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Determination of Monthly Unit Cost of Energy for Standalone Photovoltaic System in Owerri, Imo State

Umoren Mfonobong Anthony, Mfonobong Charles Uko, Ogungbemi Emmanuel Oluropo

Department of Electrical/Electronic and Computer Engineering, University of Uyo, Akwa Ibom, Nigeria

Email address:
umoren_m.anthony@yahoo.com (U. M. Anthony)

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Abstract: In this paper, simulation approach is used for determination of the monthly unit cost of energy generated from standalone PV (SAPV) power system in Imo State. The meteorological data used in the study are compiled from National Aeronautics and Space Administration (NASA) worldwide meteorological database. The meteorological data include 22-year monthly and annual averaged insolation incident on a horizontal surface (kwh/m2/day) and 22-year monthly averaged air temperature. A hypothetical electric load demand data of 5000 kWh per day is used for the simulation. The PVsyst industrial PV system planning software solution was selected to model and simulate the entire PV system. PVSyst uses life cycle cost analysis approach to determine the investment cost and unit cost of energy generated from SAPV system. According to the results, the average total energy supplied to the user (load) in a year is 1751 kWh. The economic analysis result shows that the total annual cost of energy is 246760 Naira per year at a unit cost of 141 Naira per kWh. Also, the highest unit cost of energy of 168.6 Naira/ kWh occurred in August whereas the lowest unit cost of energy of 132.7 Naira/ kWh occurred in October. The idea presented in this paper is useful for smart grid, dynamic energy pricing and energy cost management system.

Keywords: Photovoltaic System, PVSyst, De-Rate Factor, Unit Cost of Energy, Electric Load Demand

1. Introduction

Electricity is the lifeblood of the any nation's economy. It powers our homes, offices, and industries; provides communications, entertainment, and medical services; powers computers, technology, and the Internet; and runs various forms of transportation. Not only is electricity the most flexible and most controllable form of energy, its versatility is unparalleled. Without electricity the world would be a very different place. The public relies on electricity to be readily available and to perform basic functions. Given the continual rise in population and discovery of more power dependent devices and systems, electricity use has continued to be on the increase every year and at the same time, energy prices are rising and energy availability is diminishing [1, 2, 3]. With this continual growth in electricity demand as well as an increasing price, new methods of producing electricity are constantly being developed. The turn to alternative energies to produce electricity dates all the way back to the 18th century but has gained momentum recently. Alternative energy like renewable energy comes from sources that replenish themselves, such as the sun, rivers, wind, and ocean waves and tides [4, 5, 6].

Among these alternative energy sources, solar energy is one of the most important renewable energy sources that has been gaining increased attention in recent years [7, 8, 9]. Solar panels absorb the sunlight to create electricity. The governments across the globe are putting up policies to assist consumers and investor to adopt solar energy power systems in hope of supporting the "green" or sustainability movement. Solar energy is clean and free of emissions, which is great for the environment, as it does not produce pollutants or by-products harmful to nature [10, 11].

In view of the need to encourage rapid and wide-scale adoption of solar power, the cost implication of solar power systems is required. There are cost estimation tools that are used to estimate the cost of PV power system based on the total annual energy produced and the cost of acquiring, maintaining and replacing broken down components of the PV power system. In this project the monthly unit cost of energy from standalone PV system is computed. The monthly unit cost of energy useful for dynamic energy pricing and cost management system. Relevant mathematical expressions are presented for calculating the monthly unit cost of energy for photovoltaic power system.

2. Design Methodology

In this paper, simulation approach is used for the determination of the monthly unit cost of energy generated from standalone PV (SAPV) power system in Imo State. The meteorological data used in the study are compiled from National Aeronautics and Space Administration (NASA) worldwide meteorological database. The meteorological data include 22-year monthly and annual averaged insolation incident on a horizontal surface (kwh/m2/day) and 22-year monthly averaged air temperature. A hypothetical electric load demand data is used for the simulation. The PVsyst industrial PV system planning software solution was selected to model and simulate the entire PV system. PVSyst uses life cycle cost analysis approach to determine the investment cost and unit cost of energy generated from SAPV system.

