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Research Article

Simulated Technical and Economic Analysis of Off-grid Photovoltaic Power System with Back-up Generators for GSM Base Station Using PVsyst Simulation Software

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Abstract

In this research, simulated technical and economic analysis of off-grid photovoltaic power system with back-up generators for GSM base station using PVsyst simulation software is presented. The case study load profile comprising of 9 key components has peak power demand of 3325 W and daily energy demand of 58580 Wh. The solar radiation has annual mean of 4.2041 and standard deviation of 1.6018 while the temperature has annual mean of 25.32 and standard deviation of 1.1595. There is no outlier in the solar radiation but the temperature has three outliers, which are, 21.8, 28.7, 28.8. The PV power system has 60 units of PV modules and 112 units of battery for the battery bank. There is solar fraction of 1.0 is all the months except in the month of July where the solar fraction is 0.934 which required the backup generator to supply the energy short fall of 119.4 kWh in July for a total duration of for 39.83 hours. The economic analysis results show that the installation cost according is 10,969,000 Naira while the operating cost is 940,422.08 Naira per year. The unused energy cost is 56,883 naira per kWh. The feed-in-tariff for the energy generated from the solar power system is 170 naira per kWh. The payback period for the system is 4.3 years. That means after 4.3 years, the investment cost of the project will be recovered. The return on investment is 377.7% which means the project is very profitable.

Keywords

Economic Analysis of PV System, Off-grid Photovoltaic Power System, PVsyst Simulation Software, Solar Powered GSM Base Station, Technical Analysis of PV System

1. Introduction

Since the advent of Global System for Mobile Communications (GSM) network services in Nigeria, there has been rapid spread and adoption of the services across Nigeria [1-3, 24]. This has created so many jobs and facilitated many good processes in diverse fields. In the higher institutions, it has engendered e-learning solutions, online portal-based services and computer-based testing (CBT) systems that rely on network or cloud-based services [4-7]. In view of the critical

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services supported by the GSM network, it is required that the downtime of such networks should be minimal and well planned to avoid excessive loss of revenues on both the service providers and their clients [8-10, 23].

One of the major problems of the GSM services providers is the poor power supply from the Nigerian national grid [11-14]. There is perennial power shortage in Nigeria and epileptic power supply from the national grid which make the power from the national grid to be unsuitable for effective service delivery by the GSM network service providers [15-17]. Also, there is the high cost of energy for the Band A electricity consumers in Nigeria [18-20]. The poor power supply can seriously affect the GSM base stations and hence the availability of network for the users. Particularly, in the University campus where constant internet service is needed during the day, it is required that the GSM base station should be constantly powered up to serve the university community.

Accordingly, this research focus on the design of solar power system as alternative power supply for the GSM base station. The research provided the simulated design as well as the technical and economic analysis of the system using PYSyst simulation software [25, 26].

2. Methodology

2.1. The Research Process

The research process is approach using the following nine key steps:

Get the GSM base station load profile

Get the installation site geo-coordinates and the Google map visualization of the site

Get the installation site meteorological data relevant for the study using the PVsyst 7.3.1 simulation software

Conduct Statistical analysis of the meteorological data using the descriptive statistics software tool

Setup the PV tilt orientation in the PVsyst 7.3.1 simulation software

Setup the load profile in the PVsyst 7.3.1 simulation software

Setup the PV system components configurations in the PVsyst 7.3.1 simulation software

Simulate the PV system in the PVsyst 7.3.1 simulation software to obtain the system components sizes and technical performances

Setup the PV system economic analysis parameters and simulate in the PVsyst 7.3.1 simulation software to obtain the economic analysis of the PV power system.

2.2. The Load Profile of the Case Study GSM Base Station

The daily load demand profile for the GSM base station is adapted from a recent work by [21, 22] and shown in Table 1. The load profile comprising of 9 key components has peak power demand of 3325 W and daily energy demand of 58580 Wh. The distribution of the energy consumption among the load components is presented in Figure 1. The air condition is the highest load component accounting for about 49% of the entire load.

Table 1. *The daily load demand profile for the GSM base station.*

S/N	Load Description	Q T Y	Power Rating (W)	Total Power Demand (W)	Duration of opera tion (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	24	28800
4	Halogen lamp	3	200	600	12	7200
5	Aviation warning light	5	160	800	12	9600
6	LED light	5	20	100	24	2400
7	Security light	3	120	360	12	4320
8	Motion and proximity sensor	1	30	30	24	720
9	CCTV setup	1	80	80	24	1920
				3325		58680

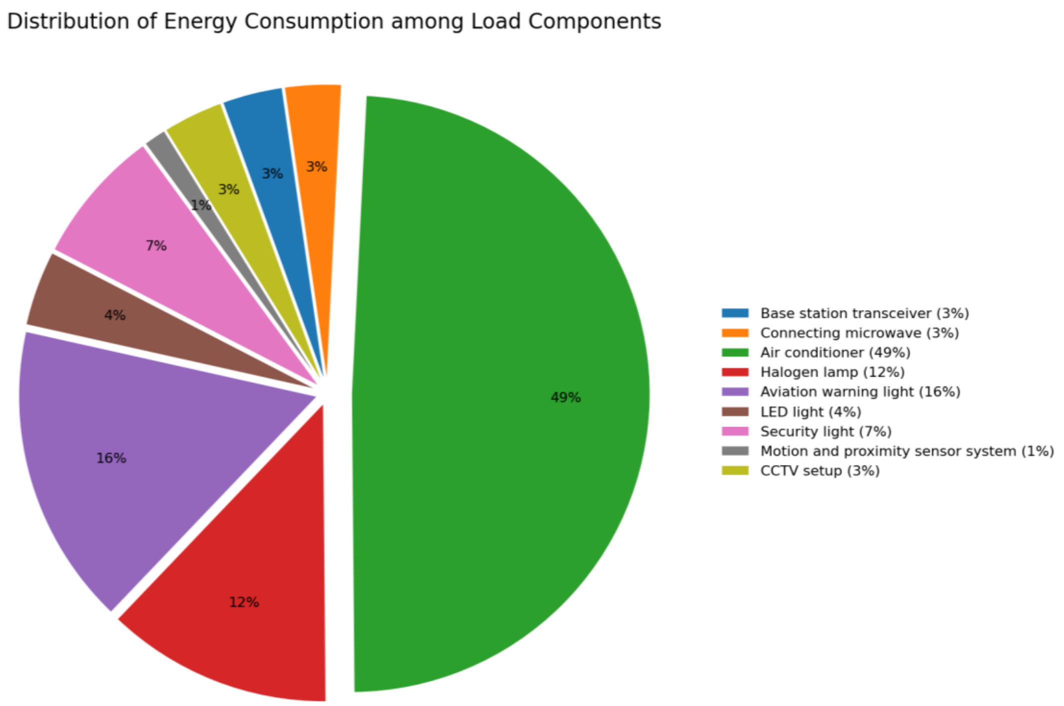

Figure 1. *The distribution of the energy consumption among the load components.*

2.3. The Installation Site Geo-coordinates and the Google Map Visualization of the Site

The installation site geo-coordinates and the Google map visualization of the site was done using the online Google Map. Notably, the case study site is in Akwa Ibom State University Obiokpa Campus. The geo-coordinate of the site is obtained through a location search on Google map and the coordinates obtained are latitude and longitude of 4.96451929968801, 7.759789035138503 respectively. The Google maps visualization of the site is presented in Figure 2.

