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Performance Evaluation of a MW-Size Grid-Connected Solar Photovoltaic Plant Considering the Impact of Tilt Angle

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Citation: Sharma, G.S.; Mahela, O.P.; Hussien, M.G.; Khan, B.; Padmanaban, S.; Shafik, M.B.; Elbarbary, Z.M.S. Performance Evaluation of a MW-Size Grid-Connected Solar Photovoltaic Plant Considering the Impact of Tilt Angle. *Sustainability* **2022**, *14*, 1444. https://doi.org/10.3390/su14031444

Academic Editors: Domenico Mazzeo and Manosh C. Paul

Received: 12 October 2021
Accepted: 18 January 2022
Published: 27 January 2022

Abstract: This paper presents a study for the estimation of generation from a large-scale, grid-interfaced solar PV plant using the PVsyst software. This study aims to investigate the effect of tilt angle on the performance of the grid-integrated solar PV plant. Two types of tilt angle test plants, i.e., a fixed tilt angle of 30° (1 MW) and two seasonal tilt angles, in summer 13° and in winter 30° (2.5 MW), have been selected at the same location in Bikaner, India. The performance of the proposed test solar power plants, rated at 1 MW (fixed tilt angle) and 2.5 MW (two seasonal tilt angles), is established by comparing the results obtained using the PVsyst software with the practical data of annual solar insolation. It is established that the radiation incident on PV modules will increase by 2.41% if two seasonal tilt angles are considered. Hence, the annual capacity utilization factor (CUF) has increased by 0.26%. Furthermore, it is established that the proposed method's performance is superior compared to the statistical methods reported in the literature.

Keywords: capacity utilization factor; performance ratio; solar PV plant; tilt angle; utility grid

1. Introduction

Solar insolation is the solar radiation incident on the earth's surface. This is converted to electrical energy using solar power plants and injected into the utility network. Recently, the share of power generated using solar photovoltaic (PV) power plants has rapidly increased in the Indian electricity grid, compared to the generation from thermal and nuclear power plants. The solar PV plants provide economic benefits, liberalization of the energy sector, and other advantages to electrical utilities, such as peak saving and support to the networks for the distribution and transmission utilities. Distributed interfacing of solar generation to the utility grid also reduces transmission and distribution losses [1]. Generally, stand-alone and small-sized grids connected to fallback solar PV plants are operated at low voltages, which range from 12 V to 48 V. This is due to the fact that storage batteries are operated at low-voltage, which makes the design of a stand-alone system at a low-voltage simple in construction, flexible, and efficient. Grid-tied PV plants are large-sized systems that generate kilowatt-hours (kWh) of electrical energy every hour. Generally, electrical power is needed at very high voltages. Hence, it becomes economical to integrate multiple solar panels with each other to design a high-voltage system that uses a single inverter arrangement. A grid-tied inverter transforms this high-voltage direct current (DC) power into an alternating current (AC) using [1,2]. Different types of studies have been reported in literature related to solar PV plants. A detailed study to describe the design and function of various components of grid-tied solar PV systems is detailed in [3]. A detailed study related to the use of tilt and azimuth angles for harnessing solar energy is reported in [4]. The variable generation of power by the solar PV plants affects the protection schemes of the utility grid. Designs of effective hybrid protection schemes for a power system network with solar energy penetration that are based on the use of signal processing techniques are reported in [5,6]. The impact of variations in PV module parameters, temperature, the height of solar PV plates from the ground, weather conditions, different geographical locations, and the diffusion of light on the generation of electrical power has been investigated in [7–10]. In [11], the authors investigated the influence of solar irradiance intensity levels considering the parameters such as ideality factor, saturation current, series resistance, and shunt resistance of polycrystalline silicon solar cells. In [12], the authors presented a study to evaluate the performance of a commercially used polycrystalline solar PV plant in the Maiduguri, Nigeria weather conditions. In [13], the authors presented a study of the PV module's performance variations on a continental scale. The authors have used mathematical formulations to estimate/evaluate shallow-angle reflectivity, spectral sensitivity, dependence of module efficiency on irradiance and module temperature, and module temperature dependency on irradiance, ambient temperature, and wind speed.

A method for global maximum power tracking of solar PV plants using an incremental conductance-based particle swarm optimization (PSO) algorithm under non-uniform operating conditions is reported in [14]. A study for analysis of solar cell degradation during open-circuit conditions in a desert region is introduced in [15,16]. A study for the measurement of irradiance, variations of irradiance with altitude, and computation of performance ratio (PR) for solar PV plants is detailed in [17–21]. The optimal sizing and placement of solar cells in a PV array are discussed in [22,23].

In grid-tied plants, various solar panels are integrated for designing solar PV arrays to run an inverter which generates high-voltage power with high efficiency. This also results in a small power loss and a small current in the cables. For grid-tied plants, energy is not stored in a battery, and high-voltage plants are an efficient arrangement [24–29]. A detailed analysis and the main problems associated with the grid-tied solar PV system are discussed in [30,31]. High-efficiency solar cells for grid-tied applications are discussed in [32,33]. A techno-economic analysis of grid-tied solar PV cells is reported in [34,35]. The sun's path is divided into four seasons, i.e., summer, autumn, winter, and spring. By observation, the sun's path is common in spring and autumn for two months. So, we merged these two seasons into the summer and winter seasons respectively, and subsequently designed a system that has two tilt angles. This is called a seasonal tilt [36].

After a detailed review of the research paper discussed in the above sections, it is established that a detailed analysis of the tilt angles of solar PV plates will help to increase the quantum of solar energy harnessed by the solar PV plants after adjusting their tilt angles at various geographical locations. This has been considered a key issue for investigations. The main contributions of the paper are detailed as follows below:

- It is established that the performance of a solar PV plant with the seasonal tilt arrangement is better compared to the fixed tilt arrangement. This is achieved by the comparison of the performance of solar PV plants for both these arrangements using simulated PVsyst reports and the actual generation of two plants at the same location. The same fact has also been established using the emulation generation data recorded in a real-time solar PV power plant.

- The impact of tilt angle on the performance of a grid-integrated solar PV plant is investigated.
- A study was performed on a practical solar PV plant located at Bikaner, India considering the two types of tilt angle test plants, i.e., fixed tilt angle of 30° (1 MW) and two seasonal tilt angles in the summer 13° and in the winter 30° (2.5 MW).
- Practical performance is evaluated in the field and compared with the results computed using the PVsyst software. It is established that radiation incident on PV modules will increase by 2.41% if two seasonal tilt angles are considered. Hence, the annual capacity utilization factor (CUF) has been increased by 0.26%.

This paper is organized into nine sections. The introductions and research contributions are discussed in Section 1. The proposed methodology and test procedure are included in Section 2. Section 3 describes the test solar PV plants used for the study. The simulation results are discussed in Section 4. The emulation results of the test solar PV plants are discussed in Section 5. The performance, or yield assessment, of solar PV plant results on the test day is discussed in Section 6. The impact of tilt angle on yearly plant performance is investigated in Section 7. A performance comparative study is included in Section 8. Finally, conclusions are included in Section 9.

2. Methodology and Test Procedure

Energy yield is defined as the net AC energy output of the system generated hourly/daily/weekly/monthly/yearly divided by the peak power of the installed PV array (Po) at STC (1000 W/m^2 solar irradiance, air mass 1.5 and 25 °C cell temperature) [37–40]. It indicates the number of hours of operation of the solar PV plant required per day at its rated capacity. Its units are kWh/kWp day. For energy yield assessment of solar PV plants, performance ratio (PR) and capacity utilization factor (CUF) are used.

2.1. Performance Ratio (PR)

PR is calculated as a percentage and describes the relationship between the real and the theoretical/possible energy output of a solar PV plant [36]. Performance ratio gives an indication of how efficiently the available solar energy (as per actual solar insolation) is converted into electrical energy by a solar PV plant. PR can be calculated on hourly/daily/weekly/monthly/yearly basis to continuously monitor the plant's performance. It accounts for all losses in the complete power generation system by taking actual value of units generated, which is influenced by many factors, with main factor being the temperature and low sun light. The PR equal to 75% indicates that 25% of the solar energy received by installed solar modules from the sun was not converted into electrical energy. IEC 61724 (2017) provides guidelines to calculate PR. The most significant and direct impacts on PV performance are due to the below-mentioned factors.

- In plane area, irradiance received by the PV array.
- PV cell temperature.
- Shading losses due to soiling or snow.

Inverter clipping occurs when the inverter cannot output more than a pre-specified power [W]. It is equal to the curtailment of power, i.e., the network may not accept the available power. PR is defined by below detailed relation.

$$PR = \left(\frac{Yf}{Yr}\right) \times 100\ \%$$

where Yf: measured total power generation output at the export energy (kWh) determined by expected total power generation on standard test conditions based on the total installed power capacity (kW) of the PV plant. Yr: total insolation measured at the PV Plant through the irradiance measurement equipment installed at the site in kWh/m^2 [39]. Yf is defined by below-detailed relation.

$$Y_f = \frac{\int P.dt}{P_{STC}} = \frac{E}{P_{STC}}$$

where P: the instantaneous power output of the array in kW. P_{STC}: the STC rated plant capacity of the array in kWp, E: Energy output of the array in kWh. Yr is defined by below-detailed relation.

$$Y_r = \frac{\int G.dt}{G_{STC}} = \frac{I}{G_{STC}}$$

where G: the instantaneous irradiance measured in the plane of the array (POA) in W/m^2, G_{STC}: the STC irradiance, i.e., 1000 W/m^2 or 1 kW/m^2, I: the insolation falling on the POA in Wh/m^2 or kWh/m^2.

$$PR\ (\%) = \left(\frac{\frac{E}{P_{STC}}}{\frac{I}{G_{STC}}}\right) \times 100$$

$$PR(\%) = \frac{\text{Energy output } \times G_{STC}}{(\text{Plant Capacity}) \times \text{Insolation}} \times 100$$

$$PR\ (\%) = \frac{\text{Energy output (kWh)} \times 1\left(\frac{\text{kW}}{\text{m2}}\right)}{\left(\text{Plant Capacity(kW)} \times \text{Insolation}\left(\frac{\text{kWh}}{\text{m2}}\right)\right)} \times 100$$

$$PR\ (\%) = \frac{\text{Energy output}}{(\text{Plant Capacity}) \times \text{Insolation}} \times 100$$

$$PR\ (\%) = \frac{\text{Energy Output}}{\text{Plant Capacity}} \times \frac{1}{\text{Insolation}} \times 100$$

$$PR\ (\%) = \text{Unit per kW Generation} \times \frac{1}{\text{Insolation}} \times 100$$

2.2. Capacity Utilization Factor(CUF)

CUF is the ratio of the total energy actually generated in kWh, compared with the theoretical energy in kWh that could have been generated in 365 days (8760 h) [41]. It does not consider the no-sun time of day of the 24 h. The *CUF* does not take into account any environmental or loss factors, like variation in irradiance, the de-rating or degradation of the panels, losses in the complete system, losses due to temperature rise, ohmic losses, grid outages, equipment outages, etc. The following formula is used to calculate the annual *CUF:*

$$CUF = \frac{\text{Actual Total Units Generated (kWh)}}{\text{Installed Plant Capacity (kW)} \times 365\text{(days)} \times 24\text{(hours)}} \times 100$$

Hence, on one hand, *PR* is a measure of the performance of a PV system, taking into account environmental factors (temperature, irradiation, losses, etc.) and on the other hand, *CUF* completely ignores all these factors because it has installed plant capacity in its denominator. But in both cases, actual energy is generated in the numerator of the formula, and this actual energy generated value is based on all considerations including design, irradiance, losses, temperatures, and any other factor that influences the generation. Therefore, both factors have a significant status in study of performance of the plant.

