Performance Assessment of 676.8 kW Grid-Tied Solar Power Generating System at S&R San Fernando, Pampanga

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Abstract- The concept of energy security has emerged as a consequence of rising energy demand in developing countries. This has demanded the use of renewable resources' untapped potential. PV systems connected to the grid have emerged as the finest large-scale renewable energy sources. Performance assessments of these grid connected plants could help in designing, operating and maintenance of new grid connected systems. A 676.8 kWp photovoltaic grid connected power plant commissioned at SNR Membership Shopping, San Fernando is one of the few commercial establishments that installed a grid tied solar PV system in Pampanga. The site is receiving a good average solar radiation of 5.50 kWh/m²/day and the five months process average temperature of about 27.16 degrees centigrade. The plant is designed to operate with a fixed angle of 30º. In this study the solar PV plant design aspects along with its annual performance is elaborated. The various types of power losses (temperature, internal network, power electronics, grid connected etc.) and performance ratio are also calculated. The performance results of the plant are also compared with the simulation values obtained from PV Syst software and the PV Gis Site Simulator. The final yield (YF) of plant ranged from 3.23 to 5.15 kWh/m²/day, and annual performance ratio (PR) of 82.5% using the PV Syst simulator. Then, it has 17.85% Capacity Utilization Factor (CUF) with the five-month period process energy generation of 396.16 MWh.

I. INTRODUCTION

Solar panels and solar panel systems are now being used to power a wide range of applications. Solar cells, in the form of solar panels, are still employed in calculators. Solar panels are a cost-effective method of generating electricity for a variety of uses. It is now more essential than ever to do everything to minimize the pressure on climate caused by greenhouse gas emissions. Solar panels are simple to maintain because they have no moving parts and theoretically less costly where they are built to last and can survive for decades if properly maintained.

The need for alternative and renewable energy sources has become necessary due to the depletion of oil and gas supplies, as well as growing worries about global warming. Renewable energy sources will help to provide affordable, reliable, and clean energy, as well as reduce environmental and health risks, expand agricultural activities, create additional income and job opportunities, and support innovation and profitable businesses. That will also benefit local communities as well as national and international sustainable development (Malene et al., 2021). Renewable energy development has expanded all over the world. In recent years, there has been a lot of advancement in the development of energy, particularly in solar energy. Solar energy is a renewable energy source that is non-depletable, site-dependent, and non-polluting. In order to reduce their reliance on nonrenewable fossil fuels, many countries are starting to use solar energy conversion technologies. Thousands of photovoltaic (PV) panels are installed across the world to power small, distant, grid-independent, or stand-alone applications. These are also used in some malls and markets, particularly in the Philippines, where solar panels are placed on their rooftops to save and conserve energy.

Electrical energy must be available on demand at all times in today's culture. However, planning, designing, constructing, and operating a power system with a zero-risk of failure is not technically or economically viable. As a conclusion, a primary goal is to meet system load needs as cost-effectively as feasible while maintaining a tolerable level of continuity and quality. It is the ability of a system to be reliable. During a defined period of time [0, t], or component to perform its needed functions under specified conditions for the duration of the time interval, no failure is permitted. It is determined by the probability of failure and the operational time gap.

II. BACKGROUND OF THE STUDY

In today's deregulated utility economy, reliability evaluation is important. Customers are looking for a great quality of service at a reasonable price point. In order for utilities to remain competitive, they need to maintain high level of reliability while keeping the capital as well as operating and maintenance cost to the barest minimum. The term "power-system reliability" refers to the capacity of a system to meet customer expectations in a wide range of ways.

S&R Membership Shopping, owned by Mr. Lucio Co, is a warehouse-style store in that is well known in selling foreign goods. S&R is a membership-shopping club modeled after the warehouse membership shopping chains introduced in the United States. The core concept is to deliver significant value to member-customers through an effective and efficient system anchored on aggressive buying, low-cost distribution and streamlined operations. S&R has won over the local market with its wide selection of imported and local items in packaging sizes that give you value for money. It is termed a warehouse-type structure because it looks like a warehouse on the inside, with a simple cuboid shape and a parapet roof.