Figure 2. *The Google maps visualization of the case study site in Akwa Ibom State University Obiokpa Campus with latitude and longitude of 4.96451929968801, 7.759789035138503 respectively.*

2.4. The Installation Site Meteorological Data Relevant for the Study Using the PVsyst 7.3.1 Simulation Software

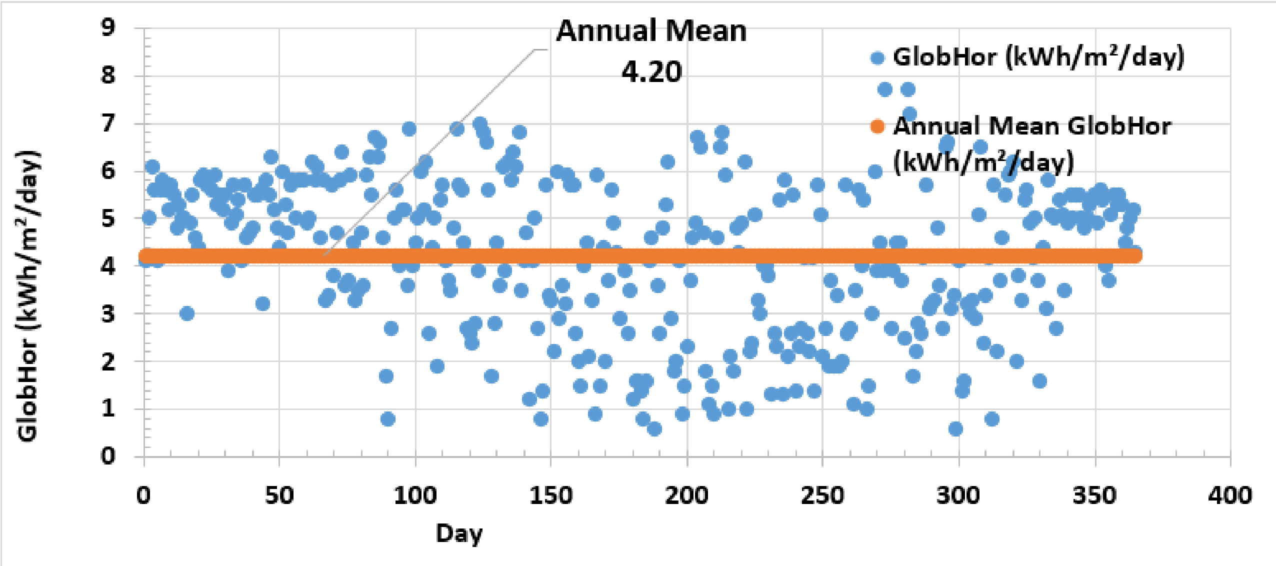

Figure 3. *The scatter plot of the daily solar radiation, (GlobHor) of the case study site done with Visual basic for application programming tool in Excel.*

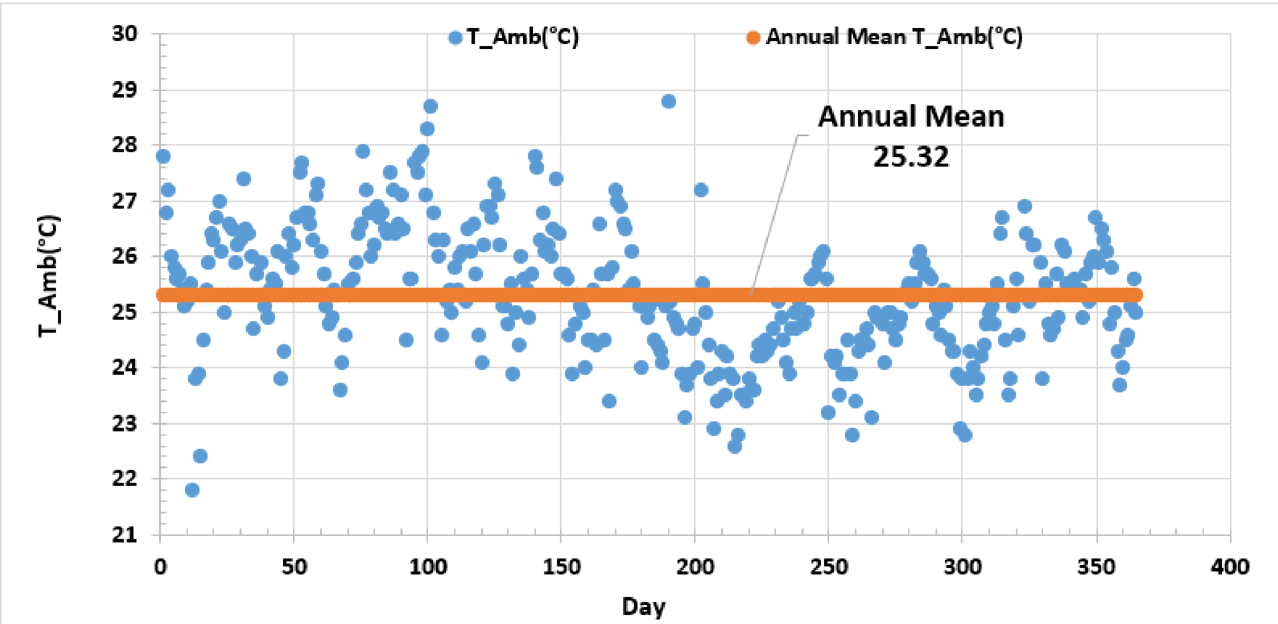

Figure 4. *The scatter plot of the daily atmospheric temperature, (T_Amb) of the case study site done with Visual basic for application programming tool in Excel.*

The scatter plot of the daily solar radiation, (GlobHor) of the case study site is shown in Figure 3. It has annual mean value of 4.2 kWh/m²/day. Also, the scatter plot of the daily atmospheric temperature, (T_Amb) of the case study site is shown in Figure 4. It has annual mean temperature value of 25.32°C.

2.5. The Setup of the PV Tilt Orientation in the PVsyst 7.3.1 Simulation Software

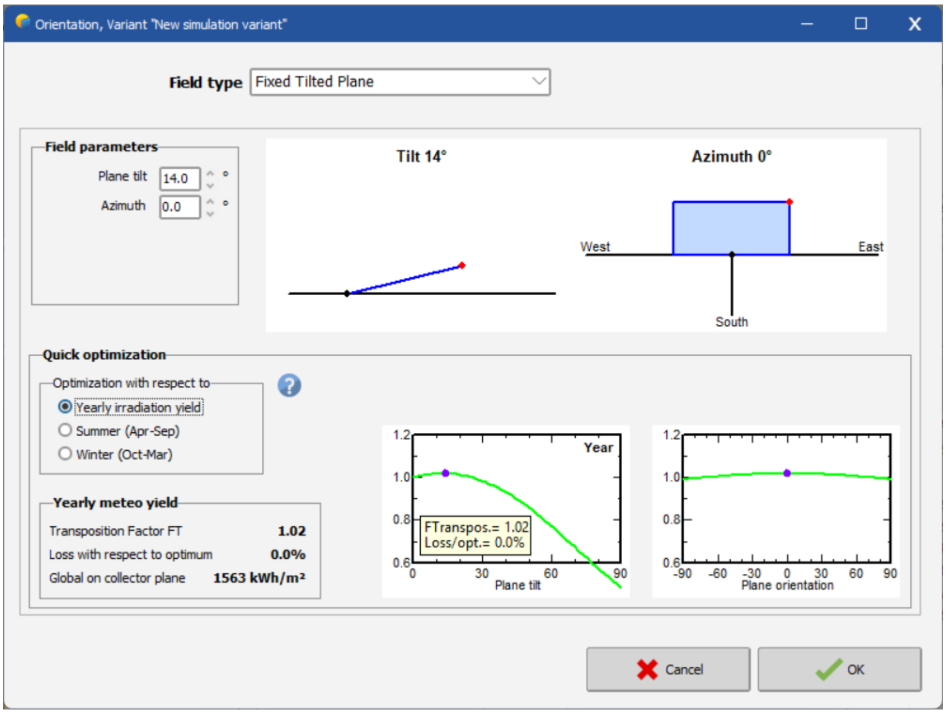

Figure 5. The screenshot showing the settings for the PV tilt orientation in the PVsyst 7.3.1 simulation software.

The screenshot showing the settings for the PV tilt orientation in the PVsyst 7.3.1 simulation software is presented in Figure 5. The annual fixed tile angle is selected. Tilt angle of 14 degrees is selected which gave a transposition factor of 1.02. This means that 2% of extra solar radiation is obtained by the optimal tilting of the PV panel.

