic diagram of the roof, as shown in Figure 1.

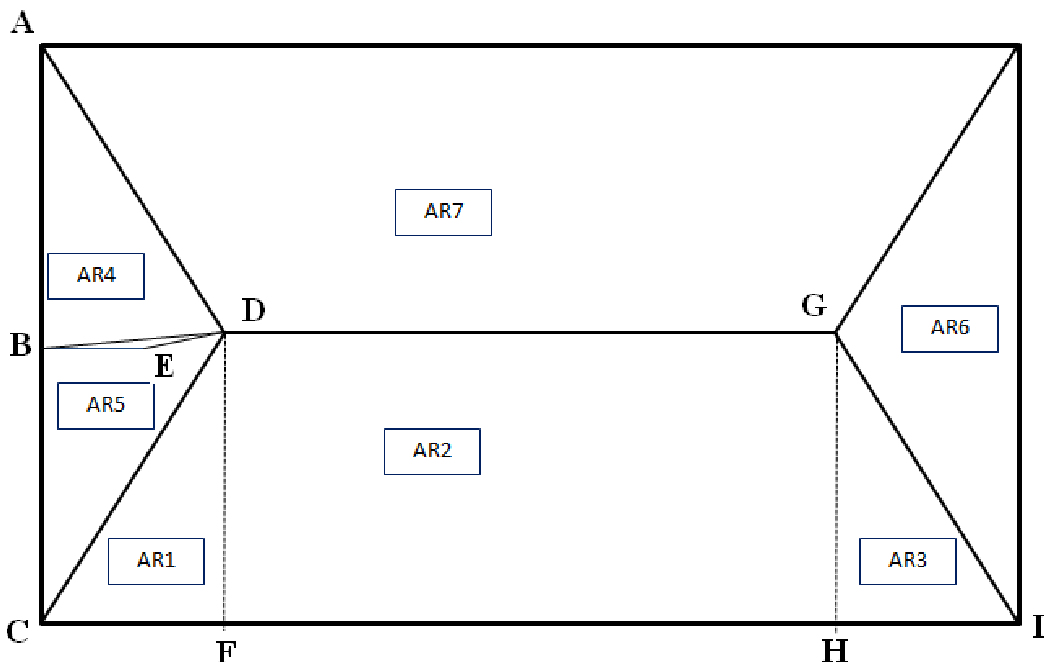

Figure 1. *The Schematic Diagram Of The Roof Of The Lecture Hall at the Faculty of Engineering of Imo State University.*

From Figure 1, the other dimensions of the roof can be calculated as follows:

$$BD = \sqrt[2]{BE^2 + DE^2} \quad (1)$$

$$CD = \sqrt[2]{BD^2 + BC^2} \quad (2)$$

$$DF = \sqrt[2]{CD^2 - CF^2} \quad (3)$$

From Figure 1, the following areas AR1, AR2, AR3, AR4, AR5, AR6, AR7 of sections of the roof can be calculated as follows:

$$AR4 = AR5 \quad (4)$$

$$AR4 = \left(\frac{BC}{2}\right) x \ (BD) \quad (5)$$

$$AR1 = AR3 \quad (6)$$

$$AR1 = \left(\frac{CF}{2}\right)(DF) \quad (7)$$

$$AR2 = (DF)(FH) \quad (8)$$

$$AR6 = AR4 + AR5 = 2 \ (AR4) \quad (9)$$

$$AR7 = AR2 + AR3 + AR2 = 2 \ (AR1) + AR2 \quad (10)$$

The total area (A_{TRF}) of the roof is given as:

$$A_{TRF} = 2(AR6) + 2\,(AR7) \quad (11)$$

The effective roof area (A_{pv}) for PV installation is given as;

$$A_{pv} = (f_o)(f_s)(A_{TRF}) \quad (12)$$

where,

$$f_o = (f_{flat})(r_{flat}) + (f_{peak})(r_{peak}) \quad (13)$$

f_o = Overall reduction factor for roof inclination with respect to optimal tilt angle

f_{flat} = Fraction of roof area that is flat roof

f_{peak} = Fraction of roof area that is flat peaked

r_{flat} = Reduction factor for roof area that is flat roof (usually, r_{flat} = 1)

r_{peak} = Reduction factor for roof area that is flat peaked (usually, r_{peak} = 0.5)

f_s = Reduction factor to account for roof area that has shading and others portion of the roof area that are used for other purposed and for panel servicing and installation (typical range of values are, $0.3 \leq f_s \leq 0.9$)