2.3. Test Procedure to Investigate Impact of Tilt Angle on Generation and Performance Estimation of Solar PV Plant

To investigate energy yield due to seasonal variation and impact of tilt angle, the grid-connected solar PV plant situated at location (28.00° N, 73.10° E) Bikaner, which is a location in desert of India above the tropic of cancer is considered. The study and analysis of impact of tilt angle and the performance of grid-connected solar photovoltaic power plants. Work included in this paper is divided into the following steps:

(1) Two types of grid-connected solar PV plants are considered, which are designated as Plant-1 (fixed tilt angle 30°) and Plant-2 (two seasonal tilt angles 13° (summer), 30° (winter)). These plants are based on configuration of large-scale grid-connected solar PV plant detailed in Figure 1.
(2) Manually extract the parameters of power generation through SCADA system. Compare the monthly performance with the simulated results using PVsyst software.
(3) To investigate the performance of both plants, the factors *PR* and *CUF* are computed using the data recorded on a particular test day of 17 October 2018 and annual data. In this procedure, the data extracted from SCADA are used to calculate *PR* along with *CUF* of that day, such as unit energy generation from inverter and solar insolation from pyranometer.
(4) To check range of good generation days in a year, the unit/kW generation range of both the test plants is compared.

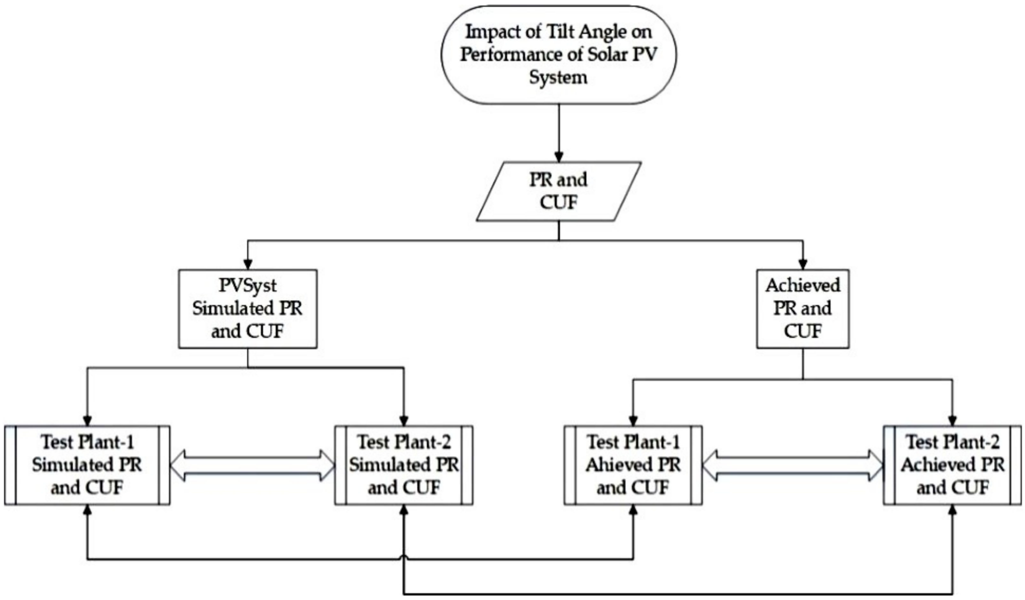


Figure 1. Test procedure of performance of solar PV plant using *PR* and *CUF*.

3. Description of Test Solar PV Plants

Grid-integrated solar PV plants are designed to operate in parallel with utility grids. In these systems, the inverter, or power conditioning unit (PCU), is the main component. The PCU converts DC power generated by the solar PV array into AC power of suitable voltage and quality so that it can be injected into the utility grid. The inverter of a solar PV plant must automatically stop injecting power when the utility grid is not energized (followed standard code UL 1741). This is an essential safety requirement for grid-integrated solar PV plants. A basic concept followed in a grid-integrated solar PV plant is illustrated in Figure 2.

The main components of a Grid solar power plant (MW capacity) are detailed below [3,37]:

- Solar photovoltaic modules, cables, multi-contact connector (MC4)
- Module mounting structures
- String Combiner Box (SCB)
- Inverters
- Transformers
- Switchgear: vacuum circuit breaker (VCB), control and relay panel (C&R panel)
- Four pole structures
- AC disconnector (Isolator)

- Meters—system meter and kilowatt-hour meter and the power evacuation line.
- Supervisory Control and Data Acquisition (SCADA)

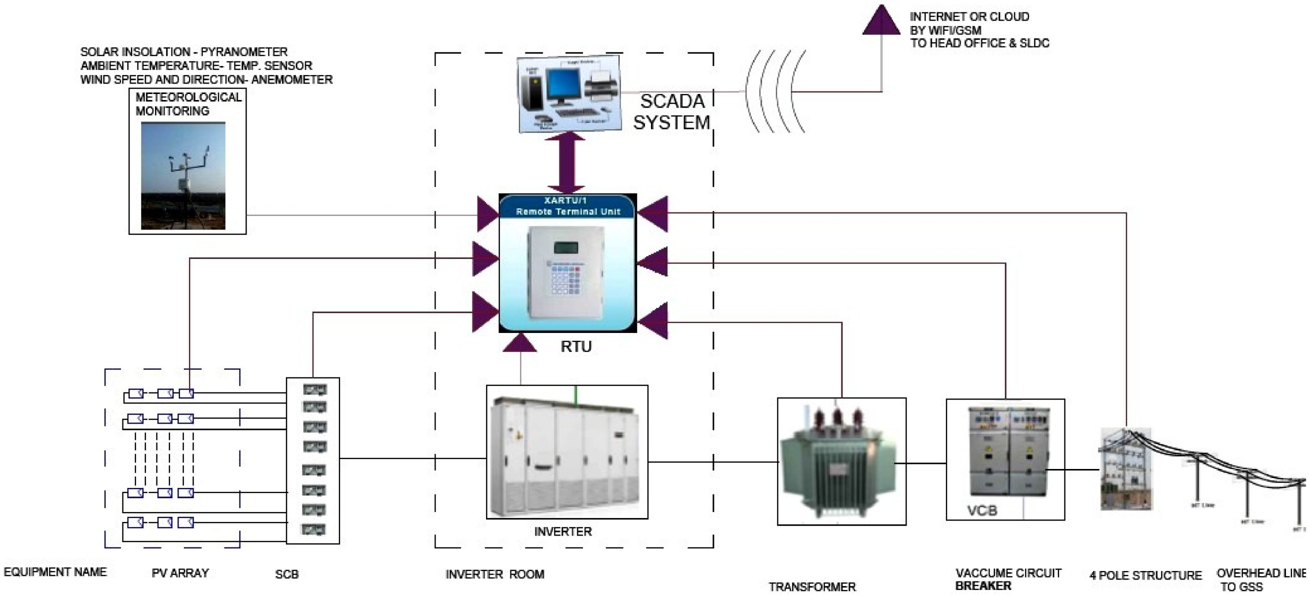


Figure 2. Basic concept followed in a large-scale grid connected to a solar PV plant.

In Figure 2, first a PV string is constructed by using the PV module as per system voltage, and then, by using SCB, all the power from the string is collected at a point using 4 or 6 mm^2 solar DC cable, and this collected power is transferred to the inverter using an underground cable. The inverter converts variable DC power to AC power. Due to the requirement for transferring this power to a GSS (grid substation), it is required that power be available at a high-voltage level of 33 kV. Hence, with the use of the power transformer, the inverter output voltage is stepped up to the 33 kV level. For the purpose of protection, a VCB (vacuum circuit breaker) is used with a protection current transformer (CT) and a potential transformer (PT) at the 33 kV voltage level. To isolate all elements of the solar PV plant from the GSS, an AC disconnector or isolator is used, which is operated only when the circuit is open-circuited by the use of the VCB to avoid flashover. Later, using a metering current transformer (CT) and a metering potential transformer (PT), a metering point is provided by the use of a transmission line. The power is transmitted to the GSS, where the infinity load is connected.

A SCADA system is able to monitor the real-time efficiency, indicating each and every parameter, such as the DC power input, AC power output, voltages, currents, weather reports, etc. This information can be used by the operation and maintenance (O&M) team to establish the general condition of the system and schedule urgent repair or maintenance activities such as cleaning, inverter room temperatures, and airflow. The plant is automatically operated and controlled by the SCADA system and is Open Platform Communications (OPC) compliant. There is a data logging, recording, and display system to continuously monitor the data for all parameters of the plant's DC/AC side. The SCADA shall be capable of communicating with all inverters and strings. It should have features for remote access to real-time data. The SCADA should be capable of generating a day-ahead schedule of generation using historical data. Additionally, the system will send the telemetry data to the local state load dispatch center (SLDC). A computer-aided data acquisition unit consists of a transducer, an analog-to-digital (A/D) converter, a multiplexer, a (de) multiplexer, and interfacing hardware and software. All data shall be recorded chronologically date wise. Reliable sensors for solar insolation, temperature, weather, and electrical parameters are to be supplied with a data logger unit. SCADA shall measure and continuously record electrical parameters and provide data in 1–15 min' interval. The

SCADA shall have features integrated with local systems, as well as remote stations via web using either a standard modem or GSM/wireless fidelity (WIFI) modem. The SCADA shall be provided with a reliable power supply, along with a backup supply for at least one hour to cater to the outage of the grid. The SCADA shall be compatible with the requirements for measuring and reporting the performance ratio (PR) and the capacity utilization factor (CUF) of the plant. The personal computer (PC)/printer (color)/workstation shall be of industrial type, rugged, and robust in nature to operate in a hostile environment. The PC will have a minimum of a 4th Generation Intel processor, and two 1 TB hard disk drives (HDD) with 4 GB RAM. The PC shall also have a 17″ TFT color monitor. A DVD drive with a writer, a USB drive, a scroll mouse, and a UPS for 4 h power backup.

To investigate the performance of a solar PV plant, two types of grid-connected solar PV plants are considered, which are designated as Plant-1 (fixed tilt angle of 30°) and Plant-2 (two seasonal tilt angles of 13° (summer), 30° (winter)). These plants are installed at the same geographical location in Bikaner, India (28.00° N, 73.10° E). These power plants were selected because Plant-2 is equipped with two tilt arrangements. Furthermore, Bikaner is situated in a desert area where high solar irradiance is available with more than 300 days of clear sky. A Google Maps view of the test solar PV plants is described in Figure 3. A technical parameter comparison table of both the test plants including, the details of location, year of installation, plant size, design parameters of plants, transformer parameters, inverter parameters, and PV module parameters is detailed in Table 1.

