Performance comparison of mono and polycrystalline silicon solar photovoltaic modules under tropical wet and dry climatic conditions in east-central India

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Abstract
This work focuses on the performance comparison of monocrystalline and polycrystalline Si solar photovoltaic (SPV) modules under tropical wet and dry climatic conditions in east-central India (21.16° N 81.65° E, Raipur, Chhattisgarh). This study would help to select the SPV module for system installation in the east-central part of the country. For comparative analysis, we used performance ratio (PR) and efficiency as figures of merit. The plane-of-array (POA) irradiance was used to determine the efficiency of the modules. The decomposition and transposition models calculated the POA values from the measured global horizontal irradiance. The data were analysed systematically for 6 months in the non-rainy season, from October 2020 to March 2021. Special attention was given to solar irradiance, ambient temperature and module temperature—the parameters that affect the performance of PV modules. The month of October showed the highest variation in irradiance and temperature. The highest average module temperatures (51–52°C) were observed in October–November, while the lowest average module temperatures (34°C for mono-Si and 36°C for poly-Si) were observed in December. The highest value of average monthly POA irradiance (568 W/m²) was observed in February and the lowest (483 W/m²) in December. The results showed that the monocrystalline SPV module performed better than the polycrystalline module under all weather conditions. The maximum observed values of mono-Si and poly-Si panel PRs were 0.89 and 0.86, respectively, in December. Thermal losses were higher with higher module temperatures in October and November, and lower in December due to lower temperatures. The energy yield was calculated from the measured data and compared with PVSyst simulations.

Graphical Abstract

Keywords: solar photovoltaic performance; climatic conditions; global horizontal irradiance; plane-of-array
Introduction

Today, electricity is the main form of energy used to run human life as well as to drive almost all business sectors. Due to rapid industrialization and urbanization, the demand for electricity is increasing continuously, which leads to overuse of conventional energy sources. Overuse of conventional energy sources is starting to pose issues like global warming. So, we need other energy sources that are free from global warming [1]. Limited availability of conventional energy sources, like petroleum, in fast-growing economies such as India is another factor that is shifting the focus from conventional energy sources to renewable energy sources [2]. India is blessed with various types of renewable energy sources. One of the primary considerations to go with renewable energy sources is climatic change [3]. Solar energy is a major renewable energy source that reduces the use of conventional energy sources and its potential is the highest in India. The growth of the solar photovoltaic (SPV) industry is very fast in India and a growing number of SPV technologies hold a large market share. But each technology has its drawbacks, which become evident when tested under different climatic conditions. There are many factors that affect the performance of SPV panels and systems. These are solar radiation, weather conditions, ambient temperature, cell temperature, wind speed, humidity, orientation and tilt angle. They either directly or indirectly affect the SPV panel performance [4, 5]. Here, solar radiation is the parameter most directly correlated with the output power of SPV modules or systems. Some other factors like shading, soiling, reflection and spectral losses also affect the SPV performance. Due to shading and soiling, some other effects come into the picture, such as hotspot formation and cell/module mismatch [6–8]. They all affect the output and efficiency of PV modules and systems. Incident irradiation on SPV panels generated electricity as well as heat. Temperature is one of the main parameters that affect the performance of SPV panels. The module temperature is normally 20–30°C higher than the ambient temperature because there is no heat dissipation from encapsulated cells [9, 10].