Now, for the lectured hall considered in this study, the measured roof data are as follows: AB = BC = 9m; CF = HI= BE= DE= 2m; FH = 32m.

Also, the reduction factors used for the calculations are: f_{flat}= 0; f_{peak} = 1, r_{flat} =1; r_{peak} = 0.5 and f_s = 0.3.

Based on the given roof dimensions and roof area reduction factors, the effective roof area (A_{pv}) for PV installation is obtained from Eq 12 is $A_{pv} \approx 35\ m^2$.

2.2. Step 2: Get the Coordinates (Latitude and Longitude) of the Project Site

In this case, the Lecture hall at the Faculty of Engineering of Imo State University (Latitude = 5.508331, Longitude =7.043366)

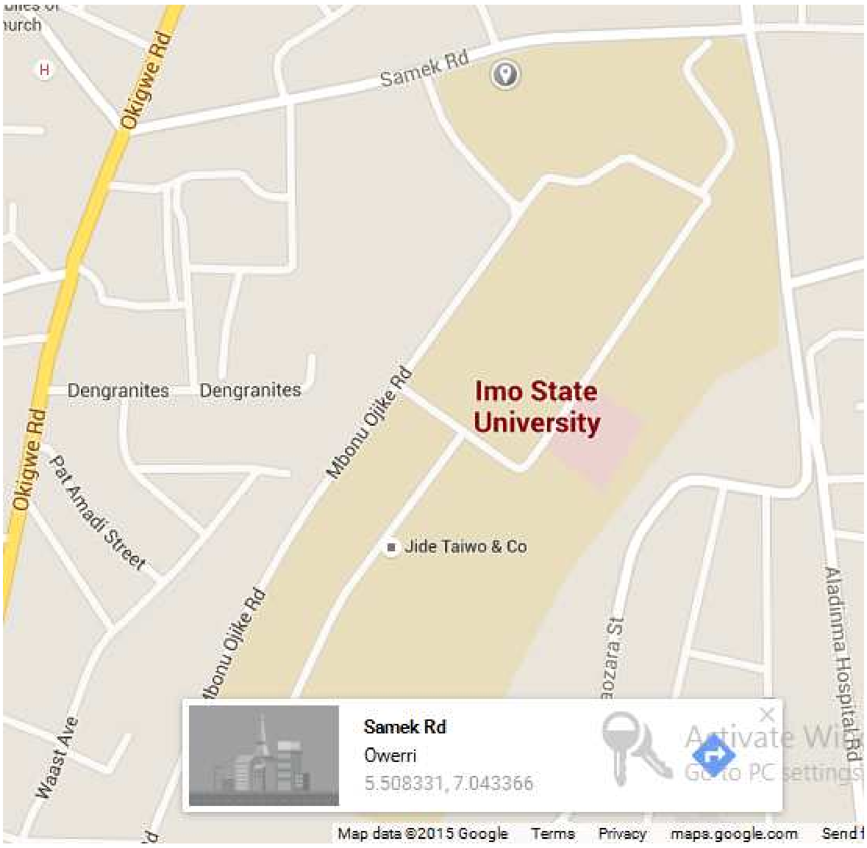

Figure 2. *Cut Section of The Google Map Coordinates For Lecture Hall at the Faculty of Engineering of Imo State University.*

2.3. Step 3: Download Solar Radiation Data

Use PVSyst tool menu to download the solar irradiation and ambient temperature data of the site from NASA website. According to Figure 3, the daily Peak Sun Hour (PSH) $G_d$is 4.70 KWh/m^2/day.