Figure 3. Test plant location map view Bikaner, Rajasthan.

3.1. Design Specifications of Plant-1 (Fixed Tilt Angle of 30°) Rated at 1 MW

The design specifications of the 1 MW (fixed tilt angle) grid-connected solar PV plant used for the proposed study are described below as follows:

- PV module rating = 300 Wp, make: Canadian Solar.
- The configuration of the mounting structure is such that each table comprises 40 modules on a table and a string of 20 modules in series.
- The SCB (String Combiner Box) will have a maximum of 24 inputs with fuses to protect the system from earth faults. For this 1 MWp solar PV plant, having a total seven SCBs are needed.

- To carry power from the PV array to the SCB, a 4 mm2 copper cable is used. Between the SCB and the inverter, a 150 mm2 aluminum cable is used.
- Inverter rating: 1000kW, Hitachi make, 1000 V system at 50 °C temperature.
- Transformer rating: two winding, 1 MVA capacity, voltage ratio of 0.300/33 kV, and impedance is 5%.
- The high-tension (HT) yard with the transformer 0.300/33 kV includes a lightning arrester (LA) and other switchyard components constructed close to the inverter for the plant.
- Switchyard: One set of 33 kV breakers, isolators, after the transformer in each plant. This arrangement will be very close to the transformer. The outdoor type, structure-mounted CT, PT, and breaker with CR panel (outdoor) have been selected. Grounding mesh covers the entire switchyard, giving an earth resistance (ER) value of less than 5 ohms. An auxiliary power supply of 220 volt AC for a spring charge motor and space heater will be provided to the CR panel and the breaker through an auxiliary transformer of 5 KVA is provided.
- Protections: Overcurrent, earth fault, over voltage, and transformer protections like OT, WT, Buchholz, etc. have been considered in every VCB (for both the transformer and feeder). The concept of the master trip relay and multi-function meter (MFM) in the control panel are used.
- A common power evacuation point at the plant end will be provided at the four pole structure where metering is provided.

Table 1. Proposed Grid-Connected Solar PV Test Plant Details and Comparison.

S. No.	Details	Plant-1	Plant-2
1	Location (Latitude, Longitude)	(28.00° N, 73.10° E)	(28.00° N, 73.10° E)
2	Altitude	212 m	212 m
3	Location name	Bikaner (Rajasthan)	Bikaner (Rajasthan)
4	Plant installation year	2015	2015
5	Plant tilt type	Fixed	2 Seasonal
6	Tilt angle	30°	13°, 30°
7	Plant AC capacity (MW)	1 MW	2.5 MW
8	Plant DC capacity (kWp)	1002	2490
9	PV module make	Canadian Solar	Canadian Solar
10	Module type	Polycrystalline	Polycrystalline
11	Module rating (Wp)	300	300
12	Nos of module	3340	8300
13	Nos. of module in a string	20	20
14	Nos. of string	167	415
15	Nos. of SCB	7	18
16	Maximum no. of input per SCB	24	24
17	Inverter make	Hitachi	Hitachi
18	Inverter rating	1000 kVA	1250 kVA
19	Inverter type	Central	Central
20	Nos of inverter unit	1	2
21	Inverter output voltage (Vac)	300V	350V
22	Transformer type	2 winding	3 winding
23	Transformer rating	1000 kVA	2500 kVA
24	Primary(LV) and Secondary(HV) winding type of transformer	star-delta	star-delta
25	Voltage ratio of transformer	0.30/33 kV	0.35/33 kV

3.2. Design Specifications of Plant-2 (Two Seasonal Tilt Angle 13° of (Summer), 30° (Winter))

The design specifications of the 2.5 MW (two seasonal tilt angles) grid-connected solar PV plant used for the study are described below as follows:

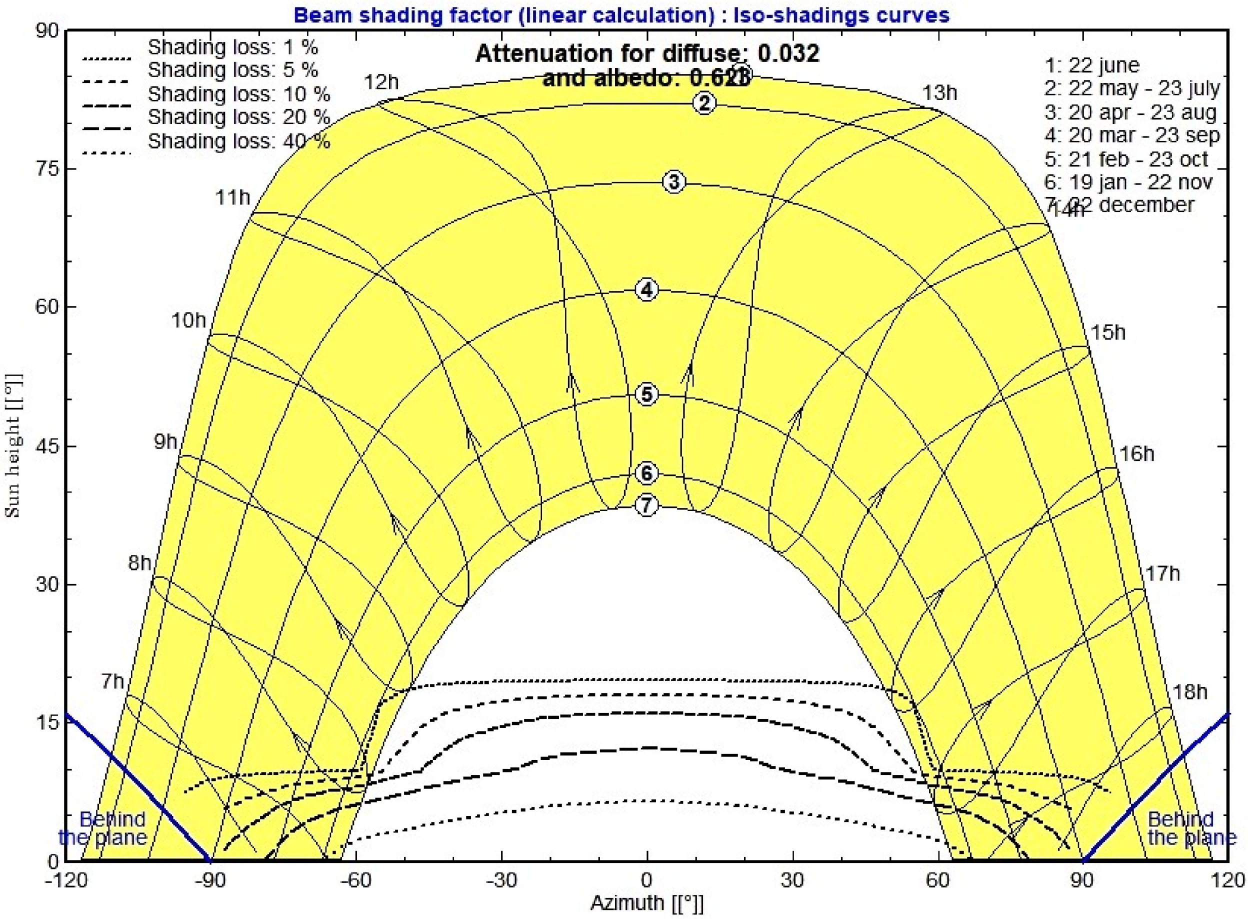
- PV module rating: 300 Wp, Canadian Solar make.
- The configuration of the mounting structure is such that each table shall be comprised of 40 modules on a string in a 2 × 20 with two seasonal tilt arrangements, and a string of 20 modules in series.
- The SCB (String Combiner Box) will have a maximum of 24 inputs with fuses to protect the system from earth faults.
- Based on the shadow analysis, the pitch is taken as 7.47 m, giving a sun-window of 6 h (i.e., 9 AM–3 PM) on 21 December.
- Inverter rating: 2 Nos of Hitachi 1250 kW, 1000 V system at 50 °C temperature.
- Transformer rating:Three winding, 2.5 MVA capacity, and voltage ratio of 0.350/33 kV, Dyn11 vector group.
- The HT yard with the transformer of 0.350/33 kV, including LA and other switchyard components, is constructed close to the inverter for the plant.
- Switchyard: One set of 33 kV breakers, isolators, after the transformer in each plant. This arrangement will be very close to the transformer. The outdoor type, structure-

mounted CT, PT, and breaker with CR panel (outdoor) have been selected. Grounding mesh covers the entire switchyard, giving an ER value of less than 5 ohms. An auxiliary power supply of 220 volt AC for a spring charge motor and space heater will be provided to the CR panel and the breaker through an auxiliary transformer of 5 kVA provided.

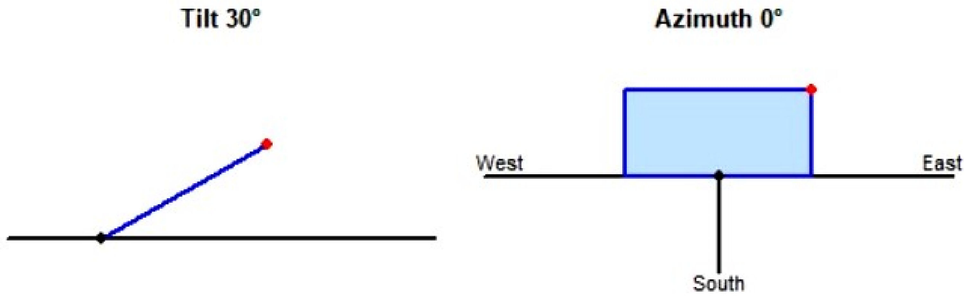
- Protections: Overcurrent, earth fault, over voltage, and transformer protections like OT (oil temperature), WT (winding temperature), Buchholz, etc. have been considered in every VCB (for both transformer and feeder). The concept of the master trip relay and MFM in the control panel are used.
- A common power evacuation point at the plant end will be provided at the four-pole structure where metering is provided.

4. PVsyst Software Simulation Result

Plant location is required in the form of latitude, longitude, and altitude along with a time zone to load a project in PVsyst software [28,37]. So, by using the database, PVsyst first loads the location details and then fetches the Metronome data file that provides the environmental data like solar insolation, horizontal and different angles with different directions, temperature, and wind speed with average data of the past 20 years. Then, by using the project design, PVsyst can select the plant type and grid connected and later can freeze the orientation, plant size, module type and size, and inverter type and size. Additionally, PVsyst can fill in the different types of losses along with the shading of the plant. By simulation, one can get the final result file. After getting final results of two different reports of plants, a final comparison table was prepared. The sun path for Bikaner's location is shown in Figure 4a. Furthermore, a visual representation of the azimuth and tilt angle selection is illustrated in Figure 4b. As per convention of PVsyst software, "in northern hemisphere, the plane azimuth is defined as the angle between south and collector plane. This angle is taken as negative toward east, i.e., goes in the anti-trigonometric direction". For example, in the south plane, azimuth = 0, in the east plane, azimuth = $-90°$. "In southern hemisphere, the plane azimuth is defined as the angle between north and collector plane. This angle is taken as negative toward east, i.e., goes in the trigonometric direction".



