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Energy analysis of utility-scale PV plant in the rain-dominated tropical monsoon climates

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ABSTRACT

To limit the adverse impact of fossil fuel-generated power, energy generation from solar photovoltaic (PV) power is gaining importance. A lot of utility-scale PV power plants are being installed in tropical regions owing to the increased sunshine hours especially during the summer season. The influence of rain on the performance of PV power plants during monsoon seasons in a tropical climate is not studied in detail. This paper analyses the operational performance of a 2 MWp photovoltaic plant commissioned at the Kuzhalmannam site, Palakkad district, Kerala State, South India. The methodology includes the analysis of standard performance metrics of the plant utilizing two-year measured data and comparison with other climates. The PV plant's average performance ratio (PR) is 73.39, with an average of 15.41% capacity utilization factor (CUF) over the study period. The most deficit generation for the PV plant is observed in the months from June to August, which are part of the Southwest monsoon season. It is observed that the monsoon seasons prevailing in the region have a more substantial influence leading to a 35% reduction in energy generation from the annual average generation. Further, a comparison with other climates revealed that the specific yield obtained in rain-dominated monsoon tropical climates is lesser than dry and temperate climates.

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1. Introduction

The Paris climate agreement came to effect from Nov 4, 2016, onwards after the National Governments agreed in 2015 to limit the global temperature below 2 °C and decided to target a 1.5 °C limit [1]. This motivated many governments to move ahead with their renewable energy initiatives to meet their emission reduction targets [2]. It is expected that Solar PV will have a higher installed capacity than coal in 2040. The installed solar PV capacity is more than 1 GW in 29 countries globally [1]. Because of the abundant solar resource, developing countries like India are giving more importance to solar power plants to meet their electricity needs [4]. The performance of solar PV plants varies according to the locations and seasons [4]. The performance assessment based on field conditions provides more useful information to the policymakers and stakeholders about the global potential of PV production [5]. Studies have been conducted for assessing the performance of solar PV power plants installed in various climatic regions of the world. (see Tables 1–4)

1.1. Literature review

Dahmoun et al. observed that the performance of a 23.92MWp PV plant installed at El Bayadh in South Algeria is in tune with the simulated values PVsyst and SolarGIS software tools [1]. South Algeria is in a dry climatic region.

An interesting study for the 6 years performance of a 99.84kWp solar PV plant in Central Greece is conducted with a three axes methodology. Based on the study, Roumpakias et al. found that the energy production has a maximum deviation of 13% from the average value which the authors say this deviation could be due to weather conditions [2]. The weather prevailing at the site is coming under the Mediterranean climatic classification.

A traditional approach in performance assessment was undertaken by Cubukcu et al. by finding all the yield parameters, loss parameters, efficiency parameters, and important performance metrics like Performance Ratio (PR) and Capacity Utilization Factor (CUF) for a 2130.7kWp PV power plant installed in eastern Turkey The plant recorded a high PR of 81.15% [3].

Two subsystems of a PV power plant installed at Shagaya Renewable Energy Park in Kuwait constituting polycrystalline and thin-film technologies are analyzed and compared for their performance. The study reveals no significant difference in a desert-dry climate for yield parameters, performance ratios, and loss parameters [5].

A solar PV plant installed in a temperate climate of Northern Jordan was analyzed by Alshare et al. and found that the 5MWp PV plant has a PR of 80% and a Capacity Factor of 18% based on the monitored data [6].

Rehman et al. has conducted detailed feasibility studies and performance projection for 40 different sites in Saudi Arabia for installing a10MWp solar PV power plant and identified the best two sites named Bisha and Najran. The sites were selected based on the techno-economic analysis including the local climatic conditions [7].

A study was conducted by Ramanan et al. at a humid tropical region of Tamilnadu by comparing the performance of two small solar roof-top PV power plants of 1kWp and 1.36kWp with different PV technologies, one with polycrystalline silicon (p-Si) and another with Copper Indium Selenium (CIS) PV modules respectively. It is found that the PV plant with CIS technology performed better than the p-Si PV plant technology in a hot humid environment. The limitation of the study is that the study is conducted with micro size roof-top PV plants and not on a utility scale [8].

Boddapati et al. has analyzed the performance of a 68.52MWp PV plant at Kurnool, Andhra Pradesh State in India, which is part of a 1000MWp Solar Park, and observed that the monthly variation of generation is because of the change in the climate parameters like solar radiation, ambient temperature, etc. It is observed that maximum generation happens in the month of March and the minimum generation happens in July in the observed period [9]. The site of Kurnool, in South India, falls in the tropical region and there is no detailed study has been conducted on the rain effect of the performance of the PV plant.

Nascimento et al. has investigated several extremes over irradiance events that happened in selected sites in Brazil which affected the MPPT input side of inverters, fuses of DC combiner boxes, etc. The authors conclude that extreme care should be taken while designing the utility-scale PV power plants considering a higher fraction of STC conditions [10].

Seme et al. have conducted a study on the performance of several PV plants installed in Slovenia in different weather seasons [11].