A wide range of geographical features are seen in India and climatic conditions also vary significantly in different regions. Most regions of India experience hot and dry, warm and humid, and composite types of climates. Different SPV technologies behave differently under these climates and influence the performance of modules and systems performance. Previous research has indicated that different SPV technologies have unlike patterns of behaviour for specific climatic conditions. Aoun et al. (2019) analysed the performance of a monocrystalline SPV panel in a harsh environment. They showed that the average monthly generation during the cold months was greater than during the hot months [11]. Tihane et al. (2020) showed that the polycrystalline technology performed better than monocrystalline under Agadir climatic conditions in Morocco. They also showed that the performance ratios (FRs) for monocrystalline and polycrystalline PV modules were 0.71 and 0.75, respectively [12]. Elibol et al. (2017) investigated FRs and module efficiency in Duzce Province (Turkey). The experimental results show that the FRs were 73%, 81% and 91% for amorphous silicon, polycrystalline and monocrystalline panels, respectively [13]. In view of these studies, it becomes apparent that a given PV technology needs to be tested under actual working conditions. The all-India survey conducted in 2018 did not study PV installations in the east-central part of the country [4]. SPV efficiency declines for higher operating temperatures, especially under hot-climatic conditions. We can enhance energy generation by SPV modules with lower cell temperatures, and environmental conditions also affect the performance of the SPV system. We can achieve a net-zero energy balance for a household by using SPV energy integration and reducing CO₂ emissions [14–16]. The present work discusses the performance of monocrystalline and polycrystalline Si solar PV modules in Raipur, Chhattisgarh, which is located in the east-central part of India. There is no study related to the SPV field in these areas and location-specific research is required to get a realistic assessment of the energy-producing potential of any SPV installation. So, the study aims to analyse the behaviour of commercially available Si SPV modules under the weather conditions of Raipur.

1 Materials and methods

The experimental set-up is located in the campus of IIT Bhilai, which is presently functioning from the premises of GEC Raipur (Chhattisgarh). Raipur (21.25° N, 81.63° E) is the capital of Chhattisgarh, with a population of >1 million. It is located near the centre of a large plain and experiences a tropical wet and dry climate. The modules are located on the rooftop of an academic building ~15 metres above the ground. Two different SPV modules, made of monocrystalline silicon and polycrystalline silicon, have been installed at a fixed-tilt angle of 21° (approximately the same as the latitude angle) facing south in direction. The characteristics of the SPV modules under standard testing conditions (STC), corresponding to a 25°C module temperature at 1000 W/m² irradiance, are specified in Table 1. A PV current–voltage (I–V) curve tracer (MECO-9009) with an I–V tracer channel selector (2 IN–1 OUT) is connected to the modules to measure the I–V curves every 12 minutes (0.2 h). A pyranometer (EKOSMS-40) is used to measure the global horizontal irradiance (GHI). We have installed sensors to measure the ambient temperature (DHT22 sensor installed in data logger) and the back-side temperature of the modules (LM35 sensor) as shown in Fig. 1.

The pyranometer used in the present work was received in early 2020 with a calibration certificate. The manufacturer has certified that recalibration is not needed before 2 years of operation. The I–V tracer also has a calibration certificate. The instruments need to be in proper working condition to minimize errors in the measurements. The instruments and sensors used in the present work were taken from fresh stock, as they were to be used for long-term studies. For performance analysis, the following parameters are required:

(i) daily solar irradiance (GHI and POA irradiance);
(ii) I–V and P–V curves of modules;
(iii) temperature of PV modules and ambient temperature.

| Specification | Mono-Si | Poly-Si |
|---------------|---------|---------|
| Efficiency    | 19.33%  | 17.27%  |
| Power output  | 375 W   | 330 W   |
| V_OC          | 48.7 V  | 46.3 V  |
| I_SC          | 9.94 A  | 9.24 A  |
| V_M            | 40.1 V  | 38.0 V  |
| I_M            | 9.36 A  | 8.70 A  |
| Temperature coefficient of power | −0.39%/°C | −0.38%/°C |
Solar radiation received at a location on the surface of Earth is categorized as global, diffuse and beam irradiation. But here we have measured only the global irradiance, which is also known as GHI. The pyranometer is used to measure the GHI on a daily basis and which is installed on a horizontal surface. For calculating the plane-of-array (POA) irradiance received on the surface of tilted modules, we have used a transposition model. GHI is the sum of the diffuse and beam (direct) irradiance. Here, GHI is recorded every 20 seconds daily. GHI values are saved in an Excel spreadsheet. Then the daily average and monthly average GHI values are calculated. The POA can be measured directly by using a pyranometer that is mounted in the same orientation as the modules. But in this article, we have estimated the POA irradiance from measured GHI, as only one pyranometer was available. Once the GHI data have been collected, the next step is to calculate the POA irradiance. This estimation involves two steps: (i) decomposition of the GHI into direct and diffuse horizontal components; and (ii) transposition of direct and diffuse horizontal irradiance to POA irradiance. The POA was estimated by using the Maxwell Direct Insolation Simulation Code Model (DISC) and Sandia Model (PV Performance Modeling Collaborative-PVPMC of Sandia National Laboratories) [17–19].