(a)

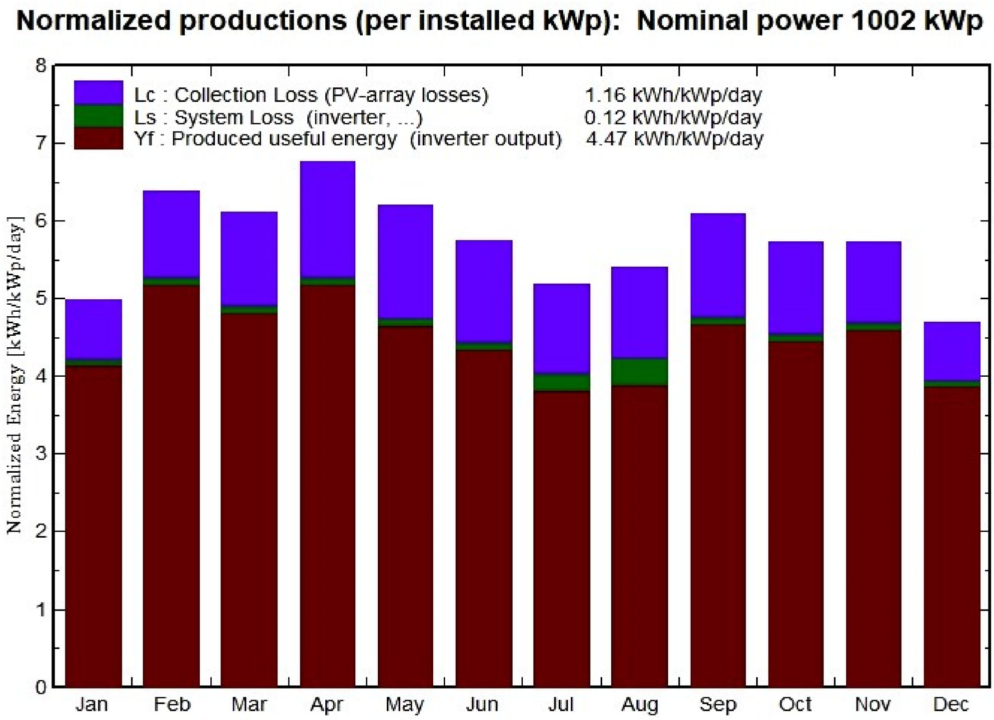


(b)

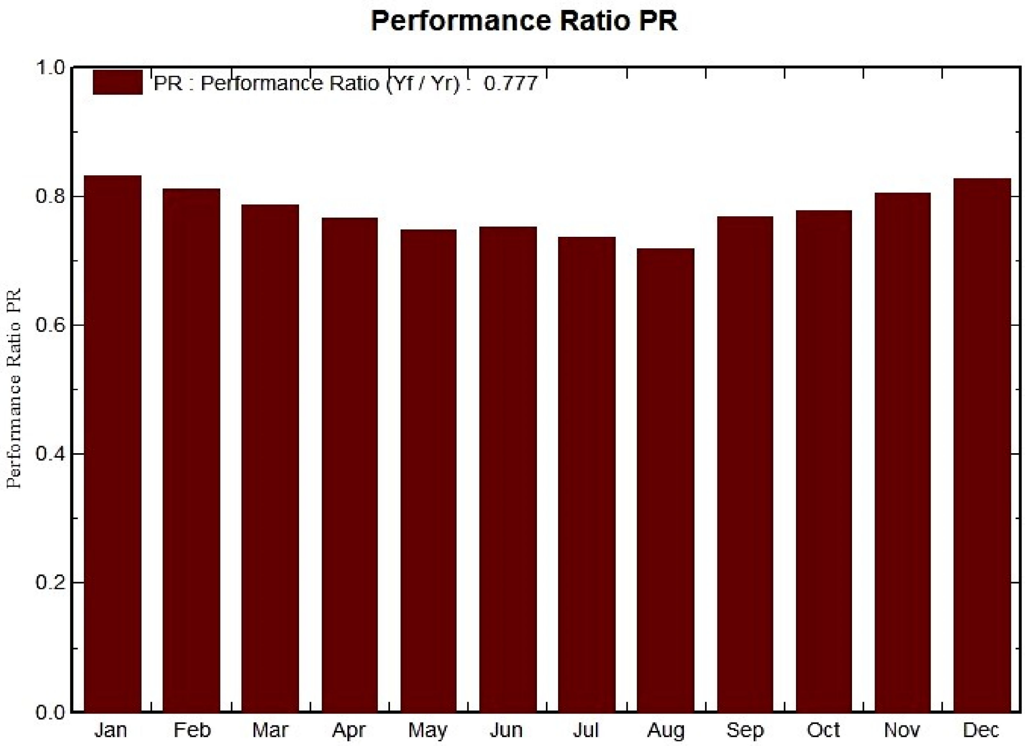
Figure 4. (**a**) Sun path generated by PVsyst (**b**) visual representation of azimuth and tilt angle selection.

4.1. PVsyst Report for Plant-1 of 1 MW Rating at a Fixed Tilt Angle of 30°

A PVsyst simulation study has been conducted with the consideration of the fixed tilt at 30° with shadow on 21st December, which is the shortest day in the Northern Hemisphere with a 7.47 m pitch. The distance between row to row (first point of row to first point of next row distance, or midpoint of first row to midpoint of next row) is called the pitch. By simulation of Plant-1 with a 30° fixed tilt orientation, the result is that it has the information of the results in table format that contains the monthly radiation and generation and also has the resultant performance ratio and per KW yearly generation values. It is illustrated in Figure 5 that Plant-1 has a 77.69% PR and 1630 kWh per kWp yearly generation. Simulated result data for Plant-1 using PVsyst are provided in Table 2. Furthermore, the loss diagram of Plant-1 is detailed in Figure 6. Loss of energy due to variations of PV in Plant-1's temperature compared to STC is observed to be equal to 9.6%.



(**a**)



(**b**)

Figure 5. PVsyst result report of Plant-1 with a 30° tilt (**a**) normalized energy (**b**) performance ratio.

Table 2. Simulated Results of Plant-1 using PVsyst.

	GlobHor kWh/m^2	T Amb °C	GlobInc kWh/m^2	GlobEff kWh/m^2	Earray MWh	E_Grid MWh	EffArrR %	EffSysR %
January	111.3	15.60	154.90	145.6	131.5	129.1	13.25	13.01
February	135.9	19.80	179.00	169.2	148.1	145.5	12.91	12.68
March	166.8	26.00	189.60	177.4	152.5	149.7	12.55	12.32
April	198.7	30.70	202.90	189.7	158.8	155.7	12.21	11.98
May	207.8	35.60	192.60	178.7	147.8	144.6	11.97	11.71
June	193	34.90	172.80	159.6	133.7	130.6	12.07	11.79
July	177.7	33.50	161.10	148.5	125.8	118.9	12.16	11.52
August	171.9	32.30	167.70	155.7	131.5	120.9	12.24	11.25
September	168.9	31.30	182.80	170.7	143.4	140.6	12.25	12.01
October	145.2	28.90	177.70	166.8	141.3	138.6	12.41	12.17
November	122.7	22.50	172.10	162.3	141.2	138.7	12.81	12.58
December	102.3	17.39	145.40	136.3	123	120.6	13.19	12.94
Year	1902.2	27.41	2098.60	1960.8	1678.5	1633.6	12.48	12.15

The symbols used in Table 2 are described here, GlobHor: horizontal global irradiation, T Amb: ambient temperature, GlobInc: global incident in collector plane, GlobEff: effective global correction for IAM and shadings, Earray: effective energy at the output of the array, E_Grid: energy injected into grid, EffArrR: efficiency of array (Eout array/rough area), EffSysR: efficiency of system (Eout system/rough area).

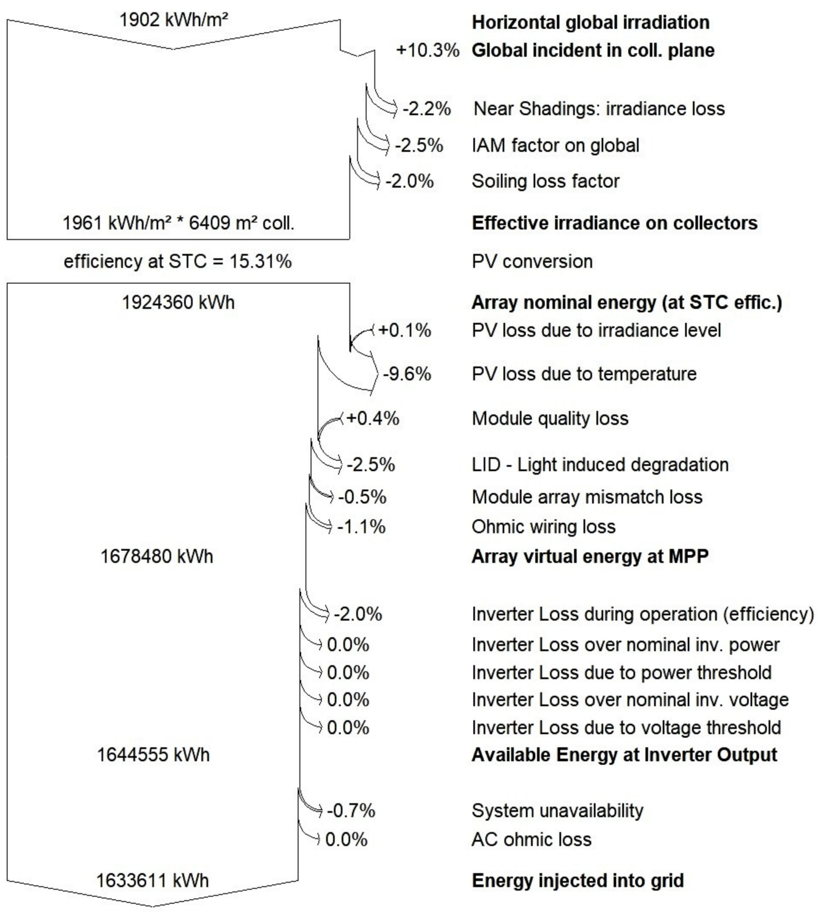
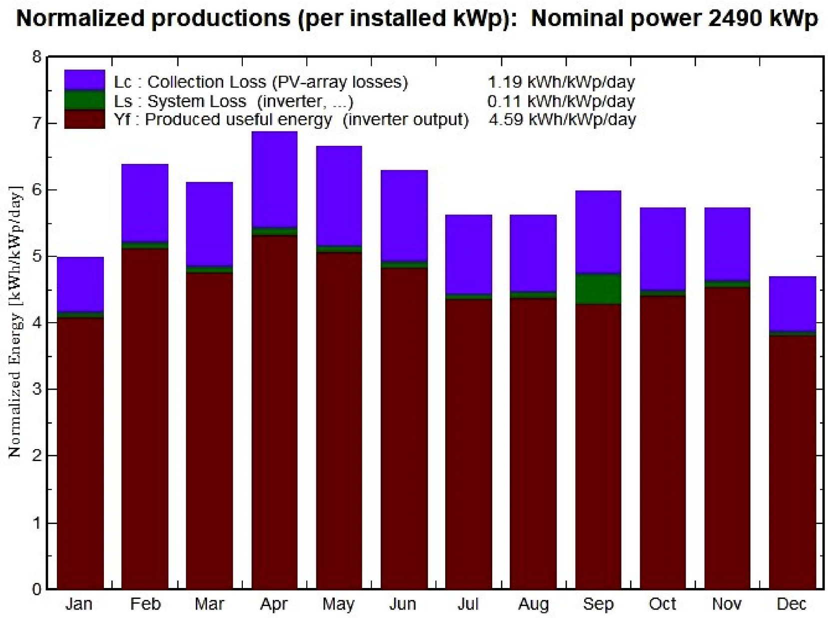