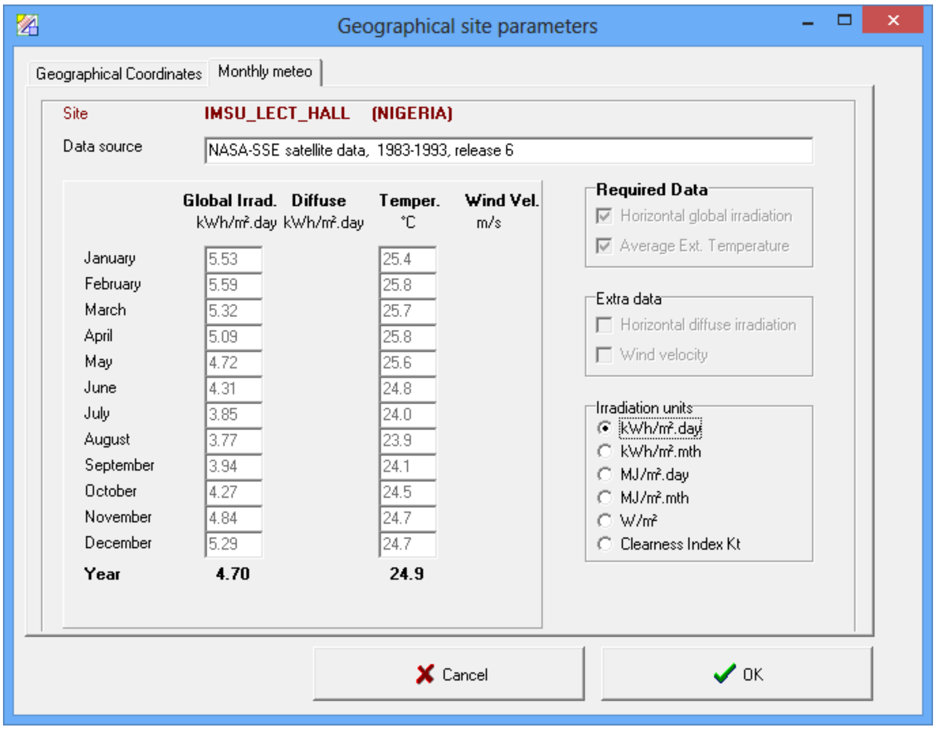

Figure 3. *The Daily Solar Irradiation On Horizontal Plane at The PV Installation Site.*

2.4. Step 4: Select Optimal Tilt Angle and PV Azimuth Angle: Use PVSyst Orientation Menu to Select the PV Panel Azimuth Angle and Optimal Tilt Angle

Generally, PV Orientation or Azimuth angle is set to Zero (0) and the optimal PV tilt angle, β_{opt} is computed as;

$$\beta_{opt} = 3.7 + 0.69|\varphi| \quad (14)$$

where φ is the latitude of the site.

With latitude of 5.51, then $\beta_{opt} = 3.7 + 0.69|5.51| = 7.519 \approx 8$.

2.5. Step 5: Size the PV Components in PVSyst

The PV system sizing can be based on two criteria, namely; the daily power demand or the available area for the PV modules. For any given daily load demand (E_L) $in\ Kwh/day$ with de-rating factors $f_{dc/ac}$and $\mathrm{f_{temp}}$, the PV size in terms of area (A_{pv}) required to meet the daily load demand is given as

$$A_{pv} = \frac{E_L}{(G_d * \eta_{pv} * f_{dc/ac} * \mathrm{f_{temp}})} \quad (15)$$

Conversely, for any given PV size in terms of area,A_{pv}, the daily load demand (E_L) the PV can satisfy is given as;

$$E_L = A_{pv}\,(G_d * \eta_{pv} * f_{dc/ac} * \mathrm{f_{temp}}) \quad (16)$$

where

A_{pv} is the PV area in m^2

E_L is the daily load demand$in\ Kwh/day$

G_d is the average daily solar global irradiation based on the global air-mass 1.5 spectrum of 1000 w/m^2. G_d is also called the Peak Sun Hour (PSH).