2.6. The Setup of the Load Profile in the PVsyst 7.3.1 Simulation Software

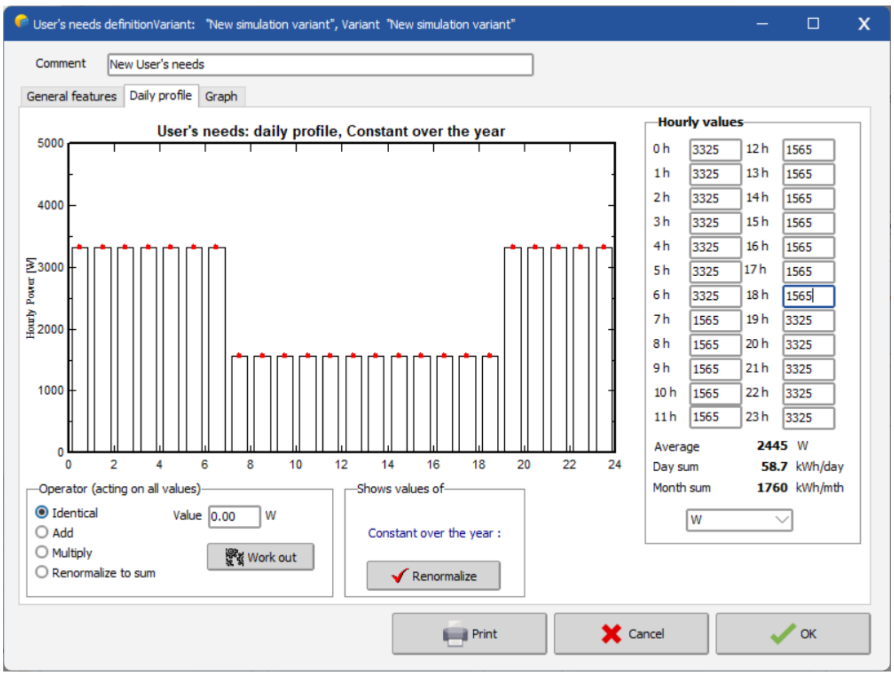

Figure 6. The screenshot showing the daily load profile settings for the PV in the PVsyst 7.3.1 simulation software.

The screenshot showing the daily load profile settings for the PV in the PVsyst 7.3.1 simulation software. According to the load profile in Table 1, the daily energy demand is 58680 Wh per day. The load profile in the PVsyst (Figure 6) shows an average power demand of 2445 W, which is the average hourly power demand obtained by dividing the 58680 by 24, (that is, 58680 Wh /24 h =2445 W). The daily energy demand of 58680 Wh per day approximates to 58.7 kWh per day in the PVsyst the software.2.7. Setup of the PV System Components Configurations in the PVsyst 7.3.1 and Simulation of the PV System

The PVsyst settings for the PV array is presented in Figure 7. Each PV model is a Si-mono panel rated at 400 Wp 32 V. There are 4 strings in series (giving a total terminal voltage 132 V). There are 15 strings of the PV module where each string has 4 PV modules in series, as shown in Figure 7. The PVsyst settings for the battery bank are presented in Figure 8. Each battery is rated as 240 Ah 12 V. There are 8 strings of batteries in series (giving a total terminal voltage 96V). There are 14 strings of the PV module where each string has 8 batteries in series, as shown in Figure 8.

The PVsyst settings for the charger controller is presented in Figure 9. A universal charger controller with MPTT converter is selected. The details of the charger controller are shown in Figure 9. The PVSYst settings for the back-up generator are presented in Figure 10. The back-up generator is a 3-kW rated generator as shown in Figure 10.

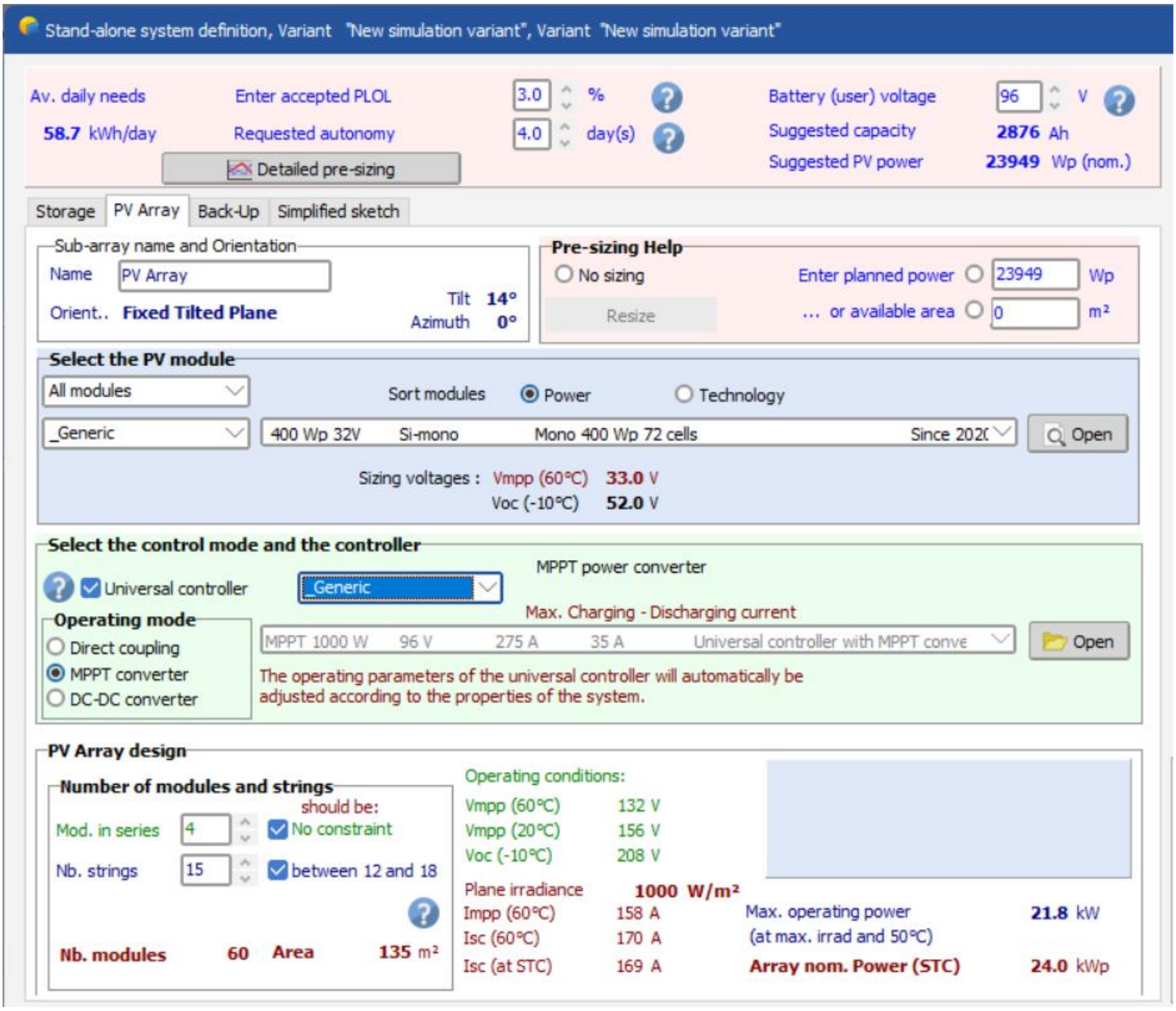

Figure 7. The PVsyst settings for the PV array.