Quansah et al. have studied the performance of different PV technologies installed in Ghana for a humid tropical climate. The study was conducted for a combined capacity of 20kWp and found that Hetero Junction Incorporated with Thin-film (HIT) technology performed better when compared with other technologies [12].

Ferrada et al. analyzed the performance of PV plants with two different technologies in the coastal climate zone of Chile. It is observed that the Performance Ratio of PV system with Thin § technology has lesser drop when compared to Mono Silicon from winter to summer [13].

Bouaichi et al. has analyzed the performance and the degradation of three different PV module technologies for the power plants

Table 1
DC & AC Energy output.

Performance parameter	Definition	Unit	Significance	Equation
AC Energy output (E_{AC}) [23]	Cumulative energy generation during the day/month/year	kWh or MWh	Energy generation is an important measure for performance	$E_{AC,m} = \sum_{d=1}^{d=N} Eac, d$
DC Energy Output (E_{DC}) [23]	Ratio of AC energy output and inverter efficiency	kWh or MWh	DC Energy output reflects the actual PV array performance	$E_{DC,m} = \frac{E_{AC,m}}{\eta_{Inv}}$

Table 2
Definition of yield parameters.

Performance parameter	Definition	Unit	Significance	Equation
Reference Yield [18].	Ratio of Plane of Array irradiance (G_{POA}) and reference irradiance (G_{STC}) (1000W/m^2)	hours/day	Reference Yield shows the solar resource availability	$Y_r = \frac{G_{POA}}{G_{STC}}$
Array yield (Ya) [18]	Ratio of DC energy output to the installed rated capacity	kWh/kWp-day	Array yield is the measure of DC performance of solar PV plants	$Y_{a,d} = \frac{E_{DC,d}}{P_{STC}}$
Final yield (Y) [3]	Ratio of AC Energy output and the installed rated capacity	kWh -day/ kWp.	Final yield is a very important parameter in the utility point of view	$Y_{f,d} = \frac{E_{AC,d}}{P_{STC}}$

Table 3
CUF and PR for utility-scale PV power plants.

Performance parameter	Significance	Equation
Capacity utilization Factor (CUF) [3]	CUF is a conventional performance metric used by developers and investors.	$CUF = \frac{E_{AC}}{P_{STC} \times 24 \times 365}$
Performance ratio (PR) [19,29].	PR is a worldwide accepted standard for measuring the performance of a PV plant performance.	$PR = \frac{Y_f}{Y_r}$

Table 4
Efficiency parameters in PV plants.

Performance parameter	Significance	Equation
PV module efficiency (η_{PV})	It is related to the quality of the PV modules used	$\eta_{PV} = \frac{P_{DC}}{G_{POA} \times A_m}$
Inverter efficiency (η_{inv})	Inverter efficiency is always crucial for PV plant performance	$\eta_{en} = \frac{E_{AC}}{E_{DC}}$
Overall efficiency (η_{all}) [11]	This parameter can be used as a general measure for the comparison of PV Plants	$\eta_{all} = \frac{P_{AC}}{G_{POA} \times A_m}$

installed in the arid climate of Morocco and observed that different technologies performed contrarily in different weather seasons [14].

Sidi et al. investigated the efficiency of two out of 17 PV arrays in a 15MWp PV system in Mauritania using the onsite data and showed the performance ratio (PR) from 63.59% to 73.56% [15]. The PR is varying up to 10% here. The limitation here is that the analysis was limited to specific arrays (arrays 1 and 17) of the solar PV system.

Kumar and Sudhakar analyzed 10 MWp seasonal tilt Solar PV plants at Ramagundam the performance from the measured onsite values. The plant works with the right amount of averaged PR (86.12%) and CUF (17.68%). In addition, PV software (PVSyst and Solar GIS) validation is also included in the study [16].

Mensah et al. not only evaluated the energy yield of 2.5 MW solar PV plants located in the northern part of Ghana but also analyzed the economic effectiveness and carbon mitigation of the plant. The main findings were annual PR (70.6%), capacity factor (16.2%), Payback period (14.95 years), and CO_2 mitigation of 3852 metric tons [17].

Padmavathi and Daniel assessed the performance of 3 MWp grid-connected SPV plants in Karnataka, India using monitored data. It was found that PR values were less than 60% in certain months due to losses from inverter failure and grid failure [18].

Goura presented the design of a 1 MW solar PV plant and determined the PR after one year of monitoring the plant [19]. Verma and Singhal examined the influence of various performance parameters and highlighted techniques to optimize energy production. In the same literature, the losses in a grid-tied solar system having an installed capacity of 20 MW were carried out [20].

Sukumaran and Sudhakar proposed 2MWp for Raja Bhoja International Airport and analyzed its performance using PV software [21].

Martinez et al. carried out extensive work on the performance of six large-scale PV power plants in the south-central region, Spain, with different topologies. It was reported that the expected efficiency of the large-scale plant varies between 10% and 12%. It was also concluded that in fixed axis PV systems, the effect of wind speed is less pronounced. The plant had an excellent Capacity use Factor (CUF) value with variation concerning peak-load demand [22].

