Performance evaluation of a standalone photovoltaic solar power system under different fixed optimal tilt angles

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***Abstract*—The performance evaluation of a standalone photovoltaic (PV) solar power system under different fixed optimal tilt angles is presented for a standalone PV power system located in the permanent site of University of Uyo, Akwa Ibom State. The solar radiation was downloaded from NASA portal into the PVSyst software. PVSyst software is used to select the optimal tilt angle for PV modules for three different scenarios; (i) yearly fixed tilt angle that gave optimal yearly average solar radiation on the tilted plane (ii) yearly fixed tilt angle that gave optimal Summer months (April, May, June, July, August and September) average solar radiation on the tilted plane (iii) yearly fixed tilt angle that gave optimal Winter months (October, November, December, January, February and March) average solar radiation on the tilted plane. The results showed that the yearly fixed tilt angle with optimal yearly average solar radiation produced the highest yearly energy of 2190 kWh but the best performance in terms of minimal loss of load probability (of 3.3 %) is obtained from the tilt angle of 0° that gave optimal Summer months average solar radiation. The worst configuration of the system is the tilt angle of 27° that gave optimal Winter months average solar radiation; it has the lowest yearly energy production of 2107 kWh, the highest loss of load probability of 9.3 % and the highest unused energy of 340 kWh per year. The idea presented in this paper will enable the solar power system designers to reconsider their choice of optimal tilt angle for the solar panels since the tilt angle with the highest energy production may not give the best performance since some of those energy may be lost as unused energy.**

Keywords— Solar Power, Solar Radiation, Performance Ratio, Tilt Angle, Loss Of Load Probability

I. INTRODUCTION

In recent years, solar photovoltaic (PV) power has become the most widely adopted renewable energy for domestic and industrial uses [1,2,3,4,5]. The use of solar power for residential power supply has been on the increase especially in the remote locations in the developing countries where the national electric power has not reached [6,7,8]. Also, rooftop solar power supply is also used especially in the urban areas where there is scarcity of free (open) space for the installation of PV modules. In any case, for PV installation on any given location, the energy production potential of the PV modules depends on several factors; among them is temperature and solar radiation incident on the PV module plane [9,10,11,12]. As such, PV power designers determine the optimal tilt angle for maximum solar radiation capture on the PV module plane [13,14,15,16,17]. Since the solar radiation at any given location varies with time all through the year, it becomes difficult to ensure optimal solar radiation capture, especially when the tilt angle is fixed.

Consequently, some PV power installations are equipped with sun tracking mechanisms to ensure continuous alignment of the solar panels to the optimal tilt angle [18,19,20]. The approach attracts extra investment and maintenance cost to the PV power system owner. In most cases, the yearly fixed optimal tilt angle is used. PVSyst software [21,22,23] provides three options, namely;

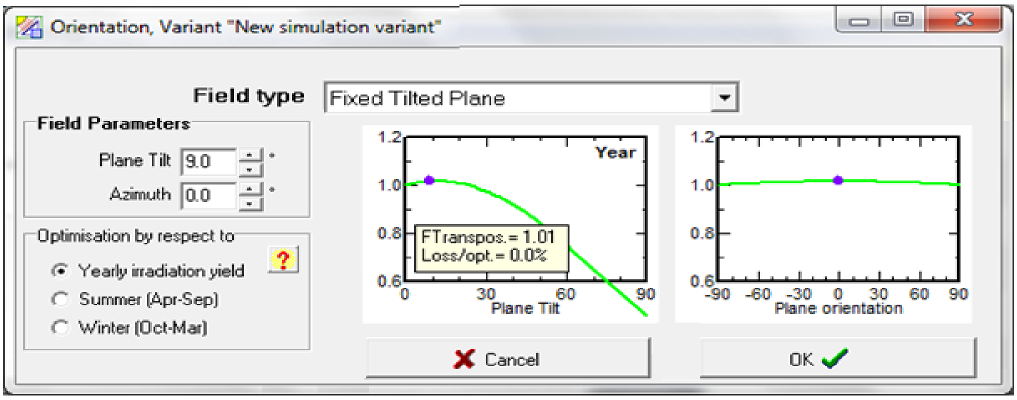
(i) Yearly fixed tilt angle that will give maximum yearly average solar radiation on the tilted plane
(ii) Yearly fixed tilt angle that will give maximum optimal Summer months (April, May, June, July, August and September) average solar radiation on the tilted plane
(iii) Yearly fixed tilt angle that will give maximum optimal Winter months (October, November, December, January, February and March) average solar radiation on the tilted plane.