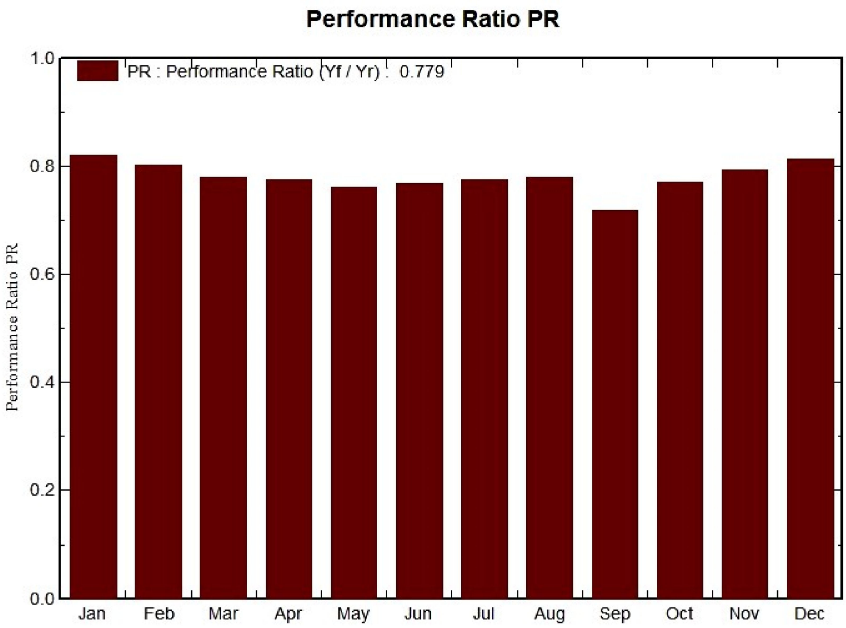
Figure 6. PVsyst Loss Diagram for Plant-1 with a 30° fixed tilt angle.

4.2. PVsyst Report of 2.5 MW Capacity Plant-2 with 13° and 30° Tilt Angles

A PVsyst simulation study has been conducted with the consideration of a seasonal tilt at 13° and 30° with shadow on 21 December with a 7.47 m pitch. By simulation of Plant-2, with 13° and 30° tilt orientations, results have information in table format that contains the monthly radiation and generation along with the resultant performance ratio and per KW yearly generation values. It is observed from Figure 7 that Plant-2 has a 77.90% PR and 1674 kWh per kWp yearly generation. The simulated result data for Plant-1 using PVsyst are provided in Table 3. Furthermore, a loss diagram of Plant-2 is detailed in Figure 8. Loss of energy due to variations in PV Plant-2's temperature compared to STC is observed to be equal to 9.8%.



(**a**)



(**b**)

Figure 7. PVsyst result of Plant-2 with 13° and 30° tilt angles (**a**) normalized production (**b**) performance ratio.

Table 3. Simulated Results of Plant-2 Using PVsyst.

	GlobHor kWh/m^2	T Amb °C	GlobInc kWh/m^2	GlobEff kWh/m^2	Earray MWh	E_Grid MWh	EffArrR %	EffSysR %
January	111.3	15.60	154.8	143.3	321.9	316.3	13.05	12.82
February	135.9	19.80	179.0	167.5	364.4	358.0	12.78	12.55
March	166.8	26.00	189.6	175.1	374.6	368.2	12.40	12.19
April	198.7	30.70	206.2	195.5	406.2	398.8	12.37	12.14
May	207.8	35.60	206.6	195.1	399.1	392.1	12.13	11.92
June	193	34.90	188.9	177.9	368.3	361.8	12.24	12.03
July	177.7	33.50	174.6	164.0	343.3	337.1	12.35	12.12
August	171.9	32.30	174.5	164.6	345.1	338.7	12.42	12.19
September	168.9	31.30	179.7	169.9	355.5	321.6	12.42	11.24
October	145.2	28.90	177.7	167.7	347.1	341.0	12.26	12.05
November	122.7	22.50	172.1	160.0	346.2	340.2	12.63	12.41
December	102.3	17.39	145.4	133.8	300.1	294.8	12.96	12.73
Year	1902.2	27.41	2149.2	2011.4	4271.8	4168.6	12.48	12.18

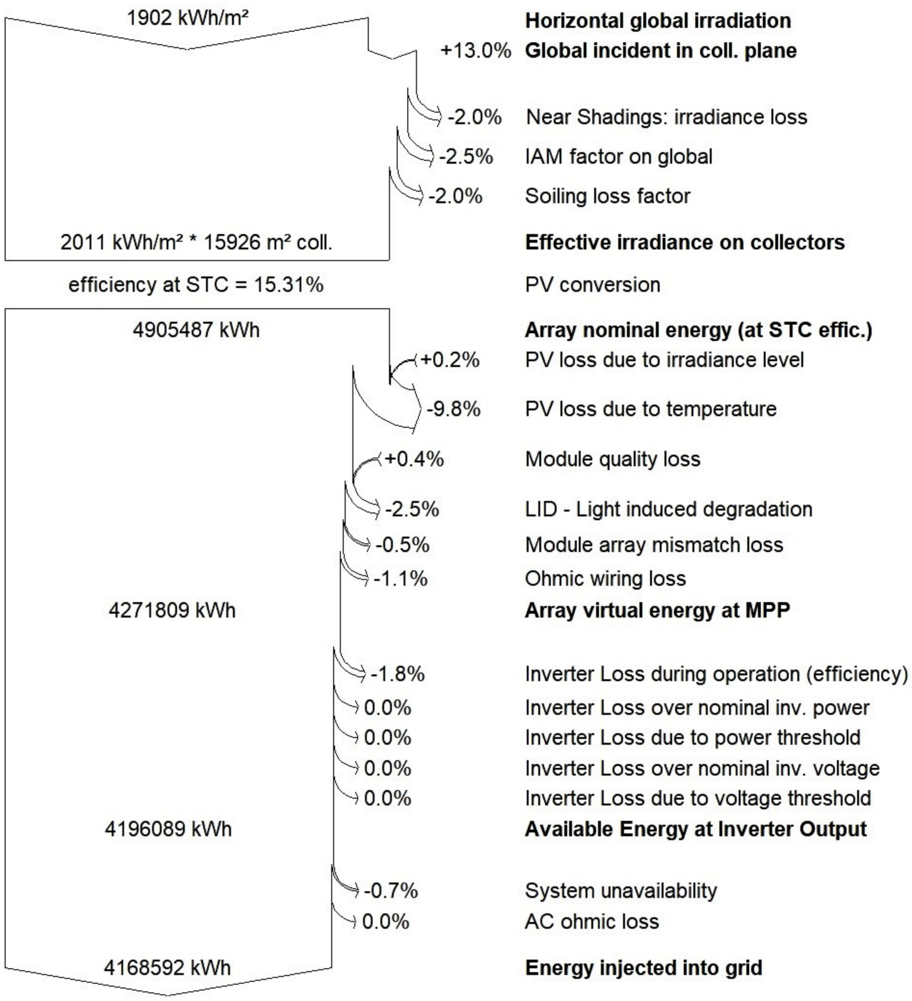


Figure 8. PVSyst loss diagram of Plant-2, 13° and 30° Tilt 2.5 MW.

4.3. PVsyst Report Final Result Comparison

To compare the PVsyst simulation results of the proposed test plants, a comparison is prepared with the help of a PVsyst report and loss diagram, detailed in Table 4. Analysis of the PVsyst simulation results, which are included in the comparison Table 4 is detailed below as follows:

- Both Plant-1 and 2, are situated in the same location, so PVsyst results of both plants have the same annual horizontal global irradiation value of 1902 kWh/m^2.
- Annual global incident radiation in the collector plane is greater in Plant-2 because of two seasonal tilt angles of 13° (summer) and 30° (winter), but Plant-1 only has a single tilt angle of 30° for the whole year.
- Both Plant-1 and 2 have shading loss as per their tilt angle and pitch distance, this is provided by PVsyst shading internal calculation.
- The incident angle modifier (IAM) factor for global radiation depends upon the selected PV module. In both plants the same module is used, so both test plants have the same value of −2.5%.
- Soiling loss factors depend upon the environmental conditions and the cycle of module washing. Both plants have the same environmental conditions and the same washing cycle. So both plants have the same value of 2.0%.
- Both plants have the same polycrystalline PV module, so module conversion efficiency is the same in both plants and equal to 15.31%. Presently, industrial, easily available modules touch 17% efficiency.
- PV loss due to irradiance level is a positive quantity which helps to increase the generation. In two seasonal plants, it is more than a fixed tilt angle plant.
- PV loss due to temperature depends upon the air circulation (wind velocity) in free-mounted solar plants and local temperature along with the PV module temperature coefficient factor [42]. So the combined result of all these factors is computed by PVsyst internal simulation.
- Module quality loss, LID (light-induced degradation), and module array mismatch loss depend on the selected module type. It is available in the. PAN file format, which is provided by the manufacturer.
- The ohmic wiring loss percentage is the same in both test plants and also has the same percentage DC ohmic loss.
- Inverter loss during operation (efficiency) depends on the selected inverter type. It is available in the. OND file format which is also provided by the inverter manufacturer.
- System unavailability loss in both plants considered is 0.7% and equal to a three-day grid outage. The three-day grid outage is considered because both plants have observed a threeday grid outage (Table 4).
- Per kWp yearly generation is greater in test Plant-2, because two seasonal tilt angles get more solar insolation.
- The performance ratio of both test plants is also nearly the same. A comparative study of PVsyst simulated resultant monthly generation data (per kWp) of proposed test plants (Plant-1 and Plant-2) are included in Table 5. Here, a 30° fixed tilt angle is used for Plant-1 and two seasonal tilt angles of 13° and 30° are used for the Plant-2. A comparison of simulated monthly per kWp generation data of both plants is provided in Table 5. Below, a detailed formula is used to compute per kWp generation peak data of plants.

$$\text{Per kWp unit generation} = \frac{\text{unit generation at that day}(\text{KWh})}{\text{plant capacity }(\text{KWp})}$$

Table 4. Proposed Test plants PVsyst loss Results.