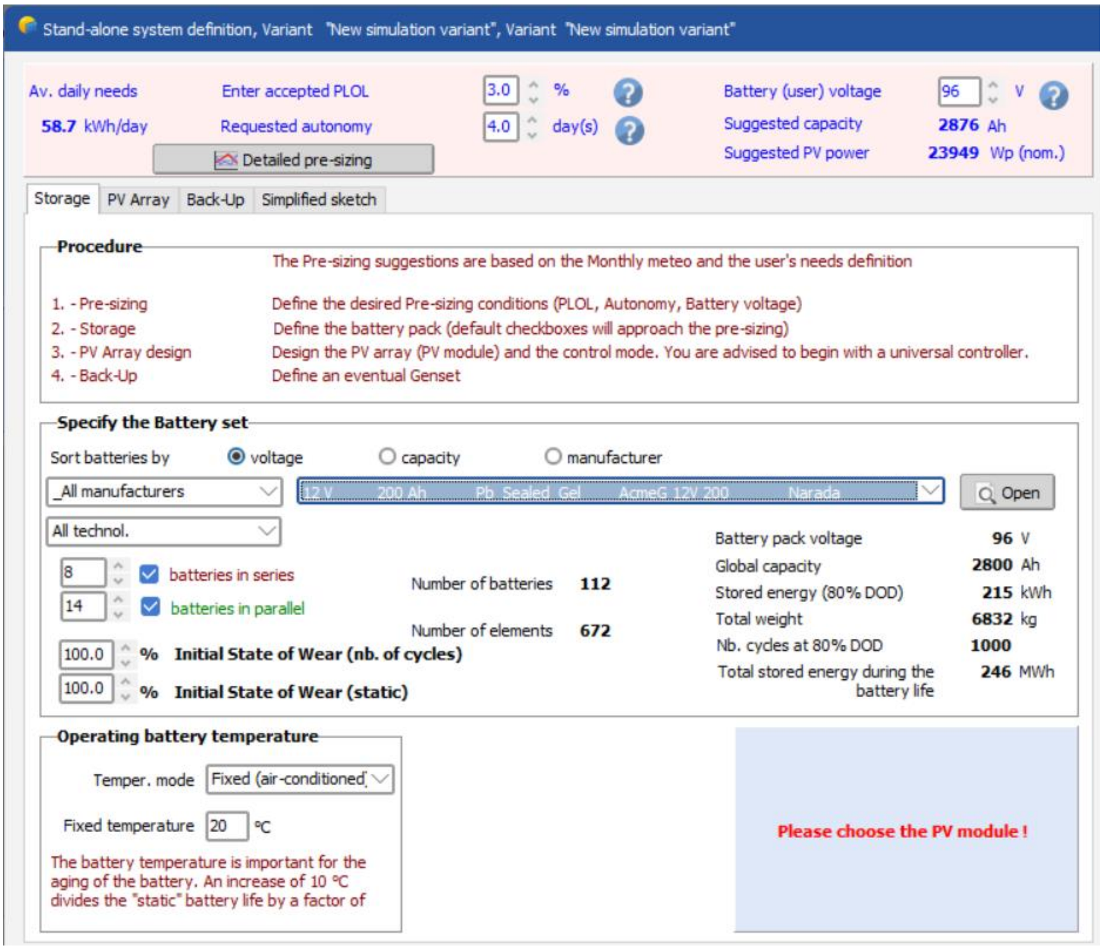

Figure 8. The PVsyst settings for the battery bank.

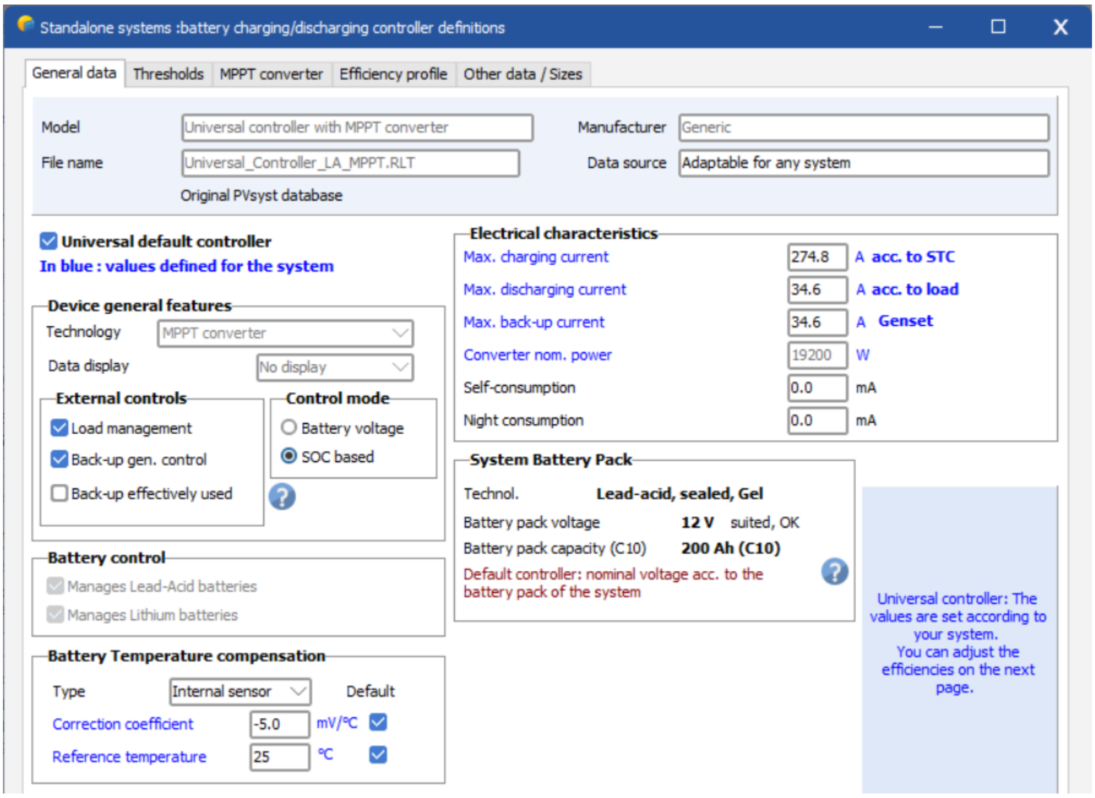

Figure 9. The PVsyst settings for the charger controller.