Necaibia et al. evaluated the impact of the desert climate on small-scale solar plant performance in a hot, dry climate, which had a reduction in yield output [23].

Daher et al. computed the PV performance parameters for the kW scale solar PV system in a maritime climate using plant energy output and meteorological data. It was observed that the lowest value of efficiency (10.29%) and Performance Ratio (76.5%) happened on a clear day with the highest module temperature (41 °C) [24]. A climate-corrected performance ratio has been determined in this study [24].

The performance of the 5kWp grid-connected system in the rooftop of building in Morocco was analyzed by Attari et al. In this paper, various PV plant losses were estimated, and found that losses are higher in summer due to soiling, dust, and lack of timely maintenance [25].

Ya'acob et al. found that a tracking PV system is effective as compared to a fixed-tilt system. This conclusion is most suited for small-scale solar systems [26]. Loss forecasting is included in the study carried out by Raj et al., 2016, for 100kWp Solar PV Power Plant [27]. Mekhilef et al. studied the effect of dust, moisture, and air velocity on photovoltaic cell efficiency and concluded that humidity decreases the performance of photovoltaic solar cells [28]. Dubey et al. observed that operating temperature influences the efficiency of solar PV modules [29].

Most of these studies analyzed the performance of the PV plants by finding the performance parameters.

1.2. Research gap

Most of the prior studies on the performance of PV power plants are carried out for finding the main performance metrics of solar PV plants installed in different geographical locations. Even though some of the studies are conducted in tropical climates, no serious effort was made to study the impact of weather, especially the influence of the monsoon season on utility-scale PV power plants. Despite the lesser intensity of solar radiation during the monsoon months, a lot of PV power plants are being installed in the rain-dominated regions for utilizing the higher radiation in the rest of the period. In order to fulfill the research gap and to understand the performance loss during monsoon seasons, a detailed study on the performance of utility-scale PV power plants in a rain-dominated tropical climate is carried out.

1.3. Objective of the study

The performance of utility-scale solar power plants is greatly influenced by the unique climate prevailing in these regions. The study aims.

- To analyze the 2 MW utility-scale solar PV plant performance in the rain-dominated tropical climate using actual operational data.
- To study the effect of the monsoon season on the energy yield and performance of a solar photovoltaic plant.
- To compare the performance of solar PV plants in rain-dominated tropical regions with other climatic locations.

2. General description of the 2MWp solar PV power plant at Kuzhalmannam

2.1. Site location and weather condition

India is geographically lying between 7^0 and 37^0 latitudes in the northern hemisphere [3]. The solar radiation (GHI) map of India indicates a solar density of above $200 W/m^2$ per month in most of the regions. Kerala state in India is part of the southern Indian peninsula close to the equator. The original climate in Kerala is characterized by two monsoon periods: southwest monsoon and northeast monsoon, with more than three months of heavy rainy seasons [30]. The Kerala climate seasons include Summer (February to May), Winter (December to January), Monsoon-South West (June to September), Monsoon –North East (October to December). The 2MWp solar power plant site is located near Kuzhalmannam junction, Kerala State in South India. The geographical coordinates of the above 2 MW location are 100 43′ 2.1″ N, 760 36′ 48.1″ E with an altitude of 96 m above mean sea level. This solar power plant is

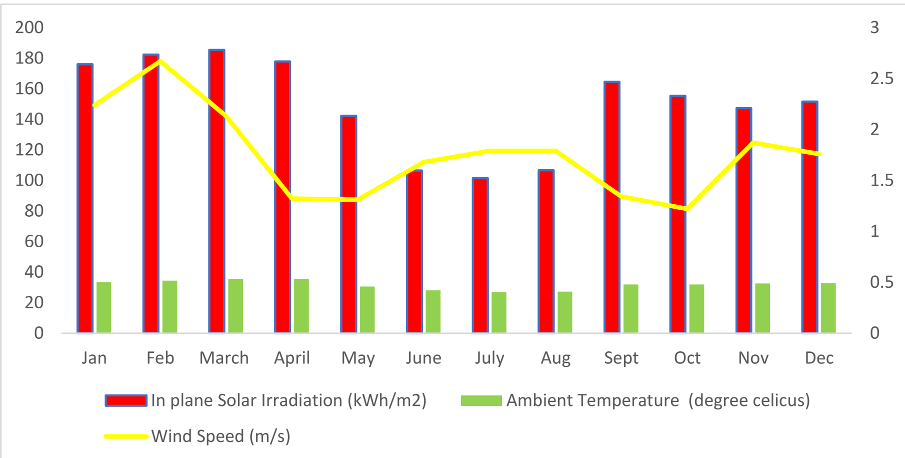

Fig. 1. Monthly variation of solar irradiance, ambient temperature, and wind speed.

connected and feeding power to the local grid facility owned by the public utility, Kerala State Electricity Board Ltd. The highest in-plane solar irradiation is recorded from January to April, with a cumulative average of 180.41 kWh/m^2. The lowest solar in-plane insolation is measured during the months of June (106.5 kWh/m^2), July (101.37 kWh/m^2), and August (106.64 kWh/m^2). This change is attributed to the southwest monsoon climate prevailing in the State of Kerala. The site receives lower solar insolation during these months. The lowest ambient temperature is measured during the southwest monsoon (June–August) when compared to the winter (December and January), which is unique for this region, where monsoon affects the solar insolation to a greater extent. The average ambient temperatures for the entire year are observed at 31.72 °C. From Fig. 1, it can be seen that apart from a dip during the monsoon period, the variation of solar irradiation and ambient temperature is nearly similar.