Each of the options will give rise to different solar radiation capture on the tilted plane of the PV module. Hence, the performance of the PV power system will be different in the three cases. Accordingly, in this paper, the impact of the different yearly fixed optimal tilt angles on the performance of a standalone solar PV power system is examined. The standalone power system is simulated using PVSyst software and the simulation results provided the requisite performance parameters for the comparative performance analysis.

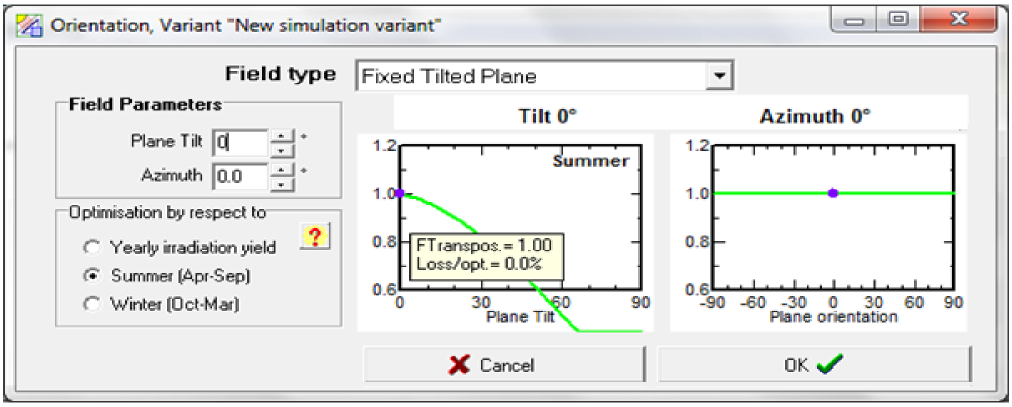
II. METHODOLOGY

The study is focused on comparing the yearly energy yield, the specific energy yield, the performance ratio and the loss of load probability for a given standalone solar power system that is simulated under three different yearly fixed optimal tilt angles. In the first scenario, the PV modules are inclined at a tilt angle that gives the maximum yearly average solar radiation capture on the tilted plane. In the second scenario, the PV modules are inclined at a tilt angle that gives the maximum Summer months (April, May, June, July, August and September) average solar radiation capture on the tilted plane. The third scenario is such that the PV modules are inclined at a tilt angle that gives the maximum Winter months (October, November, December, January, February and March) average solar radiation capture on the tilted plane.

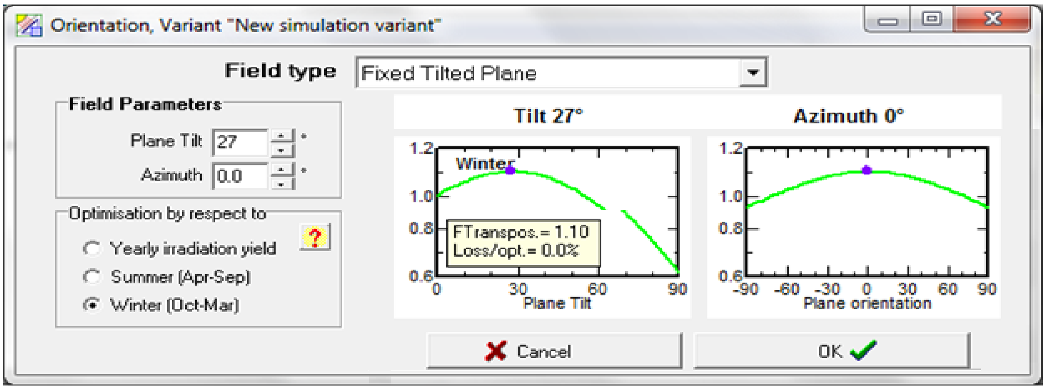
For the given case study site located inside the permanent site of University of Uyo, Akwa Ibom State, the solar radiation dataset is downloaded from the NASA website and then loaded into the PVSyst software. Then, the optimal tilt angles for the three cases listed are determined using the PVSyst software PV module orientation dialogue box and the values obtained for the three cases are shown in Figure 1.