η_{pv} is the module efficiency

$f_{dc/ac}$—DC to AC de-rating factor [%];

f_{temp}=temperature de-rating factor, dimensionless

The temperature de-rating factor, f_{temp} is given as:

$$\mathrm{f_{temp}} = 1 - (\gamma_{pv} * (T_c - T_{STC})) \quad (17)$$

where

f_{temp} = temperature de-rating factor, dimensionless

$\gamma_{pv} =$ temperature coefficient of power, that is, the absolute value of power temperature co-efficient per degree Celsius

T_c = average daily cell temperature,

T_{STC} = in degrees Celsius cell temperature at Standard Test Conditions, in degrees Celsius.

Let $f_{dc/ac}$ be the overall DC to AC de-rate factor, the $f_{dc/ac}$ is calculated by multiplying the component de-rate factors as follows;

$$f_{dc/ac} = f_{pvtol} * f_{mism} * f_{diode} * f_{dcwiring} * f_{pacwiring} * f_{soiling} * f_{sysavail} * f_{shading} * f_{suntrack} * f_{aging} \quad (18)$$

where the various derate factors are:

f_{pvtol} = de-rating factor due to PV module nameplate tolerance DC rating

f_{inv} = de-rating factor due to Inverter and Transformer

f_{mism} = de-rating factor due to Mismatch

f_{diode} = de-rating factor due to Diodes and connections

$f_{dcwiring}$ = de-rating factor due to DC wiring

$f_{pacwiring}$ = de-rating factor due to AC wiring

$f_{soiling}$ = de-rating factor due to Soiling

$f_{sysavail}$ = de-rating factor due to System availability

$f_{shading}$ = de-rating factor due to Shading

$f_{suntrack}$ = de-rating factor due to Sun -tracking

f_{aging} = de-rating factor due to Age

The value of each derate factor is greater than zero but less or equal to 1. Consequently,

$$0 < f_{dc/ac} \leq 1.$$

The daily power demand can be determined from

$$P_L = \frac{E_L}{h_d} \quad (19)$$

where h_d is the average number of hours the power is delivered per day. Consequently, for the sizing of the PV system, $h_d$and $P_L$are selected in the user's daily load demand. Accordingly, the other parameters to be selected in PVSyst for the sizing include; the loss of load probability; the days of autonomy; the system DC voltage; the battery, the PV module and the regulator/inverter.

2.6. Step 6: Simulate in PVSyst to Obtain the Technical Performance Parameters of the System

At this point, PVSyst use the inputs parameters to generate the output energy and other technical performance parameters of the system.

2.7. Step 7: Simulate in PVSyst to Carry out Economic Analysis of the System

At this point, the life circle cost analysis tool in PVSyst is used to determine the economic performance of the PV system. The economic analysis requires input such as the cost of acquisition, installation and replacements of each PV components, as well as tax and interest rate for loan.

4. The Simulation Results for the Lecture Hall at the Faculty of Engineering of Imo State University

Figure 4. shows the simulation parameters for the various system components; a total PV module area of 34.6 m^2 is used and it accommodated 42 PV modules, each with 50 Wp. Also, there are 7 PV module in series and 6 PV modules in parallel.