I–V and P–V curves have been recorded by using an I–V curve tracer (MECO-9009), which is also known as a PV analyser. It is used to vary the load and then measure the current and voltage. This instrument gives us $V_{oc}$, $V_{max}$, $I_{sc}$, $I_{max}$, I–V and P–V curves. By using these data, we analyse the behaviour of SPV modules under various climatic conditions.

The temperatures of the modules are measured by using LM35 sensors. Sensors are attached to the back side of modules, as shown in Fig. 1. Ambient temperature is measured by using a DHT22 sensor, which is attached to the data logger, as shown in Fig. 1. These data are taken every 20 seconds on a daily basis. A custom-made data logger saves daily values in an Excel spreadsheet. Then the daily average and monthly average values of various parameters such as GHI and temperature can be calculated and plotted.

The energy generated by an SPV module is an important benchmark of its productivity. The energy yield of an SPV module has been calculated based on the outdoor measurements performed under various climatic conditions during the period of October 2020 to March 2021. The energy generation of the SPV module is the integrated sum of the maximum power ($P_{max}$) values of the SPV module, which are recorded in time steps $\tau$ (taken as 12 minutes).

The energy of an SPV module can also be calculated based on the Equivalent Hours of Full Sunlight (EHFS), which is also known as the peak Sun hours. It is defined as the number of equivalent hours receiving 1000 W/m² of irradiance, which can be described for a particular day. For the EHFS calculation (by using the GHI),
we define the per-day average GHI value, then multiply it by the day length and divide by 1000 W/m². The same thing is done for a month and the average value is taken. In this way, we can estimate the monthly average values for any month of the year. Now, the output energy of the SPV module is the module-rated power (Wp) multiplied by the EHFS (Wp × EHFS). GHI, POA irradiance, module and ambient temperatures have been measured or estimated from morning (7 AM) to evening (5 PM). The energy yield, efficiency and PR are calculated from morning (8 AM) to evening (4 PM). This is done because the I–V/P–V data of the modules were recorded only between 8 AM and 4 PM due to the limited memory of the I–V tracer. Modules were cleaned on alternate days.

For comparative analysis, we also calculated the energy using PVSyst software (version: 7.2). This software is mainly used by architects, engineers and researchers to study and simulate SPV systems. For our study, we selected the location, set proper orientation according to our site and selected SPV modules with similar specifications as used for outdoor experiments from its database and simulated them. The simulation results give the total energy production, which is compared with outdoor experimental analysis [20].

1.1 Statistical evaluation

The collected data are summarized by using statistical analysis. During analysis, we have calculated the mean (average), standard deviation and standard error of the mean (SEM) [21]. These are used in all types of statistical studies, as shown in the following:

\[
\text{Mean}(\bar{x}) = \frac{\sum x_i}{n} \quad (1)
\]

\[
SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n - 1}} \quad (2)
\]

\[
SEM = \frac{SD}{\sqrt{n}} \quad (3)
\]

where \(x_i\) is the considered parameter (temperature, irradiance, power, energy, efficiency, PR) and \(n\) is the number of data items considered. We have also used the median in some plots. Suppose the \(n\) observations are arranged in ascending order. In that case, the median is the middle item if the number of observations is odd and is the mean of two middle items if the number of observations is even.