The S&R Member Shopping in San Fernando, Pampanga installed a Grid- tied Solar PV System and started using it last august, 2021. The grid-tied solar PV system is a form of solar system continuously connected to the electrical power grid. Grid-tied does not require batteries, and also in the case of off-grid solar systems. Grid-tied solar programs allow the home to use solar energy when possible, or to divert excess electricity back into the grid. To decrease electricity expenses and conserve energy through the use of a renewable energy source, the company's owners installed a grid-tied solar panel on top of the warehouse in order to maximize the building's usage.

III. STATEMENT OF THE PROBLEM

With the increase in renewable energy generation, a trade-off not only between the payback period of renewable energy investment and the lifetime of PV panels is essential but on how to maintain and monitor its performance and efficiency, if it is still working the way it was intended in its working condition. An effective solar PV system installation requires knowledge on their operational performance in various climates (Makrides et al., 2010). Because the Philippines is not a member of an international energy agency, there are no studies or discussions on solar photovoltaic power facilities that meet the IEC 61 724 standard (IEA, 2014). As a response, it's important to monitor the performance of the Philippines' large-scale grid-connected solar power.

IV. OBJECTIVE OF THE STUDY

The performance of 676.8 kW_p grid connected solar photovoltaic power plant was carried out in this work with the following objectives:

1. To determine the average Photovoltaic (PV) plant actual energy generated data, gathered from the Solar PV System in the given period of time (January to May 15, 2022).
2. To analyze technical performance using a simulation software in getting the energy yield per year, array yield, reference yield, and system yield losses.
3. To compare the actual performance data with the simulated data of PVSYST and PV GIS.

The researchers conducted this study to help the S&R Management and give details about the system they bought and installed in their place. This also gives them information and update about the impact of the project. The researchers also conducted this study for the benefit of the electrical engineering students to boost their knowledge and skills in analyzing and interpreting the gathered data during the conducted online interview. They also conducted this study to be used by the future electrical engineering students that will serve as their reference and guide for their expected project study. For them to identify the use of each part of the project study and how to conduct the study properly.

The study will only take place in S & R Membership Shopping, San Fernando, Pampanga, and the gathering of information will be done through online interviews with the people mentioned below:

1. Mrs. Aidaly Castro (Warehouse Manager, SNR San Fernando, Pampanga)
2. Mr. Joel Cruz (Supervisor in Electrical Department, SNR San Fernando, Pampanga)
3. Robert Marlon T. Pereja (Chief Operating Officer, SPECTRUM)

The study will mainly assess the performance of the PV system from the rooftop to the room where the inverters are placed. The researchers will gather information from the contractor company that installed the system and the PV maintenance utility head through observing the behavior of the system from the time it was installed up to now.

1. DESCRIPTION OF THE SOLAR PV-GRID SYSTEM

A grid-connected PV system consists of solar panels, inverters, a power conditioning unit and grid connection equipment. It has effective utilization of power that is generated from solar energy as there are no energy storage losses. When conditions are right, the grid-connected PV system supplies the excess power, beyond consumption by the connected load to the utility grid. But, in standalone systems batteries are used to store energy or else energy has to be directly connected to load.

1.1. Geographical location of the site

The S&R Membership Shopping's 676.8kW solar power plant is located at a latitude of 15°02'51''N, longitude of 120°41'26''E and an altitude of 8 m. The S&R San Fernando, Pampanga chose their rooftop area for the building of its 676.8kW Solar Plant because it is in a geographically advantageous location that allows it to absorb more solar radiation throughout the year, as solar power is entirely dependent on the sun's insolation.

1.2. Plant layout

1.) The total rating of the plant is 676.8kW occupied over 6, 620 m^2 area of land. The plant has the generating capacity of about 125 kW thus total of sixteen blocks combined to form a 625 kW generation capacity. Three phases double fed primary winding transformer is used. Converted AC power from the two inverters is fed to these two primaries of the transformer. Each string consists of 30 modules. Total 30 modules are connected to a one main string combiner. Each inverter is connected with one main string combined box. Total 5 inverters are connected to the main panel.

2.) The plant is installed in such a way that it is cost effective, more reliable, and more energy output. During nights when there is no power generation due to lack of solar radiation, the power is taken back from grid for internal power requirement. The power is utilized for lighting, initial starting of the batteries, control room appliances.

