Analysis Of Carbon Balance, Aging Effect, Energy Production And Loss Factors For A Grid-Connected Solar Power System Used For Powering GSM Base Station

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***Abstract*— In this work, analysis of carbon balance, aging effect, energy production and loss factors for a grid-connected solar power system used for powering GSM base station is presented. The base station with daily energy demand of 25392 Wh/day has site geo-coordinates of 5.04013621263276, 7.975427331154321 with mean daily temperature of 24.9 °C and annual total of daily solar radiation of 1713.2 kW/m^2/year or 4.7 kW/m^2 /day. The PVSyst simulation results for the solar power system showed that 12 PV panels each rated at 200 Wp with a total area of 19.6 m^2 was used along with 4.0 kWac inverter. The system had PV module degradation of 0.4 % per year and module quality loss of 2.5 %. The system also had annual performance ratio (PR) of 79.7 % with total of 3329.5 kWh of energy injected into the grid in one year. The aging analysis showed that the performance ratio dropped from 79.7 % in the first year to 68.7% after 25 years which is about 13.8 % drop in performance over the system life time. Again, about 30.5 tCo2 were saved over the lifetime of the solar power system.**

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***Keywords*— Carbon Balance, System Aging, Energy Production, Loss Factors, Grid-Connected, Solar Power System, GSM Base Station**

1. INTRODUCTION

In Nigeria today, GSM communication network has greatly revolutionized the telecommunication industry [1,2]. It has enabled internet access to remote areas across Nigeria and has helped to reduce the digital divide [3,4,5]. Moreover, the increasing transition to e-platforms in the education sector has been facilitated by the wide spread connectivity occasioned by the ubiquitous GSM networks across Nigeria [6,7,8]. Particularly, due to the large population of students in the campuses of higher learning and the increasing application of Internet-ready facilities in learning, many GSM service providers have installed their base stations in many university, college of education and polytechnic campus across Nigeria [9,10].

Apart from the high exchange rate and high cost of living, the heavy reliance on fossil fuel for powering the GSM base stations in many sites in Nigeria has been one of the key challenges in the GSM industry [11]. Besides, the fossil fuel power supply is not environmentally friendly. It pollutes the environment with carbon emissions which are harmful to the environment and in many cases, it also causes some noise pollution [12]. In addition, the fossil fuel is not renewal as such it is among those source that are not sustainable [13]. In view of these challenges, the GSM service providers are now turning to solar power supply systems as alternative energy solution for their base stations [14,15]

In this work, therefore, the grid-connected solar power system for powering a GSM base station is presented. Beyond the design of the solar power system, the focus is further directed to analyzing the carbon balance and the degradation that occurs in the system performance due to aging. Also, the study considered the energy yield of the power system and the attendant system losses.

2. METHODOLOGY

This paper considered the solar power system deployed for powering a GSM base station located in front of ELF lecture hall at University of Uyo main campus. The site is shown on the Google map in Figure 1. The study focused on using PVSyst software for carrying out the analysis of carbon balance, aging, normalized energy production and loss factors for a solar power system used for powering a GSM base station. In order to accomplish the objective, first, the daily energy demand profile of the based station is determined, as shown in Table 1. According to the data in table 1, the daily energy demand of the base station is given in Table 1 as 25392 Wh/day. Secondly, the PVSyst was used to download the solar radiation and atmospheric temperature datasets of the base station location from the NASA portal. In this case, the base station site geo-coordinates 5.04013621263276, 7.975427331154321 were used in the PVSyst meteorological data download dialogue box shown in Figure 2 to download the requisite the solar radiation and atmospheric temperature datasets from the NSA portal. The graph of the mean of the daily solar radiation for the GSM base station is given in Figure 3 while that of the atmospheric temperature is given in Figure 4.

Thereafter, the optimal tilt angle for the installation of the PV panels was determined using the PVSyst PV module orientation tool and the screenshot of the optimal tilt orientation of the PV panel is shown in

Figure 5. The location has optimal tilt angle of 12 ° (shown in Figure 5), mean daily temperature of 24.9 °C (shown in Figure 4) and annual total of daily solar radiation of 1713.2 kW/m^2/year or 4.7 kW/m^2 /day (shown in Figure 3)

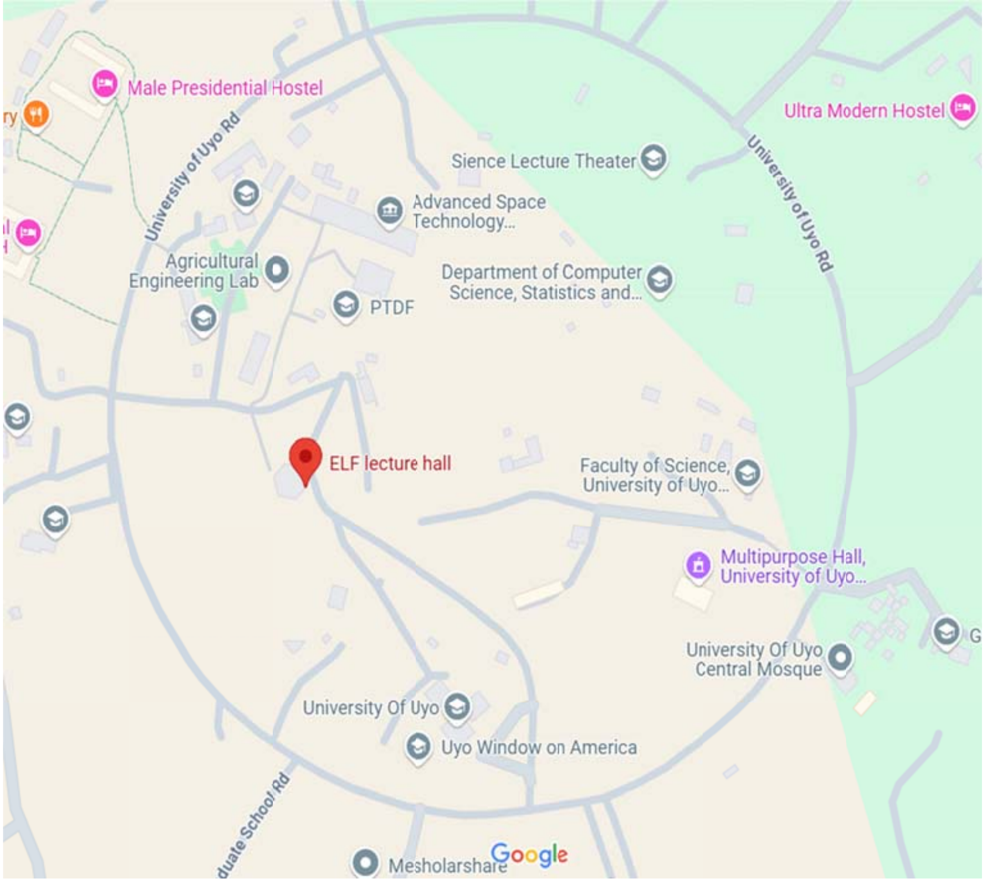

Figure 1 The location of the GSM bas station near the ELF lecture hall University of Uyo main campus (site coordinates: 5.04013621263276, 7.975427331154321)