2 Result and discussion

2.1 Solar Irradiance

Fig. 2 shows the comparison between the daily average measured GHI and the daily average estimated POA values. As seen from the figure, the POA irradiance values are consistently higher than the measured GHI values during the experimental duration from October 2020 to March 2021. From 21 September to 21 March, the Sun is in the southern hemisphere as observed from Earth. So, the module orientation (21° with respect to horizontal and facing south) ensures that the in-plane radiation is more than that received on a horizontal surface. The difference in the POA and GHI values are insignificant when the irradiance values are low. Also, under cloudy conditions, the beam radiation is low and consequently the difference in the GHI and POA values becomes negligible. The maximum difference between the values is obtained on sunny days. When the sky is clear, the beam radiation on a tilted surface is higher compared to on a horizontal surface. That is why the sunny days show the maximum difference between the GHI and POA irradiance values.

In general, the peaks observed in the figure correspond to sunny days with relatively high irradiance and the valleys correspond to cloudy or rainy days with relatively low irradiance. The months of October and March show relatively lower variations in measured GHI and estimated POA values compared to other months. As mentioned above, the difference in beam radiation received on a horizontal surface and a tilted surface is higher on sunny...
days. And this difference is even more discernible on sunny days in winter months of December, January and February because the maximum solar elevation angle is relatively low in these months. For the location in IIT Bhilai at which the panels are installed, the height of the Sun at 12 noon was 59.8° on 15 October 2020, 45.6° on 15 December 2020, 48° on 15 January 2021 and 67.1° on 15 March 2021. These data were obtained from PVSyst and show that due to the lower solar elevation angle in the winter months, the difference in measured GHI and estimated POA values is higher compared to that in October and March, which have a higher elevation angle.

Fig. 3 shows the daily maximum and minimum values of the GHI and the POA irradiance values. The monthly peak GHI solar irradiance ranges from 847 to 1100 W/m² and the monthly peak POA solar irradiance ranges from 1007 to 1204 W/m². The monthly minimum GHI solar radiation ranges from ~15 to 31 W/m² and the monthly minimum POA solar irradiance ranges from 15 to 36 W/m². These values were taken from morning (7 AM) to evening (5 PM), but for PV applications generally, irradiance values of <100 W/m² are not considered. As discussed above, for low values and for cloudy days, the GHI and POA irradiance values do not show significant differences.

Figs. 4 and 5 show the monthly average GHI and POA irradiance, respectively (white triangles). The monthly average GHI values range from ~425 to 531 W/m² and the monthly average POA irradiance ranges from 472 to 568 W/m². In the box and whisker plot shown below, the upper line shows the maximum value and the lower line shows the minimum value of our data set. The middle line (red colour) shows the median of our data set and the white triangle shows the average value of our data set.

It can be clearly observed from the graph that out of the 6 months studied in the present work, March is the month with the highest amount of received GHI. The average and median values for March are higher than the corresponding values for other months. On average, December and January receive lower radiation compared to the other four months. It is because of the fact that the winter solstice occurs in December and the elevation of the Sun in the sky is not as high as in other months of the year. For our location, the lowest value of solar elevation angle is 45.4°, which occurs on 22 December. October 2020 showed the maximum variation in GHI values. It showed a highest GHI value of 1100 W/m², but the average value was lower than the values obtained in November 2020, February 2021 and March 2021. This happened because the month of October 2020 had several cloudy days in addition to several sunny days. So, a significant difference in the maximum and minimum values was obtained. A similar observation can be made for the month of November 2020. The highest monthly average POA was observed in the month of February, closely followed by March, as shown in Fig. 5. Unlike the GHI graph, the POA graph shows that the month of February has a slightly higher average value of POA irradiance than March. Due to the south-facing PV module placed at an angle of 21° with respect to ground, the tilted surface gets higher beam irradiance and hence the overall POA irradiance increases.

### 2.2 Ambient temperature and module temperature

The ambient temperature is an important factor for analysing the performance of SPV modules. Fig. 6 shows the monthly profile of ambient temperature at the location of IIT Bhilai. Fig. 6 shows that high ambient temperatures are observed in the month of March 2021. The average monthly ambient temperature ranges from ~26°C to 33°C (white triangles). The maximum temperature recorded in a single day was 40°C, which was recorded in the month of March. As can be seen, the minimum ambient temperature was 19°C recorded in February 2021. The measurements of temperature were performed between 7 AM and 5 PM daily. February shows the highest variation in maximum and minimum temperatures.

