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Short-term performance variations of different photovoltaic system technologies under the humid subtropical climate of Kanpur in India

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Abstract: The study discusses the short-term performance variations of grid-connected photovoltaic (PV) systems installed in Kanpur, India. The analysis presents a holistic view of the performance variations of three PV array technologies [multi-crystalline (multi-Si), copper indium gallium diselenide and amorphous silicon] and two inverter types (high-frequency transformer and low-frequency transformer). The analysis considers the DC–AC conversion efficiency of the inverter, system performance through performance ratio (PR) calculations, energy variations between fixed and tracking systems and the comparison between calculated and simulated data for the examined period. The energy output difference between the tracking and fixed systems of the same PV technology show that these are dependent on differences in temperature coefficient, shading and other system related issues. The PR analysis shows the effect of temperature on the multi-Si system. The difference between the simulated and measured values of the systems was mostly attributed to the irradiance differences. Regarding the inverter evaluation, the results showed that both inverter types underperformed in terms of the conversion efficiency compared with nameplate values.

1 Introduction

Precise and regular evaluation of photovoltaic (PV) system performance is vital for the continuing development of the PV industry. The examination of system performance can produce important information for future research and can provide an evaluation of the quality of the system for manufacturers, installers and customers [1]. Performance monitoring enables the identification of malfunctions and operational issues and can give an insight into requirements for system maintenance. Monitoring also helps to avoid economic losses because of operational issues, especially for large PV plant operators. According to IEA PVPS Task 2, the lack of detailed monitoring contributes to the lack of long-term and reliability performance experience [2]. The performance ratio (PR) is the most commonly used index for assessing the performance of PV systems. According to IEC 61724, it is defined as the ratio of a PV system's actual energy yield to its reference energy yield [3]. During the last 20 years the average PR has been improved from around 0.65–0.85 [4]. Apart from the development of the technology, this improvement could also be partly attributed to PV system performance monitoring.

India has recently seen a surge in the installation of PV systems, since the introduction of the Jawaharlal Nehru National Solar Mission. In 2013 alone, 1 GW of PV capacity was added and the rate of installation of grid-connected PV systems is expected to increase further [5]. It is important to study system performance in Indian conditions to gain knowledge for the best exploitation of these systems. This paper discusses the short-term performance variations of grid-connected PV systems installed at the Indian Institute of Technology Kanpur (IIT-Kanpur), Solar Energy Research Enclave (SERE). This is a new PV research installation built specifically for the purpose of understanding field performance of different PV technologies under Indian conditions. This installation is one of the first in India to have a detailed monitoring system and the analysis takes into account the limited installer experience in the case of sensors and data acquisition systems (DAS).

Kanpur is located in the state of Uttar Pradesh and has a humid sub-tropical climate. This location has an average annual ambient temperature of 25.1°C, with monthly values ranging from 15.8 to 32.1°C, and an average relative humidity of 54.0%, with monthly values ranging from 30.6 to 82.3% [6]. The challenges presented by the operating environment include high-ambient temperatures and high levels of dust deposition on the PV array, making regular cleaning essential.

2 Field performance studies

The manufacturer specifications for the PV system components alone are not sufficient to accurately predict PV operation under various climatic conditions. Hence, PV field performance monitoring and data analysis are necessary for the better understanding and development of PV systems field behaviour [7]. This section presents some operational and environmental factors that affect the system operation, as well as some studies regarding the system field performance at various sites.

It is known that the measured values could differ depending on the measuring instrument used because of different angular and spectral responses [8]. For example, in Germany, on an annual average, the irradiation measured by crystalline silicon (c-Si) sensors is 2–4% lower than that measured by pyranometers [4]. Hence, the annual PR of a PV system located in Germany would be higher if it is calculated based on a c-Si sensor measurement. This has to be taken into account when PR values are being compared.

Both spectral irradiance distribution and temperature influence amorphous silicon (a-Si) module performance, while c-Si module performance is mainly influenced by the module temperature. Specifically, a-Si module efficiency increases under high temperatures because of annealing of light induced degradation. A