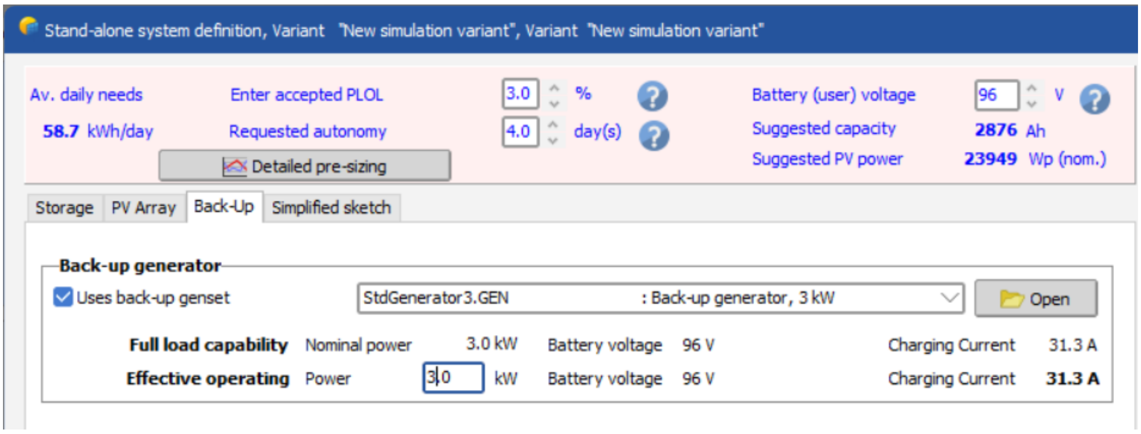

Figure 10. *The PVsyst settings for the back-up generator.*

2.8. Economic Analysis of the PV Power System Using the PVsyst 7.3.1 Simulation Software

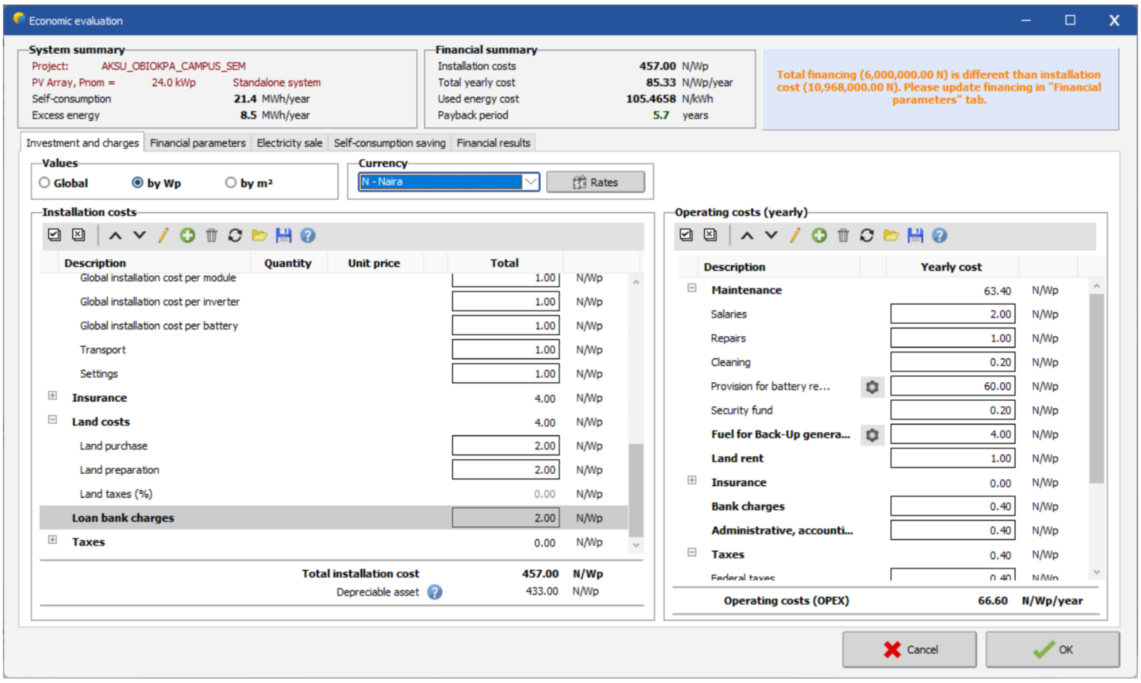

Figure 11. *The screenshot showing the input for the investment and charges in the PVSyst economic analysis dialogue box.*

At this point the input parameters for the economic analysis are supplied through the PVsyst economic analysis input dialogue box shown in Figure 11. Nest the economic analysis simulation is conducted in the PVsyst 7.3.1 software to obtain the economic analysis results for the PV power system.

3. Results and Discussion

3.1. Results on the Technical Analysis

The screenshot showing the result on the energy yield, energy delivered and solar fraction is presented in Figure 12. The solar fraction of 1.0 shows that all the energies required by the user or load are provided by the solar power for all the months of the year except in the month of July where the solar fraction is 0.934 which is less than 1.0.

However, the Loss of Load (Pr_LOL) and duration of loss of load (T_LOL) for the system in the month of July, as shown in Figure 13 is 0, indicating that there was not power outage in the month of July due to the short fall in energy supply from the solar power system. This is because the backup generator supplied the short fall of 119.4 kWh worth of energy in the month of July alone, as shown in Figure 13.

New simulation variant

7 parameters defined for this table :
GlobHor - Global horizontal irradiation
GlobEff - Effective Global, corr. for IAM and shadings
E_Avail - Available Solar Energy

EUnused - Unused energy (battery full)
E_User - Energy supplied to the user
E_Load - Energy need of the user (Load)
SolFrac - Solar fraction (EUsed / ELoad)

	GlobHor kWh/m²	GlobEff kWh/m²	E_Avail kWh	EUnused kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	161.2	176.0	3561	1547	1819	1819	1.000
February	146.7	153.7	3094	1366	1643	1643	1.000
March	148.8	147.4	2984	1147	1819	1819	1.000
April	138.0	129.3	2639	736	1760	1760	1.000
May	131.1	117.8	2390	546	1819	1819	1.000
June	106.2	93.8	1905	87	1761	1760	1.000
July	100.4	90.0	1812	45	1819	1819	0.934
August	106.0	97.7	1990	80	1819	1819	1.000
September	102.9	98.9	1999	137	1761	1760	1.000
October	114.1	114.1	2306	477	1819	1819	1.000
November	126.3	134.1	2722	797	1760	1760	1.000
December	153.4	169.4	3451	1536	1819	1819	1.000
Year	1535.2	1522.1	30852	8501	21417	21418	0.994

Figure 12*. The screenshot showing the Result on the Energy Yield, Energy Delivered and Solar Fraction.*

New simulation variant — Energy Use

7 parameters defined for this table :
EArray - Effective energy at the output of the array
E_Load - Energy need of the user (Load)
E_User - Energy supplied to the user

E_BkUp - Back-up Generator Energy
SolFrac - Solar fraction (EUsed / ELoad)
T_LOL - Duration of "Loss of Load" (user not supplied)
Pr_LOL - Probability of "Loss of Load"

	EArray kWh	E_Load kWh	E_User kWh	E_BkUp kWh	SolFrac ratio	T_LOL Hour	Pr_LOL %
January	2097	1819	1819	0.0	1.000	0	0.00
February	1803	1643	1643	0.0	1.000	0	0.00
March	1919	1819	1819	0.0	1.000	0	0.00
April	1986	1760	1760	0.0	1.000	0	0.00
May	1937	1819	1819	0.0	1.000	0	0.00
June	1918	1760	1761	0.0	1.000	0	0.00
July	1876	1819	1819	119.4	0.934	0	0.00
August	2016	1819	1819	0.0	1.000	0	0.00
September	1964	1760	1761	0.0	1.000	0	0.00
October	1927	1819	1819	0.0	1.000	0	0.00
November	2013	1760	1760	0.0	1.000	0	0.00
December	1992	1819	1819	0.0	1.000	0	0.00
Year	23448	21418	21417	119.4	0.994	0	0.00

Figure 13*. The screenshot showing the Result on Loss of Load (LOL) and Power Supply from the Backup Generator.*

The results in Figure 14 show that the backup generator has to supply the shortfall in the energy for 39.83 hours in the month of July. Also, the energy required is about 3.653 kWh per day, as shown in Figure 15. The loss of load would have occurred on 5th of July as well as from 19th to 20th of July, (as shown in Figure 15). As shown in Figure 16 and Figure 17, the duration of the backup energy supply on 5th of July will be 5.128 hours, and as shown in Figure 17, the duration of the backup energy supply from 19th of July to 29th of July will be 14.79 hours.

The results in Figure 18 show that the fuel consumption of the backup energy supply in the month of July will be 71.6565 liters. The detailed breakdown of the fuel consumption for the backup generator on the 5th of July and for the 19th to 20th of July are presented in Figure 19.

