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Performance of solar photovoltaic installations: Effect of seasonal variations

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Abstract

A 20 kW_p Solar Photovoltaic (SPV) system was set up on the library roof-top in Indian Institute of Science, Bangalore, India. This roof-top photovoltaic (RTPV) system partly powers the Central Office of IISc. The main objective of setting up this SPV system was to study the performance of solar plants under different seasons and climatic conditions of Bangalore. The system has been producing an average daily yield of approximately 80 kWh for the past two years which translates to an annual yield of 28.9 MWh. The overall yield of the system up to 14th September 2015 is 70 MWh. This work focuses on the evaluation of the performance of SPV systems using the popular grading systems, namely Capacity Utilization Factor (CUF) and Performance Ratio (PR). The CUF of the SPV system is 16.5%, which lies within the range of CUF of well-performing solar plants located in India. Average Performance Ratio (PR) of the SPV system is around 85%, which indicates that the performance of the SPV system is satisfactory. PR of the SPV system is correlated with the behaviour of SPV modules in different seasons, with module temperature (T_{mod}) as the key factor of comparison. In summer, the SPV modules attain maximum efficiency (η_{max}) at T_{mod} of 45 °C, but in winter, it is at 55 °C. In summer, for $T_{mod} > 45$ °C, module efficiency (η) reduces by 0.08% per degree rise in temperature. In monsoon, for $T_{mod} > 35$ °C, η reduces by 0.04% per degree rise in temperature. In post-monsoon period, for $T_{mod} > 38$ °C, η reduces by 0.06% per degree rise temperature. However, in winters, the modules attain η_{max} at T_{mod} of 55 °C, without much drop in efficiency. This is mainly because of intermittent natural cooling that takes places at the surface of the modules, due to cool breeze and lower ambient temperatures.

Keywords: Solar; Renewable; Energy; Power; Efficiency; Module temperature

1. Introduction

The performance of a solar photovoltaic system (SPV) is dependent upon many site-specific factors such as latitude, season, cloudiness, and air pollution. Hence, a detailed analysis of the performance of SPV systems will provide valuable information for the prediction of the performance of such systems in the future in order to improve power system planning and demand-side management. In 2013, a photovoltaic park with a capacity of 171.36 kW_p was installed in Sitia, Crete and its performance evaluation showed an annual yield was in the range 335.45–869.68 kWh and the Performance Ratio (PR) was 67.36% (Kymakis et al., 2008). In 2013–14, a 15 kW_p grid-connected SPV system located in Mumbai, India was evaluated for economic viability. The monthly production of this SPV system was around 1800 kWh, thus saving around 1.6 tonne of CO_2 emission into the atmosphere (Shivalkar et al., 2015). A 2 kW_p grid-connected SPV system located

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in Nis, Republic of Serbia showed that the performance ratio of the system during the period 2013–14 was 93.6%, with a capacity utilization factor of 12.88% (Mediavilla et al., 2013). Significant findings in the field of power electronic circuits, such as inverters, charge controllers and voltage stabilizers, have contributed for the improvement in the energy conversion systems. For instance, a comparative analysis of DC to AC inverters has shown that transformerless inverters performed better than a conventional system (Milosavljevic et al., 2015). In parallel with the above mentioned findings, there are research activities focussing on maximizing of the existing SPV modules. In 2013, an experiment demonstrating the cooling of SPV modules with temperature controlled solar collector was conducted in Turkey. This mechanism, called a PVT System, uses the heat of the SPV module to cool the PV surface by employing a heat exchanger. The efficiency of the PV modules with cooling was found to be 13%, whereas for the modules without cooling, it was 10%. The PVT system lowers the module temperature by 10–20 °C, which increases the electrical output of the PV system by 5–10% (Conserval Engineering Inc., 2015). In 2012–13, the study focussing on the influence of ambient temperature and wind-speed on the performance of a monocrystalline SPV system installed in Tripura, India, concluded that ambient temperature ranging between 20 and 38 °C has a positive correlation with the efficiency of the PV system (Bhattacharya et al., 2014). In 2011, the influence of angle of tilt of PV, albedo of earth, building azimuth and shading effects on power generation of SPV modules were studied to optimize the performance of a Building Integrated Photovoltaic (BIPV) system located in Korea. The efficiency of this BIPV system during different months were compared. According to this study, the power generation is more influenced by the above factors in summer than in winter. This study also concludes that the influence of each of the above factors on the performance of BIPV vary during each season (Yoo, 2011).