2.2. PV module and solar array

The PV Power Plant was constructed using 260kWp ReneSola to make polycrystalline solar PV modules. The plant consists of a total of 321 strings, and each string is having 24 numbers of solar modules in series. There are 14 String Combiner Boxes (SCBs) in the plant where the strings are connected. The SCBs are divided into two sections, and each section is connected to the input of each inverter. The approach road is dividing the entire solar array of the 2 MW solar PV plant into two islands, and each island of PV modules is connected to each of the inverters. All solar modules are ground-mounted on the strong mechanical structure, fixed at 12^0 tilt with south orientation and zero azimuth.

2.3. Power Conditioning Units/Inverters

Two numbers of high-frequency PWM Power Conditioning Units (Inverters) are used in the PV power plant, which is Hitachi make (HIVERTER-NP201i-100KW) with a capacity of 1 MW each. Each inverter with the MPPT system is connected with seven numbers of String Combiner Boxes from the DC side. The nominal output voltage of the three-phase grid-connected inverter is 300 V. The Maximum AC power of the inverter is 1100 kW with 1200 kW DC power with a transformer-less design. The MPPT voltage range of the inverter is DC 460V–900V. The inverter is having a peak efficiency of 98.6% at minimum DC input voltage. Two inverters are placed conveniently at the Control/Inverter Room of the 2 MW Kuzhalmannam Power Plant site. Both inverters were equipped with a ducting facility for heat dissipation. The inverters have display features for reading the instantaneous readings of power, DC input voltages, AC output voltage in all phases, frequency, solar irradiance, etc.

2.4. Balance systems

Balance of the system includes a 2.5MVA Transformer, String Combiner Boxes (SCBs), DC and AC Cables, Earthing systems, Lightning Arrestors, SCADA systems for monitoring of the PV plant, Power Evacuation Facility, Metering arrangement, etc. Two MW Kuzhalmannam PV power plant has a 2.5 MVA transformer with two primary windings connected to the stars and a secondary winding connected to the delta.

3. Methodology

3.1. Data acquisition from the SCADA system

Kuzhalmannam 2 MW, a solar PV power plant, is integrated with SCADA for recording, storing, and transfer of data to the central computer and remote terminal units. An integrated SCADA system records regular intervals of solar irradiance, generation of energy, wind speed, ambient temperature, and module temperature. It stores information in the server and retrieves the information to update the monitors in the control room. Data recording is in accordance with the IEC Standard 61724 monitoring guidelines [18]. The operational data of the SPV power plant, along with radiation data, are retrieved from the SCADA for the period ranging from Jan 1 to Dec 31 during the years 2018 and 2019. At the 11 kV interconnection point, an energy meter was installed by the local utility for metering and billing purposes, which would also serve to register net exports and imports into the grid. The energy meter is fixed by the local service at the interconnection point for metering, and billing purpose is used for accounting for the energy export and import to the grid. The plant performance is evaluated with reference to the climate data and the impact of weather patterns prevailing at the site.

3.2. Energy analysis: Performance Indicators of PV plants

International Electrotechnical Commission (IEC 61724) defines the set of measures for the performance evaluation of solar power plants [24]. The standardized performance metrics allow us to better evaluate PV systems of different configurations and locations.

Energy Output: DC Energy Output and AC Energy Output are the main indicators of the performance of the PV power plant for the specified period.

Yield parameters: These parameters represent the energy generation of solar PV plant generation concerning installed peak power. It is found after normalizing the PV plant energy output.

CUF and PR of Utility-scale PV plants: Capacity Utilization Factor (CUF) and Performance Ratio (PR) are the most critical performance matrices used in analyzing and comparing the performance of PV powerplants.

Efficiency parameters: The efficiency parameters for the PV power plant are PV module, inverter, and overall efficiency. System efficiencies are normalized to the array area.

Loss parameters: The energy loss occurs in a solar PV plant during photoelectric conversion and DC to AC conversion. It is represented in terms of array losses and system losses.

Comparison with other climates: A comparison of the PV plant performance was done based on this study's results with plants located in different climates around the world (Algeria, Kuwait, Jordan) (see Table 5). The specific yield of the plant was estimated for the reported PV plant in the literature for comparison. Table 6 provides the selected site for comparison.