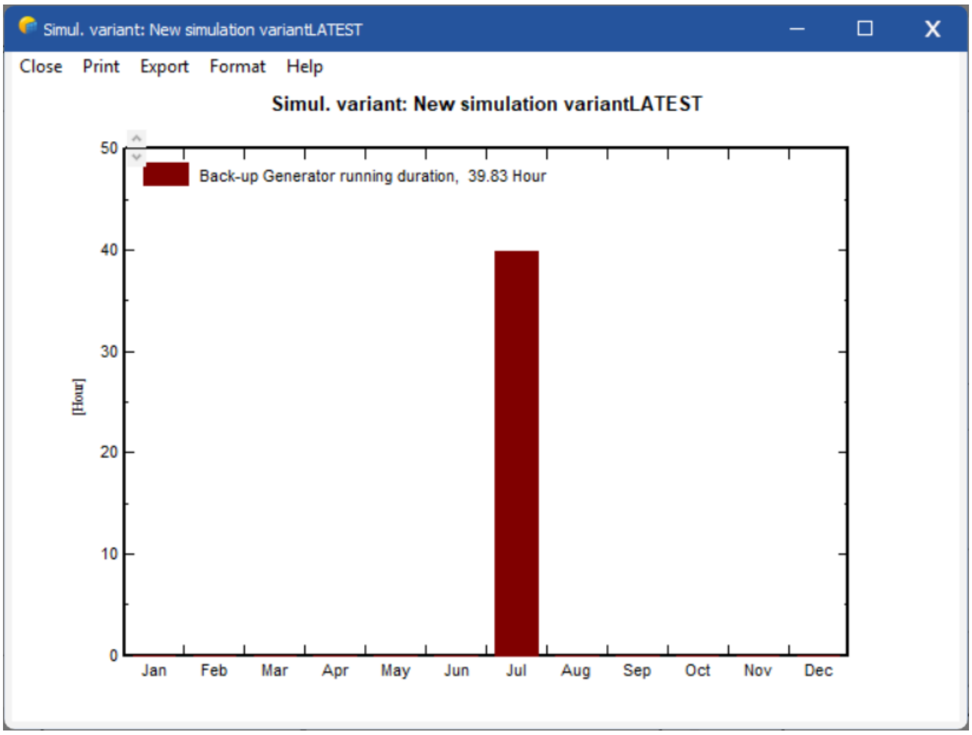

Figure 14*. The screenshot showing the Result on Loss of Load Duration which is also the Backup Generator Running Per Month for a Whole Year.*

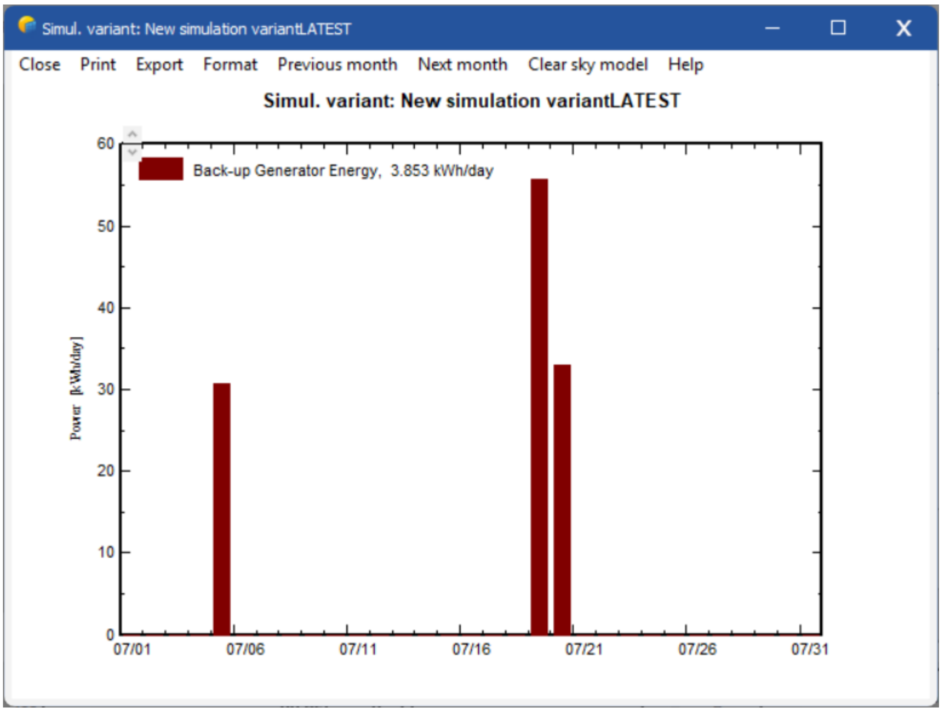

Figure 15*. The screenshot showing the Result on Loss of Load Energy per day in July which is also the amount of energy supplied by the Backup Generator per day in July.*

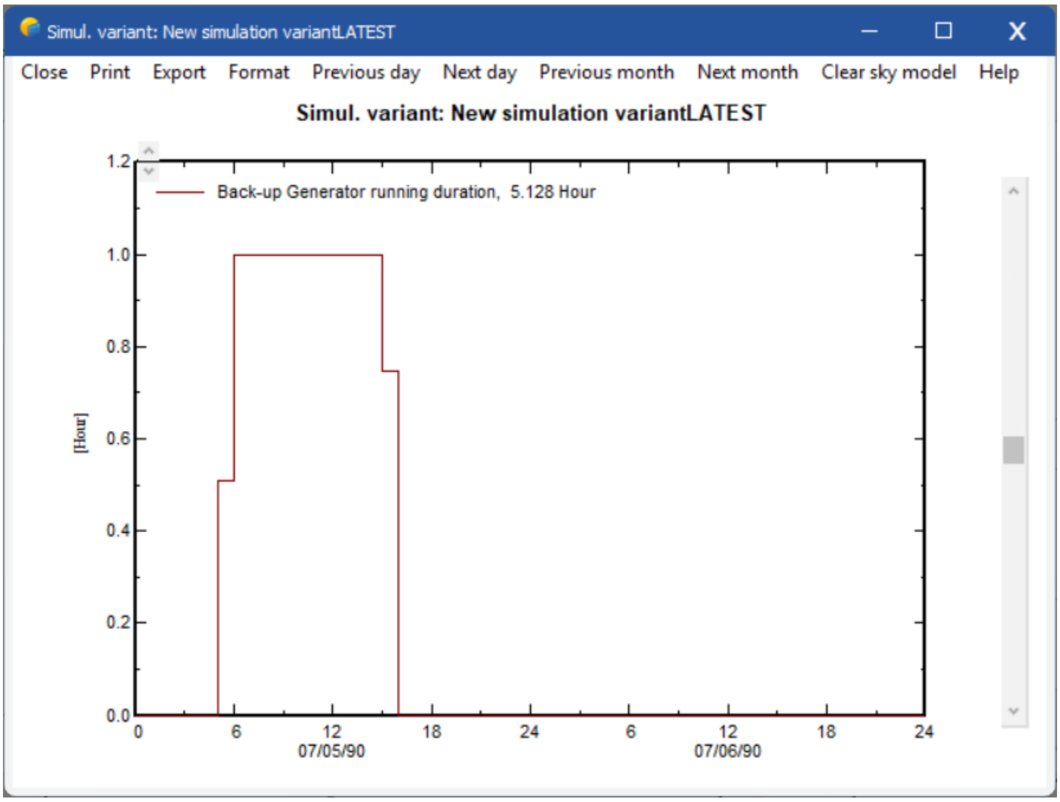

Figure 16. *The screenshot showing the Exact Time the Loss of Load will Occur on 5th of July.*