Table 1 The daily energy demand profile for the GSM base station

S/ N	Load Description	QTY	Power Rating (W)	Total Power Demand (w)	Duration of operation (h)	Energy Demand (Wh)
1	Base station transceiver	2	40	80	24	1920
2	Connecting microwave	1	75	75	24	1800
3	Air conditioner	1	1200	1200	16.5	19800
4	Halogen lamp	3	200	12	12	144
5	Aviation warning light	5	160	12	12	144
6	LED light	5	20	12	24	288
7	Security light	3	120	12	12	144
8	Motion and proximity sensor system	1	30	24	24	576
9	CCTV setup	1	80	24	24	576
				1451		25392

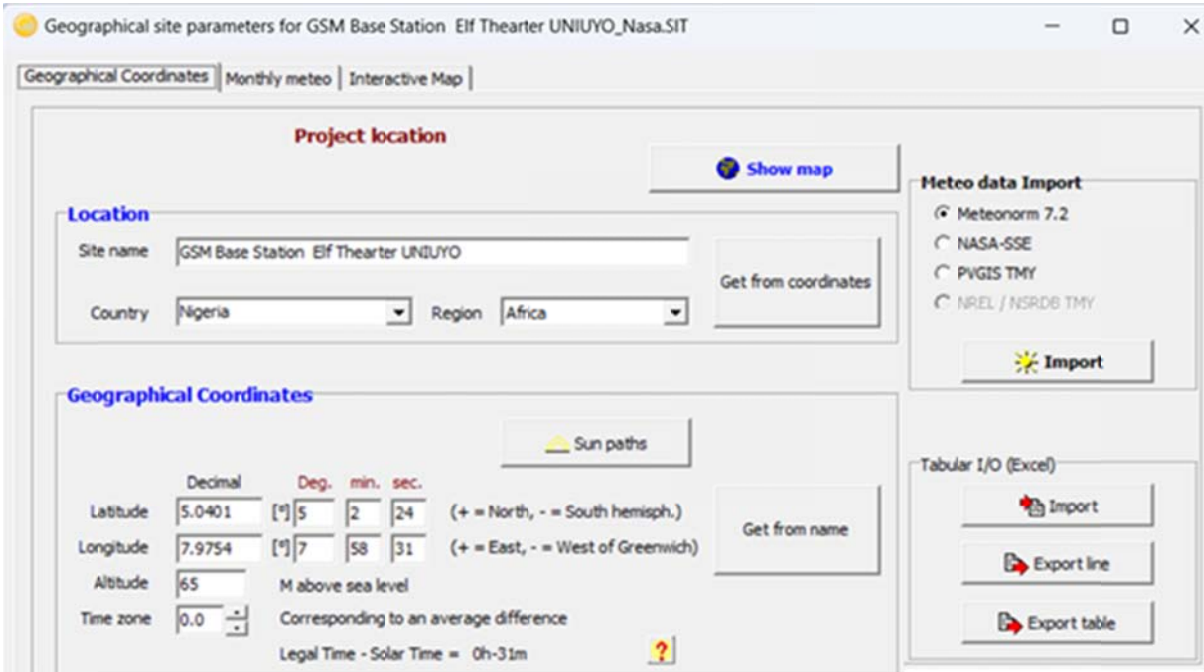

Figure 2 The screenshot of the PVSyst dialogue box for downloading the solar radiation and atmospheric temperature from the NASA portal

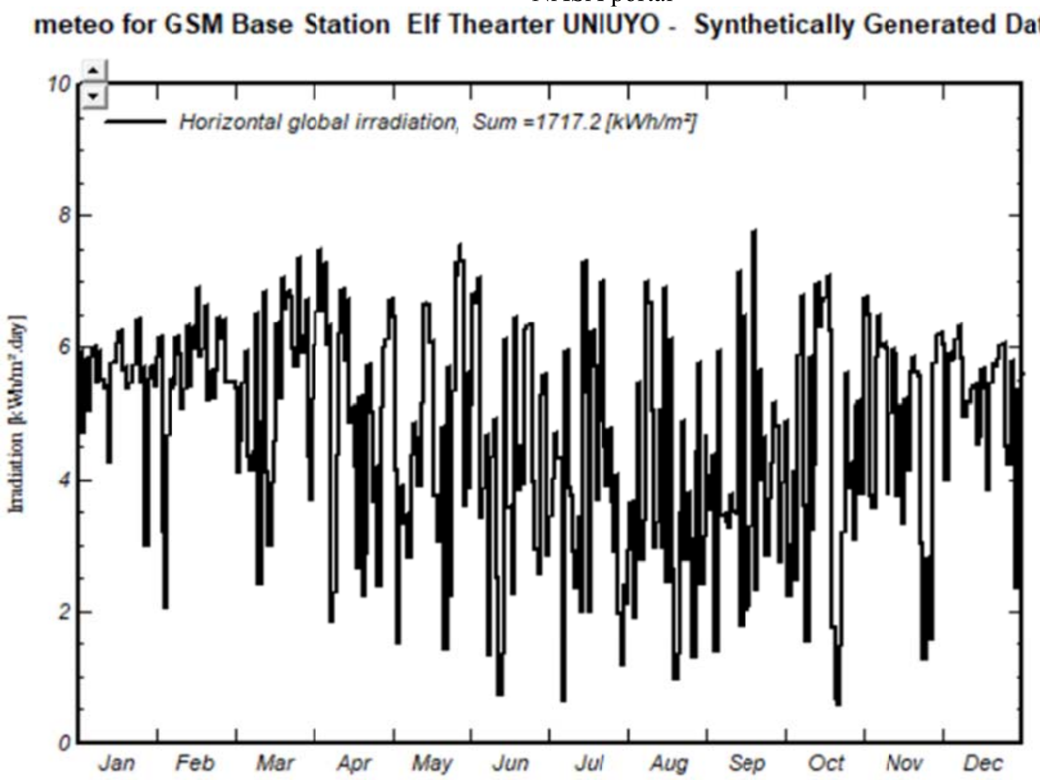

Figure 3 The graph of the mean of the daily solar radiation for the GSM base station