1.3. Tilt Angle

There is no tilt angle because the solar panels are mounted in the roof of the establishment. The PV array is kept as equal to the latitude of the corresponding location to get maximum solar radiation. The roof of the SNR San Fernando has an angle of 30º so this solar plant is in the fixed angle of 30° from the day it was first operated up until now.

Figure 1: Schematic Diagram of SNR's 676.8kW Solar Plant

An overview of a kilowatt scale grid-connected solar PV power plant is schematically shown in Fig. 1. The main components include: (Jaggar, et. al)

a. Solar PV Panels: These are made of solar cells which convert the falling light from the Sun directly into electricity. The photovoltaic effect is a semiconductor effect in which solar radiation falling onto the semiconducting PV cells generates charge carrier movement. The output from a solar PV cell is direct current (DC) electricity.

b. String Combiner Box: combines the multiple DC input coming from the panel termination and converts these into one DC output. It provides additional protection with input fuses & surge protection devices.

c. Inverters: They convert the DC power to AC power for connection to the utility grid. Many modules in series strings and parallel strings are connected to the inverters through String Combiner Boxes.

d. Main Panel: Where the five inverters are connected in parallel and serves as the main circuit breaker in the PV System

e. Step-up transformers: The output from the inverters generally requires a further step-up in voltage to reach the AC grid voltage level. The step up transformer takes the output from the inverters to the required grid voltage (for example 25 kV, 33 kV, 38 kV, 110 kV depending on the grid connection point and requirements).

f. The grid connection interface: This is where the electricity is exported into the grid network. The substation will also have the required grid interface switchgear such as circuit breakers and disconnects for protection and isolation of the PV power plant as well as generation and supply metering equipment. The substations are often external to the PV power plant boundary and are typically located on the network operator's property.

1.1. Specification of solar panel

The solar panels mounted at 676.8kW grid tied solar power plant are of 450w rating and made up of mono-crystalline. These panels have an efficiency of 20.4% and are of fixed type. Mono-crystalline panel ratings are open circuit voltage (VOC) of 49.1V and short circuit current (ISC) of 11.60 A. It has a maximum operating temperature of 42 ± 3° centigrade. The solar panels are installed in such a way that structure to structure and leg center to center distance is at 4 m. The distance between panels (Panel to panel) is of 25 mm. Distance between grounds to lower edge of the module is 400 mm.

1.2. Power conditioning units

Inverter converts DC power to usable AC power. The system has five (5) inverters, the rating of voltage per inverter is 680 V as an input. Each inverter has a rated power output of 125 kW. Therefore, the total rated power output of 5 inverters is 625 kW. The inverter's output is automatically synchronized with the grid's voltage and frequency.

Table 1: System Description

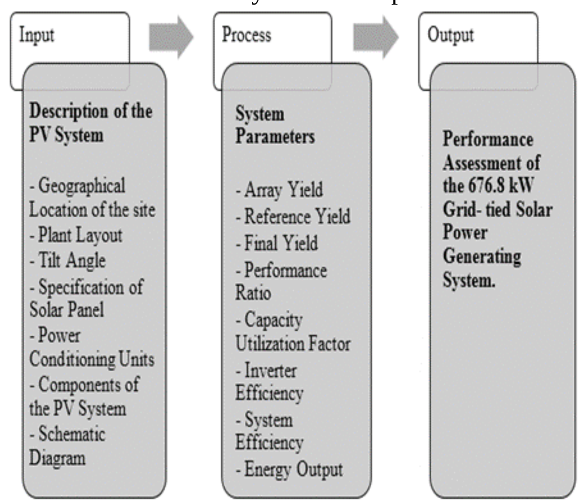

Figure 2: Conceptual Framework

As shown in Figure 2, the researchers will gather set of relevant data provided by the S&R and data obtained by the researchers thru online interview which includes the description of the PV system; Geographical location of the site, plant layout, tilt angle, specification of solar panel, power conditioning units, components of the PV system and its schematic diagram. After gathering this information, the researchers will simulate and measure the system parameters given; array yield, reference yield, final yield, performance ratio, capacity utilization factor, inverter efficiency, system efficiency and energy output. The output of the study is to assess the performance of the 676.8 kW Grid- tied Solar Power Generating System.

V. METHODS

The performance of grid connected solar photovoltaic power system work in this paper is divided in three stages.