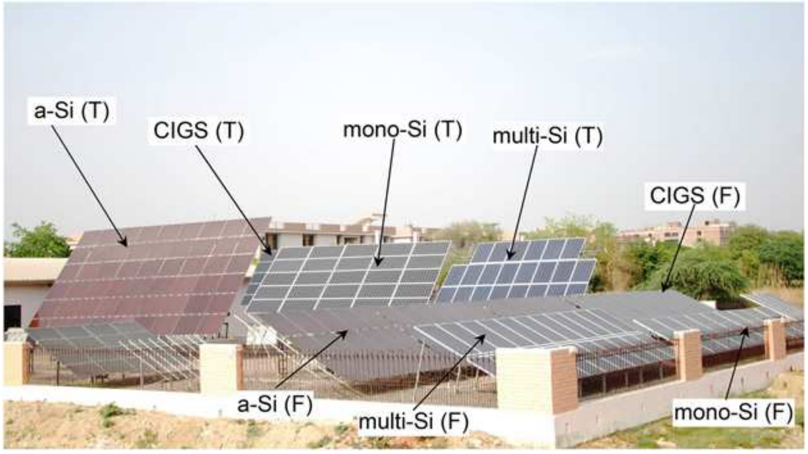


Fig. 1 *PV systems installed at SERE*

study in Kusatsu (Japan) on the outdoor performance of a-Si and c-Si modules for the years of 2004 and 2005 demonstrated that the PR of c-Si modules decreased when the module temperature increased and explained the dependence of the output voltage on the module temperature. In addition, there were more days with PR above 80% in autumn compared with days in spring, demonstrating the seasonal annealing effect of the a-Si modules. 'The recovered performance in summer continued through autumn, demonstrating that a-Si PV modules have a temperature history effect on performance' [9]. The study concluded that the investigation of the outdoor performance of the a-Si modules was more complicated than for c-Si modules because of light-induced degradation and annealing effect. The need for using a different evaluation method for a-Si modules from the one used for the c-Si modules was also revealed [9].

Field performance of six grid-connected PV systems installed at Brunei Darussalam, with a nominal power rating of 200 kW each, was analysed following the IEA performance guidelines. The location has a tropical climate with significant insolation fluctuations because of clouds. The field data for mono c-Si (mono-Si), multi-crystalline (multi-Si), a-Si, CIS, microcrystalline (nc-Si/a-Si) and Heterojunction with intrinsic thin layer (HIT) PV technologies were acquired over a year period. It was observed that the CIS system was the closer to its rated performance throughout the year, with the highest efficiency ratio, followed by the a-Si and HIT systems. The a-Si system had the highest array yield and PR; followed by HIT. The Mono-Si system showed the poorest field performance [10]. Another study conducted under a similar climate, in Malaysia, for mono-Si, multi-Si and a-Si PV technologies found that the multi-Si system had the highest PR followed by mono-Si and a-Si systems [11]. However, the results of this study were only for four days, two clear and two cloudy days. On the clear days the c-Si systems had very high PR compared with the a-Si system while in the cloudy days a-Si had similar PR to the c-Si systems. This is in contrast to the Brunei Darussalam study, which noted that a-Si efficiency was consistent on both clear and cloudy days, while c-Si technology efficiency decreased during cloudy days [10].

Table 1 Effective days for the daily PR calculations

Month	Effective days (irradiance measurements)	Effective days (temperature measurements)
October	18	18
November	19	19
December	2	2
January	3	3
February	21	8
total	63	50

Finally, a study that considered the uncertainty in PV performance parameters for three different sites in Europe showed that the annual PR uncertainty in low irradiance sites could reach 4.5%, while for high irradiance sites it is lower (around 2.5 to 3.5%). These uncertainty values were attributed to the environment of the location and the setup of the instrumentation. It was also noted that field measurement uncertainty had less influence on the performance indicators than the irradiance measurement uncertainty, which was much higher. Even though this study tried to express an upper limit for performance uncertainty, it was acknowledged that they had used conservative estimates [12]. It is quite difficult to interpret performance results from different studies, as there are many variables involved in the measurement and calculations procedure. Hence, the more detailed the description of a study, the better the understanding of its results.

3 PV systems and monitoring system description

Eight grid-connected PV systems, each of approximately 5 kW rated power, have been installed at SERE. There are four PV array technologies: mono-Si, multi-Si, copper indium gallium diselenide (CIGS) and a-Si. Each of these technologies is installed on both fixed and tracking structures. The fixed systems are south facing with a tilt angle of 26.5° (equal to the site latitude).

Fig. 1 shows the installation at SERE, with the fixed tilt systems in two rows at the front of the compound (to the right-hand side of the picture) and the pedestal mounted tracking systems positioned behind them. There are also two small stand-alone arrays