2.1. Determination of the PV Electric Energy Output

For any given daily load demand (E_L) $in\ Kwh/day$ with de-rating factors and the PV size in terms of area (A_{pv}) required to meet the daily load demand is given as [12, 13, 14, 15, 16];

$$A_{pv} = \frac{E_L}{(G_d * \eta_{pv} * f_{dc/ac} * f_{temp})} \quad (1)$$

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 [12, 13, 14, 15, 16];

$$E_L = A_{pv}\ (G_d * \eta_{pv} * f_{dc/ac} * f_{temp}) \quad (2)$$

Where

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

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

G_d is the solar global insolation based on the global air-mass 1.5 spectrum of 1000 w/m^2

η_{pv} is the module efficiency

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

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

The DC to AC de-rate factor, $f_{dc/ac}$ is the overall DC to AC de-rate factor which is calculated by multiplying the component de-rate factors [12, 13, 14, 15, 16]. In most cases, the overall default value of 0.77 will provide a reasonable estimate for modelling the energy production.

The temperature de-rating factor is given as [12, 13, 14, 15, 16];

$$f_{temp} = 1-(\gamma_{pv} * (T_c - T_{STC})) \quad (3)$$

where

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

γ_{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.

For example, assume the average ambient temperature is 25°C (T_a) and the module is polycrystalline. The average daily effective cell temperature is [12, 13, 14, 15, 16];

$$Tc = Ta + 25 = 25 + 25 = 50 \quad (4)$$

$$Tc = 25 + 25 = 50 \text{ when } Ta = 25°C$$

In the above formula the absolute value of the temperature coefficient [$\gamma_{pv} = 0.5\%/°C$] and cell temperature at Standard Test Conditions is 25°C. Therefore the effective derating factor due to temperature is: 1-(50 – 25) x 0.5%=1-12.5%=1-0.125=0.875.

2.2. Life Cycle Cost Analysis

The process of identifying and documenting all the costs involved over the life of an asset is known as Life Cycle Costing (LCC). Life-cycle cost analysis (LCCA) is a method for assessing the total cost of system/facility or equipment ownership [17, 18, 19]. It takes into account all costs of acquiring, operating, maintaining and disposing of a system. Analyzing costs over the life of a facility or equipment is key to understanding return on investment and to making investment decisions based on true costs versus initial costs [17, 18, 19].

The life cycle cost (LCC) method is used to estimate the cost of the proposed PV system. The LCC of an item consists of the total costs of owning and operating an item over its lifetime, expressed in today's money. The costs of the PV system include acquisition costs, operating costs, maintenance costs, and replacement costs. Table 1 gives the list of the components of the data used in the LCC analysis.

Table 1. *List of Components Of The Data Used In The LCC Analysis.*

Item	Variable Name	Cost
PV module	$C_{cv/wp}$	₦ /WP
Battery	$C_{b/ah}$	₦ /Ah
MPPT charger	$C_{cg/a}$	₦ /A
Inverter	$C_{inv/w}$	₦ /W
Installation	C_{inst}	10% of PV cost
O&M/yr	$C_{o\&m}$	2% of PV cost

The LCC of the PV system includes the sum of all the Present Worths (PWs) of the costs of the PV modules, batteries, MPPT charger controllers, inverter, the cost of the installation and the operation and maintenance (O&M) cost of the system [20, 21, 22, 23]. In this study, the lifetime, N of all the PV system items is considered to be 25 years, except that of the battery which is considered to be 5 years. Therefore, an extra 4 groups of batteries should be purchased, after 5 years, 10 years, 15years and 20years. The inflation rate is i and a discount or interest rate is d%. The PWs of all the items are calculated as follows [20, 21, 22, 23]:

$$\text{PV array cost, } C_{PV} = C_{cv/wp} * PV_{wp} \quad (5)$$

$$\text{Initial cost of batteries, } C_b = C_{b/ah} * b_{ah} \quad (6)$$

The PW of the first extra group of batteries (purchased after N=5 years) Cb1PW is calculated from:

$$C_{b1PW} = C_b * \left(\frac{(1*i)}{(1*d)}\right)^N \text{ where } N=5 \quad (7)$$

The Present Worth (PW) of the second extra group of batteries (purchased after N=10 years) C_{b2PW}, the third extra group (purchased after N=15 years) C_{b3PW} and the fourth extra group (purchased after N=20 are respectively calculated from:

$$C_{b2PW} = C_b * \left(\frac{(1*i)}{(1*d)}\right)^N \text{ where } N=10 \quad (8)$$

$$C_{b3PW} = C_b * \left(\frac{(1*i)}{(1*d)}\right)^N \text{ where } N=15 \quad (9)$$

$$C_{b4PW} = C_b * \left(\frac{(1*i)}{(1*d)}\right)^N \text{ where } N=20 \quad (10)$$