(1) Manually extract the parameters of power generation through recording the actual data gathered in the company's software.

(2) Compare the performance with the PVSYST software.

(3) Compare the performance with the PV GIS.

The performance parameters are developed by International Energy Agency (IEA) (Ayompe et al., 2011) for analyzing the performance of solar PV grid interconnected system. Many performance parameters are used to define the overall system performance with respect to the energy production, solar resource and overall effect of system losses. The various parameters are the performance ratio, final PV system yield and reference yield.

SYSTEM PARAMETERS (Marion et al., 2005; Sharma and Chandel, 2013)

a. Array yield

It is equal to the time which the PV plant has to operate with nominal solar generator power P_o to generate array DC energy E_a. Its units are $kWh/d*kW_p$.

$$Y_A = E_A/P_O$$

Where, Array energy output per day $E_A = I_{dc}*V_{dc}*t$ (kW h),

I_{dc} = DC current (A)

V_{dc} = DC voltage (V)

P_0 = Nominal Power at Standard Test Condition (STC).

d = Day; t = Elapsed time

b. Reference yield

The reference yield is the total in-plane irradiance H divided by the PV's reference irradiance G. It represents the under ideal conditions obtainable energy. If G equals 1 kW/m^2, then Y_r is the number of peak sun hours or the solar radiation in units of kW h/m^2. The Y_r defines the solar radiation resource for the PV system. It is a function of the location, orientation of the PV array, and month-to month and year-to-year whether variability.

Its units are h/d.

$$Y_R = [kW\ h/m^2]/1\ kW/m^2.$$

$$Y_R = H_t/G_o$$

Where,

H_t = Total Horizontal irradiance on array plane (Wh/m^2),

Irradiance - a measurement of the amount of light that comes from something (OED)

G_o = Global irradiance at STC (W/m^2).

c. Final yield

The final yield is defined as the annual, monthly or daily net AC energy output of the system divided by the peak power of the installed PV array at standard test conditions (STC) of 1000 W/m2 solar irradiance and 25 °C cell temperature. Its units are kW h/d∗kWp.

$$Y_F = E_{PV,AC}/P_{maxG,STC}$$

d. Performance ratio

The performance ratio is the final yield divided by the reference yield. Performance ratio can be defined as comparison of plant output compared to the output of the plant could have achieved by taking into account irradiation, panel temperature, availability of grid, size of the aperture area, nominal power output, temperature correction values.

$$P_R = Y_F/Y_R.$$

e. Capacity Utilization Factor (CUF)

It is defined as real output of the plant compared to theoretical maximum output of the plant. CUF = Energy measured (kW h)/ (365∗24∗installed capacity of the plant).

f. Inverter efficiency

The inverter efficiency appropriately called as conversion efficiency is given by the ratio of AC power generated by the inverter to the DC power generated by the PV array system. The instantaneous inverter efficiency is given by,

$$\eta_{inv}=P_{AC}/P_{DC}.$$

g. System efficiency

The instantaneous daily system efficiency is given as PV module efficiency multiplied by inverter efficiency.

$$\eta_{sys,T} = \eta_{PV,T} * \eta_{inv,T}$$

h. Energy output or energy fed to utility grid

The energy generated by the PV system is the measure of energy across the inverter output terminals for every minute. It is defined as the total daily monitored value of AC power output and the monthly AC energy generated.

Simulation using PV SYST and PV GIS (Khumar, et. al, 2015)

PV syst software (http://www.pvsyst.com, 2015) is one of the simulation software developed to estimate the performance of the solar power plant. It is able to import meteo data from many different sources as well as personnel data. This software is capable of evaluating the performance of grid-connected, stand-alone and pumping systems based on the specified module selection. The program accurately predicts the system yields computed using detailed hourly simulation data.