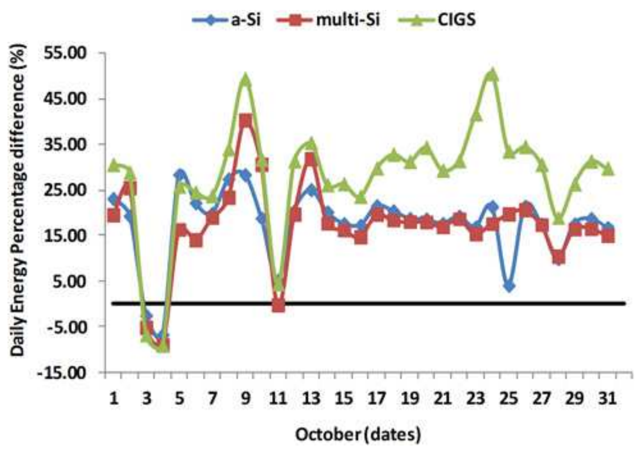


Fig. 2 *Daily percentage energy difference between fixed and tracking systems during October*

positioned to the sides of the fixed systems but these are not included in this study. The PV systems (based on technology) started operation at different times during 2013. The CIGS systems began operation at the beginning of May, the mono-Si systems at the beginning of July and the a-Si and multi-Si systems at the end of July. Hence, for comparison purposes, the analysis of yield data in this study starts in August 2013. The last data sets considered are for March 2014, although monitoring of the site continues.

Daily PR calculations have been made mainly for October, November and February. Owing to technical issues there were no weather data before October 2013 and during December 2013. Useful data were obtained for only three out of 31 days in January. These three days in January and another two days in December have been analysed and their results are integrated in the total sum of the effective days. The term ‘effective days’ is defined as all days with a monitoring fraction ≥0.95. Table 1 presents the number of days considered for the daily PR calculations for each month. The 3rd column gives the number of days where ambient temperature readings were available. The mono-Si systems are excluded from the energy and performance analysis because of the small sample of data acquired throughout the analysis period.

Field and weather data are measured through a DAS and the data are recorded on a dedicated personal computer (PC). The monitoring system is custom-built for the installation. A software algorithm in National Instruments Labview interfaces the PC with the DAS. Field measurements (voltage, current and power) are taken at 1-second intervals and then are averaged and recorded at 1-minute intervals. The same procedure is followed for the weather data (normal, horizontal and in-plane irradiance for the fixed and tracking mounted systems, ambient and module temperature, relative humidity, wind speed and wind direction).

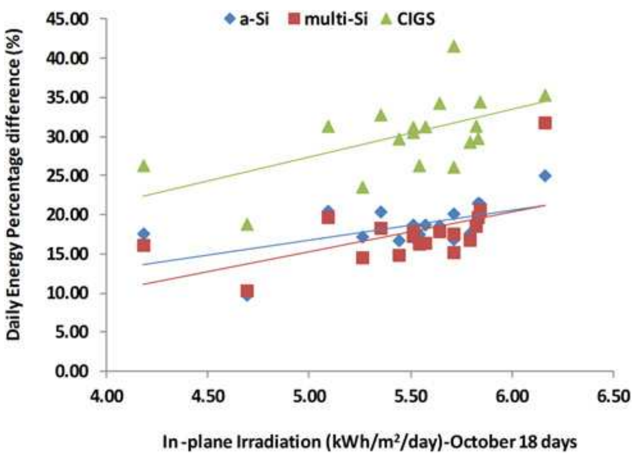


Fig. 3 *Daily percentage energy difference between fixed and tracking systems as a function of daily in-plane irradiation on the fixed systems*

Table 2 Average monthly differences between the energy yield of the fixed and tracking structures

Monthly gain between tracking and fixed PV systems			
	a-Si	multi-Si	CIGS
August-13	22.72	19.24	31.96
September-13	25.65	28.50	34.02
October-13	19.14	19.21	29.76
November-13	17.28	16.76	34.48
December-13	28.12	15.46	37.58
January-14	14.65	10.71	26.21
February-14	20.67	16.43	29.45
March-14	25.43	20.34	34.24
average per technology	21.71	18.33	32.21

Table 3 Variation in average gain as a result of module rating tolerances

Average gain between tracking and fixed PV systems over all eight months				
	Minimum calculated	Nominal calculated	Maximum calculated	Nominal simulated
a-Si	15.91	21.71	27.79	34.20
multi-Si	12.70	18.33	24.25	31.87
CIGS	25.26	31.21	38.83	31.68

Owing to operational issues with the pyranometer that measured the in-plane irradiation on the tracking systems, the PR calculations refer only to the fixed structure PV systems. A system inspection identified two modules with cracked glass, one each on the CIGS fixed and a-Si tracker systems, thought to be because of thermal expansion since the cracks are observed to propagate from a fixing point. It is not yet clear whether the damage will affect