Controller cost, $C_{controller} = C_{cg/a} * Controller_A$
Inverter cost $C_{inv} = C_{inv/w} * Inv_w$
Installation cost C_{inst}=0.1 *C_{PV}
Maintenance cost per year $C_{\left(\frac{M}{yr}\right)}$ =0.2 *C_{PV}

The PW of the maintenance cost CMPW can be calculated using the maintenance cost per year $\left(C_{\left(\frac{M}{yr}\right)}\right)$ and the lifetime of the system (N=25 years), from:

$$C_{MPW} = C_{\left(\frac{M}{yr}\right)} * \left(\frac{(1*i)}{(1*d)}\right) * \left[\frac{\left(1-\left(\frac{(1*i)}{(1*d)}\right)^N\right)}{\left(1-\left(\frac{(1*i)}{(1*d)}\right)\right)}\right]^N \quad (11)$$

The life cycle of the PV system can be calculated as follows:

$$LCC = C_{PV} + C_b + C_{b1PW} + C_{b2PW} + C_{b3PW} + C_{b4PW} + C_{controller} + C_{inv} + C_{inst} + C_{MPW} \quad (12)$$

The annualized LCC (ALCC) of the PV system in terms of the present day Naira can be calculated using the following equation:

$$ALCC = LCC * \left[\frac{\left(1-\left(\frac{(1*i)}{(1*d)}\right)^N\right)}{\left(1-\left(\frac{(1*i)}{(1*d)}\right)\right)}\right]^N \quad (13)$$

Finally, the unit electrical cost (cost of 1 kWh) can be calculated as follows:

$$\text{Unit electrical cost} = \frac{ALCC}{365*E_L} \quad (14)$$

2.3. Determination of the Monthly Unit Cost of Energy

The standalone PV (SAPV) system is simulated using PVSyst 5.21. At the end of the simulation the PVSyst generates results that include the unit cost of energy from the SAPV. The unit cost of energy from the PVSyst is based on the yearly total energy supplied to the load. As such, the result from PVSyst is the annual average unit cost of energy. The monthly energy supplied to the load can then be used to determine the monthly unit cost of energy. Let the total annual cost of energy be: C_{annual}; let the annual unit cost of energy be: U_{annual}; let the total energy supplied to the user in the a year be: E_{annual}; let the unit cost of energy for the month i be: U_i and let the total energy supplied to the user in the month i be: E_i. Now

$$C_{annual} = E_{annual}(U_{annual}) \quad (15)$$

The total annual energy that will be supplied to the user if the energy to the user is maintained at the month i's value if denoted as $E_{m(i)}$ where;

$$E_{m(i)} = 12\ (E_i) \quad (16)$$

Then,

$$C_{annual} = E_{m(i)}(U_i) = 12\ (E_i)(U_i) \quad (17)$$

Therefore,

$$12\ (E_i)(U_i) = E_{annual}(U_{annual}) \quad (18)$$

$$U_i = \frac{E_{annual}(U_{annual})}{12\ (E_i)} \quad (19)$$

3. The Simulation and Results

The load demand is shown in Table 2 is used for the analysis

Table 2. *The Hypothetical Load Used For The Analysis.*

Total Watts/Day	Hours/Day	Wh/day	kWh/day
2500	5	12500	12.500

The requisite input data are entered into the PVSyst. The data include among others, the meteorological data, the load demand, the battery sizing data, PV module sizing data, inverter, along with the input data for the economic analysis. Figure 1 shows a screenshot of the input for the economics analysis.

Figure 2 shows the hypothetical daily load demand, as presented in the simulation results. The hypothetical load has daily power demand of 2500watts which runs for an average of 5 hours per day resulting in daily energy demand of 12500Wh/day.

According to Figure 3, the PV system supplies about 96% of the load demand. The remaining 4 % of the load demand cannot be met. The total energy supplied to the user (load) in a year is denoted in Figure 3 as E_User where the annual E_User is 1751 kWh. The economic analysis result, figure 4 shows the total annual cost of energy is 246760 Naira per year at a unit cost of 141 Naira per kWh.