(a)



(b)



(c)

Figure 1 The three different optimal tilt angles: (a) the optimal yearly average solar radiation(a) the optimal Summer months average solar radiation (a) the optimal Winter months average solar radiation

The performance parameters used to compare the PV power system in the three cases include the yearly energy yield, the performance ratio, the specific energy yield, the solar fraction, the loss of load probability and the missing energy. The yearly energy output (E_Y) of a PV system is given as [25,26];

$$E_Y = 365(P_k)(P_r)(H_i) \quad (1)$$

Where E_Y is in kWh,P_k is the total peak power rating of the installed PV array (P_k is in kW), P_r is the performance ratio of the system and H_i is the monthly or yearly average of the daily global radiation on the plane of the PV module (H_i is in kWh/m^2).

The Performance Ratio (P_r) is computed as [24,27]:

$$P_r = \frac{E_Y}{E_t} = (\eta_{pr})(\eta_{rl})(\eta_{sys}) \quad (2)$$

Where

- E_Y is the actual annual electrical energy yield
- E_t is the target yield annual electrical energy yield.
- η_{pr} is the pre-conversion efficiency of the PV system which accounts for losses due to shading, dirt, snow and reflection.
- η_{rl} is the relative module efficiency which accounts for the module efficiency and temperature dependence of the PV module
- η_{sys} is the system efficiency which accounts for losses in the electrical components of the system and they include the losses in the electrical wires, inverters and transformers.

The specific energy yield (Y_s) is given as;

$$Y_s = \frac{E_Y}{P_k} \quad (3)$$

The solar fraction (Sf), the loss of load probability along with the missing energy and the other required performance parameters are generated as part of the PVSyst simulation result for the system. The solar fraction (usually expressed in fraction between 0 and 1 or in percentage) gives the percentage of the required total annual energy that is supplied by the PV power system. The complement of the solar fraction is the loss of load probability (LoLP), which gives the percentage of the total annual energy demand that is not supplied by the PV power system.

$$\text{LoLP}(\%) = (1 - \text{Sf})100 \quad (4)$$

Where f is the solar fraction expressed in fraction between 0 and 1. A solar fraction of one (1) means that all the annual energy demand is supplied with zero (0 %) loss of load probability. A solar fraction of 0.95 means that 95 % of the annual energy demand is supplied with (5 %) loss of load probability. The percentage of the total annual energy demand that is not supplied by the PV power system is referred to as the missing energy (usually expressed in kWh). The PYSyst software generates all the mentioned parameters as part of its simulation results. It also provides the duration of time in number of hours per year that the missing energy (or loss of load) will last. Finally, for the simulation, a daily 5 kWh energy demand is used.

III. RESULTS AND DISCUSSION

The schematic diagram of the standalone PV power system is shown in Figure 1.

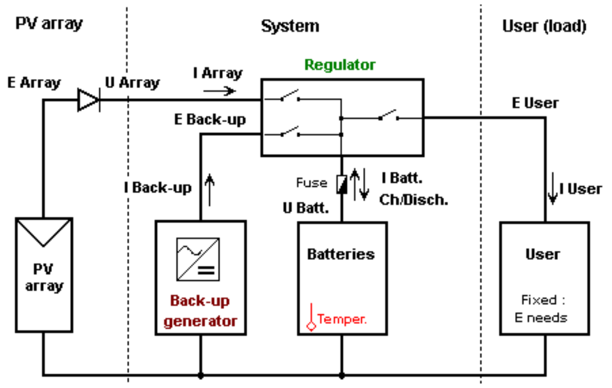


Figure 2: The schematic diagram of the standalone PV power system

The simulation parameters for the system are shown in Figure 3. According to Figure 3, about 24 of 12 V 100 Ah deep cycle batteries are needed. The batteries are connected in three banks with 8 batteries on each battery bank. The three battery banks are then connected series. Also, PV array consist of nineteen 80 Wp 40V uCSiaSiH PV modules.