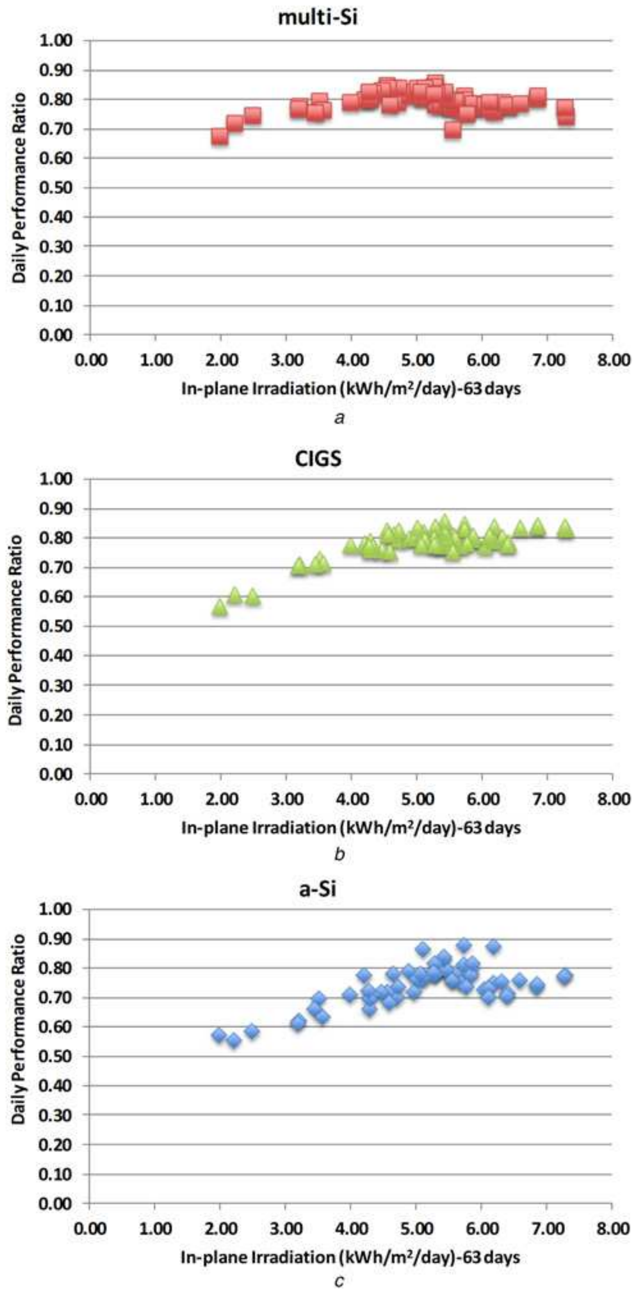


Fig. 4 *Daily PR of the systems against daily in-plane irradiation*

Table 4 In-plane irradiation, ambient temperature, PR plus PVsyst average PR range for all the technologies over the studied period

(a)

	PR a-Si		PR multi-Si		PR CIGS	
	Min.	Max.	Min.	Max.	Min.	Max.
October	0.71	0.88	0.76	0.82	0.78	0.85
November	0.67	0.84	0.81	0.86	0.76	0.86
February	0.53	0.75	0.61	0.78	0.53	0.76
total average for all 63 days	0.74		0.78		0.76	
PVsyst average over the same period	0.75		0.73		0.76	

(b)

	Irradiation (kWh/m^2/day)		Ambient temperature	
	Min.	Max.	Min.	Max.
October	4.18	6.16	24.74	27.77
November	4.24	5.41	18.63	26.01
February	1.96	7.27	16.81	20.75
Range for all the effective days	1.96	7.27	14.31	27.77

module performance in the short term, although it could be expected that there will be long-term implications.

The level of dust in Kanpur is high because of local industry. This requires regular cleaning of the modules to ensure good energy production. Normally, weekly cleaning is recommended for moderate dust accumulation and daily cleaning is recommended in the case of intense dust accumulation [13]. Since this is a research installation inside the IIT campus, all the arrays are cleaned on alternate days during the week. The pyranometers are cleaned less often, giving some uncertainty in the irradiance readings.

4 Analysis of short-term performance

4.1 Difference in energy yield between tracking and fixed PV systems

Generally, the analysis of the energy rating of a system is more complicated than the analysis of its power rating [4]. However, system evaluation based on energy output could be considered more robust than a power-based evaluation [14].

As expected, for all the technologies, the tracking system has a higher energy yield than the fixed system, the relative difference depending on the weather conditions. Figs. 2 and 3 show the percentage difference in output for the three technologies by day and by the irradiation level, respectively, during October. It has been observed that sometimes, at low irradiation levels, the fixed system production is slightly better than for the tracking systems. This leads to a negative energy percentage difference, with the fixed output as the basis.