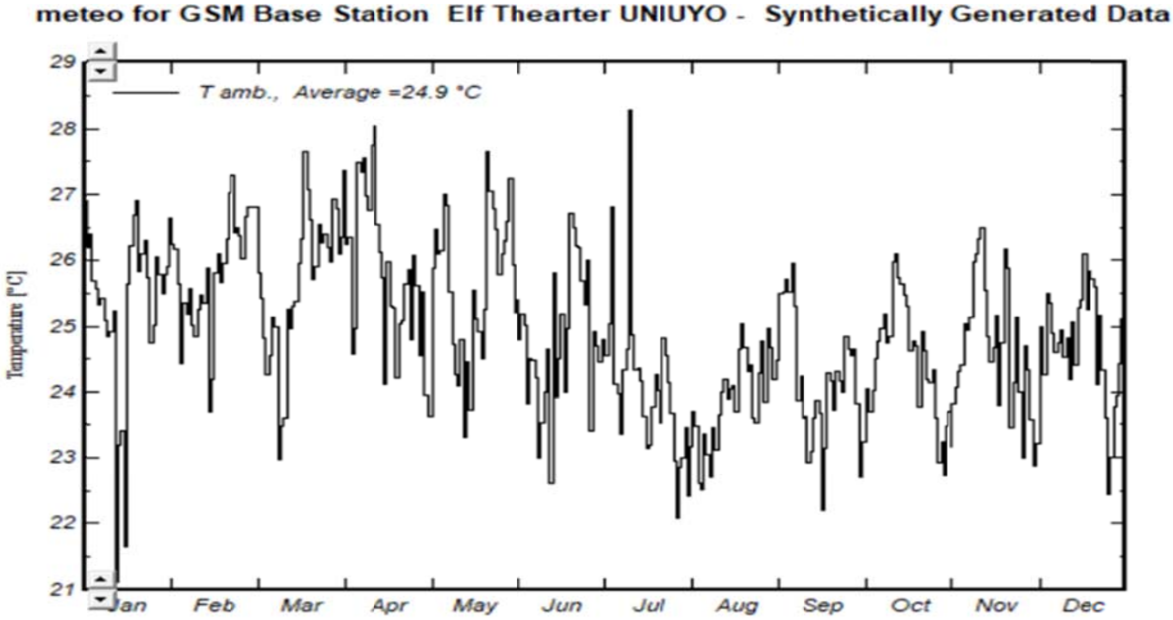

Figure 4 The graph of the mean of the daily atmospheric temperature for the GSM base station

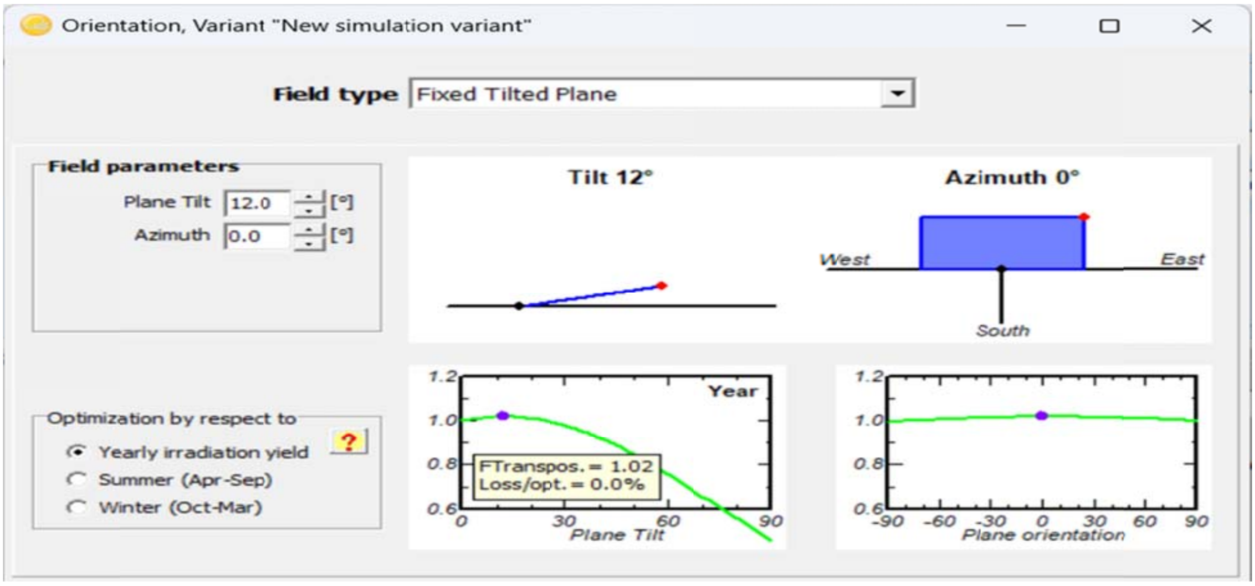

Figure 5 The screenshot of the optimal tilt orientation of the PV panel

The PVSyst uses the schematic diagram of grid-connected solar power system shown in Figure 6 to select and size the grid-connected solar power system. The PVSyst main dialogue window for selecting and sizing of the PV array and inverter in the grid-connected solar power system is shown in Figure 7. According to the screenshot in Figure 7, a total of 12 PV modules each rated at 200 Wp was used to generate the solar power for the system. Also, a 40 kW 50 Hz inverter was selected. The graph for the variation in efficiency with temperature and solar radiation for the solar panel is shown in Figure 8. The selected PV panel has conversion efficiency of 12.36 % at Standard Test Condition (STC) with temperature at 25 °C and solar radiation at 1000 W/m^2. However, in operation, the PV conversion efficiency varies, as shown in Figure 8, with both the temperature and the solar radiation, dropping to as low as 7.5 % at high temperature of 70 °C .

Furthermore, the graph of the temperature effect on the operation of the inverter is show in Figure 9. The results showed that the nominal power rating of the inverter is 4.0 kWac up to a temperature of 50° C. However, below the 50° C the power rating can be up to 4.5 kWac while the operating power drops to zero at about 60 ° C. This clearly indicate carrying capacity of the inverter under various temperatures.