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Grid-Connected System: Simulation parameters

Project :	**IMSU_LECT_HALL_GCBRTPV**			
Geographical Site		**IMSU_LECT_HALL**	**Country**	**NIGERIA**
Situation	Latitude	5.5°N	Longitude	7.0°E
Time defined as	Legal Time	Time zone UT+1	Altitude	112 m
	Albedo	0.20		
Meteo data :	EKET HEALTH FACILITIES from NASA-SSE, Synthetic Hourly data			
Simulation variant :	**No shading effects**			
	Simulation date	25/10/15 19h24		
Simulation parameters				
Collector Plane Orientation	Tilt	8°	Azimuth	0°
Horizon	Free Horizon			
Near Shadings	No Shadings			
PV Array Characteristics				
PV module	CIS Model	**SCG 50-HV-F**		
	Manufacturer	Sulfurcell		
Number of PV modules	In series	7 modules	In parallel	6 strings
Total number of PV modules	Nb. modules	42	Unit Nom. Power	50 Wp
Array global power	Nominal (STC)	**2.10 kWp**	At operating cond.	2.06 kWp (50°C)
Array operating characteristics (50°C)	U mpp	236 V	I mpp	9 A
Total area	Module area	**34.6 m²**		
Inverter	Model	**Convert 2700**		
	Manufacturer	Solar Fabrik		
Characteristics	Operating Voltage	125-600 V	Unit Nom. Power	2.1 kW AC

Figure 4. *Cut Section of The Screenshot Of The Simulation Parameters As Presented In The PVSyst Software.*

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Grid-Connected System: Main results

Project :	**IMSU_LECT_HALL_GCBRTPV**			
Simulation variant :	**No shading effects**			
Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	8°	azimuth	0°
PV modules	Model	SCG 50-HV-F	Pnom	50 Wp
PV Array	Nb. of modules	42	Pnom total	**2.10 kWp**
Inverter	Model	Convert 2700	Pnom	2.10 kW ac
User's needs	Unlimited load (grid)			
Main simulation results				
System Production	**Produced Energy**	**2804 kWh/year**	Specific prod.	1335 kWh/kWp/year
	Performance Ratio PR	86.0 %		
Investment	Global incl. taxes	1769250 Naira	Specific	843 Naira/Wp
Yearly cost	Annuities (Loan 10.0%, 20 years)	207815 Naira/yr	Running Costs	0 Naira/yr
Energy cost		**74.1 Naira/kWh**		

Figure 5. *Cut Section of The Screenshot Of The Main Result As Presented In The PVSyst Software.*

According to the main result, Figure 5, the yearly energy output of the system is 2804 Kwh/year while the performance ratio is 86%. This means that about 14% of the total energy produce by the PV modules are either lost or not supplied to the load. The losses are shown in the loss diagram of Figure 6.