Fig. 2 shows that all the technologies follow a similar trend as can be seen from the trend-lines. A few days in each month show a variation in the trend between the technologies, because of a difference in the output of the tracking system. For example, on the 24th of October, the fixed systems have similar energy yields, while the CIGS tracking system yield is greater than that of a-Si and multi-Si tracking systems. When a negative percentage difference is observed, it occurs on days with low energy yields and when the difference in energy is small, consistent with a combination of measurement accuracy and manufacturer tolerance on module rating.

The average monthly percentage differences, expressed as the percentage gain of the tracking system compared with the fixed system are shown in Table 2. The average monthly gain across the whole period for all technologies is 24.08%, but there is significant variation between the three technologies.

There are four possible causes for the difference in behaviour between the technologies. First, different module types have different temperature coefficients. The tracking array will operate at a higher module temperature than the fixed array for most days because of higher irradiance values. The effect on the electrical output will vary depending on the temperature and irradiance. As is observed, the multi-Si array would be expected to have the lowest tracking gain. a-Si would be expected to have a higher gradient of gain with irradiation level, but it is observed to be lower compared with the other technologies, which cannot be explained by the temperature coefficient. The second possible reason is the close proximity of the systems which may lead to some shading, particularly in the case of the CIGS fixed system, which is sometimes shaded by the mono-Si fixed array in front and perhaps by the stand-alone system, which is also sited in front but to the side. This leads to a reduced fixed array output and hence an observed higher gain from the unshaded tracking system. Third, the output measurements include the effect of the inverter matching and efficiency, which will differ between technologies. The a-Si and multi-Si systems have the same inverter model, while the CIGS system has a different inverter model. This aspect requires further investigation to establish its contribution. Finally, the tolerance in module ratings for the different technologies has to be considered.

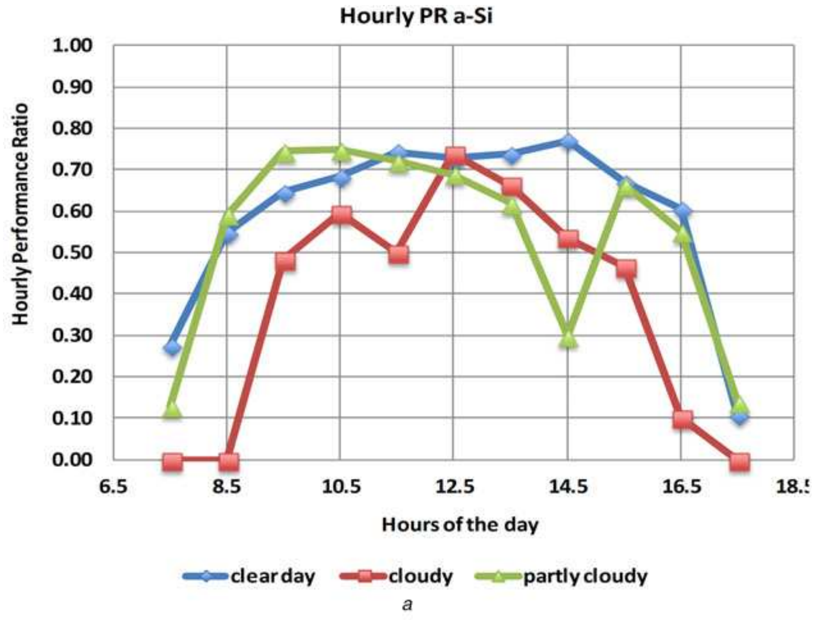
The energy yield gain values in Table 2 assume nominal rating for all modules in both systems. Using the declared manufacturer tolerances, the range of the possible gains is shown in Table 3. A system simulation, with the same electrical configuration, similar module types (according to the STC) and the PVGIS-CMSAF solar data [15, 16] for Kanpur, is carried out in PVsyst (Version 5.1.3) [17]. The nominal simulated gain for the three technologies is shown in the last column.

The percentage gains shown by the a-Si and multi-Si systems are lower than would be expected for this location according to the PVsyst simulations. The simulations gave a monthly gain of around 25–40% for the same period of the year depending on the

Table 5 Percentage difference between PVsyst and measured data

Pvsyst against measured data over three months

Month	Irradiation difference, %	a-Si Specific yield difference, %	multi-Si Specific yield difference, %	CIGS Specific yield difference, %
October	22.91	25.75	25.75	29.37
November	35.75	29.39	17.95	26.86
February	24.70	31.62	19.35	24.14
Average	27.79	28.92	21.01	26.79