4. Results and discussion

4.1. Effect of Irradiance on energy output

Fig. 2 shows the PV power plant's monthly average production of AC output with irradiance. The monthly total energy generation of the PV system during the reference period (Jan 1 – Dec 31, 2018) varied from the highest generation of 2,88,285 kWh to the lowest production of 1,46,224 kWh in March and July respectively. The total annual energy injected into the grid during the monitoring period was 27, 01, 467 kWh with an average monthly energy output of 2,251,22 kWh. The AC energy generated from the solar plant throughout the year clearly follows the In-plane solar irradiation (kWh/m^2/month) at the site. The summer months have a comparative upper edge for solar energy generation than the winter months, though the higher ambient temperature affects the energy output.

The energy output from the solar power plant is naturally low because of the lesser in-plane irradiation observed during the southwest monsoon months, which has got a higher impact on solar radiation received at the site. The lowest energy generation (1,46,224 units) occurs in July due to the reduced solar irradiation during the peak monsoon climate. The dip in solar radiation during July and August of 2018 was unprecedented because of the heavy rain that happened in the region during this month. The generation is high during the summer months.

4.2. Performance ratio and capacity factor

PR is a post-installation quality performance metric. It establishes the level of performance of PV plants based on irradiation and availability of the grid. Generally, the PR of solar plants in tropical regions ranges from 75% to 85%. The remaining 15%–25% losses in performance shall be in the account of temperature, weather conditions, losses of the power system, cable losses, near shading losses, IAM, Mismatch, Soiling, and LID effect. The highest average monthly PR is 78.37% during March, and the lowest average monthly PR was documented at 72% during the rainy month of July. Further, due to the higher ambient temp in April, the thermal loss is increased and PR is reduced during this month. As observed, the PR and AC energy output show a dip in monsoon seasons. As a general observation, it is observed that there is no dramatic rise or dips in PR values for the PV power plant except for some variation during the rainy season. The average PR was found as 74.91% which is satisfactory.

Generally, on average, CF of solar PV plants varies from 15 to 20%.CF is a measure of pre-estimating the plant's generation capacity/availability using yearly average solar irradiation. The 2 MWp power plant's average capacity utilization factor (CF) value is about 15.61%. The highest CF is obtained in March (19.99%) while the lowest is in July (10.14%). As in Fig. 3, in the month of July, the CF value is lower due to lower output during the monsoon months. The summary of the performance of the 2MWp solar power plant during the measured period from 2018 to 2019, is summarized in Table 7.

4.3. System yields

Fig. 4 details the variation of several yield factors of the solar power plant during the measured period. The reference yield is maximum during March (185.38 h/month) and minimum during July (101.37 h/month). The highest and lowest value of final yield also happens during the same months with a maximum of 143.93 h/month and a minimum of 73.00 h/month. It can be seen that the yield has higher values from February to April when compared to other months, obviously due to higher solar insolation. Also, yield values in the year are observed to be lowest during the rainy season. This is typical for the humid tropical geographical region where the monsoon seasons have a more significant impact on the yield parameters.

4.4. System efficiencies

The PV module efficiency rose from 12.03% in January to a value of 12.66% in March, followed by variations until September (Fig. 5). The highest PV module efficiency of 12.78% occurred in the month of December, obviously due to optimum solar insolation and a comparatively cooler climate. The lower efficiency in the rainy month of July 11.74% can be traced to the drop in energy output.

Table 5
Loss parameters in PV Plants.

Performance parameter	Unit	Significance	Equation
Array Capture Loss (La) [3]	kWh/(kWp-day)	This loss is due to the variation of actual irradiance and reference irradiance	$L_A = Y_R - Y_A$
System Loss (L_S) [3]	kWh/(kWp-day)	Highlights the importance of the selection of inverter & AC cables	$L_S = Y_A - Y_F$

Table 6
Site selection for comparison.

S. No.	Name of site	Country	Climate classifcation	Reference
1	El Bayath (23.39MWp)	Algeria	Dry (Bwh)	[1]
2	Shagaya Park (11.15MWp)	Kuwait	Dry (Bwh)	[5]
3	Irbid (5MWp)	Jordan	Temperate (Csa)	[6]
4	Kuzhalmannam (2MWp)	Kerala, India	Humid tropical climate	This study

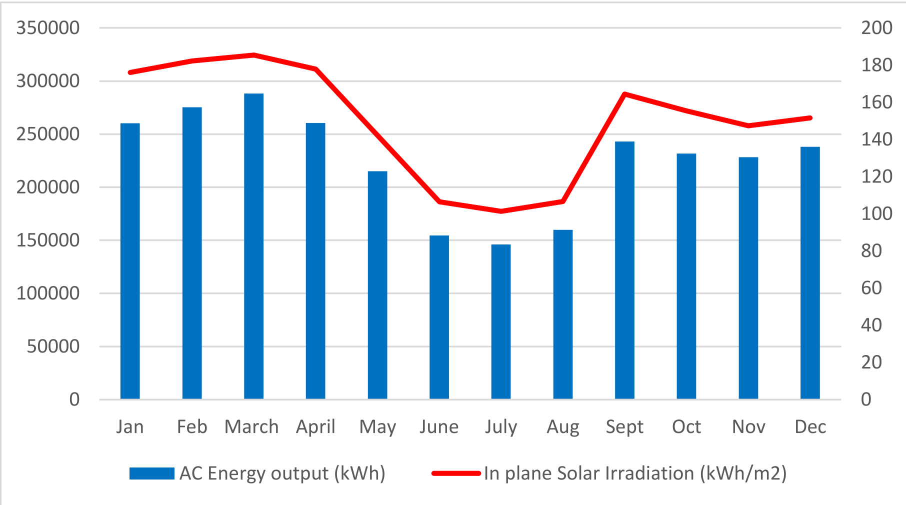

Fig. 2. Monthly variation of AC energy output with irradiance during the reference year.