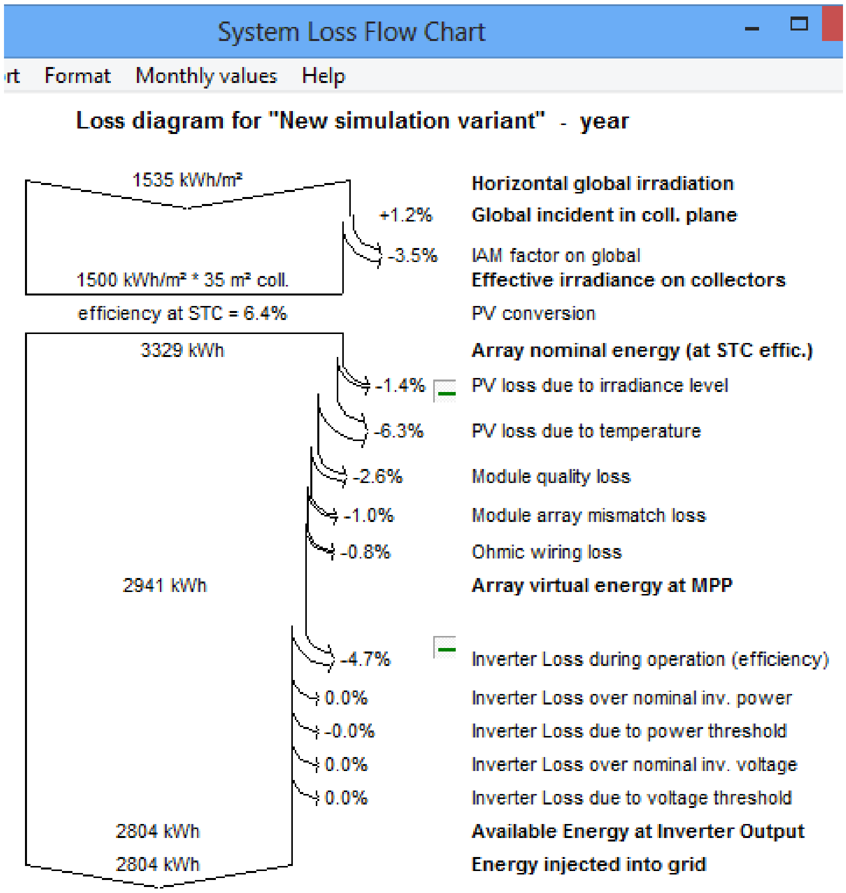


Figure 6. *Cut Section of The Screenshot Of The Loss Diagram As Presented In The PVSyst Software.*

From the daily energy output diagram of Figure 7, the effective efficiency of the PV under its operating conditions is computed to be 5.59%as against 12.6% module efficiency at Standard Test Condition (STC) as shown in Figure 8.

$$\eta_{pv} = \left\{\frac{(5.8\ Kwh/day)}{(3Kwh/m^2/day)(34.6m^2)}\right\} \text{x}100\% = 5.59\%$$

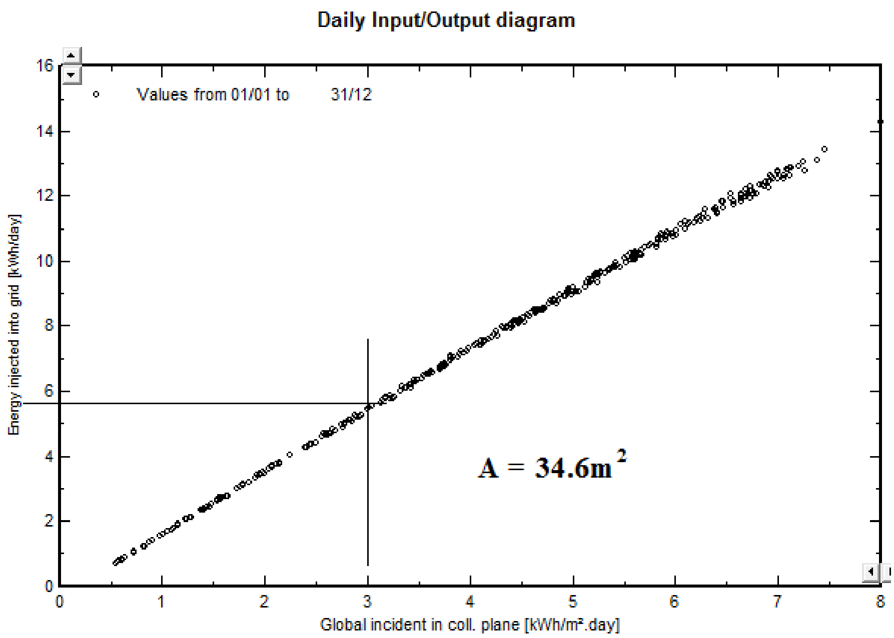


Figure 7. *Cut Section of The Screenshot Of The Daily Output Diagram As Presented In The PVSyst Software.*