The behaviour of SPV systems installed in different locations is a function of the atmospheric and local conditions. Unless a thorough investigation is carried out for the location, it is difficult to predict the performance and energy production capability. It becomes important to carry out field tests and scientific analysis of the data at the location. In this connection, Divecha Centre for Climate Change, Indian Institute of Science (IISc), Bangalore installed a 20 kW_p grid-interactive SPV system atop J.R.D. Tata Memorial Library (shown in Fig. 1), to study the performance of SPV systems in the city. This SPV system was commissioned in April, 2013 and has been performing optimally to date. This project was partly funded by Ministry of New and Renewable Energy (MNRE) during a drive to power heritage buildings of the country using solar power. The system partially powers the Main Administrative Building of IISc, which is over hundred years old and is identified as a Heritage Site. This building is situated at a distance of around 300 m from the Library.

Fig. 1. Ariel view of the 20 kW_p grid-interactive SPV system.

The SPV modules are oriented towards the south with an inclination of 13°, which is the latitude of the location. The SPV system covers an area of 204 sq. m that includes array to array clearance of 1.5 m. Net PV area of the SPV system is 145 sq. m. The system consists of 100 polycrystalline silicon PV modules of 200 W_p each. Each module consists of 72 cells and each cell has an area of 219.8 sq. mm. In order to achieve optimal system voltage, 20 modules are connected in series to form an array and five such arrays are connected in parallel. The SPV system is mounted on cubical concrete pedestals having edge-dimension of 300 mm each. Since the plant is atop the library building that is 50 years old and houses many rare vintage journals and books, the SPV system had to be installed without tinkering with the rooftop surface to avoid water leakage in the building during monsoon season. The pedestals of approximate weight of 80 kg have been positioned such that their dead weight exists only on the beams present beneath the floor. One array is mounted on 12 pedestals. The overall weight at the point of contact of each pedestal and the roof is 120 kg. The module mounting structures are made up of galvanized mild steel and are mounted on the concrete pedestals. The structures are designed to withstand a wind velocity of 160 km/h. The SPV system is being protected by a lightning arrester, super-earth kits and isolator switches to avoid voltage surges.

An array junction box is provided where the output of each array is combined and fed as the input for the Power Conditioning Unit (PCU). A 20 kVA wall-mounted PCU is used in the system. This PCU doesn't employ a transformer and hence, popularly called TL inverters. TL inverters use a computerized multi-step process and electronic components to convert DC to high frequency AC, back to DC, and ultimately to standard-frequency AC. TL PCU has 2% higher efficiency than the conventional PCU. Additionally, without the transformer, the inverter becomes compact and more affordable. TL inverters use electronic (rather than mechanical) switching, thus reducing the amount of heat and ‘hum’ generated by the unit. The PCU being used consists of two MPPTs (Maximum Power Point Trackers). The main benefit of a PCU consisting of two MPPTs is that it enables the installation to be considered as two different systems. This means that some SPV modules can be placed on a north-facing roof and some on a west-facing roof, without worrying about the lower irradiance on one side dragging the whole system down. In other words, the dual MPP tracker enables the user to install more modules and generate higher energy on a limited roof space (Civic Solar Inc., 2014).

A remote monitoring system called Solar-Log has been installed in the inverter room of the SPV plant which records the real-time data and maintains the database of the previous data. This equipment has the remote access facility and transmits the real-time data to the server. The GHI and power output data are being collected at an intervals of 5 min. The power generation patterns from the SPV system during various seasons corresponding to changes in weather conditions are studied.