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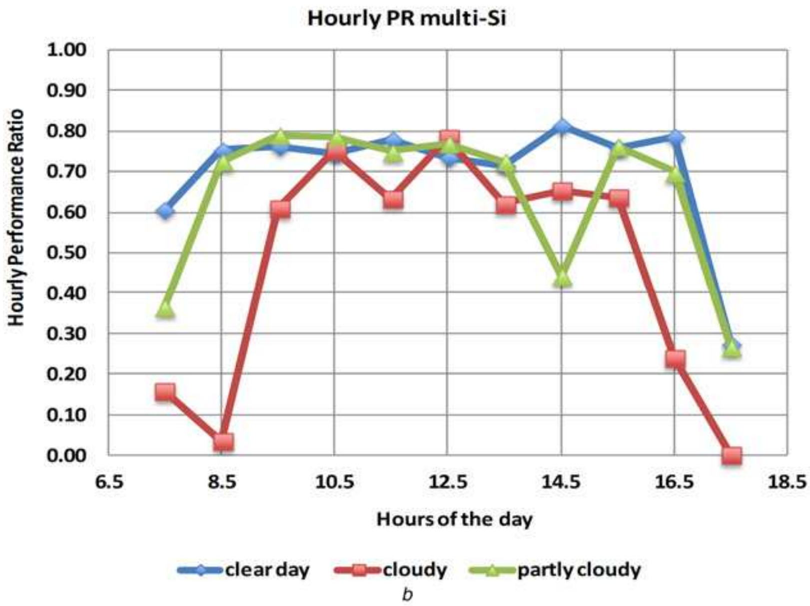

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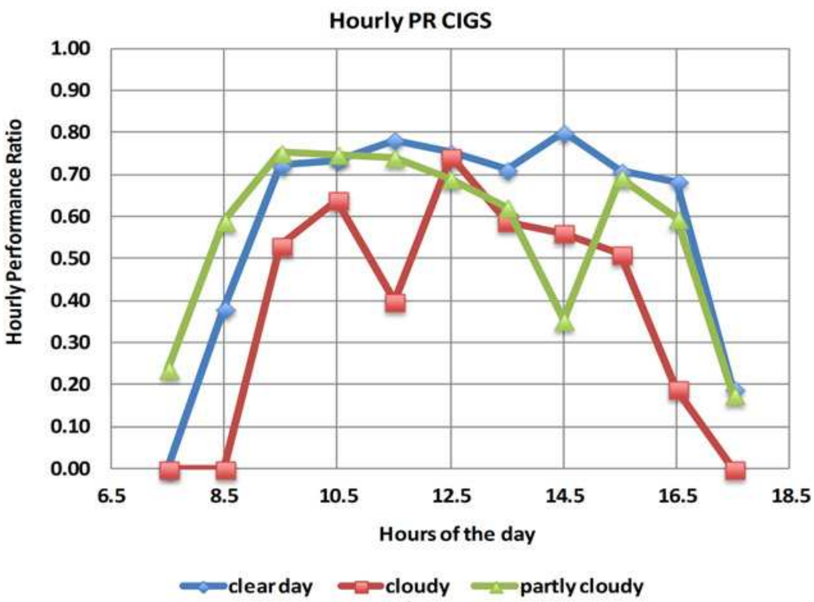

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Fig. 5 *Hourly PR for each technology in three different daily irradiance conditions*

Table 6 Average daily irradiation and ambient temperature for the selected days

	Average daily temperature, °C	Average daily irradiation (kWh/m^2)
clear sky	17.90	6.37
partly cloudy	19.63	3.43
Cloudy	17.05	1.96

technology. The simulated gain shown in Table 3 is the average for the months considered.

The CIGS systems results are in line with the PVsyst simulations, but it is known that there is some shading of the fixed system. The temperature data in the simulations has similar values to the measured data, except for December and March when the PVsyst values were 15 and 10% lower, respectively, thus lowering the relative tracking gain in practice. The PVsyst irradiation values for October, November, February and March (the months for which sufficient solar data were available) were 18.4–35.8% higher than those measured. This would also result in the relative tracking gain being less in practice compared with the simulation.

4.2 PV PR variations

Variations in the daily PR of the PV systems operating in the sub-tropical climate of Kanpur have been examined. As mentioned previously, results are presented only for the fixed systems. Lower PR values are obtained at low irradiation levels, as expected, most likely because of lower inverter efficiency and perhaps some low light level effects at module level. A decrease in the PR of the multi-Si system is also seen at high irradiation levels and is attributed to increased module temperature losses. This is confirmed by examining the dependence of the daily PR on ambient temperature, where the multi-Si system shows a decrease at temperatures above 25°C. Neither the a-Si nor the CIGS systems show a notable decrease in PR at high ambient temperatures, although they show a greater reduction in PR at low light levels, perhaps because of mismatch with the inverter.