In this software, putting the require parameters like the capacity of the solar panel, the capacity of the inverter, the overall capacity of the system and the tilt angle. *(See Appendix H)*

PVGIS is a web application that allows the user to get data on solar radiation and photovoltaic (PV) system energy production, at any place in most parts of the world. *(See Appendix H)*

VI. RESULTS AND DISCUSSION

Actual Data Gathered

Month in the year 2022	Temperature (°C)	Horizontal Irridiance, H_t (kWh/m²)	Daily Energy Generation (MWh)	Monthly Sum of Energy (MWh)	Total Energy Generated (MWh)
January	25.2	139.5	2.74	82.22	391.16
February	25.8	156.3	2.70	75.56	
March	27.4	177.3	3.29	102.12	
April	28.8	186	2.73	82.03	
May	28.6	165.3	3.28	49.23	

Table 2: Total Energy Generated during Various Months

Table 2 shows the actual gathered data from the company's software (*See Appendix I*). From the month of January to May 15, 2022. The second column shows the average temperature per month from the system in the given period of time. The 4th column indicates the daily energy generation and the last column indicates the total energy generated per month. The highest energy is generated from the month of March and the lowest is in the month of April in the first five months. The total energy generated in the last column was obtained by adding the monthly sum of energy shown in column 4.

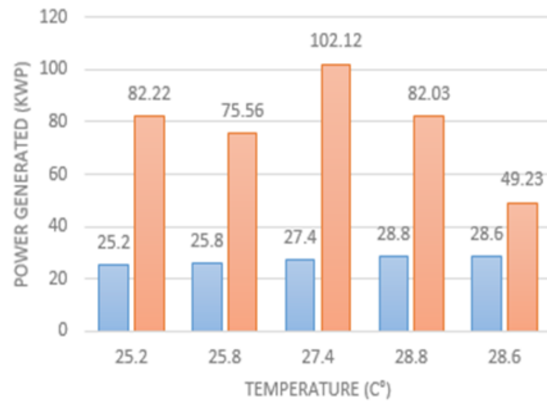

Figure 3: Solar Irradiance vs Peak Power

Solar irradiance absorbed by solar modules is converted to useful power. The power output varies with the solar insolation and an ambient temperature. A monthly average peak power and temperature result is shown in Fig. 3 to understand the effect of irradiance and Temperature on power output of the system. When the temperature increases, the power generation also increases but there are instances that even when the temperature is high, the power generation is low (see Figure 3).

Power Generation

The data is collected manually through the company's software. The highest monthly sum of energy generation was 102.12 MWh in the month of March and the lowest was 82.03 MW h in the month of April. This is all because of the seasonal tilt of the solar panels and the amount of solar radiation that is absorbed from the sun. Thus, the researchers did not consider the month of May as the lowest because the recorded data in from May 1- 15. The total energy generated in the span of 5 months from January 2022 to May 15, 2022 is 396.16 MW. (*See table 2)*

Capacity Utilization Factor

The annual average value of CUF factor is nearly 17.85%. Based on the five months operation. Higher the capacity utilization factor lower will be the cost of electricity generation.

Simulation Using PV SYST

The maximum energy is generated in the month of March (107.6 MW h) and minimum energy is in the month of August (67.8 MW h). The total amount of energy that is injected into the grid for the entire year is 1036.5 MW h. (*See table 3)*

New simulation variant
Customised table

	GlobHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	EffArrR %	EffSysR %
January	139.6	26.20	170.4	168.0	96.5	94.8	16.42	16.13
February	152.3	26.68	175.5	172.9	99.5	97.7	16.43	16.13
March	189.8	28.03	196.1	192.3	109.6	107.6	16.20	15.90
April	187.7	29.25	173.2	168.8	97.1	95.3	16.24	15.94
May	163.6	29.63	139.3	135.0	79.5	78.0	16.53	16.23
June	168.5	28.27	136.6	132.1	78.4	77.0	16.64	16.34
July	164.4	27.86	135.9	131.5	78.2	76.7	16.67	16.36
August	134.0	27.53	119.6	116.0	69.1	67.8	16.76	16.43
September	128.8	27.15	125.5	122.4	72.0	70.6	16.62	16.30
October	163.5	27.68	178.9	175.7	101.3	99.5	16.41	16.11
November	126.6	27.13	147.1	144.7	84.3	82.8	16.62	16.32
December	126.9	26.71	157.7	155.4	90.2	88.6	16.59	16.29
Year	1845.8	27.68	1855.8	1814.9	1055.7	1036.5	16.49	16.19

Table 3: Balances and Main Results

Balances and Main Results

Based on the Table 3, the annual global horizontal irradiation is 1845.8 kW h/m2. Global incident energy that is incident on the collector plane annually is 1855.8 kW h/m2. Total energy obtained from the output of the PV array is 1055.7 MW h.