2. Performance analysis of the SPV system

The performance analysis of an SPV system involves evaluation of various instantaneous parameters that are recorded by the data acquisition system incorporated in the SPV system. The parameters considered in this study are yield, incident solar radiation (Global Horizontal Irradiance – GHI), module temperature and ambient temperature. These parameters are measured from dawn to dusk. However, the effective period of generation (EPG) is the period during which the instantaneous power output is at least 25% of the installed capacity, which is in the period 08:00–16:00 h.

The monthly yield, $Y_{\text{net (m)}}$ of the SPV system during the study period considered is shown Fig. 2. The highest $Y_{\text{net (m)}}$ of the study period was in March 2014 with 3132 kWh and least was in July with 1579 kWh, corresponding to summer and monsoon months. The highest and lowest daily yields of the SPV system in the period considered was 120 kWh and 40 kWh, respectively, with corresponding specific yields, S_{day} of 6 kWh/kW$_p$ and 2.0 kWh/kW$_p$, respectively. The net annual yield, $Y_{\text{net (annual)}}$ during this period was 28.9 MWh with an annual average daily specific yield, $S_{\text{day (avg)}}$ of 4.1 kWh/kW$_p$. The total yield of the system up to 14th September, 2015 is 70 MWh and the annual average daily yield over the study period is 83 kWh. Since coal is the major source of electricity in India, installation of the SPV system has avoided at least 23 tonnes of carbon di-oxide (CO_2) emission into the atmosphere per year (taking the amount of CO_2 emission as 800 g per kWh of electricity production from coal fired thermal plants) (International Energy Agency, 2013) because the Main Administrative Building of IISc has drawn that much less power from the grid.

The trend of monthly average daily sunshine period (EPG), t_s, is shown in Fig. 2. During the months July and August, the sunshine period was lower due to south-west monsoon over Indian subcontinent, which reflected on the Y_{day} of the PV system. Fig. 3 represents the

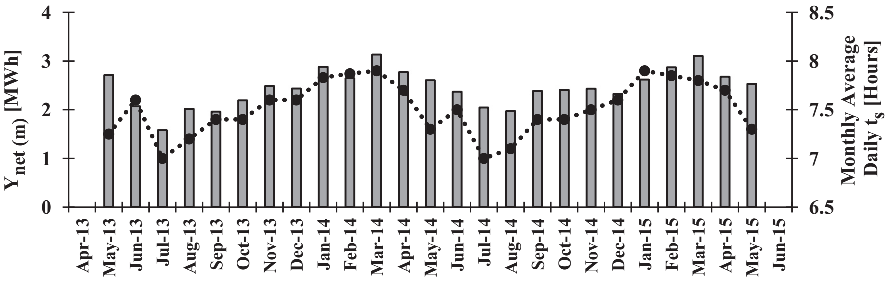

Fig. 2. Variation of monthly yield, $Y_{\text{net (m)}}$ corresponding to average daily sunshine period, t_s, during the period 2013–15. The bars denote monthly yield and circles denote monthly average daily sunshine period.

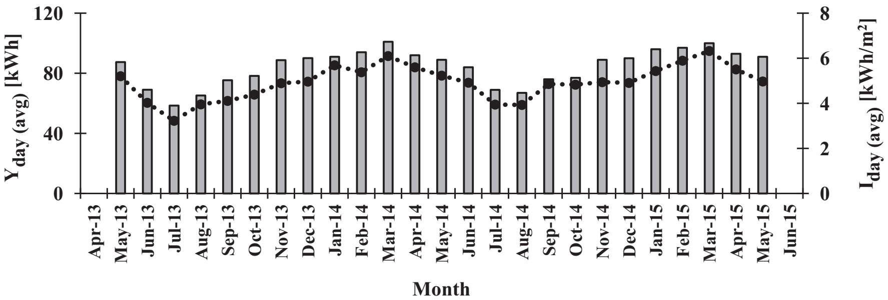

Fig. 3. Variation of monthly average daily yield, $Y_{\text{day (avg)}}$ corresponding to monthly average daily GHI, $I_{\text{day (avg)}}$, during the period 2013–15. The bars denote monthly average daily yield and circles denote monthly average daily GHI.