S. No.	LOSS Factor	Test Plant			
		PLANT-1 (1 MW)		PLANT-2 (2.5 MW)	
		Magnitude of Quantity	**%**	**Magnitude of Quantity**	**%**
1	Horizontal global irradiation (kWh/m^2)	1902	-	1902	-
2	Global incident in collector plane	-	10.3%	-	13.0%
3	Near Shadings: irradiance loss		−2.2%		−2.0%
4	IAM factor on global		−2.5%		−2.5%
5	Soiling loss factor		−2.0%		−2.0%
6	Effective irradiance on collectors [(kWh/m^2)*(m^2)]	1961 × 6409	-	2011 × 15,926	-
7	PV conversion	15.31%	-	15.31%	-
8	Array nominal energy (at STC.) (kWh)	1,924,360	-	4,905,487	-
9	PV loss due to irradiance level	-	0.10%	-	0.2%
10	PV loss due to temperature		−9.60%		−9.8%
11	Module quality loss		0.40%		0.4%
12	LID (Light induced degradation)		−2.50%		−2.5%
13	Module array mismatch loss		−0.50%		−0.5%
14	Ohmic wiring loss		−1%		−1.1%
15	Array virtual energy at MPP (kWh)	1,678,480	-	4,271,809	-
16	Inverter loss during operation (efficiency)	-	−2%	-	−1.8%
17	Inverter loss over nominal inv. Power		0.0%		0.0%
18	Inverter loss due to power threshold		0.0%		0.0%
19	Inverter loss over nominal inverter voltage		0.0%		0.0%
20	Inverter loss due to voltage threshold		0.0%		0.0%
21	Available energy at inverter output	1,644,555	-	4,196,089	-
22	System unavailability	-	−0.7%	-	−0.7%
23	Energy injected into grid (kWh)	1,633,611	-	4,168,592	-
24	Per kWp generation	1630	-	1674	-
25	Performance ratio	-	77.69%	-	77.90%

Table 5. Comparison of Simulated per kWp Generation.

Test Plant	Monthly Energy of Plant Injected to Grid (kWh/kWp)	
	Plant-1 (1002 kWp)	Plant-2 (2490 kWp)
January	128.8	127.0
February	145.2	143.8
March	149.4	147.9
April	155.4	160.2
May	144.3	157.5
June	130.3	145.3
July	118.7	135.4
August	120.7	136.0
September	140.3	129.2
October	138.3	136.9
November	138.4	136.6
December	120.4	118.4
Year	1630.3	1674.1

For a graphical comparison of both test plants on monthly tilt angle generation variation, a graph on unit/kWp level is prepared and depicted in Figure 9. From Figure 9, it is analyzed that the two seasonal Plant-2 gives more generation with the 13° tilt angle in the month of summer from April to August, while in the remaining months, both plants give the same level of generation.

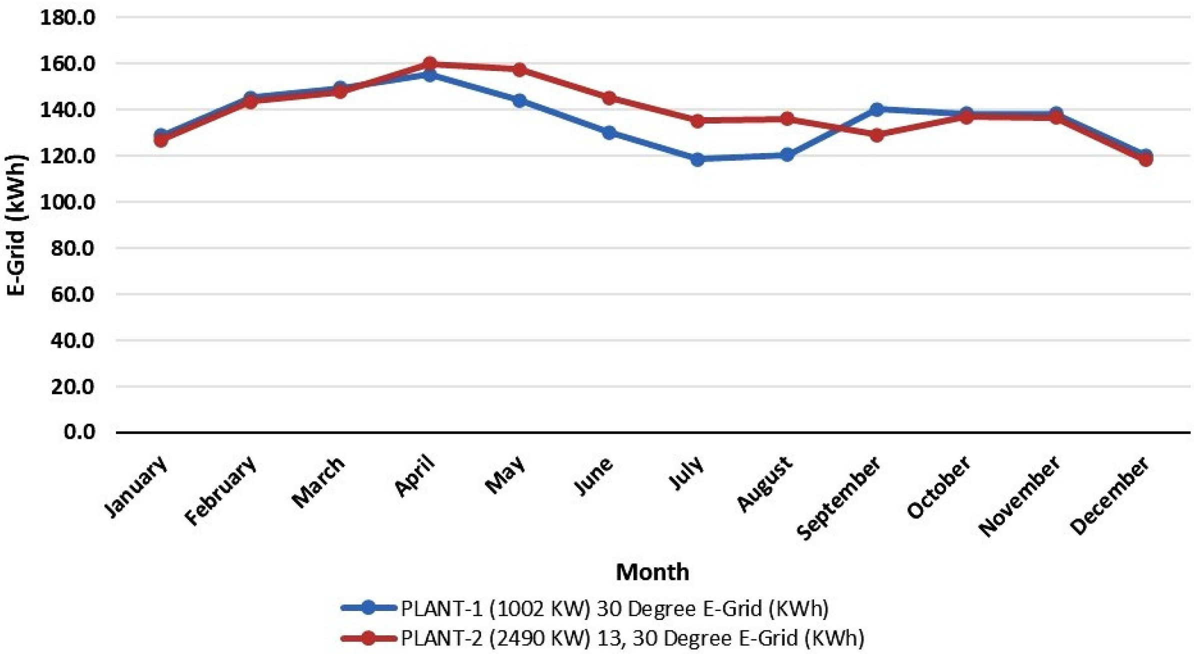


Figure 9. PVsyst simulated output result monthly graphical comparison on per kWp of Plant-1 with a 30° fixed tilt and Plant-2 with 13° and 30° two seasonal tilt.

5. Emulation Result of Test Solar PV Plants

To emulate the impact of the tilt angle on real-world solar PV plants, the monthly generation of both proposed test plants is considered. To compare both test plants, the per kWp monthly generation for each month is shown in Table 6.

Table 6. Proposed Test Plants Monthly per kWp Generation.

Season Type	Month	Monthly Generation in kWh/KWp	
		Plant-2	**Plant-1**
Winter	January-18	143.6	132.4
	February-18	128.4	123.2
	March-18	157.8	160.8
Summer	April-18	142.5	147.3
	May-18	145.1	154.9
	June-18	119.0	123.6
	July-18	117.9	128.3
	August-18	139.5	148.5
	September-18	135.4	136.5
Winter	October-18	135.7	134.7
	November-18	114.2	117.8
	December-18	128.3	122.3
Yearly generation		1610	1607

The emulated impact of tilt angle is illustrated in Figure 10. It is established that by using two seasonal tilt angles, one can get more generation in the months of April, May, June, July, August, and September. In the month of March, both plants give maximum generation as compared to other months because in March, the PV module gets conditions near the STC (standard test condition), i.e., ambient temperature at nearly 25 °C and radiation of 1000 W/m^2.

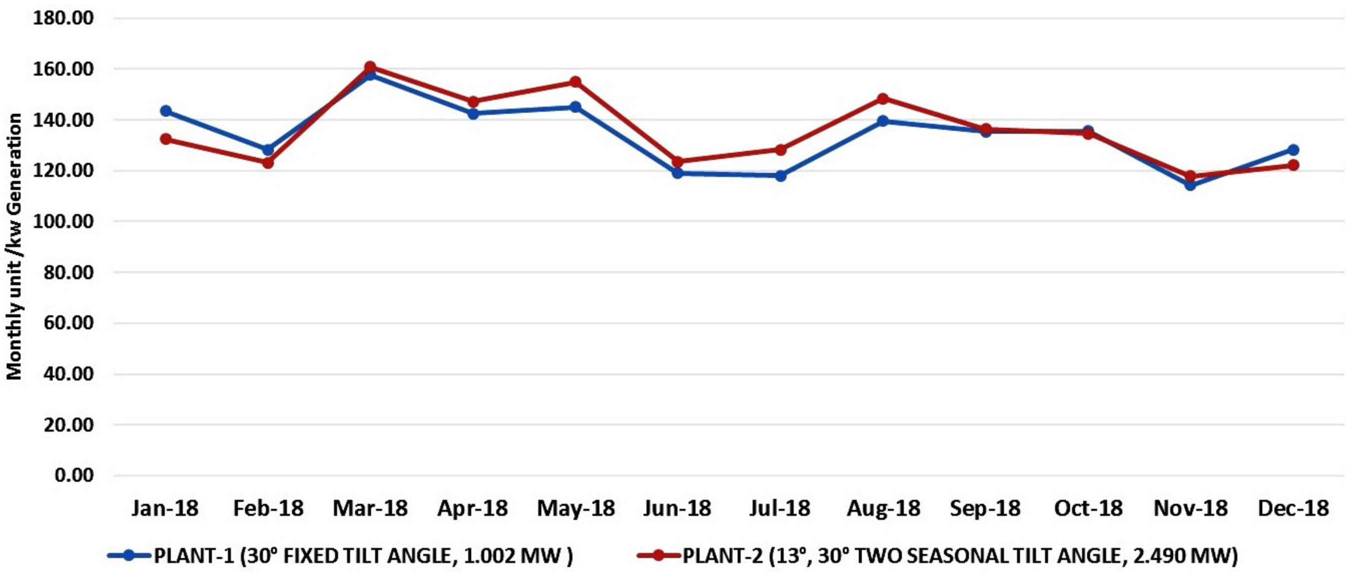


Figure 10. A graphical comparison of actual monthly output on per kWp of Plant-1 at a 30° fixed tilt angle and Plant-2 with 13° and 30° two seasonal tilt angles.

The generation range comparison of the proposed test plants in terms of units per kW is illustrated in Table 7. A comparison of per unit kWp generation for different days by the fixed tilt and two seasonal tilt angle plants is shown in Figure 11. From the analysis of Figure 11, the results are concluded as below as follows:

- Both plants are off for three days.

- The units per kWp generation range from zero to three units, for both plants that are nearly the same. Plant-1 generates zero to three units for 24 days whereas Plant-2 generates for 22 days.
- Again, for a range ofthree to four units per kWp, both plants give the same number of days. Plant-1 generates three to four units for 52 days, whereas Plant-2 generates for 51 days.
- For ranges between four and five, Plant-1 generates more than is covered by Plant-2 in a range of more than five. Because of this excess generation range of more than five, Plant-2 gives more generation as compared to Plant-1.
- If more than four units per day per kWp are considered for a clear sky, then the Bikaner location has more than 290 days with a clear sky.

Table 7. Generation Range Comparison of Proposed Test Plants in Terms of Unit per kWP.