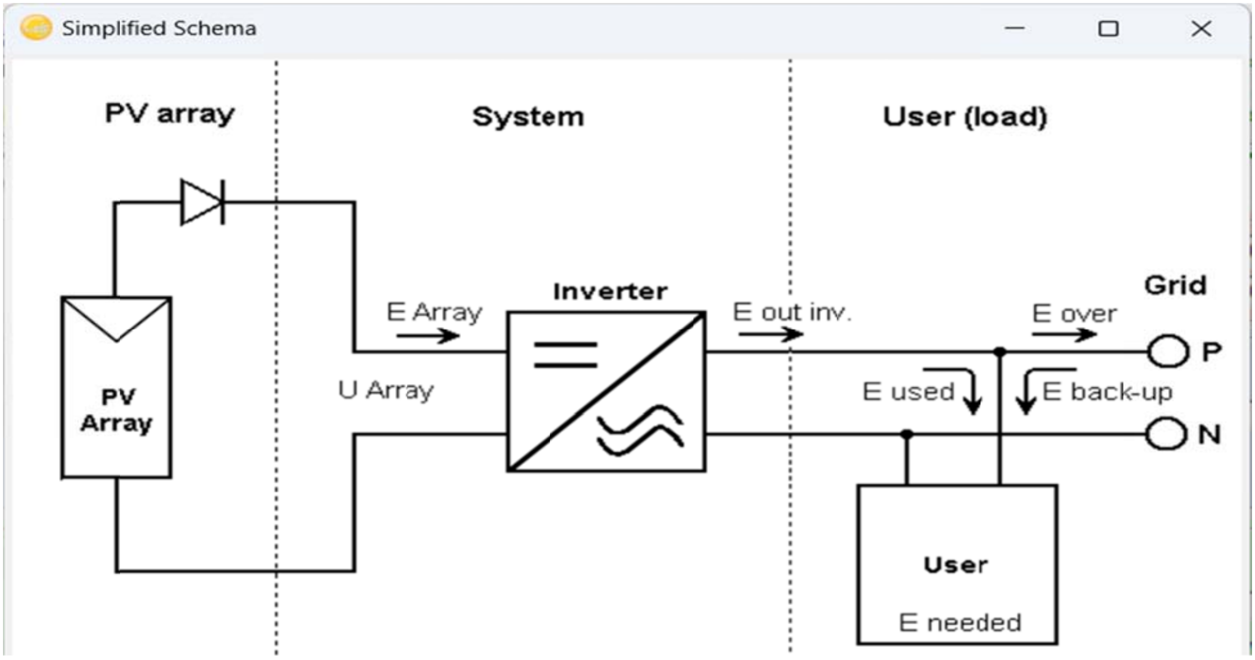

Figure 6 The PVSyst schematic diagram of grid-connected solar power system

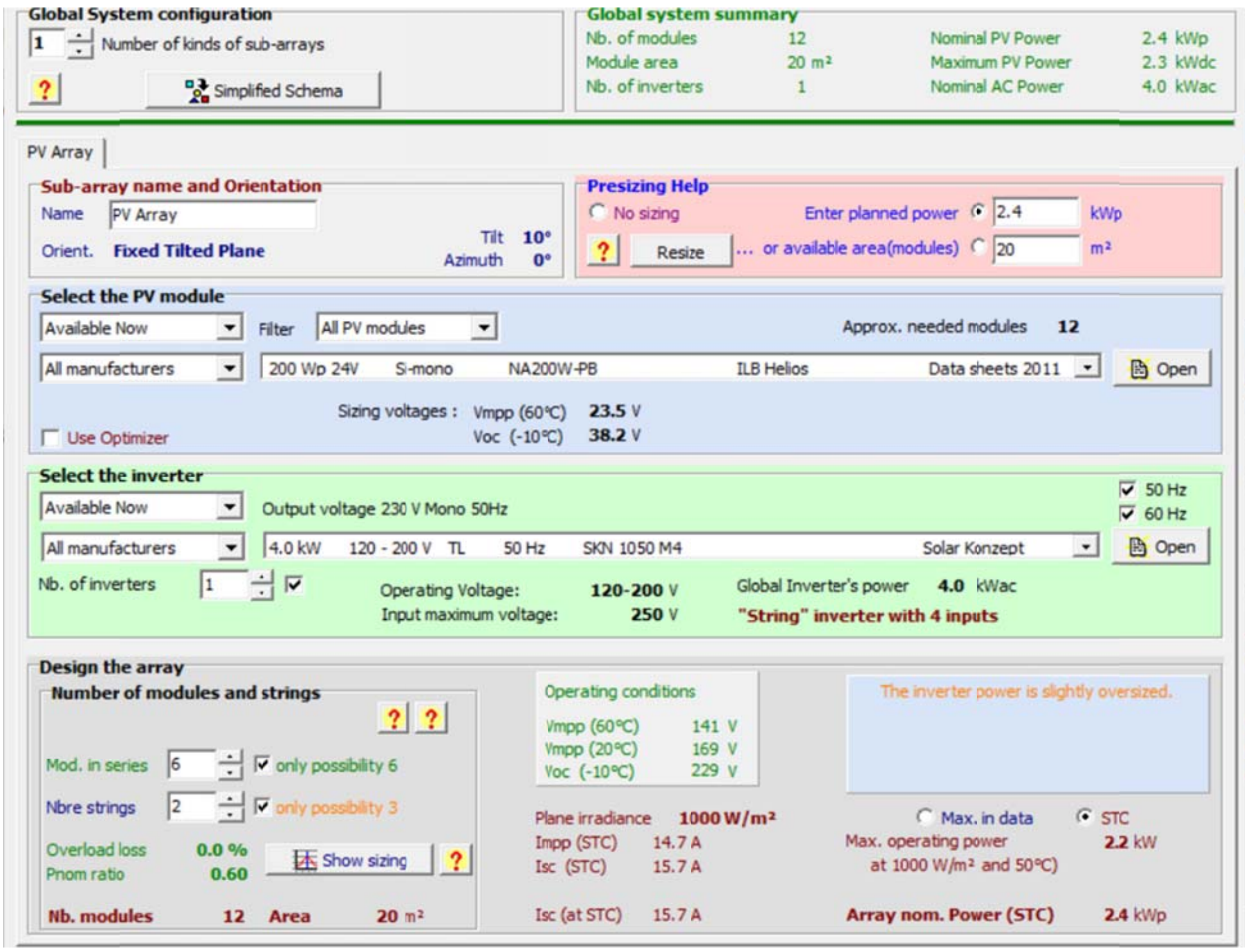

Figure 7 The PVSyst main dialogue window for selecting and sizing of the PV array and inverter in the grid-connected solar power system