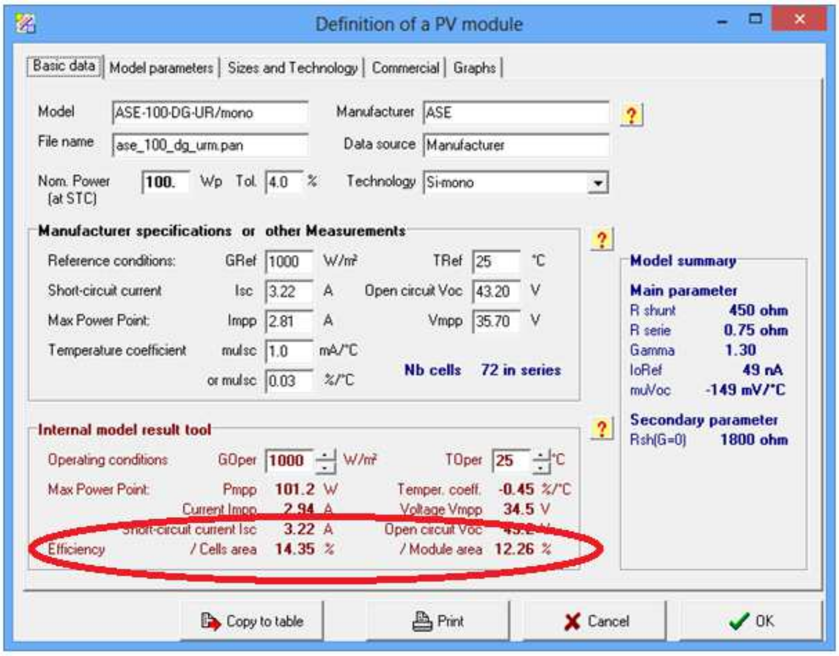
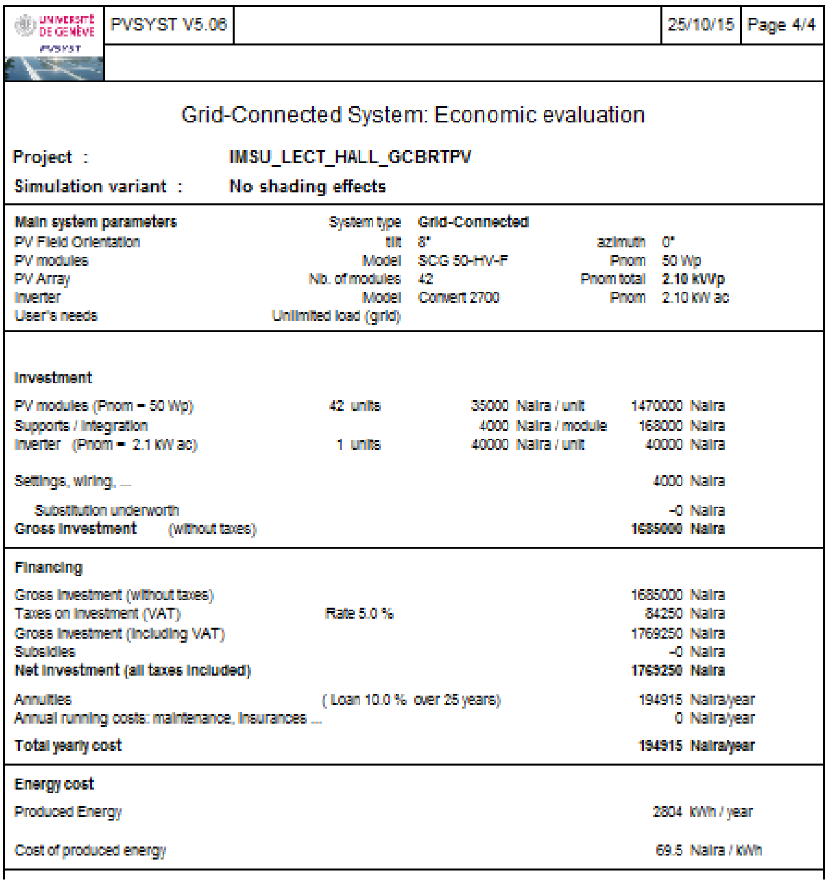


Figure 8. *The PV Efficiency at Standard Test Condition (STC).*

Figure 9 gives the economic analysis result. The unit cost of energy is 69.5 Naira per KWh. The yearly cost of the of the project is 194,915 Naira and the Gross investment cost for the project is 1,1685,000 Naira. The project lifetime is 25 years.