From figure 4, it can be seen that C_{annual} = 246760 Naira per year and U_{annual} =141 Naira per kWh. From the result in Table 3, the highest unit cost of energy of 168.6 Naira/ kWh occurred in August whereas the lowest unit cost of energy of 132.7 Naira/ kWh occurred in October.

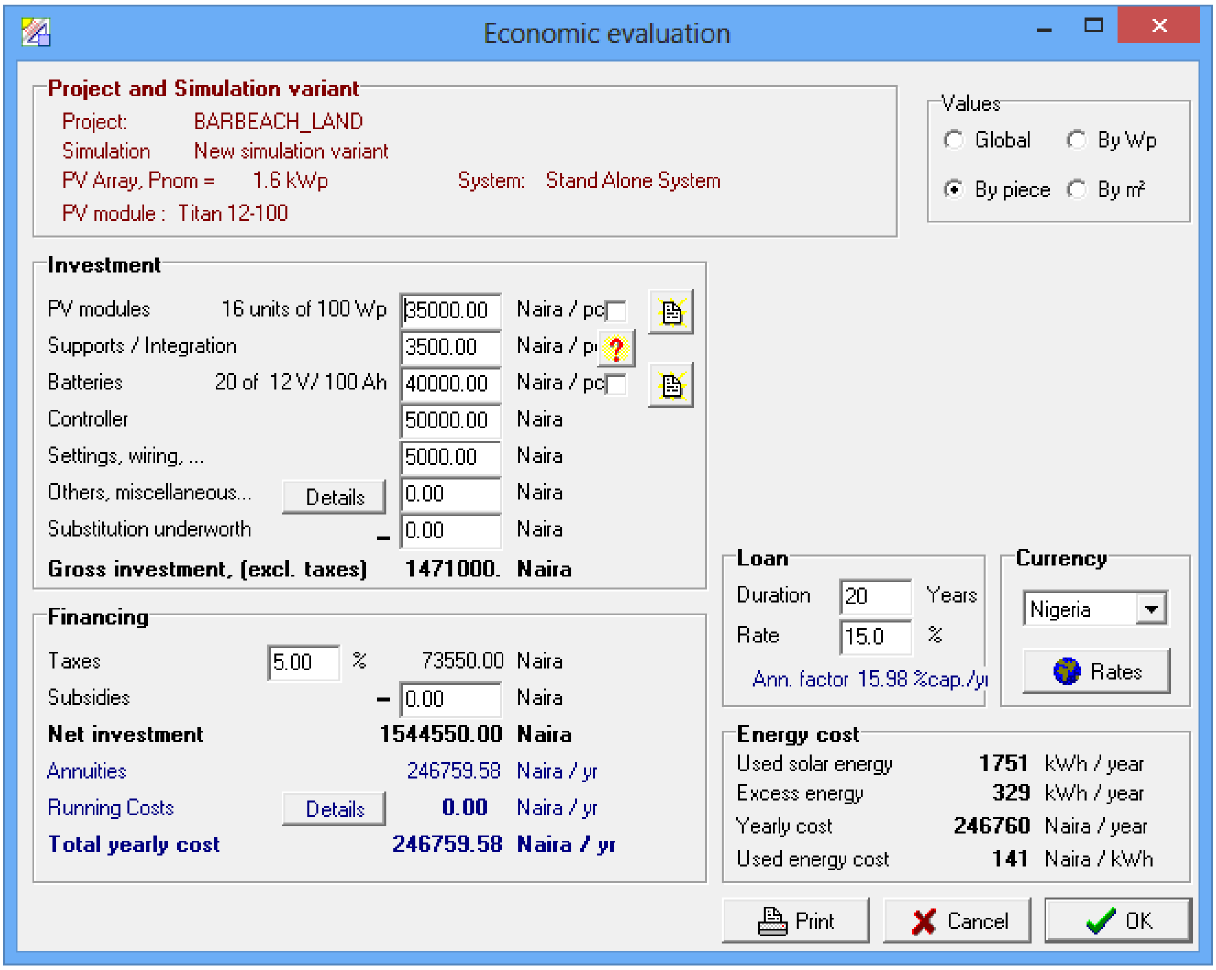
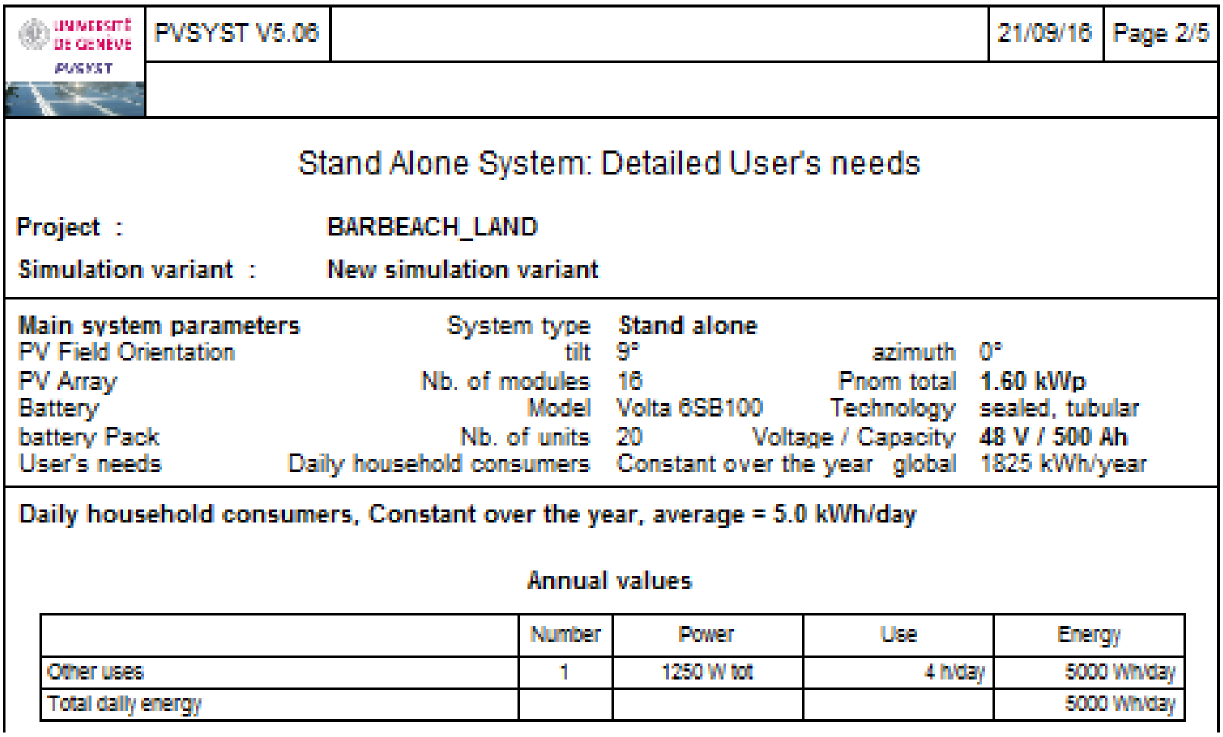