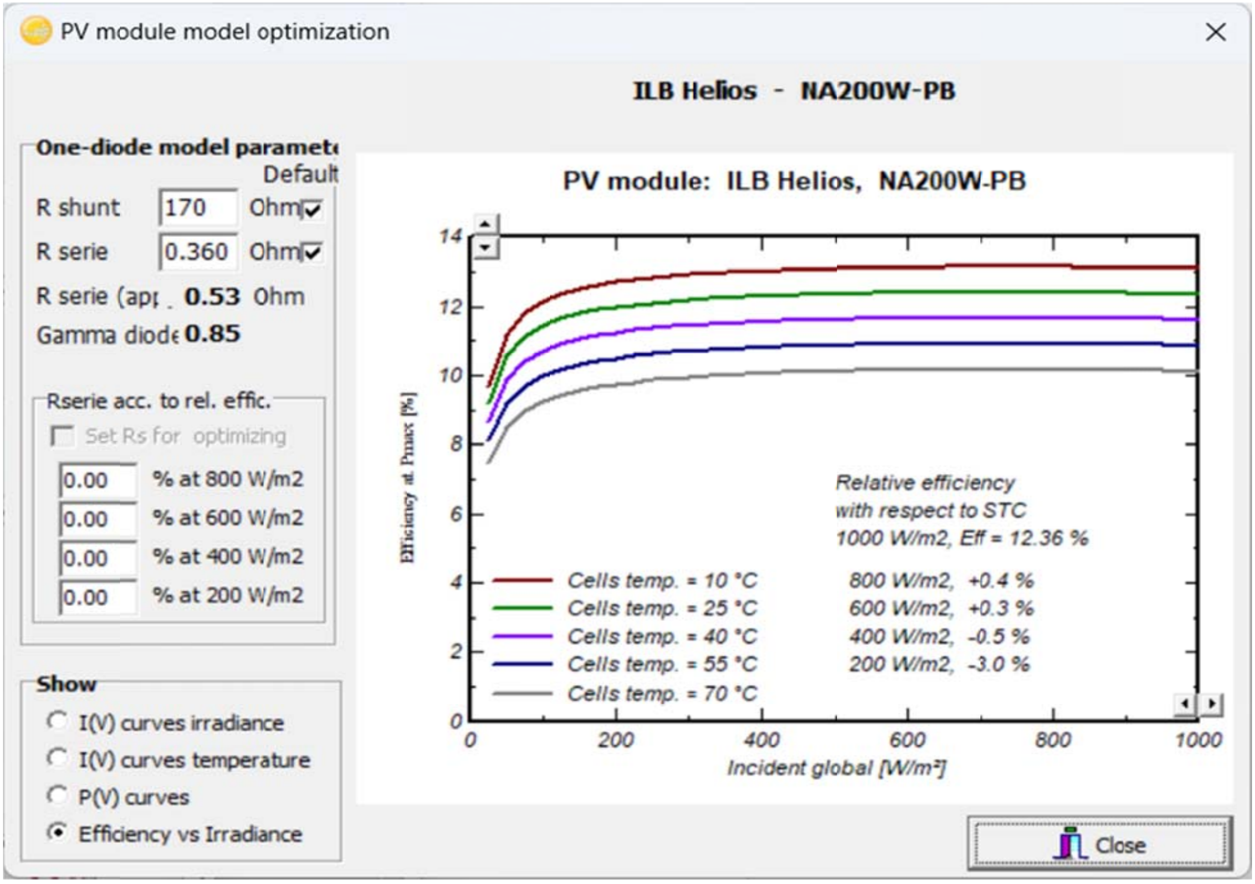

Figure 8 The graph for the variation in efficiency with temperature and solar radiation for the solar panel

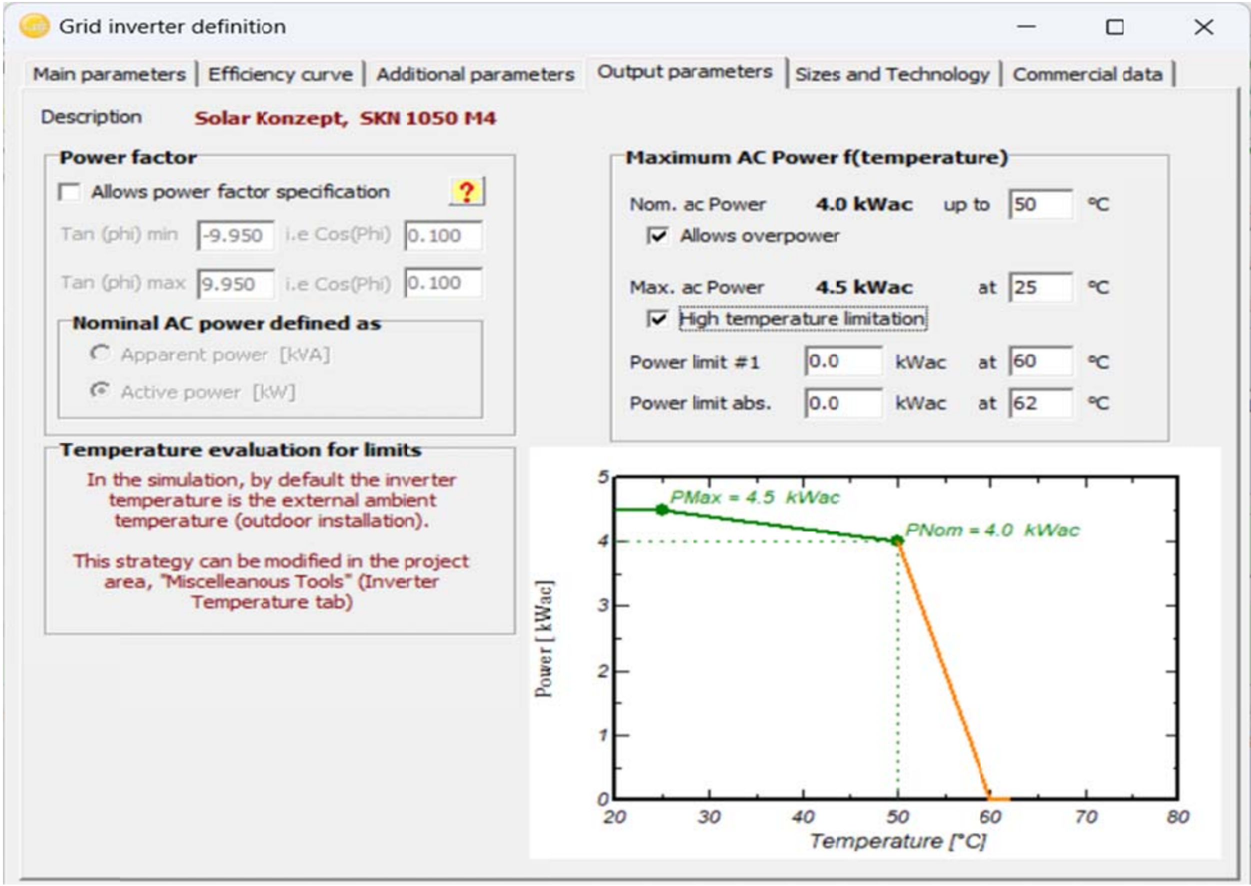

Figure 9 The graph of the temperature **effect on the operation of the inverter**

3. RESULTS AND DISCUSSION

The system components configurations for the simulation process in PVSyst is shown in Figure 10. The components configuration results in Figure 10 show that about 12 PV panels each rated at 200 Wp with a total area of 19.6 m^2 was used along with 4.0 kWac inverter. The system had PV module degradation of 0.4 % per year and module quality loss of 2.5 %.

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Grid-Connected System: Simulation parameters

Project :	**GSM BASE STATION**			
Geographical	**GSM Base Station Elf Thearter UNIUYO**		*Country*	**Nigeria**
Situation	*Latitude*	*5.04° N*	*Longitude*	*7.98° E*
Time defined as	*Legal Time*	*Time zone UT*	*Altitude*	*65 m*
	Albedo	*0.20*		
Meteo data:	**GSM Base Station Elf Thearter UNIUYO**	*NASA-SSE satellite data 1983-2005 - Synthetic*		

Simulation variant :	**New simulation variant**	
	Simulation date	*21/01/25 05h59*
	Simulation for the	**1st year of operation**

Simulation parameters	*System type*	**No 3D scene defined, no shadings**		
Collector Plane Orientation	*Tilt*	*10°*	*Azimuth*	*0°*
Models used	*Transposition*	*Perez*	*Diffuse*	*Perez, Meteonorm*
Horizon	*Free Horizon*			
Near Shadings	*No Shadings*			
User's needs :	*Unlimited load (grid)*			

PV Array Characteristics				
PV module *Si-mono*	*Model*	**NA200W-PB**		
Original PVsyst database	*Manufacturer*	*ILB Helios*		
Number of PV modules	*In series*	*6 modules*	*In parallel*	*2 strings*
Total number of PV modules	*Nb. modules*	*12*	*Unit Nom. Power*	*200 Wp*
Array global power	*Nominal (STC)*	**2400 Wp**	*At operating cond.*	*2184 Wp (50°C)*
Array operating characteristics (50°C)	*U mpp*	*148 V*	*I mpp*	*15 A*
Total area	*Module area*	**19.6 m²**	*Cell area*	*17.2 m²*
Inverter	*Model*	**SKN 1050 M4**		
Original PVsyst database	*Manufacturer*	*Solar Konzept*		
Characteristics	*Operating Voltage*	*120-200 V*	*Unit Nom. Power*	*4.00 kWac*
Inverter pack	*Nb. of inverters*	*1 units*	*Total Power*	*4.0 kWac*
			Pnom ratio	*0.60*