New simulation variant
Normalized Performance Coefficients

	Yr kWh/m²/day	Lc ratio	Ya kWh/kWp/day	Ls ratio	Yf kWh/kWp/day	Lcr ratio	Lsr ratio	PR ratio
January	5.50	0.887	4.60	0.082	4.52	0.163	0.015	0.822
February	6.27	1.022	5.25	0.094	5.15	0.163	0.015	0.822
March	6.33	1.106	5.22	0.095	5.13	0.175	0.015	0.810
April	5.77	0.987	4.78	0.087	4.69	0.173	0.015	0.812
May	4.49	0.709	3.79	0.069	3.72	0.158	0.016	0.827
June	4.55	0.692	3.86	0.070	3.79	0.152	0.016	0.833
July	4.38	0.660	3.72	0.068	3.66	0.151	0.016	0.834
August	3.86	0.564	3.29	0.064	3.23	0.146	0.017	0.837
September	4.18	0.640	3.54	0.068	3.47	0.153	0.016	0.831
October	5.77	0.946	4.83	0.087	4.74	0.164	0.015	0.821
November	4.90	0.751	4.15	0.075	4.08	0.153	0.015	0.832
December	5.09	0.787	4.30	0.077	4.22	0.155	0.015	0.830
Year	5.08	0.813	4.27	0.078	4.19	0.160	0.015	0.825

Table 4: Array Yield and Reference Yield

Reference Yield, Final Yield and Performance Ratio

Table 4 indicates that the annual average reference yield is 4.19 and the annual final yield using the simulation of PV Syst is 5.08. And the table shows the annual average performance ratio is 82.48%.

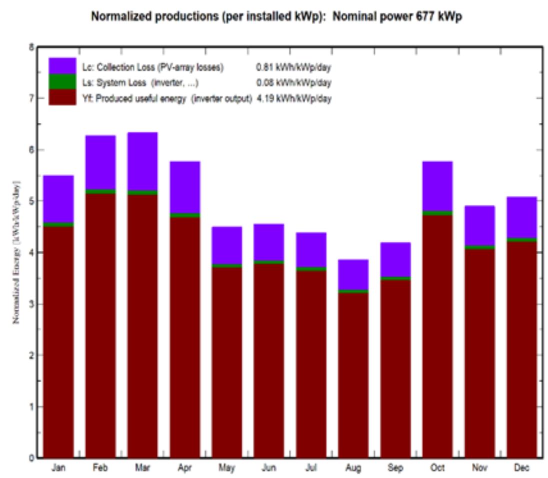

Figure 4: Normalized Energy per Month

Normalized Productions

The LC value is recorded as 0.81kWh/kW p/day and the LS value is recorded as 0.08 kW h/kW p/day in the same way YF is given as 4.19 kW h/kW p/day.

Loss Diagram

The global horizontal irradiance is 1846 kW h/m2. The effective irradiation on the collector plane is 1815 kW h/m2. The solar energy incident on the solar panels will convert into electrical energy. After the PV conversion, the nominal array energy is 1231MWh. The efficiency of the PV array is 19.66% at standard test condition (STC). Array virtual energy obtained is 1060 MW h. After the inverter losses the available energy obtained at the inverter output is 1036MWh. See (Table 5)