The module temperature depends on the ambient temperature and the solar irradiance. STC, corresponding to a 25°C module temperature at 1000 W/m² of irradiance, are not observed in
the outdoor experiment. The average monthly module temperature ranges from 34°C to 52°C (white triangles) and the maximum module temperature recorded was 81°C for the mono-Si PV module in October 2020. For the poly-Si PV module, the average monthly module temperature ranges from 37°C to 52°C (white triangles) and the maximum module temperature recorded was 79°C in October 2020. SPV module temperatures can be lower or higher than the ambient temperature, which is dependent on the climate condition and irradiance, and can be observed by analysing Figs 5–8.

As we know, incident radiation on the panel surface generates electricity as well as heat. Normally, commercial panels can convert 15–20% of the incoming irradiation into electricity and the remaining part simply causes lattice vibration in the material (Si) and generates heat. The generated heat does not dissipate properly from encapsulated solar cells. Therefore, the module or cell temperature is higher than the ambient temperature. The module temperature also depends on the operating point, optical properties, packing density of the cells and shading effects. In the winter season (December, January and February), the temperature of the panel was lower than the ambient temperature in the morning time. With increased solar radiation, the temperature of the panel increased and went higher than the ambient temperature. We have observed that the monthly average temperature of the panel increases gradually with the monthly solar irradiance.

The effect of temperature on SPV panel behaviour can be understood by the temperature coefficient of power of the panels. A large temperature coefficient decreases the performance of the SPV panel. Here, thermal losses have been evaluated by multiplication of the temperature coefficient by the temperature difference between the panel temperature and the panel tested temperature (25°C) [22]. The temperature coefficient

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**Fig. 4:** Monthly global horizontal irradiance (GHI) profile. In the box and whisker plot, the upper line shows the maximum value and the lower line shows the minimum value of the data set. The middle line (red colour) shows the median of the data set and the white triangle shows the average value of the data set.

**Fig. 5:** Monthly plane-of-array (POA) irradiance profile.
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is $-0.39\%$ per degree Celsius for the mono-Si PV panel and $-0.38\%$ per degree Celsius for the poly-Si PV panel given by the manufacturer, as shown in Table 1. The average monthly thermal losses of different PV panels are shown in Fig. 9. The figure shows that lower thermal losses were observed in December and significantly higher losses were seen during October and November.

When we compare Figs 7, 8 and 9, then we can clearly say that thermal losses are higher with higher module temperatures in October and November and lower in December. Thermal losses increase gradually from December 2020 to March 2021 according to the increase in the temperature of the modules. We also observed that the temperature rise of the poly-Si PV panel is higher compared to that of the mono-Si PV panel. Hence, thermal loss is higher for the poly-Si panel. When we compare the performance of the PV modules, we see from Figs 9, 13, 14 and 15 and Table 2 that the PR and energy generation were lower in October and November 2020 compared to other months. It shows that higher module temperatures increase the thermal losses and decrease the performance of modules.

2.3 Performance analysis

Power output, efficiency, energy generation and PR are the main parameters to analyse the performance of modules, systems and plants. The solar irradiance is the main environmental factor that affects the performance of the SPV modules. For comparing the performance of the modules, we have used the output power under different irradiance and temperature conditions. Fig. 10 and 11 show the output of SPV modules with respect to incident irradiance. We can clearly observe that the output power of each module (mono- and poly-Si) increases with increasing the solar irradiance.
As expected, the power output of both the modules in low irradiance is not significant but under high irradiance, modules deliver higher power.