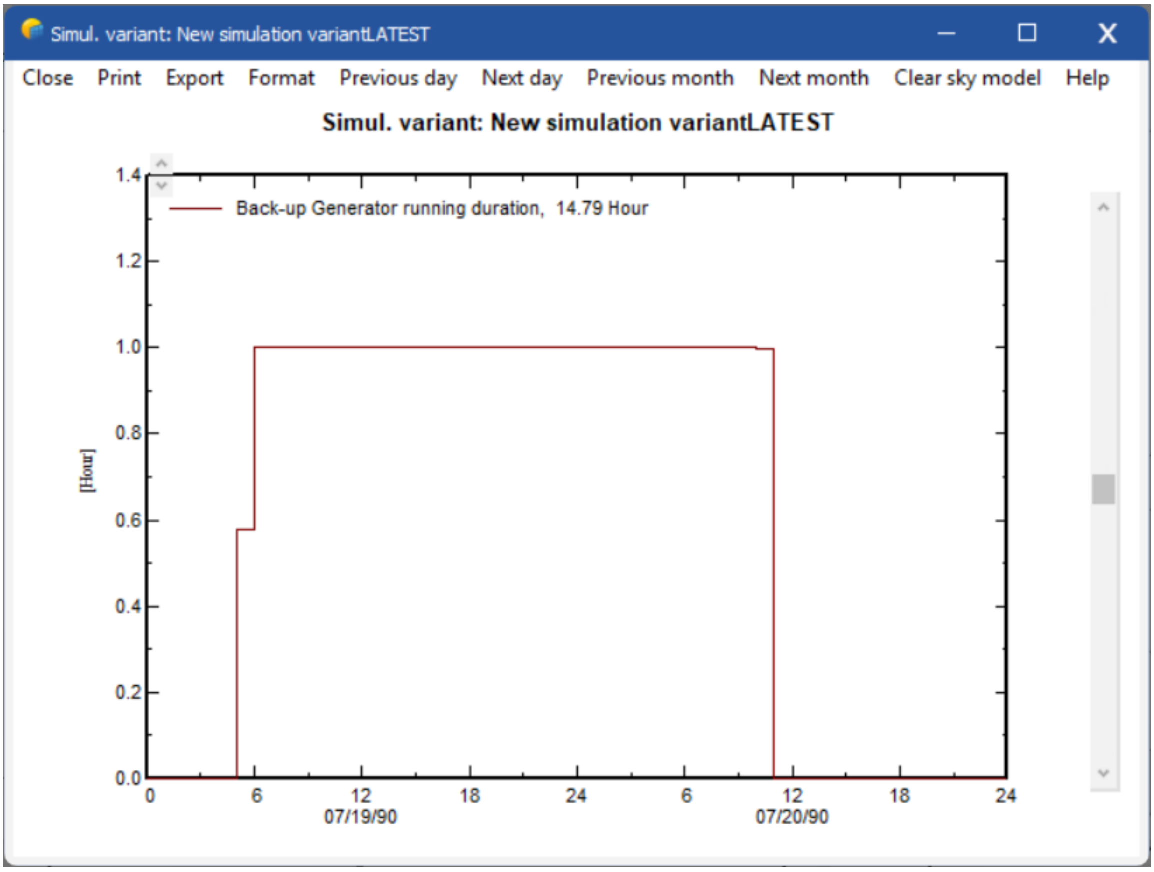

Figure 17. *The screenshot showing the Exact Time the Loss of Load will Occur from 19th to 20th of July.*

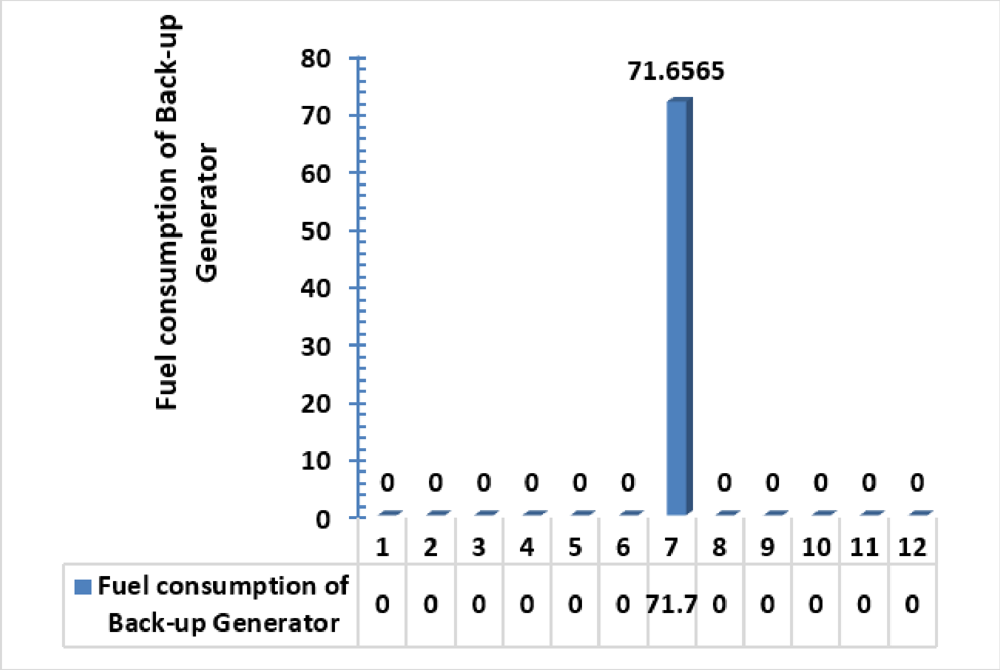

Figure 18. *The screenshot showing the fuel consumption of the Back-up Generator per month for a whole year.*

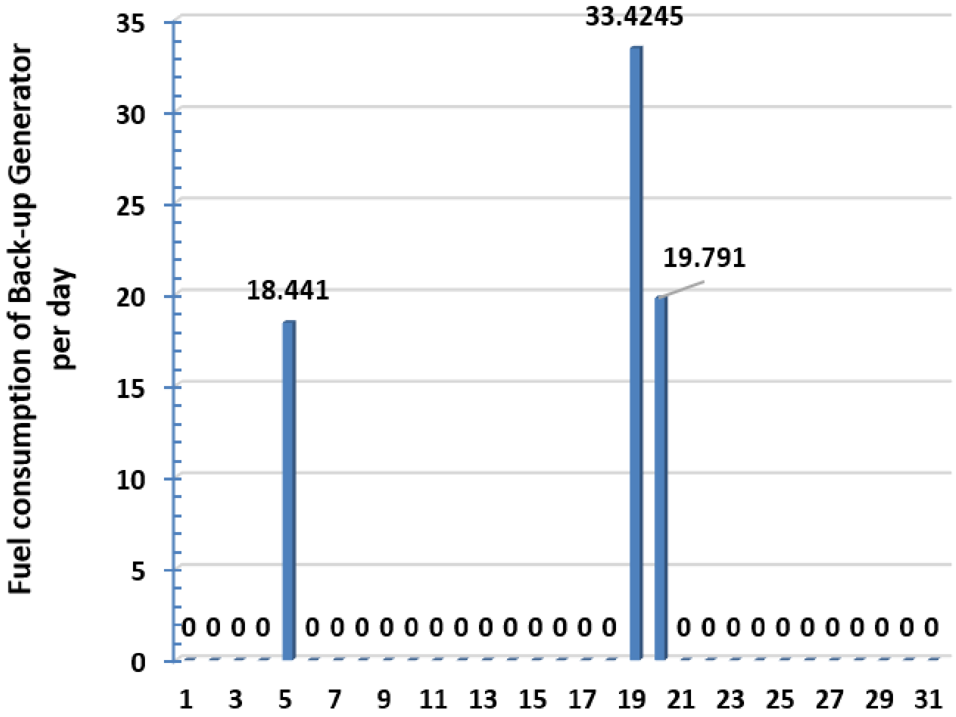

Figure 19. *The screenshot showing the fuel consumption of the Back-up Generator per day for the month of July.*

3.2. The Results of the Economic Analysis

The results of the economic analysis of the solar power plant are presented in this section. The details of the cost of the system are presented in Figure 20 and Figure 21. The installation cost according to Figure 21 is 10,969,000 Naira while the operating cost is 940,422.08 Naira per year. The unused energy cost is 56,883 naira per kWh.

Cost of the system

Installation costs

Item	Quantity units	Cost N	Total N
PV modules			
Mono 400 Wp 72 cells	60	44,000.00	2,640,000.00
Supports for modules	60	800.00	48,000.00
Batteries	112	25,714.29	2,880,000.00
Controllers			2,160,000.00
Back-up generator			2,640,000.00
Other components			
Accessories, fasteners	1	24,000.00	24,000.00
Wiring	1	24,000.00	24,000.00
Combiner box	1	24,000.00	24,000.00
Monitoring system, display screen	1	24,000.00	24,000.00
Measurement system, pyranometer	1	24,000.00	24,000.00
Surge arrester	1	24,000.00	24,000.00
Studies and analysis			
Engineering	1	24,000.00	24,000.00
Permitting and other admin. Fees	1	24,000.00	24,000.00
Environmental studies	1	24,000.00	24,000.00
Economic analysis	1	24,000.00	24,000.00
Installation			
Global installation cost per module	60	400.00	24,000.00
Global installation cost per inverter	1	24,000.00	24,000.00
Global installation cost per battery	112	214.29	24,000.00
Transport	1	24,000.00	24,000.00
Settings	1	24,000.00	24,000.00
Insurance			
Building insurance	1	24,000.00	24,000.00
Transport insurance	1	24,000.00	24,000.00
Liability insurance	1	24,000.00	24,000.00
Delay in start-up insurance	1	24,000.00	24,000.00
Land costs			
Land purchase	1	48,000.00	48,000.00
Land preparation	1	48,000.00	48,000.00
Loan bank charges			48,000.00
		Total	10,968,000.00
		Depreciable asset	10,392,000.00

Figure 20. The screenshot showing the part I of the results for the cost of the system.