PV Array loss factors				
Thermal Loss factor	*Uc (const)*	*20.0 W/m²K*	*Uv (wind)*	*0.0 W/m²K / m/s*
Wiring Ohmic Loss	*Global array res.*	*169 mOhm*	*Loss Fraction*	*1.5 % at STC*
Module Quality Loss			*Loss Fraction*	*2.5 %*
Module Mismatch Losses			*Loss Fraction*	*1.0 % at MPP*
Strings Mismatch loss			*Loss Fraction*	*0.10 %*
Module average degradation	*Year no*	*1*	*Loss factor*	*0.4 %/year*
Mismatch due to degradation	*Imp RMS dispersion*	*0.4 %/year*	*Vmp RMS dispersion*	*0.4 %/year*
Incidence effect, ASHRAE parametrization	*IAM =*	*1 - bo (1/cos i - 1)*	*bo Param.*	*0.05*
Spectral correction	*FirstSolar model. Precipitable water estimated from relative humidity*			

Coefficient Set	C0	C1	C2	C3	C4	C5
Monocrystalline Si	0.85914	-0.02088	-0.0058853	0.12029	0.026814	-0.001781

Figure 10 The system components configurations for the simulation process in PVSyst

The results on energy yield, performance ratio and energy injected into the grid are shown in Table 2 while the results on the monthly hourly sum of the energy injected into the grid are presented in Table 3. According to the results in Table 2, the system had annual performance ratio (PR) of 79.7 % with total of 3329.5 kWh of energy injected into the grid in one year. Also, the month of July had the highest PR of 80.5 %. The month of January had the highest energy yield of 370.2 kWh and highest energy injected into the grid with a value of 356.4 %.

Again, according to the results in Table 3, the highest value of the monthly hourly sum of the energy injected into the grid was 455.7 kWh and it occurred at the 11^{th} hour or 11 am local time. Also, for hours less than 5, (that is from midnight to 5 am) and also for hours greater than 17 (that is from 5 pm to the midnight) no energy was injected into the grid. These hours are mainly hours of negligible solar radiation at which point the base station will depend on the backp power supply which is the grid or any alternative solution.

Table 2 The results on energy yield, performance ratio and energy injected into the grid

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR
January	171.4	53.63	25.35	186.5	181.4	370.2	356.4	0.796
February	156.5	55.16	25.76	164.8	160.4	325.4	312.9	0.791
March	164.9	68.82	25.68	166.8	161.9	330.3	317.3	0.793
April	152.7	68.10	25.77	149.0	144.3	295.1	282.9	0.791
May	146.3	67.58	25.65	138.2	133.3	275.6	263.4	0.794
June	129.3	63.30	24.77	120.8	116.2	243.2	231.9	0.800
July	119.4	66.03	24.05	112.6	108.4	228.9	217.7	0.805
August	116.9	68.20	23.94	112.9	108.8	229.2	217.9	0.804
September	118.2	68.10	24.15	117.6	113.5	237.8	226.6	0.803
October	132.4	67.27	24.45	136.4	132.0	271.4	259.2	0.792
November	145.2	58.50	24.68	155.4	150.8	309.6	296.9	0.796
December	164.0	53.01	24.70	180.0	175.0	360.0	346.4	0.802
Year	1717.2	757.70	24.91	1741.1	1685.9	3476.8	3329.5	0.797

Legends:				
	GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
	DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
	T_Amb	T amb.	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	PR	Performance Ratio

Table 3 The results on the monthly hourly sum of the energy injected into the grid

Monthly Hourly sums for E_Grid [kWh]

	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
January	0.0	0.0	0.0	0.0	0.0	0.0	6.8	19.5	32.0	42.3	47.6	49.5	48.2	43.5	34.5	22.4	9.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
February	0.0	0.0	0.0	0.0	0.0	0.0	5.5	16.7	28.2	36.9	41.8	44.4	43.1	38.1	30.1	19.8	8.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
March	0.0	0.0	0.0	0.0	0.0	0.0	5.8	17.5	28.8	36.7	43.6	43.6	42.1	39.0	31.0	21.6	8.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
April	0.0	0.0	0.0	0.0	0.0	0.0	6.7	17.9	27.9	35.9	40.0	38.7	37.0	32.3	25.2	16.5	5.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
May	0.0	0.0	0.0	0.0	0.0	0.0	6.6	16.7	25.4	32.3	35.4	36.5	34.8	30.9	24.9	15.3	5.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
June	0.0	0.0	0.0	0.0	0.0	0.0	5.5	14.7	22.5	28.4	32.3	32.0	29.8	26.7	21.1	14.2	5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
July	0.0	0.0	0.0	0.0	0.0	0.0	4.7	13.1	20.3	26.2	30.2	31.1	28.7	25.7	20.1	12.8	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
August	0.0	0.0	0.0	0.0	0.0	0.0	4.6	13.1	21.7	28.1	31.8	30.5	27.7	23.9	20.0	12.4	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
September	0.0	0.0	0.0	0.0	0.0	0.0	6.7	15.1	21.3	28.3	31.0	30.7	30.3	26.6	19.6	12.8	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
October	0.0	0.0	0.0	0.0	0.0	0.0	8.8	18.9	27.0	33.1	36.1	32.5	33.3	30.1	22.5	13.4	4.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
November	0.0	0.0	0.0	0.0	0.0	0.0	10.2	21.4	30.6	35.2	38.9	38.1	38.9	36.9	27.1	15.3	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
December	0.0	0.0	0.0	0.0	0.0	0.0	9.6	22.5	33.7	42.2	46.1	48.0	46.2	41.0	30.9	19.1	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Year	0.0	0.0	0.0	0.0	0.0	0.0	81.6	207.2	319.3	405.6	454.8	455.7	440.1	394.7	307.1	195.6	73.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0

The results for the normalized system energy yield and loss factors for the PV array are presented in Figure 11. The results show that the losses incurred from the PV array constituted about 16.7 % of the total energy yield. The loss attributed to the inverter constituted about 3.5 % while energy delivered to the end user (the based station) is about 79.8 % of the total energy yield. This is how the annual mean PR was estimated as 79.8 %.

The results of the aging analysis as shown in Table 4 captured the degradation in the energy injected into the grid (Figure 12) and the drop in performance ratio all through the life time of the solar power system (Figure 13. The results showed that the performance ratio dropped from 79.7 % in the first year to 68.7% after 25 years which is about 13.8 % drop in performance over the system life time.