Fig. 12 shows the variation in module efficiency as a function of irradiance. It is the most important parameter that shows energy-conversion efficiency. As an energy-conversion system,
the efficiency of a module is denoted as the ratio of the power output to the power input [11, 23, 24]:

$$\eta = \frac{P_m}{P_{STC}}$$  \hspace{1cm} (4)

We can observe that the efficiencies are much lower than the STC values even when the irradiance value is close to 1000 W/m². It happens because the ambient and cell temperatures are much higher than the STC value. Under low irradiance, the module efficiencies are low, but for high irradiance values, the module efficiencies are higher. The mono-Si PV module is more efficient than the poly-Si module under all irradiance conditions (Fig. 12), although the difference is not significant for low-irradiance conditions.

PR is the most important and commonly used parameter for analysing the performance of different SPV technologies. It is the ratio of the actual and theoretical energy output values of a PV
module or system. It describes the performance of a SPV module/system during a particular time period. It is expressed by the following equation according to the IEC 61724 standard [11, 25, 26]:

$$PR = \frac{E_{dc} \times G_{STC}}{P_{STC} \int_{t_o}^{t_n} G \, dt}$$

where $E_{dc}$ is the energy produced by the SPV module, $G_{STC}$ is the solar irradiance under STC, $P_{STC}$ is the nominal power under STC and $G$ is the time-varying incident solar irradiance during time period $t_o$ to $t_n$.

Figs. 13 and 14 show the daily average PRs and monthly average PRs of mono-Si and poly-Si PV panels from October 2020 to February 2021. From the figures, it can be inferred that the winter month of December showed the highest PR values for both types of modules. The overall PR was 0.89 and 0.86 for mono-Si and poly-Si modules, respectively. In general, the winter period, extending from late November to mid-February, had many days on which the PR values were >0.9. Throughout the studied time period, there are some days on which there is no significant variation between the PR of the mono-Si PV panel and the poly-Si
PV panel because these days were cloudy and we know that in low irradiance, the difference in efficiency of the modules is not significant. Based on the PR results, we can say that the monocrystalline Si PV module is more efficient than the polycrystalline Si PV module under different weather conditions in the studied location in east-central India.

2.4 Specific yield

The output energy of the PV modules is another important indicator of the performance of the modules. It is the most useful and informative parameter from a user’s viewpoint. We have recorded the I-V/P-V curves of the modules regularly over the long experimental duration (October 2020 to February 2021) to evaluate their energy yield. The energy generated by the SPV module is the time-integrated sum of the maximum power \( P_{\text{max}} \) values of the SPV module, which are recorded in time steps \( \tau \) (taken as 12 minutes). The energy of the SPV module is calculated by the following equation [25, 27]:

\[
E_{\text{dc}} = \tau \sum_{\tau} P_{\text{max}}
\]  

EHFS has been used to calculate the energy of the SPV module by the following equation [28].

\[
E_{\text{dc}} = W_p \times EHFS
\]
Specific yield \( Y \) in kWh/kWp) is also commonly used for comparison purposes of the SPV system. It is defined as the total produced direct-current (DC) energy \( E_{dc} \) (kWh) over the rated installed capacity \( P_{dc} \) (kWp) [29]:

\[
Y = \frac{E_{dc}}{P_{dc}}
\]

Table 2 shows the monthly per-day average and monthly energy generation of the mono-Si and poly-Si panels, which has been calculated by using different methods and also using PVSyst software for comparative analysis.

Fig. 15 shows the monthly per-day average energy generation of the mono-Si and poly-Si PV panels from October 2020 to February 2021. We can observe that the measured energy generated by the modules shows an increase as we go from October to February. February shows the highest energy generation in the studied time period. The energy-yield trend observed in Fig. 15 is different from the PR graphs shown earlier. A combination of irradiance and temperature conditions is responsible for this behaviour. As seen from Figs 4 and 5, and Figs 7 and 8, the month of February 2021 had a high value of average POA irradiance and relatively low average module temperature values. This favourable condition led to a higher overall energy generation in February compared to the other 4 months. The November average irradiance was more than the December average irradiance, but the energy generation was higher in December because of the lower ambient and module temperature than in November (Table 2).

Table 2 and Fig. 15 clearly show that the energy calculated by software and using EHFS are not the same as the energy measured actually in outdoor conditions. Software databases take long-term average values of irradiance, temperature, and average daily sunshine hours. These values may differ significantly from the long-term average values when we study the PV performance for only a single year or season. So, energy generation depends on many factors such as irradiation, temperature, weather conditions and geographical location, and need to be measured in actual field conditions.