Plant Unit/kWp Generation Range	Number Days of Generation Range	
	Plant-1	Plant-2
unit = 0 (plant off)	3	3
0 < unit < 3	24	22
3 <= unit < 4	52	51
4 <= unit < 5	193	175
5 <= unit	93	114
Total day	365	365

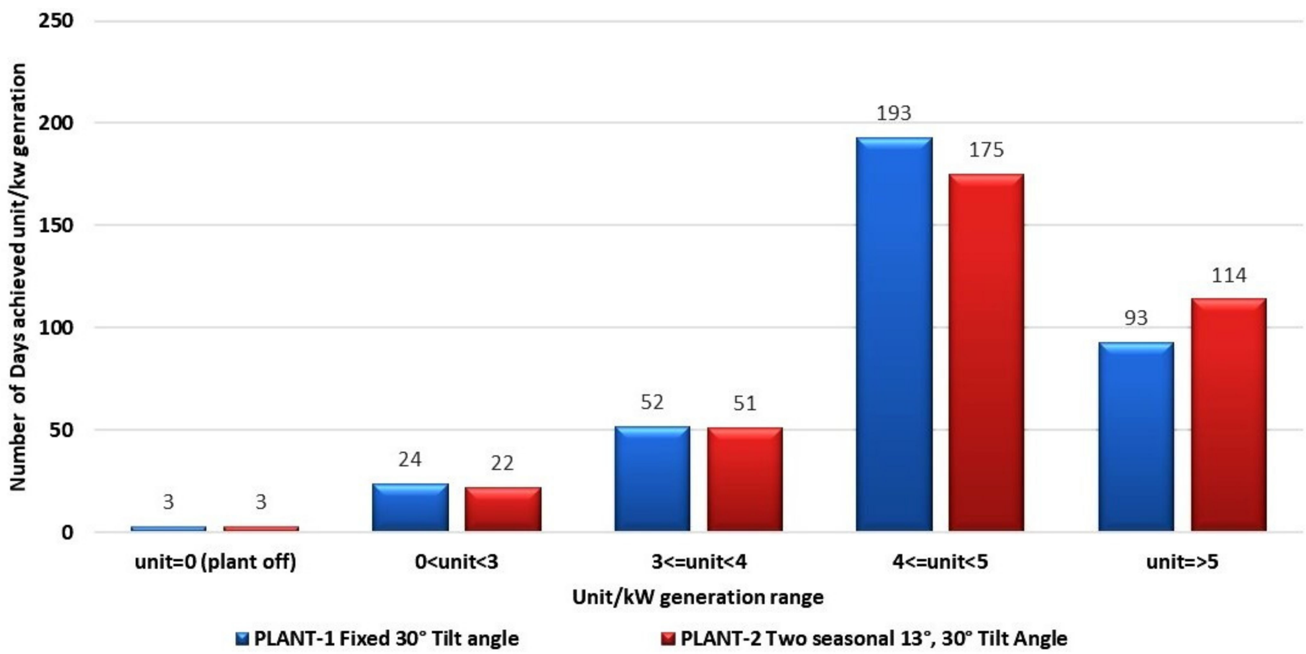


Figure 11. A comparison of per unit kWp generation for different days for fixed tilt and two seasonal tilt angle plants.

Here, impact of till angle on plant performance is highlighted. As per Sun-Earth Geometry, sun moving everyday East to West and seasonally moving from Tropic of cancer to Tropic of Capricorn, to get maximum optimized solar insolation, for fixed tilt and seasonal tilt PV plant, choose PV module direction toward South for Northern hemisphere and towards North in Southern hemisphere and tilt angle selected as per facing toward Tropic of Equator. In this optimized selection for MW size solar PV plant, to reduce the shadow loss pitch selection as per 9 AM to 3 PM Sun window on 21 DEC (in Northern Hemisphere) and 21 June (in Southern Hemisphere). Physically, as per techno commercial optimization, if tilt angle is high then there is a need to increase pitch to reduce row to row shadow loss. This will increase the land size, cable length and ohmic loss. So to optimize these parameters, there is need of optimized tilt angle and pitch.

As per design optimization, to optimize temperature loss there is a need to select proper tilt angle and air circulation because of PV cell designed for STC condition (Solar insolation 1000 W/m^2, AM 1.5 and temperature 25 °C). If solar insolation increases, PV cell converts solar energy to electrical energy as per cell efficiency. Energy which is not transformed to electrical energy will either increases the temperature of cell or it will be transmitted from the PV cell. This rise in temperature reduces the cell efficiency. This temperature variation is observed from sunrise to sun set and season to season. To calculate temperature loss, the PVsyst software simulation is used. For low plant tilt angle dust deposition is high which increases the temperature of PV cell and also increases the soiling loss. So there is need of selection of more than 10° slope to reduce dust deposition with the help of gravitation.

6. Performance or Yield Assessment of Solar PV Plant Results on the Test Day

To investigate the daily performance, or yield assessment, of a solar PV plant, solar insolation and inverter generation data are used to calculate PR and CUF. The test was performed on the day of 17th of October 2018. In the month of October (winter season), both test plants were at a 30° tilt angle. The solar insolation data was extracted from a pyranometer situated at the test plant's location and measured. The solar insolation graphical representation is shown in Figure 12 where the x-axis indicates time and the y-axis indicates the pyranometer reading (in W/m^2).

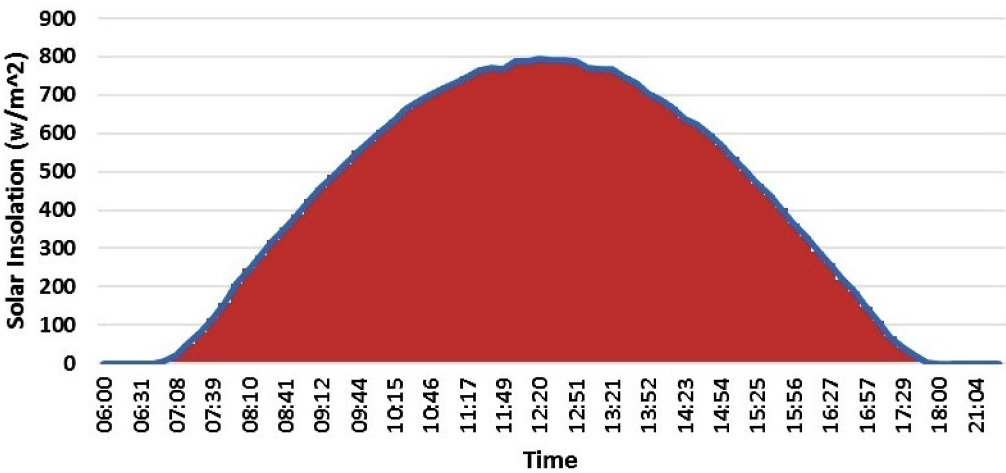


Figure 12. Solar insolation graph.

To investigate the daily PR, the primary need for cumulative inclined solar insolation and the energy output of that day, the energy outputs of the test day were extracted from the SCADA and, to find out the cumulative inclined solar insolation, the area under the curve was calculated as shown in Figure 12. To get optimal results, use the trapezoidal rule. A typical trapezium is shown in Figure 13.

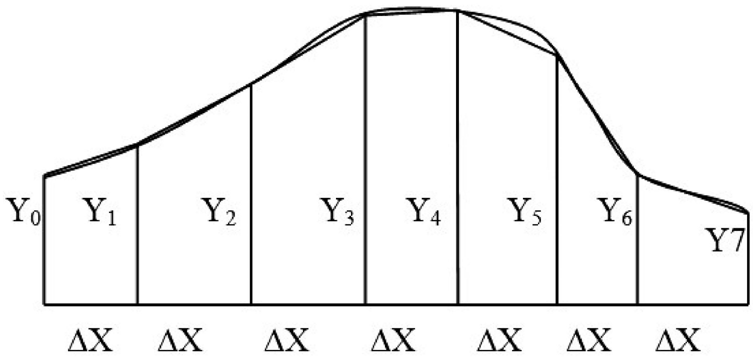


Figure 13. Area under curve using trapezoidal rule.

Total area under curve is given by using trapezoidal formula = $\frac{1}{2}$*(ΔX)*(Y1 + Y0) + $\frac{1}{2}$*(ΔX)*(Y2 + Y1)+ . . . (minute-Watt/m^2).

Total cumulative inclined Insolation = $\frac{\textit{Total area under the curve}}{60*1000}$ (KWh/m^2) = 5.257258 (KWh/m^2).

To calculate the *PR* of a solar PV plant on test day, the formula used was as follows and results are shown in Table 8:

$$PR(\%) = \frac{\text{Energy output}}{(\text{Plant Capacity}) * \text{Insolation}} \times 100$$

Table 8. Daily Yield Assessment of Plants for 17 October 2018.

Parameter	Test Plant-1	Test Plant-2
Plant capacity (kWp)	1002	2490
Plant tilt angle on 17 October 2020	30 Degree	30 Degree
Cumulative solar insolation (kWh/m^2) (*Yr*)	5.257258	5.257258
Energy output (kWh) (*Yf*)	4020	10019
Test day performance ratio (*PR*)	76.3%	76.5%
Test day capacity utilization factor (*CUF*)	16.7%	16.8%

To calculate the daily CUF on test day, the following formula was used and the results of both test plants are shown in Table 8:

$$\text{Daily } CUF = \frac{\text{Actual Total Units Generated (kWh)}}{\text{Installed Plant Capacity (kWp)} \times 1(\text{day}) \times 24(\text{hours})} \times 100$$

The performance of the solar PV plant on the test day 17 October 2018, followed the results from Table 8.

- On test day, the *CUF* of both Plant-1 and Plant-2 is close and have values of 16.7% and 16.8%, respectively. As per the Indian climate, the *CUF* varies from 12.67% to 20.04% [41].
- The PRs of both Plant-1 and Plant-2 on test day are nearly as close and have values of 76.3% and 76.5%, respectively. This value is low as compared to PVsyst's simulated yearly average *PR* because of degradation after three years of plant installation.
- Both test plants performed very well on the daily basis of energy yield assessment.

7. Impact of Tilt Angle on Yearly Plant Performance

A combined visualization of monthly unit/kWp simulated and actual generation has been carried out, considering the methodologies detailed in [43–47] and illustrated in Figure 14. It can be easily visualized that in the summer months, the two seasonal Plant-2 performs better as compared to the fixed tilt plant in both simulation and actual, and it satisfies the design of PV plants on an annual basis. The following are the observations from the graphs of Figure 14:

- Both plants' units per kWp monthly generation, PVsyst simulated and actual generation, followed in a similar manner. Some months, PVsyst and actual generation are on the same level, while some months have some variation because PVsyst considers the past 20 years of average data to provide simulated generation.
- Minimum generation comes in the month of December due to low sun radiation on the 30° tilt angle along with foggy weather.
- Plant-1 PVsyst's simulated monthly generation data gives peak generation in the month of April (155 units/kWp), but in actuality, the month of March (158 units/kWp) gives peak generation.
- Plant-2 PVsyst's simulated monthly generation data gives peak generation in the month of April (160 units/kWp), but in actuality, the month of March (161 units/kWp) gives peak generation.