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Stand Alone System: Simulation parameters

Project :	**UNIUYOTILTAGNL**				
Geographical Site		**UNIUYOPERMSITE**		**Country**	**Nigeria**
Situation		Latitude	5.0°N	Longitude	8.0°E
Time defined as		Legal Time	Time zone UT+1	Altitude	49 m
		Albedo	0.20		
Meteo data :	UNIUYOPERMSITE from NASA-SSE, Synthetic Hourly data				

Simulation variant :	**UNUYO_TAMAL**				
		Simulation date	26/12/18 06h59		

Simulation parameters

Collector Plane Orientation		Tilt	8°	Azimuth	0°

PV Array Characteristics

PV module	uCSi-aSi:H	Model	**NA-801 WP**		
		Manufacturer	Sharp		
Number of PV modules		In series	1 modules	In parallel	19 strings
Total number of PV modules		Nb. modules	19	Unit Nom. Power	80 Wp
Array global power		Nominal (STC)	**1.52 kWp**	At operating cond.	1.44 kWp (50°C)
Array operating characteristics (50°C)		U mpp	46 V	I mpp	31 A
Total area		Module area	**20.0 m²**		

PV Array loss factors

Thermal Loss factor		Uc (const)	29.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind velocity = 1m/s.)				NOCT	45 °C
Wiring Ohmic Loss		Global array res.	16 mOhm	Loss Fraction	1.0 % at STC
Module Quality Loss				Loss Fraction	5.0 %
Module Mismatch Losses				Loss Fraction	1.5 % (fixed voltage)
Incidence effect, ASHRAE parametrization		IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05

System Parameter		System type	**Stand Alone System**		
Battery		Model	**Dural SC**		
		Manufacturer	Electrona		
Battery Pack Characteristics		Voltage	36 V	Nominal Capacity	800 Ah
		Nb. of units	3 in series x 8 in parallel		
		Temperature	Fixed (20°C)		
Regulator		Model	General Purpose Default		
		Technology	Undefined	Temp coeff.	-5.0 mV/°C/elem.
Battery Management Thresholds		Charging	41.0/39.2 V	Discharging	35.3/37.8 V
		Back-Up Genset Command	35.5/38.7 V		
User's needs :		Daily household consumers	Constant over the year		
		average	5.0 kWh/Day		

Figure 3: The simulation parameters for the system

The same simulation parameters are used to simulate the standalone system in three different yearly fixed tilt angles; (i) using the tilt angle that gives optimal yearly average solar radiation on the tilted plane (ii) using the tilt angle that gives optimal Summer months (April, May, June, July, August and September) average solar radiation on the tilted plane (iii) using the tilt angle that gives optimal Winter months (October, November, December, January, February and March) average solar radiation on the tilted plane.

The result for the tilt angle of 8° that gives optimal yearly average solar radiation on the tilted plane is shown in Figure 4. The results in Figure 4 show that the energy produced per year is 2190 kWh and the yearly specific energy yield of the PV array is 1441 kWh per kWp power of the PV array. Also, the loss of load probability is 4.1 % . This means that the solar power system did not meet the energy demand of the user in about 4.1 % of the total time in a year (which is about 15 days). The yearly unused energy is 322 kWh while the yearly missing energy is 74 kWh. The system performance ratio is 66.4 %.

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Stand Alone System: Main results

Project :	**UNIUYOTILTAGNL**
Simulation variant :	**UNUYO_TAMAL**

Main system parameters	System type	**Stand alone**		
PV Field Orientation	tilt	8°	azimuth	0°
PV Array	Nb. of modules	19	Pnom total	**1.52 kWp**
Battery	Model	Dural SC	Technology	vented, vehicle starting
battery Pack	Nb. of units	24	Voltage / Capacity	**36 V / 800 Ah**
User's needs	Daily household consumers	Constant over the year	global	1825 kWh/year

Main simulation results				
System Production	**Available Energy**	**2190 kWh/year**	Specific prod.	1441 kWh/kWp/year
	Used Energy	1751 kWh/year	Excess (unused)	322 kWh/year
	Performance Ratio PR	66.4 %	Solar Fraction SF	95.9 %
Loss of Load	Time Fraction	4.1 %	Missing Energy	74 kWh

Figure 4: The result for the tilt angle that gives optimal yearly average solar radiation on the tilted plane

The result for the tilt angle of 0° that gives optimal summer month's average solar radiation on the tilted plane is shown in Figure 5. The results in Figure 5 show that the energy produced per year is 2156 kWh and the yearly specific energy yield of the PV array is 1418 kWh per kWp power of the PV array. Also, the loss of load probability is 3.3 % . This means that the solar power system did not meet the energy demand of the user in about 3.3 % of the total time in a year (which is about 12 days). The yearly unused energy is 274 kWh while the yearly missing energy is 59 kWh. The system performance ratio is 67.7 %.