Here, it cannot be concluded that the mono-Si PV panel generation is higher than poly-Si PV panel generation only because of the higher power rating of the mono-Si PV panel. As mentioned in the introduction section, Tihane et al. [12] found that poly-Si panels had a higher value of PR than mono-Si panels under Moroccan conditions.

Using Equation 8 and Table 2, we can present the specific yield of panels for 5 months. For the mono-Si panel, the specific yield is calculated as 677.17, 690.24 and 563.55 kWh/kWp using the simulation, EHFS and measured methods, respectively. For the poly-Si panel, the specific yield is calculated as 683.27, 690.42 and 549.12 kWh/kWp using the simulation, EHFS and measured methods, respectively. Here, the specific yield is higher for the poly-Si panel, resulting from the simulation and EHFS calculation. But the specific yield is higher for the mono-Si module, resulting from outdoor measurement. So, the highest yield is produced by the mono-Si panel under Raipur conditions.

Therefore, it is essential to study different PV technologies at a particular geographical site to make an informed decision. Upon analysing Figs 13 and 14, we can clearly observe that the mono-Si PV panel is more efficient than the poly-Si PV panel at the geographical location of Raipur. So, the higher power rating of the mono-Si module combined with its higher efficiency leads to a significantly improved performance than the poly-Si module. After analysing all the results, we can conclude that the mono-Si PV panel is more efficient and preferable than the poly-Si PV panel under the climatic conditions of Raipur in east-central India.

However, for a user to make a more informed decision, the cost of PV modules should be taken into account. This cost analysis is not the main objective of the present work, but some observations can be made. The cost of the mono-Si module was ~1500 Rupees (USD 20) higher than that of the poly-Si module. So, a residential or low-power user, say of ≤5 kW, can pay the extra amount and install mono-Si modules, and get his investment back within a shorter time. For such small systems, the higher cost of mono-Si modules may be justified. On the other hand, large-scale system operators that utilize tens of thousands of modules may still prefer to go with poly-Si modules to lower the initial amount of required capital.

3 Conclusion

The performance comparison of poly-Si and mono-Si SPV modules under the tropical wet and dry climatic conditions at Raipur (IIT Bhilai) has been carried out. The purpose was to determine which SPV module provided more efficiency and energy under various weather conditions. In the market, a wide range of SPV technologies are available and it is important to have information about their performance under different climatic conditions. This study will help to select the SPV module for system installation in the east-central part of the country.

For calculating the efficiency of the modules, we first calculated the POA irradiance by using measured values of GHI. This estimation used decomposition (DISC) and transposition (Sandia) models. This estimate is necessary to calculate the efficiency and PR of the PV modules.

The power generation of both the panels is not significant under low-irradiance conditions and differ by <1 percentage point at a GHI value of 400 W/m². However, the mono-Si PV module outperforms the poly-Si module under all conditions studied in the present work. The mono-Si PV panel displayed more efficiency, a higher PR and a higher specific yield \( Y \) than the poly-Si PV panel in the geographical location of IIT Bhilai. So, mono-Si PV panels may be preferred in east-central India. During the study, we observed that the maximum average ambient temperature was recorded in the month of March, but the maximum average module temperature was observed in the month of November. Thermal losses are higher with higher module temperatures in October and November, and lower in December due to low temperatures. Thermal losses increased gradually from December 2020 to March 2021 according to the increase in temperature of the modules. Thermal losses are higher for the poly-Si PV panel due to a higher temperature rise than the mono-Si PV panel. Energy generation was maximum in the month of February for both the panels and minimum in October. The mono-Si PV panel is more costly than the poly-Si PV panel. But the performance of the mono-Si PV panel is better than that of the poly-Si PV panel. So, both residential and small system users can recover the extra investment in a few years and can get profit in terms of energy and money in the long run.

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Conflict of interest statement

None declared.

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