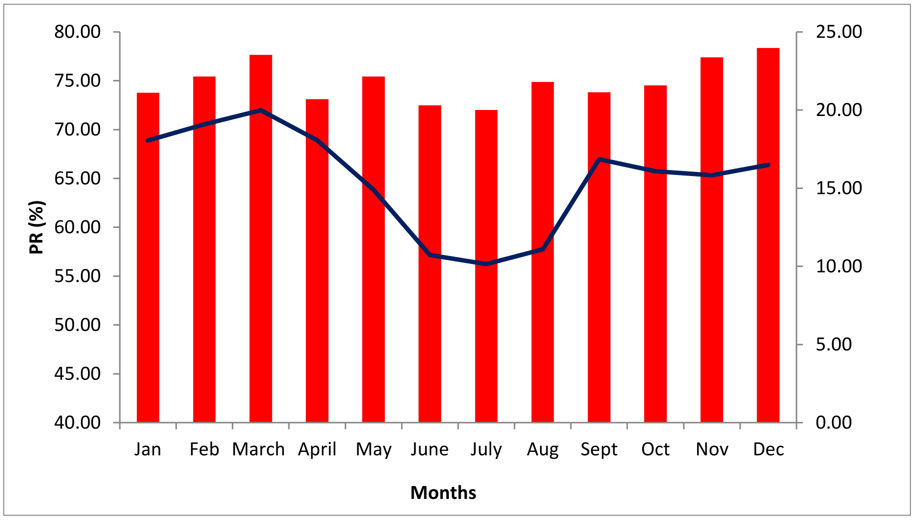

Fig. 3. Monthly variation of PR and CF during the Reference year.

Table 7
Summary of the 2 MW PV Plant performance.

Performance parameter	Unit	2018	2019	Average
Annual energy generation	MWh/year	2701.47	2709.6	2705.53
Monthly average generation	MWh	225.12	225.8	225.46
Average daily generation	kWh	7420.78	7423.56	7422.17
Average performance ratio	%	74.91	71.87	73.39
Average capacity utilization factor	%	15.39	15.44	15.41

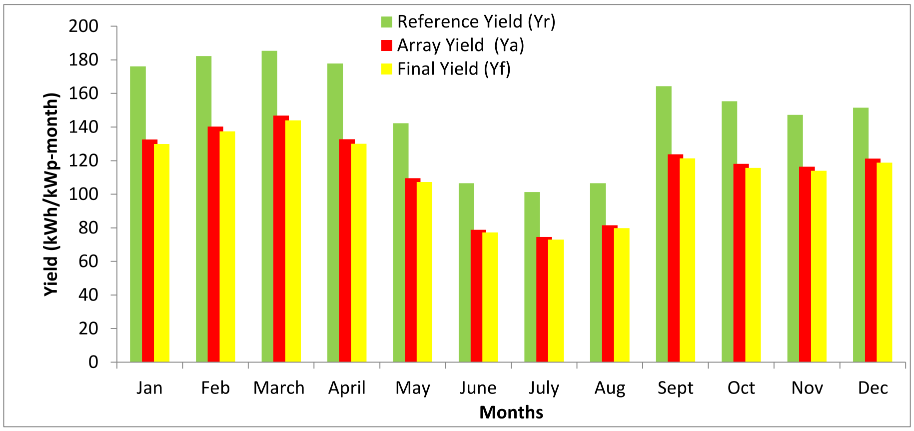

Fig. 4. Monthly variation of Reference Yield, Array Yield, and Final Yield during the Reference year.

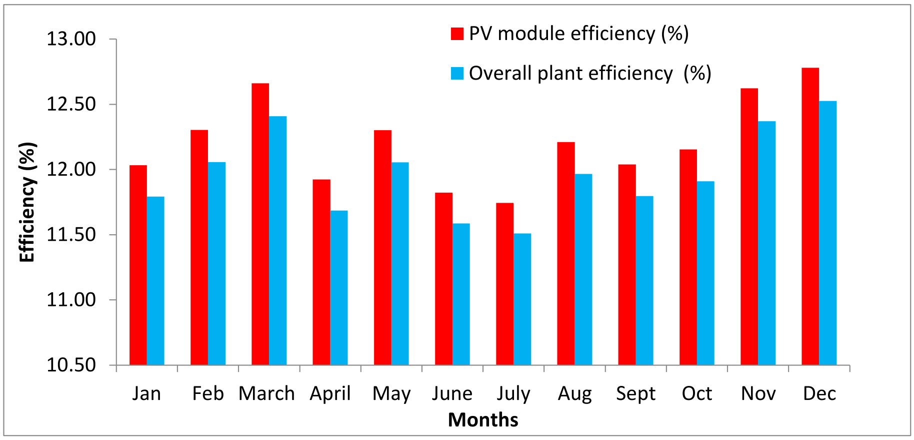

Fig. 5. Monthly variation of PV Module and Overall plant efficiency during the reference year.