Cost of the system

Operating costs

Item	Total N/year
Maintenance	
Salaries	48,000.00
Repairs	24,000.00
Cleaning	4,800.00
Provision for battery replacement	576,000.00
Security fund	4,800.00
Fuel for Back-Up generator	96,000.00
Land rent	24,000.00
Bank charges	9,600.00
Administrative, accounting	9,600.00
Taxes	
Federal taxes	9,600.00
Subsidies	-72,000.00
Total (OPEX)	734,400.00
Including inflation (2.00%)	940,922.08

System summary

Total installation cost	10,968,000.00 N
Operating costs (incl. inflation 2.00%/year)	940,922.08 N/year
Excess energy (battery full)	8.5 MWh/year
Used solar energy	21.4 MWh/year
Used energy cost	56.883 N/kWh

Figure 21. The screenshot showing the part II of the results for the cost of the system.

The details of the financial analysis of the system is presented in Figure 22 and Figure 23. The results in Figure 22 show 6,000,000 Naira are funds provided by the owner out of the 10,969,000 Naira required for the initial investment cost of the system. The remaining 4,969,000 are borrowed funds for which tax need to be paid. The feed-in-tariff for the energy generated from the solar power system is 170 naira per kWh.

The payback period for the system is 4.3 years. That means after 4.3 years, the investment cost of the project will be recovered. The return on investment is 377.7% which means the project is very profitable. The details of the profit are presented in Figure 23.

Financial analysis

Simulation period

Project lifetime 25 years Start year 2026

Income variation over time

Inflation	2.00 %/year
Production variation (aging)	0.30 %/year
Discount rate	3.00 %/year

Depreciable assets

Asset	Depreciation method	Depreciation period (years)	Salvage value (N)	Depreciable (N)
PV modules				
Mono 400 Wp 72 cells	Straight-line	25	0.00	2,640,000.00
Supports for modules	Straight-line	25	0.00	48,000.00
Batteries	Straight-line	25	0.00	2,880,000.00
Controllers	Straight-line	25	0.00	2,160,000.00
Back-up generator	Straight-line	25	0.00	2,640,000.00
Accessories, fasteners	Straight-line	20	0.00	24,000.00
		Total	0.00	10,392,000.00

Financing

Own funds 6,000,000.00 N

Electricity sale

Feed-in tariff 170.0000 N/kWh

Return on investment

Payback period	4.3 years
Net present value (NPV)	41,425,354.95 N
Internal rate of return (IRR)	46.22 %
Return on investment (ROI)	377.7 %
Paid dividends	2,034,891.99 N

Figure 22*. The screenshot showing the of the results for the financial analysis of the system.*

Financial analysis

Detailed economic results (kN)

Year	Electricity sale	Own funds	Run. costs	Deprec. allow.	Taxable income	Taxes	After-tax profit	Divid. 3.00%	Cumul. profit	% amorti.
0	0	6,000,000	0	0	0	0	0	0	-6,000,000	0.0%
1	3,640,896	0	734,400	415,920	2,490,576	124,529	2,781,967	83,459	-3,299,061	24.6%
2	3,651,818	0	749,088	415,920	2,486,810	124,341	2,778,390	83,352	-680,162	48.5%
3	3,662,774	0	764,070	415,920	2,482,784	124,139	2,774,565	83,237	1,858,958	71.7%
4	3,673,762	0	779,351	415,920	2,478,491	123,925	2,770,486	83,115	4,320,499	94.1%
5	3,684,783	0	794,938	415,920	2,473,925	123,696	2,766,149	82,984	6,706,603	115.9%
6	3,695,838	0	810,837	415,920	2,469,081	123,454	2,761,547	82,846	9,019,355	136.9%
7	3,706,925	0	827,054	415,920	2,463,952	123,198	2,756,674	82,700	11,260,783	157.4%
8	3,718,046	0	843,595	415,920	2,458,531	122,927	2,751,525	82,546	13,432,862	177.2%
9	3,729,200	0	860,467	415,920	2,452,814	122,641	2,746,093	82,383	15,537,514	196.4%
10	3,740,388	0	877,676	415,920	2,446,792	122,340	2,740,372	82,211	17,576,608	215.0%
11	3,751,609	0	895,230	415,920	2,440,459	122,023	2,734,356	82,031	19,551,966	233.0%
12	3,762,864	0	913,134	415,920	2,433,810	121,690	2,728,039	81,841	21,465,357	250.4%
13	3,774,152	0	931,397	415,920	2,426,836	121,342	2,721,414	81,642	23,318,508	267.3%
14	3,785,475	0	950,025	415,920	2,419,530	120,977	2,714,474	81,434	25,113,095	283.7%
15	3,796,831	0	969,025	415,920	2,411,886	120,594	2,707,212	81,216	26,850,751	299.5%
16	3,808,222	0	988,406	415,920	2,403,896	120,195	2,699,621	80,989	28,533,066	314.9%
17	3,819,646	0	1,008,174	415,920	2,395,553	119,778	2,691,695	80,751	30,161,585	329.7%
18	3,831,105	0	1,028,337	415,920	2,386,848	119,342	2,683,426	80,503	31,737,815	344.1%
19	3,842,599	0	1,048,904	415,920	2,377,775	118,889	2,674,806	80,244	33,263,219	358.0%
20	3,854,126	0	1,069,882	415,920	2,368,324	118,416	2,665,828	79,975	34,739,224	371.4%
21	3,865,689	0	1,091,280	414,720	2,359,689	117,984	2,656,425	79,693	36,167,183	384.5%
22	3,877,286	0	1,113,105	414,720	2,349,461	117,473	2,646,708	79,401	37,548,480	397.1%
23	3,888,918	0	1,135,367	414,720	2,338,830	116,942	2,636,609	79,098	38,884,428	409.2%
24	3,900,585	0	1,158,075	414,720	2,327,790	116,389	2,626,120	78,784	40,176,305	421.0%
25	3,912,286	0	1,181,236	414,720	2,316,330	115,816	2,615,233	78,457	41,425,355	432.4%
Total	**94,375,824**	**6,000,000**	**23,523,052**	**10,392,000**	**60,460,772**	**3,023,039**	**67,829,733**	**2,034,892**	**41,425,355**	**432.4%**

Figure 23*. The screenshot showing the of the detailed economic analysis results for the financial analysis of the system.*

4. Conclusion

In this research, technical and economic analysis of an off-grid solar power system based on photovoltaic (PV) approach is presented. The PV off-grid solar (PVOGS) power system is meant to power a Global System for Mobile Communications (GSM) base station located in one of the campuses of Akwa Ibom State University. The PV power system design included a back-up generator to supply power to the critical load during potential power shortage moments from the solar power source. The PVOGS power system was modeled and simulated using the popular PVSYst simulation software for PV power systems.

In all, the research provided the requisite technical information for contingency management in the energy supply to the GSM base station. It also provided the economic analysis details that will be used to justify the expenditure on the power system due to it very short payback period of 4 years compared with the life cycle period of 25 years.

Abbreviations

GSM	Global System for Mobile Communications
CBT	Computer-based Testing
PV	Photovoltaic
LOL	Loss of Load
PVOGS	PV Off-grid Solar

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Conflicts of Interest

The authors declare no conflicts of interest.

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