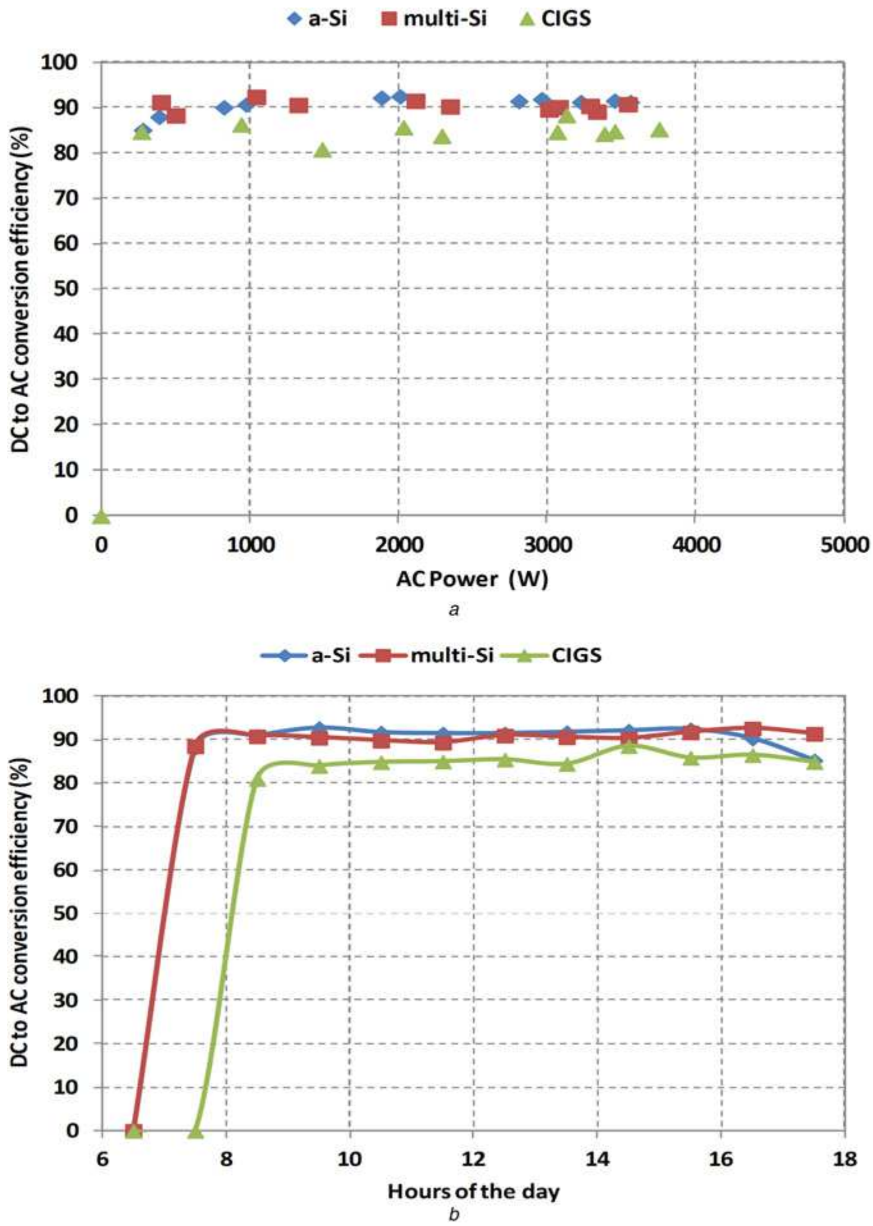

Fig. 6 *DC–AC conversion efficiency curves of the inverters for the clear day*

a Conversion efficiency against AC power
b Conversion efficiency against hours of the day

At mid-range irradiation levels, CIGS system has similar PR values to the multi-Si system. Meanwhile, at high and low irradiation levels, CIGS PR values are, respectively, higher and lower than the multi-Si system. The relatively better performance of CIGS at high irradiation levels is attributed to its lower temperature coefficient. Among the three systems for the analysed period, a-Si has the worst performance since it has the lowest PR values and the difference with the other two systems becomes greater at low and high irradiation levels. The average daily ambient temperature over the period of these measurements was generally below 25°C, leading to low module temperatures at low irradiance levels and therefore a slower annealing of light-induced defects. Alternatively, the change in performance may be at least partially because of spectral effects [18], although we do not have on-site spectral measurements to allow an assessment of this effect to be made. At high irradiance level, it is likely that the effect is because of a reduction in the electrical efficiency of the module for increasing irradiance. Fig. 4 shows the calculated daily PR for the multi-Si, CIGS and a-Si fixed systems as a function of daily irradiation.