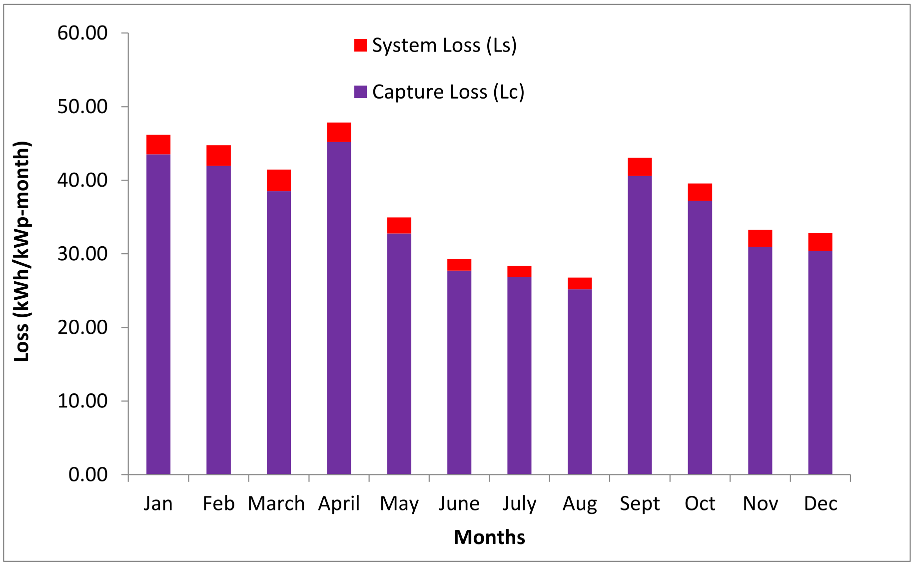

Fig. 6. Monthly variation of system and capture losses during the reference year.

The overall plant efficiency follows the PV module efficiency throughout the year with a slight difference, which is attributed to the system losses that include inverter losses and AC losses. The overall efficiency of the PV plant varies from a maximum of 12.78% in December to a minimum of 11.51% in July. The average efficiency of the PV plant is comparable to the PR values which also depend mainly on the weather conditions during the season. The highest efficiency of the plant in certain months is obviously due to better solar insolation and relatively lower module temperatures compared to the summer months.

4.5. System losses

The capture loss is highest in the month of April (45.18 kWp/kWh per month) due to the combined effect of high solar irradiation and ambient temperature (Fig. 6). The rainy month of July recorded the lowest PV capture loss of 26.88 kWh/kWp. It can be seen that capture loss is less during the southwest monsoon months except for September, owing to the increased intensity of solar radiation.

System losses have minimal effect on solar power plant energy output. System losses and capture losses are lower in rainy months, obviously due to less generation (kWh/kWp) and lower ambient temperature. Since the capture losses are less, the PV Modules are comparatively clean during rainy months. System losses (Inverter Losses, AC-DC transmission losses, transformer losses) are not explicitly affected by the rain.

5. Discussion

5.1. Effect of monsoon on energy generation (2018 & 2019 data)

For a better understanding of the effect of monsoon on energy generation, the energy generation is analyzed based on the various local weather conditions.

Summer (February to May): 4 months.

Winter (December to January): 2 months.

South West Monsoon (SW) (June to September): 4 months.

North-East Monsoon (NE) (October to December).: 3 months.

The AC solar generation of the plant during 2018 and 2019 has been studied for various seasons and is presented in Fig. 7.

There is an apparent dip in solar generation during the heavy rainfall season (SW: Southwest monsoon), and the significant effect of rain on the AC generation is evident in the consecutive years as well. This is in direct correlation with the rainy months that consistently occur during June, July, and August in this climatic zone. This is an example of a typical regional weather pattern that significantly affects the solar energy production associated with a dramatic increase in cloud cover and rainfall during the southwest monsoon seasons. When comparing the solar generation during climate seasons, the highest production occurs during the summer season (Feb, March, April & May) in both 2018 and 2019. This clearly establishes a finding that rainfall affects the output of a solar power plant in a humid tropical region like Kerala since it affects the solar radiation directly and hence the electricity generation. The percentage drop in energy generation and losses during SW monsoon seasons due to rainfall reaches up to 36% compared to the annual average generation.

5.2. Comparison with other climates

Specific production or specific yield is used as an index to compare the performance of PV plants across various climates. As observed in Fig. 8, the distribution of the specific yield of a PV power plant in different months in a humid tropical region is unique when compared with the other climatic regions. The dips in the specific yield seen during the months of June, July, and August in a humid tropical region are due to the predominant rainy seasons. The locations in Algeria and Kuwait are dry climates without any rain whereas Jordan experiences occasional rain. Based on the reported and analyzed data, the results clearly show that hot and dry climates provide higher specific yields than temperate and rain-dominated tropical climates. This is due to the prolonged hours of solar irradiance availability. However, detailed long-term and degradation analysis will provide more insights into the performance of the plants.