Figure 10 shows the daily output energy of the rooftop PV system. The daily output energy of less than 2 kWh/day occured in the months of June to November whereas daily output energy greater than 13 kWh/day occured in the months of January, February, September and December.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Grid-Connected System: Economic evaluation

Project : IMSU_LECT_HALL_GCBRTPV
Simulation variant : No shading effects

Main system parameters	System type	Grid-Connected		
PV Field Orientation	tilt	8°	azimuth	0°
PV modules	Model	SCG 50-HV-F	Pnom	50 Wp
PV Array	Nb. of modules	42	Pnom total	2.10 kWp
Inverter	Model	Convert 2700	Pnom	2.10 kW ac
User's needs	Unlimited load (grid)			

Investment			
PV modules (Pnom = 50 Wp)	42 units	35000 Naira / unit	1470000 Naira
Supports / Integration		4000 Naira / module	168000 Naira
Inverter (Pnom = 2.1 kW ac)	1 units	40000 Naira / unit	40000 Naira
Settings, wiring, ...			4000 Naira
Substitution underworth			-0 Naira
Gross investment (without taxes)			**1685000 Naira**
Financing			
Gross investment (without taxes)			1685000 Naira
Taxes on investment (VAT)	Rate 5.0 %		84250 Naira
Gross investment (including VAT)			1769250 Naira
Subsidies			-0 Naira
Net investment (all taxes included)			**1769250 Naira**
Annuities	(Loan 10.0 % over 25 years)		194915 Naira/year
Annual running costs: maintenance, insurances ...			0 Naira/year
Total yearly cost			**194915 Naira/year**
Energy cost			
Produced Energy			2804 kWh / year
Cost of produced energy			69.5 Naira / kWh

Figure 9. *Cut Section of The Screenshot Of The Economic Analysis Result As Presented In The PVSyst Software.*

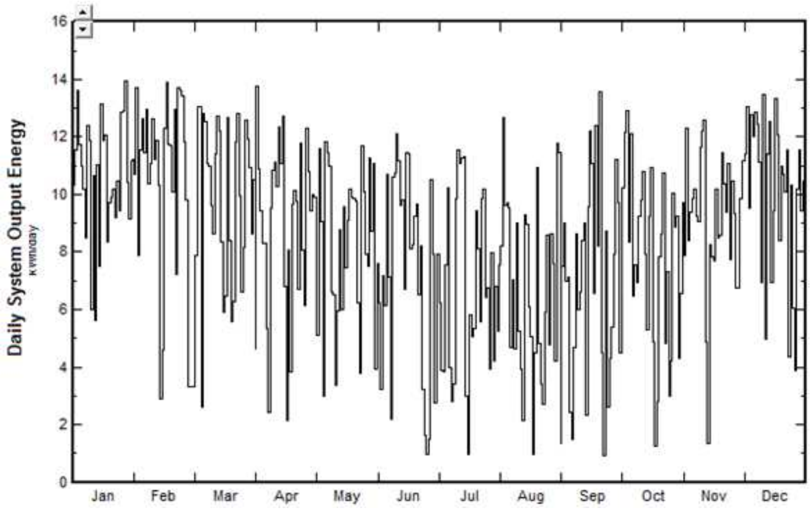

Figure 10. *Cut Section of The Screenshot Of The Daily System Output Energy As Presented In The PVSyst Software.*

5. Conclusion

Simulated techno-economic analysis of a Building Rooftop PV (BRFPV) power system for Lecture hall at the Faculty of Engineering of Imo State University is presented in this paper. The BRFPV installed at the rooftop of the Lecture hall hasyearly energy output of 2804 KWh/year while the performance ratio is 86% and unit cost of energy of 69.5 Naira per KWh. Essentially, the BRFPV can satisfy a yearly load demand of 2804 KWh or equivalent daily load demand of 7.69KWh.

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