Table 4 presents the PR, in-plane irradiation and ambient temperature range for all the technologies studied for the relevant months. It also includes the average PR values from the PVsyst simulations for the same period. During these months the temperature varies by 14°C, which is relatively small, while there is a large range of irradiation values. For the period considered, the average PR values are very similar to the simulated PR values except for the multi-Si technology, with the simulated value being an underestimate.

Table 5 shows the percentage difference between the simulated and the measured values of in-plane irradiation and specific yield for each technology, with the measured values as the basis.

Considering the averages, it can be clearly seen that the difference in the specific yield is because of the irradiation difference. For these three months, the average PVsyst irradiation values are around 28% higher. A similar difference is observed in a-Si and CIGS specific yields (around 29% and 27%, respectively). Multi-Si system has the smallest yield difference of 21% and the simulated PR value is lower than that measured (Table 4a).

For the studied period, it can be concluded that PVsyst simulations give fair estimates of PR values for both a-Si and CIGS systems, while they underestimate the multi-Si system, and that irradiation difference has the greatest influence on the yield difference. However, there is uncertainty associated with the measured values and the fact that the pyranometer was not cleaned as often as the PV arrays. In the latter case, the average irradiation difference would be smaller and consequently the calculated PR values would be lower.

4.3 Hourly PR variations and inverter efficiency

On the basis of the irradiance levels (i.e. clear sky, partly cloudy and cloudy), three days in February have been chosen for an hourly analysis of PR variations. Inverter conversion efficiency is one of the main factors influencing PR. Hence, an analysis of the inverter conversion efficiency of the systems is also included in this section. As in the previous case, the multi-Si, a-Si and CIGS fixed systems are assessed.

Fig. 5 presents the hourly PR for each technology for the selected days. Table 6 presents the daily average ambient temperature and in-plane irradiation. It can be seen that a-Si has poorer performance than the other two technologies on all days. The reduced output of the a-Si array at low and high irradiance values has already been discussed in Section 4.2. The CIGS and multi-Si systems have similar performance on the clear and partly cloudy days but on the cloudy day multi-Si performs better. Finally, it is noted that multi-Si system has the best performance, among all the technologies, during the morning hours, when the system starts its operation. The performance difference of multi-Si and CIGS may be attributed to the CIGS inverter threshold.

All the PV systems considered in this study are single-phase grid-connected systems. The inverters are from two different manufacturers, all rated at 5 kW nominal power. The multi-Si and a-Si systems have the same high frequency transformer type inverter from the same manufacturer, while the CIGS system has low-frequency transformer type inverter from different manufacturer. The three systems considered have their arrays connected in a central configuration to the inverter.

The DC–AC conversion efficiency of a grid-connected PV inverter is defined as the ratio of the inverter AC output power to the DC input power of the inverter (1) [19]

$$\eta_{\text{inv}}(t) = \frac{P_{\text{AC}}(t)}{P_{\text{DC}}(t)} \times 100 \tag{1}$$

where $P_{\text{DC}}(t)$ is the DC power input from the PV array to the inverter and $P_{\text{AC}}(t)$ is the AC power output from the inverter. DC to AC efficiency is dependent on the inverter-array sizing, DC voltage and ambient temperature [20–23]. Fig. 6 shows the DC–AC conversion efficiency curves derived from the measured data for the clear day (because of issues with the DAS the data for the partly cloudy and cloudy days were not in a usable form).

Irrespective of the manufacturer, these efficiency curves are significantly lower than those shown in the inverter data sheets. Possible reasons for lower efficiency are the inverter-array sizing and the lower voltage because of the high temperature conditions for the PV module operation. In this case, the inverter-array sizing is more likely to be the cause of the lower efficiency since the daily ambient temperature for the clear day was 17.9°C. Moreover, the inverter threshold setting for the CIGS system needs to be re-considered, as can be seen from Fig. 6*b*.

5 Conclusions

The paper analyses the energy percentage difference between the tracking and fixed structure PV systems and the daily PR for the systems installed at the IIT-Kanpur. It has been observed that the energy percentage difference is significantly lower than the simulated value acquired by PVSyst for two of the technologies. This may be partially attributed to temperature effects, shading, inverter matching and module tolerances. However, it is shown that the difference between the simulated and measured values of the systems was mostly because of the difference in irradiation values. The effect of temperature on the PR is observed for multi-Si at high irradiation levels, whereas the thin film technologies do not show a decrease under these conditions. Nevertheless, the multi-Si system was the most stable technology in terms of performance during the examined period since it provides a good match between the expected and the calculated results. Regarding the inverter evaluation, the results showed that although the inverters met the Indian standards, both inverter types underperformed in terms of the conversion efficiency at the experimental location. For the low-frequency transformer type inverter, which is connected with the CIGS system, an issue with the inverter threshold was revealed from the short-term analysis.

6 Acknowledgments

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