6. Conclusion

This research work analyses the performance of a utility-scale solar PV power plant installed in a humid tropical climatic condition with prominent monsoon seasons. Accordingly, a 2MWp Utility-scale PV system located in Kuzhalmannam, in the Palakkad District of Kerala, South India, was analyzed to study its effectiveness. The key conclusions to be drawn are as follows:

The PV plant's average performance ratio (PR) is 75.02, with an average of 15.63% capacity utilization factor (CF) over the study period. The annual generation from the PV Plant is 2701467 kWh, with an average daily generation of 7420.780 kWh.

The electricity generation during the summer months is highest because of the higher solar radiation during the season in this region. The electricity generation during winter months is also reasonably good because of the cleaner atmosphere and moderately lower temperature.

System and capture losses are lower in rainy months, obviously due to lesser generation and solar radiation. It is, therefore, worthwhile to conclude that the rain events do not necessarily affect the system losses and, thus, the performance ratio of the plant.

The energy generation of this PV plant is mainly affected by the southwest monsoon season, especially from June to August due to

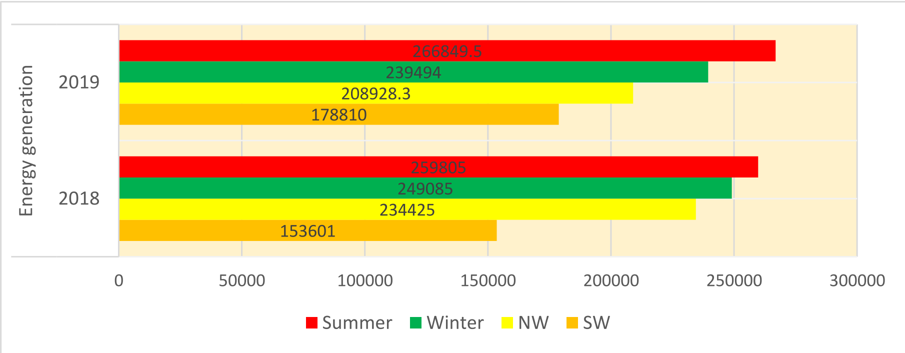

Fig. 7. Variation of Average AC generation (kWh) among seasons for 2018 and 2019.

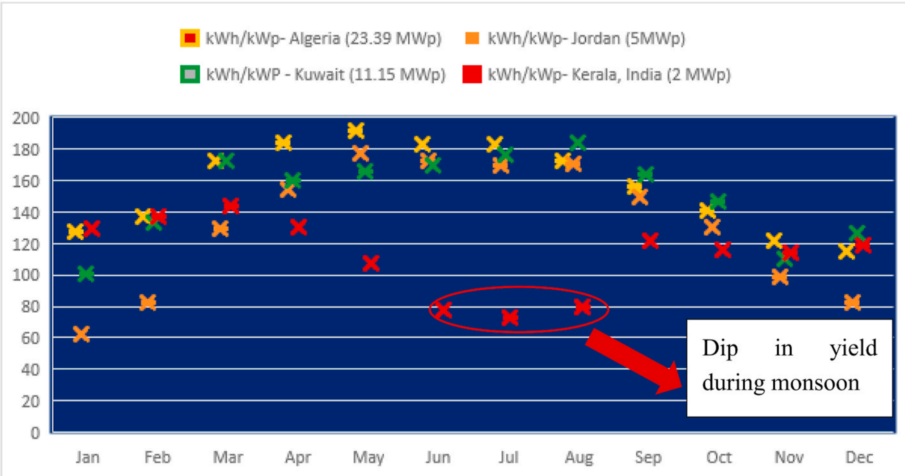

Fig. 8. Comparison of monthly specific yield at different climatic regions.

rain. The percentage drop in energy generation during SW monsoon seasons is as high as 36% compared to the annual average generation.

The energy generation of the solar PV power plant located in a humid tropical climate with monsoon seasons shows the characteristics typical to this region and it is comparatively lower than dry and temperate climate.

Author contributions

AjithGopi: Conceptualization, Writing – original draft, Resources. K. Sudhakar: Formulation, Supervision, Visualization, Writing – review & editing. W K Ngui: Supervision, Formal analysis, Visualization. IKirpichnikova: Resources, Formal analysis, Visualization. Erdem Cuce: Writing – review & editing. Review & editing, Visualization, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in the manuscript. The opinions/views/facts/findings/insights/discussions in the manuscript are solely of the authors and do not necessarily reflect the opinion of any organization involved directly or indirectly. The assumptions and case studies reported within this article are only examples and are based on minimal open-source information. The authors are not responsible for any consequences thereof with the use of information presented in work. All rights reserved to the rightful owner.No copyright infringement intended.The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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