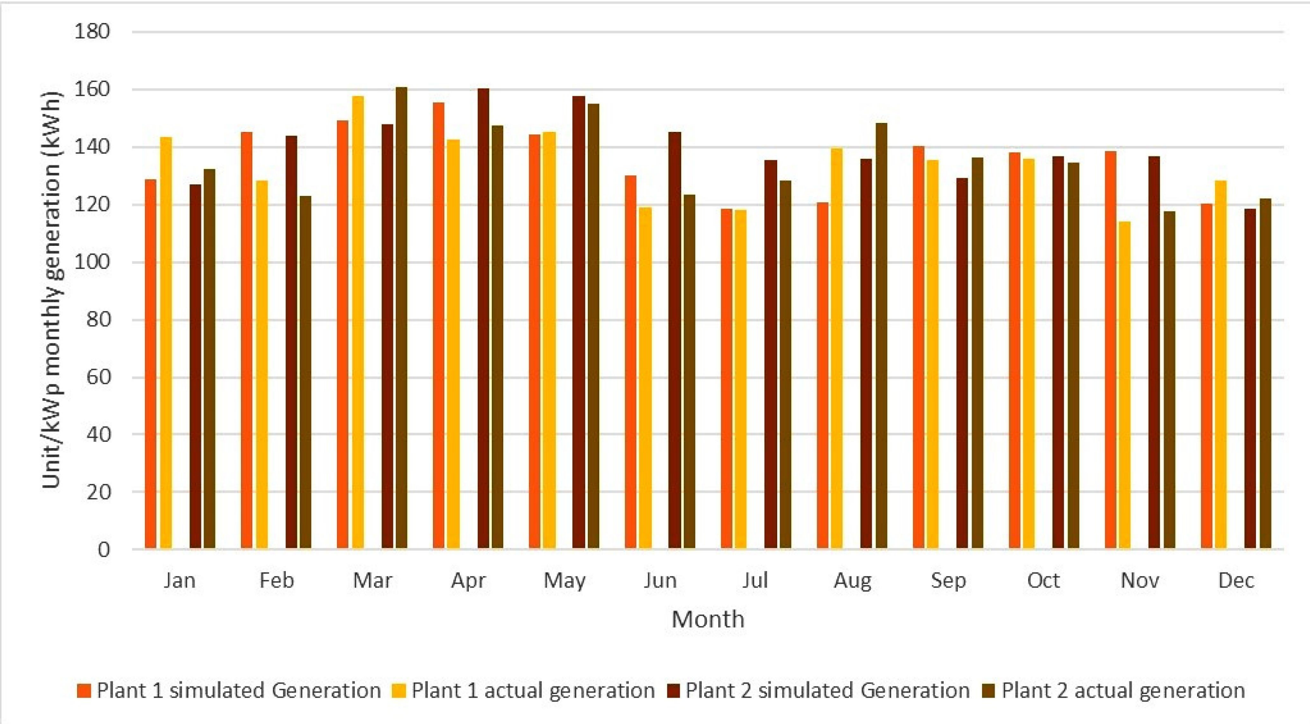


Figure 14. Unit/kWp monthly generation comparison of both plants (simulated and actual).

To check the impact of tilt on yearly plant performance, all PVsyst simulated and emulated data are collected in Table 9. Finally, the concluded results from Table 10 are as follows:

1. The global horizontal insolation computed from the PVsyst's simulated output is the same for both the fixed and two seasonal tilt plants, as both are in the same location.
2. As compared to Plant-1, which has a fixed tilt angle of 30°, Plant-2 has more enhancements in solar insolation due to two seasonal tilt angles.
3. Plant-2 has more PR as compared to Plant-1 because Plant-2 has lower shading loss in the summer season, along with lower inverter efficiency loss.
4. Plant-2 has 2.70% more units per kWp generation compared to Plant-1 because of more input fuel (solar insolation).
5. Plant-1 and Plant-2 both give lower values as compared to PVsyst's simulated value.

6. The plants were installed in 2015. First year degradation is already considered in PVsyst's report (LID loss of 2.5% (1.8% + 0.7%) as per solar PV module manufacturer's data sheet. In the second year in 2016, plants have 0.7% degradation, in the third year in 2017, plants had a 0.7% degradation, and in the fourth year in 2018 plants again had a 0.7% degradation. So, after four years had passed, plants both have 2.1% degradation (first year not considered, in next three years have 0.7 % each year degradation)
7. So, in year 2018, after consideration of degradation, Plant-2 also has more generation targets as compared to Plant-1.
8. Plant-2 has only 1.42% more generation as compared to Plant-1. The reason behind it is as detailed below.
    - Plant-1 has low degradation or damage because of the lack of any effect or mechanical damage during the tilt angle change procedure. Plant-1 gives 0.71% more generation as compared to the three-year PVsyst generation target.
    - However, Plant-2 gives 0.51% low generation as compared to after three years PVsyst generation target. Because during the tilt angle change process period, due to improper handling, some modules may get some minor cracks.
9. Plant-2 gives 0.26% more *CUF* (18.61%) as compared to Plant-1 (18.35%), because of the two seasonal tilt angles, which means with an increasing number of tilt angles, *CUF* may increase. If *CUF* increases, then the cost of solar power reduces.
10. Losses (in terms of percentage) for Plants-1 and 2 computed using the PVsyst software and recorded on the real-time power plants installed at Bikaner, India are provided in Table 10. It is observed that losses computed using the PVsyst software are comparable with the real-time losses recorded on the power plants.

Table 9. Impact of Tilt Angle and Yearly Plant Performance.

Data Type	Parameters	Plant Name	Plant-1 (Fixed Tilt Angle 30°)	Plant-2 (Two Seasonal Tilt Angle 13°, 30°)	Percentage Variation Compared to Fixed and Two Seasonal Tilt Angles
		Formula	**X**	**Y**	**(Y − X)/X × 100**
PVsyst sim-ulated re-sultant data	Global Horizontal Insolation	A	1902	1902	0.00%
	Insolation Enhancement due to Inclination (Yr)	B	2098.6	2149.2	2.41%
	% PR	C	77.69%	77.90%	0.27%
	PVsyst simulated unit/kWp generation	D	1630	1674	2.70%
	After 3 years degradation generation Target	E = D × 0.993 × 0.993 × 0.993	1596	1639	2.70%
Test plant actual data	Achieved actual plant Unit/kWp generation (Yf)	F	1607	1630	1.42%
	Inclined Insolation (Yr)	G	2106	2145	1.85%
Comparative data study	% excess or low generation as compare to PVsyst target generation	(D − F) × 100/D	1.4%	2.6%	
	% excess or low generation as compare to degraded target generation	(E − F) × 100/E	−0.71%	0.54%	
	Achieved annual PR or system efficiency (ηsys)	Annual PR = (F × 100)/G	76.32%	76.00%	
	CUF of actual plant genera-tion	F × 100/(1 × 365 × 24)	18.35%	18.61%	

Table 10. Loss Comparison of Solar PV Power Plants.

Method of Loss Computation	Plant-1	Plant-2
PVsyst software simulation	22.3%	22.10%
Recorded on real time power plant	23.7%	24%

8. Performance Comparative Study

The performance of the proposed fixed tilt angle (Plant-1) and two seasonal tilt angles (Plant-2) is compared with the methods reported in [48] in terms of PR and CUF and provided in Table 11. In [48], the authors presented the analysis of the 2.5 kW PV system installed in Algeria by collecting the data from the field, and the analysis was carried out by simple statistical methods. In [49], the authors presented a study for the analysis of the performance of a grid-connected solar photovoltaic (PV) system installed on the terrace of a building in Algiers. A database of radiometric and electrical data was prepared, and the performance was evaluated by simple statistical analysis of the data set. In [50], the authors presented a study for the performance assessment of two photovoltaic arrays made of different silicon photovoltaic technologies. An empirical analysis of meteorological and electrical parameters was conducted, and mathematical models of efficiency in relation to module temperature were determined. It is observed from Table 9 that the accuracy of the performance evaluation of the solar PV data has improved using the proposed method of study with the help of the PVsyst software. Furthermore, the CUF has improved by the use of two seasonal tile angles. In Table 11, higher values of PR and CUF for the Plant-1 and Plant-2 are obtained for the following reasons:

- The cleaning of the plants is performed as per the specified time cycle. Delays in cleaning time are eliminated.
- Maintenance of all equipment in the plants is performed as per specified schedules.
- The tilt angles of Plant-2 changed as per the time cycle specified in the specifications.
- Fault frequency is reduced by preventive maintenance.

Table 11. Performance Comparative Study.

S. No.	Reference	PR (%)	CUF (%)
1	[48]	73.82%	7.91%
2	[49]	71%	13.14%
3	[50]	74.59%	12.69%
4	Proposed (Plant-1)	76.32%	18.35%
5	Proposed (Plant-2)	76%	18.61%

9. Conclusions

This paper presents a detailed study of the solar PV plant. The performance of the MW-capacity grid-connected solar PV plant is evaluated using a PVsyst software simulation, and then compared it with actual plant units considering per kWp generation on an annual basis. This is concluded that in the practical environment, two seasonal PV plant give 1.4% more energy generation and 0.26% more CUF, as compared to a fixed tilt angle plant at location on 28° latitude nearly above the Tropic of Cancer, in the Indian desert climate. A fixed tilt angle plant can generate energy more than 1600 units per kWp easily. Maximum energy generation is observed in the month of March, and both test plants show good performance ratios in the range between 76% and 77%, nearly close enough to the PVsyst simulated PR after a degradation for a period of three years, along with a good range of CUF between 18% and 19% as per the Indian climate. The efficacy of the proposed approach is better compared to the statistical approaches reported in the literature.

Author Contributions: Conceptualization, G.S.S., O.P.M., M.G.H., B.K., S.P., M.B.S. and Z.M.S.E.; methodology, G.S.S., O.P.M., M.G.H., B.K., S.P., M.B.S. and Z.M.S.E.; software, G.S.S., O.P.M., M.G.H., B.K., S.P., M.B.S. and Z.M.S.E.; validation, G.S.S., O.P.M., M.G.H., B.K., S.P., M.B.S. and Z.M.S.E.; formal analysis, G.S.S., O.P.M., M.G.H., B.K., S.P., M.B.S. and Z.M.S.E.; investigation, G.S.S., O.P.M., M.G.H., B.K., S.P., M.B.S. and Z.M.S.E.; resources, G.S.S., O.P.M., M.G.H., B.K., S.P., M.B.S. and Z.M.S.E.; data curation, G.S.S., O.P.M., M.G.H., B.K., S.P., M.B.S. and Z.M.S.E.; writing—original draft preparation, G.S.S., O.P.M., M.G.H., B.K., S.P., M.B.S. and Z.M.S.E.; writing—review and editing, G.S.S., O.P.M., M.G.H., B.K., S.P., M.B.S. and Z.M.S.E.; visualization, G.S.S., O.P.M., M.G.H., B.K., S.P., M.B.S. and Z.M.S.E.; supervision, O.P.M., S.P. and B.K.; project administration, G.S.S., O.P.M., M.G.H., B.K., S.P., M.B.S. and Z.M.S.E.; funding acquisition, Z.M.S.E. All authors have read and agreed to the published version of the manuscript.

Funding: The author extends their appreciation to the Deanship of Scientific Re- 388 search at King Khalid University under for funding this work through General Research 389 Project under Grant number (RGP.1/255/42).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated or analyzed during this study are included in this published article.

Conflicts of Interest: The authors declare no conflict of interest.

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