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Stand Alone System: Main results

Project :	**UNIUYOTILTAGNL**
Simulation variant :	**UNUYO_TAMAL**

Main system parameters	System type	**Stand alone**		
PV Field Orientation	tilt	0°	azimuth	0°
PV Array	Nb. of modules	19	Pnom total	**1.52 kWp**
Battery	Model	Dural SC	Technology	vented, vehicle starting
battery Pack	Nb. of units	24	Voltage / Capacity	**36 V / 800 Ah**
User's needs	Daily household consumers	Constant over the year	global	1825 kWh/year

Main simulation results				
System Production	**Available Energy**	**2156 kWh/year**	Specific prod.	1418 kWh/kWp/year
	Used Energy	1766 kWh/year	Excess (unused)	274 kWh/year
	Performance Ratio PR	67.7 %	Solar Fraction SF	96.8 %
Loss of Load	Time Fraction	3.3 %	Missing Energy	59 kWh

Figure 5: The result for the tilt angle that gives optimal Summer months average solar radiation on the tilted plane

The result for the tilt angle of 27° that gives optimal Winter months average solar radiation on the tilted plane is shown in Figure 6. The results in Figure 6 show that the energy produced per year is 2107 kWh and the yearly specific energy yield of the PV array is 1386 kWh per kWp power of the PV array. Also, the loss of load probability is 9.3 %. This means that the solar power system did not meet the energy demand of the user in about 9.3 % of the total time in a year (which is about 34 days). The yearly unused energy is 340 kWh while the yearly missing energy is 167 kWh. The system performance ratio is 65 %.

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Stand Alone System: Main results

Project : **UNIUYOTILTAGNL**

Simulation variant : **UNUYO_TAMAL**

Main system parameters	System type	**Stand alone**		
PV Field Orientation	tilt	27°	azimuth	0°
PV Array	Nb. of modules	19	Pnom total	**1.52 kWp**
Battery	Model	Dural SC	Technology	vented, vehicle starting
battery Pack	Nb. of units	24	Voltage / Capacity	**36 V / 800 Ah**
User's needs	Daily household consumers	Constant over the year	global	1825 kWh/year

Main simulation results				
System Production	**Available Energy**	**2107 kWh/year**	Specific prod.	1386 kWh/kWp/year
	Used Energy	1658 kWh/year	Excess (unused)	340 kWh/year
	Performance Ratio PR	65.0 %	Solar Fraction SF	90.8 %
Loss of Load	Time Fraction	9.3 %	Missing Energy	167 kWh

Figure 6: The result for the tilt angle that gives optimal Winter months average solar radiation on the tilted plane

In all, the results show that the yearly fixed tilt angle with optimal yearly average solar radiation produced the highest yearly energy but the best performance in terms of minimal loss of load probability (of 3.3 %) is the tilt angle of 0° that gives optimal Summer months average solar radiation. The worst configuration of the system is the tilt angle of 27° that gives optimal Winter months average solar radiation; it has the lowest yearly energy production of 2107 kWh, the highest loss of load probability of 9.3 % and the highest unused energy of 340 kWh per year.

IV. CONCLUSION

PVSyst software is used to select the optimal tilt angle for PV modules for three different scenarios; one, yearly fixed tilt angle with optimal yearly average solar radiation on the tilted plane; two, yearly fixed tilt angle with optimal Summer months average solar radiation on the tilted plane and three, yearly fixed tilt angle with optimal Winter months average solar radiation on the tilted plane. The PVSyst software is used to simulate the standalone PV power system under the three different tilt angles and the performance of the system are examined and compared for the three different tilt angles. The results shows that though the configuration with maximum yearly average solar radiation on the tilted plane produced the highest amount of energy it is not the best configuration the loss of load probability is considered. Rather, the second configuration with yearly fixed tilt angle with optimal Summer months average solar radiation on the tilted plane gave the best loss of load probability . The idea presented in this paper will enable the solar power designers to reconsider their choice of optimal tilt angle for the solar panels since the tilt angle with the highest energy production may not give the best performance since some of those energy may be lost as unused energy.

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