Figure 1. *Economic Analysis Dialogue Box.*



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Stand Alone System: Detailed User's needs

Project : BARBEACH_LAND

Simulation variant : New simulation variant

Main system parameters	System type	**Stand alone**		
PV Field Orientation	tilt	9°	azimuth	0°
PV Array	Nb. of modules	16	Pnom total	**1.60 kWp**
Battery	Model	Volta 6SB100	Technology	sealed, tubular
battery Pack	Nb. of units	20	Voltage / Capacity	**48 V / 500 Ah**
User's needs	Daily household consumers	Constant over the year	global	1825 kWh/year

Daily household consumers, Constant over the year, average = 5.0 kWh/day

Annual values

	Number	Power	Use	Energy
Other uses	1	1250 W tot	4 h/day	5000 Wh/day
Total daily energy				5000 Wh/day

Figure 2. *The User's Daily Load Demand.*

Simulation variant : New simulation variant

Close Print Export Help

New simulation variant

Balances and main results

	GlobHor	GlobEff	E Avail	EUnused	E Miss	E User	E Load	SolFrac
	kWh/m²	kWh/m²	kWh	kWh	kWh	kWh	kWh	
January	163.7	169.0	231.0	57.58	0.12	154.9	155.0	0.999
February	153.7	155.2	215.2	66.38	0.10	139.9	140.0	0.999
March	169.2	165.5	227.0	64.07	0.15	154.9	155.0	0.999
April	156.3	148.3	196.7	36.56	0.11	149.9	150.0	0.999
May	147.6	136.6	170.5	10.73	0.06	154.9	155.0	1.000
June	121.2	111.7	130.5	0.08	20.33	129.7	150.0	0.864
July	122.4	113.0	137.8	5.00	19.63	135.4	155.0	0.873
August	123.4	116.4	138.1	0.15	32.99	122.0	155.0	0.787
September	122.7	117.6	144.2	7.05	0.04	150.0	150.0	1.000
October	141.0	139.3	167.6	3.49	0.02	155.0	155.0	1.000
November	148.5	151.3	189.6	16.40	0.06	149.9	150.0	1.000
December	160.3	167.0	225.7	61.86	0.12	154.9	155.0	0.999
Year	1730.1	1690.8	2173.9	329.35	73.73	1751.3	1825.0	0.960

Figure 3. *The SAPV Systems Solar Fraction.*

Table 3. *The Monthly Energy Yield and Unit Cost Of Energy, where Annual Average Energy Yield,* E_{annual} *=1751.4 kWh and Annual Unit Cost Of Energy,* $U_{annual} = 141$ *Naira/ kWh.*

	Energy Delivered To The Load	**Energy Demand**	**SolFrac**	**Annual Energy Yield Based On The Output Of Month i,** $E_{m(i)}$	**Monthly Unit Cost Of Energy,** U_i
	kWh	kWh		kWh	Naira/ kWh
January	154.9	155	0.999	1858.8	132.8
February	139.9	140	0.999	1678.8	147
March	154.9	155	0.999	1858.8	132.8
April	149.9	150	0.999	1798.8	137.2
May	154.9	155	1	1858.8	132.8
June	129.7	150	0.864	1556.4	158.6
July	135.4	155	0.873	1624.8	151.9
August	122	155	0.787	1464	168.6
September	150	150	1	1800	137.1
October	155	155	1	1860	132.7
November	149.9	150	1	1798.8	137.2
December	154.9	155	0.999	1858.8	132.8
Year	1751.3	1825	0.96	1751.4	141.0

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Stand Alone System: Economic evaluation

Project : **BARBEACH_LAND**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Stand alone**		
PV Field Orientation	tilt	9°	azimuth	0°
PV Array	Nb. of modules	16	Pnom total	**1.60 kWp**
Battery	Model	Volta 6SB100	Technology	sealed, tubular
battery Pack	Nb. of units	20	Voltage / Capacity	**48 V / 500 Ah**
User's needs	Daily household consumers	Constant over the year	global	1825 kWh/year

Investment

PV modules (Pnom = 100 Wp)	16 units	35000 Naira / unit	560000 Naira
Supports / Integration		3500 Naira / module	56000 Naira
Batteries (12 V / 100 Ah)	20 units	40000 Naira / unit	800000 Naira
regulator / converter			50000 Naira
Settings, wiring, ...			5000 Naira
Substitution underworth			-0 Naira
Gross investment (without taxes)			**1471000 Naira**

Financing

Gross investment (without taxes)		1471000 Naira
Taxes on investment (VAT)	Rate 5.0 %	73550 Naira
Gross investment (including VAT)		1544550 Naira
Subsidies		-0 Naira
Net investment (all taxes included)		**1544550 Naira**
Annuities	(Loan 15.0 % over 20 years)	246760 Naira/year
Maintenance		0 Naira/year
insurance, annual taxes		0 Naira/year
Provision for battery replacement	(lifetime 8.4 years)	0 Naira/year
Total yearly cost		**246760 Naira/year**

Energy cost

Used solar energy	1751 kWh / year
Excess energy (battery full)	329 kWh / year
Used energy cost	141 Naira / kWh

Figure 4. *The Economic Analysis Result.*

4. Conclusion

In this paper, simulation approach is used for the determination of the monthly unit cost of energy generated from standalone PV (SAPV) power system in Imo State. The meteorological data used in the study are compiled from National Aeronautics and Space Administration (NASA) worldwide meteorological database. The meteorological data include 22-year monthly and annual averaged insolation incident on a horizontal surface (kwh/m2/day) and 22-year monthly averaged air temperature. A hypothetical (assumed) electric load demand data of 5000 kWh per day is used for the simulation. The PVsyst industrial PV system planning software solution was selected to model and simulate the entire PV system. PVSyst uses life cycle cost analysis approach to determine the investment cost and unit cost of energy generated from the PV system. The average total energy supplied to the user (load) along with unit cost of energy in a year and in each month are determined.

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