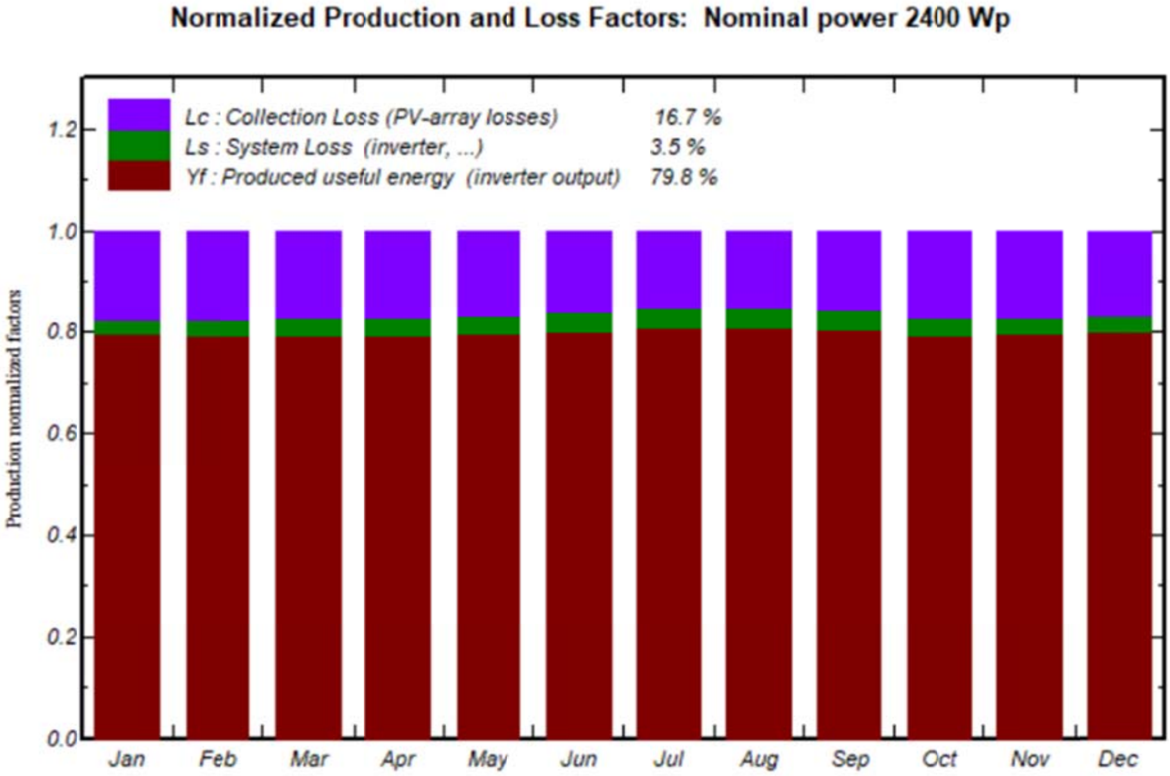

Figure 11 The normalized system energy yield and loss factors for the PV array

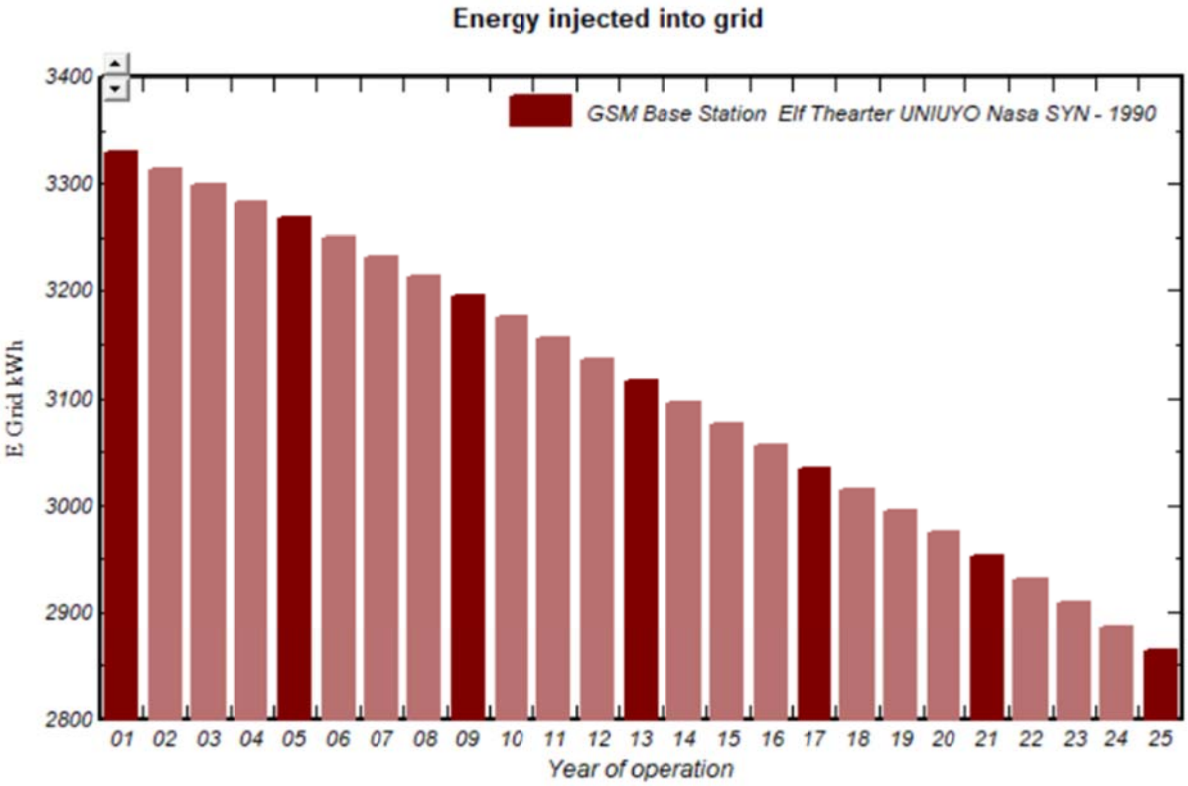

Figure 12 The degradation in the energy injected into the grid all through the life time of the solar power system.

Table 4 The results of the aging analysis

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Grid-Connected System: Ageing Tool

Project : **GSM BASE STATION**

Simulation variant : **New simulation variant Simulation for the year no 3**
Simulation for the 1st year of operation

Main system parameters	*System type*	**No 3D scene defined, no shadings**		
PV Field Orientation	*tilt*	*10°*	*azimuth*	*0°*
PV modules	*Model*	*NA200W-PB*	*Pnom*	*200 Wp*
PV Array	*Nb. of modules*	*12*	*Pnom total*	**2400 Wp**
Inverter	*Model*	*SKN 1050 M4*	*Pnom*	*4000 W ac*
User's needs	*Unlimited load (grid)*			

Ageing Parameters	*Time span of simulation*	*25 years*		
Module average degradation	*Loss factor*	*0.4 %/year*		
Mismatch due to degradation	*Imp RMS dispersion*	*0.4 %/year*	*Vmp RMS dispersion*	*0.4 %/year*
Meteo used in the simulation				
#1 GSM Base Station Elf Thearter UNIUYO Nasa SY	*Years*	*1990*	*Years simulated*	*1,6,11,16,21,25*