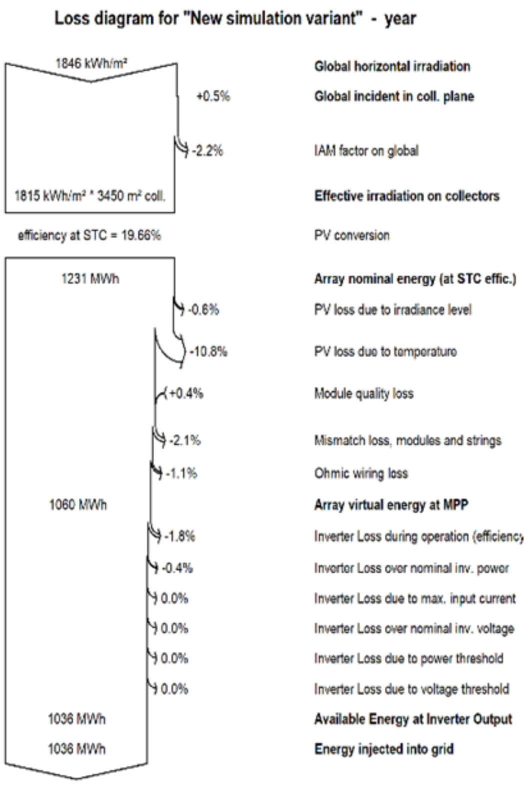

Figure 5: Loss Diagram

Simulation using solar PV GIS

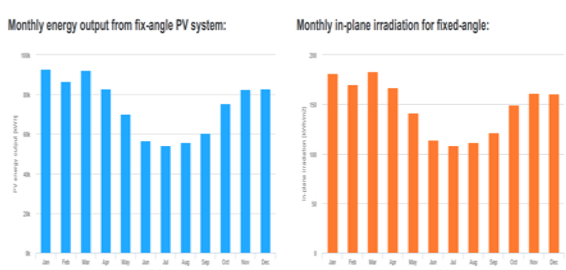

Figure 6: Energy Output and In- Plane Irradiation

Global Horizontal and In-plane Irradiation

The plant has more global irradiation in the month of March (183.4 kW h/m^2) correspondingly more daily sum of global irradiation is recorded. The plant has more global in-plane irradiation in the month of March (196.1 kW h/m^2) correspondingly more daily sum of global in-plane irradiation was recorded. (See Table 5 and Table 3, GlobInc)

	E_m (kWh)	$H(i)_m$ (kWh/m^2)	SD_m (kWh)
January	92877.6	181.1	4603.9
February	86576.1	170.3	4696.6
March	92076.1	183.4	4142.6
April	82748.5	167.2	4314.1
May	70142.6	141.7	4469.4
June	56820.1	114.0	5631.9
July	54119.3	108.5	6662.4
August	55775.5	111.3	4416.6
September	60482.5	121.3	7186.4
October	75272.6	149.4	7421.9
November	82464.9	161.3	7653.7
December	82768.6	160.7	6018.1

Table 5: Energy output per month

PV Electricity Production

The plant generated more electricity in the month of January (92.877 MWh) correspondingly it has more daily sum of specific electricity produced. The share of monthly electricity of March is 9.6% which is almost equal to the month of December. (See table 5)

	Actual Data (MWh)	PV Syst (MWh)	PV Gis (MWh)
January	82.22	94.8	92.88
February	75.56	97.7	86.58
March	102.12	107.6	92.08
April	82.03	95.3	82.75
May	49.23	78.0	70.15
June	--	77.0	56.82
July	--	76.7	54.12
August	--	67.8	55.78
September	--	70.6	60.48
October	--	99.5	75.27
November	--	82.8	82.46
December	--	88.6	82.77

Table 6: Performance Comparison

The results obtained from the obtained actual data system is compared with PVSYST and PV-GIS Software. The results are presented in Table. The actual performance closely matches with the simulated performance of PV Syst and PV GIS in the first 5 months of 2022. (See Table 6)

CONCLUSION

A performance study of 676.8 kW peak grid tied solar power generating system installed at SNR Membership Shopping, San Fernando, Pampanga was evaluated on annual basis. The following conclusions are drawn from the study.

- Maximum total energy generation of 102.12 MW h was observed in the month of March and lowest total energy generation of 82.03 MW h was observed in the month of April.
- As far as the comparison of monitored data with PV Syst and PV GIS simulation results, plant is operating nearer to the predicted generation of energy modeling software.

The study enables to identify the best location and PV technology for large-scale solar photovoltaic implementation project in the Philippines. This data is useful for determining the plant's operational benefits based on net energy output. The PV system's monitored data and operating experience can be used in future large-scale projects.

RECOMMENDATIONS

The researchers recommend for the future researchers to make a one year data gathering process for the performance assessment in the Solar PV System. This will serve as a credible data for assessing the performance of an establishments. Five months is not that enough to perform the assessment. And as for the future researchers, the researchers suggest to also gather the other actual parameters said in the study (array yield, reference yield, and the final yield). The researchers also recommend to put some interventions if the desired output is not met.

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