	#1	#1	#1
Year	E Grid	PR	PR loss
	kWh		%
1	3328.8	0.797	0%
2	3313.6	0.793	-0.5%
3	3298.5	0.789	-0.9%
4	3283.3	0.786	-1.4%
5	3268.1	0.782	-1.8%
6	3253	0.778	-2.3%
7	3234.4	0.774	-2.8%
8	3215.9	0.77	-3.4%
9	3197.4	0.765	-3.9%
10	3178.9	0.761	-4.5%
11	3160.3	0.756	-5.1%
12	3140.7	0.752	-5.7%
13	3121	0.747	-6.2%
14	3101.4	0.742	-6.8%
15	3081.7	0.737	-7.4%
16	3062.1	0.733	-8%
17	3042.5	0.728	-8.6%
18	3023	0.723	-9.2%
19	3003.4	0.719	-9.8%
20	2983.9	0.714	-10.4%
21	2964.3	0.709	-10.9%
22	2940.6	0.704	-11.7%
23	2917	0.698	-12.4%
24	2893.3	0.692	-13.1%
25	2869.7	0.687	-13.8%

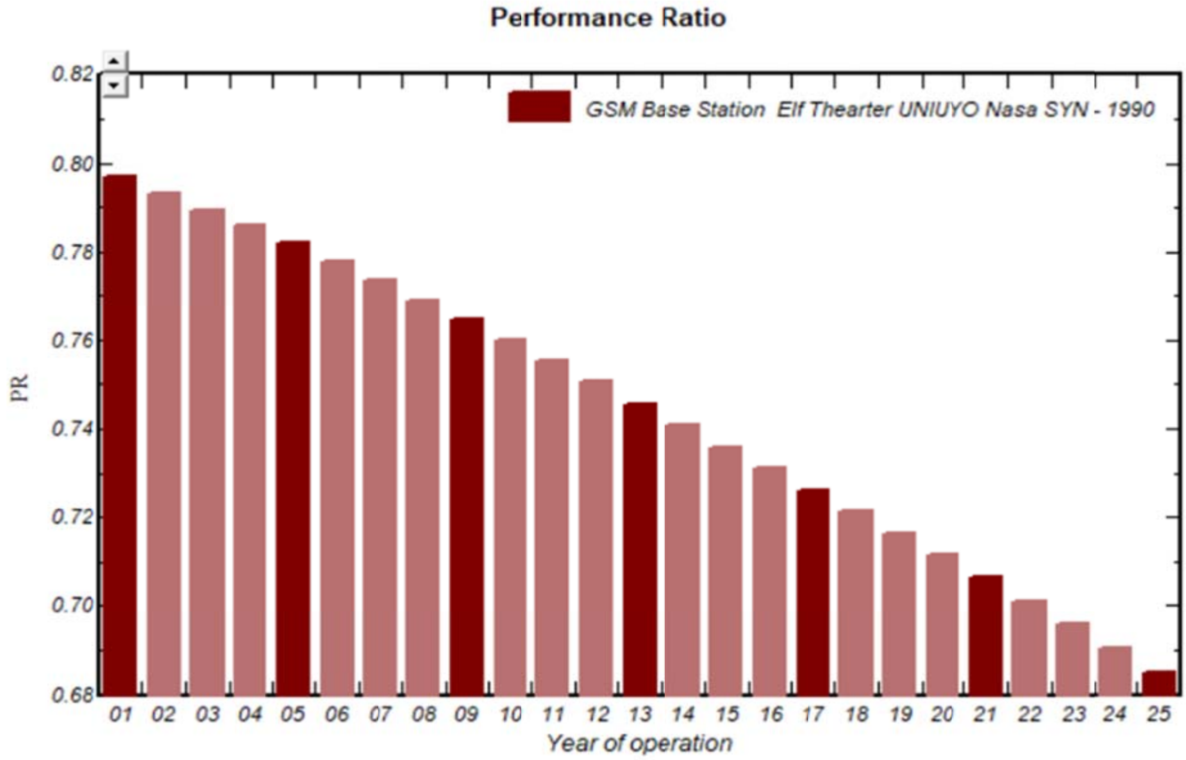

Figure 13 The degradation in the drop in performance ratio all through the life time of the solar power system.

The carbon balance shows that carbon emission that is saved by using the solar power option. The carbon balance results for the solar power system, shown in Figure 4 and Figure 5 show that about 30.5 tCo2 were saved over the lifetime of the solar power system.

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Grid-Connected System: CO2 Balance

Project : **GSM BASE STATION**

Simulation variant : **New simulation variant**

Main system parameters	*System type*	**No 3D scene defined, no shadings**		
PV Field Orientation	*tilt*	*10°*	*azimuth*	*0°*
PV modules	*Model*	*NA200W-PB*	*Pnom*	*200 Wp*
PV Array	*Nb. of modules*	*12*	*Pnom total*	**2400 Wp**
Inverter	*Model*	*SKN 1050 M4*	*Pnom*	*4000 W ac*
User's needs	*Unlimited load (grid)*			

Produced Emissions	**Total:**	**4.43 tCO2**		
	Source:	*Detailed calculation from table below*		
Replaced Emissions	**Total:**	**40.2 tCO2**		
	System production:	*3335.31 kWh/yr*	*Lifetime:*	*30 years*
			Annual Degradation:	*1.0 %*
	Grid Lifecycle Emissions:	*402 gCO2/kWh*		
	Source:	*IEA List*	*Country:*	*Nigeria*
CO2 Emission Balance	**Total:**	**30.5 tCO2**		

System Lifecycle Emissions Details:

Item	Modules	Supports
LCE	1713 kgCO2/kWp	2.68 kgCO2/kg
Quantity	2.40 kWp	120 kg
Subtotal [kgCO2]	4111	322

Figure 14 The carbon balance results for the solar power system.

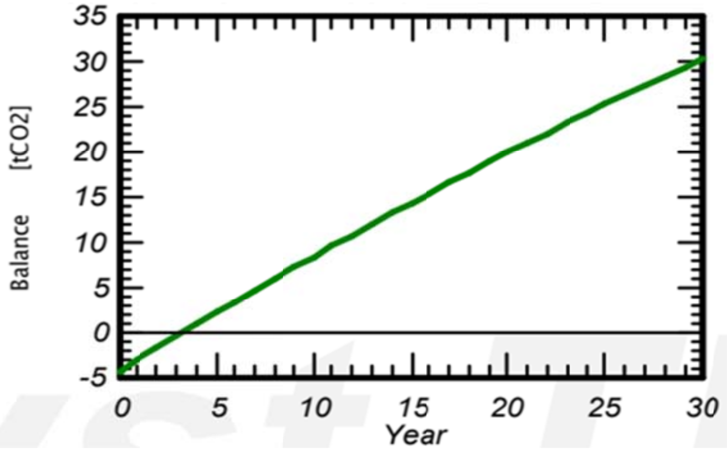

Figure 15 The carbon balance plot over the lifetime of the solar power system.

4. CONCLUSION

Grid-connected solar power system design and analysis using PVSyst software is presented. The analysis focused on determination of the carbon balance, the aging or degradation in the system performance due to aging and also on the energy yield and energy loss factor of the system. All the analysis are done through simulations conducted using PVSyst software. The results showed that aging can cause significant degradation in the system performance. Also over 30 tons of carbon dioxide can be save over the lifetime of the solar power system for the base station.

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