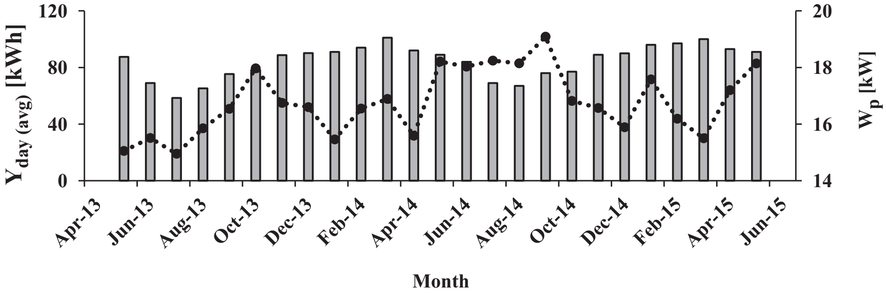

Fig. 4. Variation of monthly average daily yield, $Y_{\text{day (avg)}}$ corresponding to peak power of the month, W_p, during the period 2013–15. The bars represent monthly average daily generation and circles represent peak power of the month.

variation in the monthly average Y_{day} corresponding to monthly average I_{day}.

Fig. 4 represents the variation of Y_{day} with peak power, W_p. It is clear from Fig. 4 that the daily GHI, $I_{(\text{day})}$ was high during the summer months – January, February, March and April. The highest peak power of the study period attained was on 12th October, 2013, rising up to 19.9 kW. On this day, the PCU exhibited an efficiency of 1.4% higher than the rated efficiency. The average peak power of this month was 17.97 kW. However, the instantaneous peak power rising up to 99% of installed capacity cannot be taken into account while judging the performance of the SPV system and hence could be misleading.

2.1. Grading of the SPV System

The yield of the SPV system which is the most important metric of an SPV system is directly related to the following system-level metrics (Chakraborty et al., 2015):

- Capacity Utilization Factor (CUF).
- Performance Ratio (PR).

SPV systems are graded based on these system-level metrics. These metrics are a function of both atmospheric and electrical parameters. The grading indices of the above mentioned factors are totally different from each other as each of these factors account for a wide range of parameters. Detailed analysis of these factors are discussed in the following sections.

2.1.1. Capacity utilization factor

The Capacity Utilization Factor (CUF) of the SPV system is the ratio of actual energy generated by the SPV system to the equivalent energy output from a similar system that works 24 h a day (Re-solve, 2014). CUF of the SPV system is calculated as shown below:

$$\begin{aligned} \text{CUF} &= \frac{\text{Annual yield}}{20\ \text{kW} \times 24\ \text{h} \times 365\ \text{days}} \times 100 \\ &= \frac{28{,}882\ \text{kWh}}{20\ \text{kW} \times 24\ \text{h} \times 365} \times 100 = 16.5\% \end{aligned} \tag{1}$$

CUF of the SPV system is 16.5% and is well within the range of average CUF of all the roof top SPV systems in India, which is 16–17% (Bridge to India, 2015). CUF is dependent on the location. For example, the average CUF of SPV system located in Arizona, USA is 19%, whereas in Massachusetts, USA, it is 13–15% (Academia, 2015). The CUF of the system is mainly dependent on the GHI at the location of the SPV system and the cell efficiency of the SPV modules.

2.1.2. Performance ratio

One of the most important variables for evaluating the performance of a SPV system is the Performance Ratio (PR). Specifically, PR is the ratio of the actual yield and theoretically calculated yield. PR is expressed as a percentage and remains as a factor of comparison of all PV systems installed in different locations of the world. As PR is measure of the quality of a PV system independent of its location, PR is often called ‘Quality Factor’. PR illustrates the proportion of the energy that is actually available for export to the grid after deduction of energy loss and energy consumption for operation. The energy losses also include thermal losses and conductor losses. The closer the PR value determined for a PV system approaches 100%, the more efficient is its operation. However, 100% PR cannot be achieved in ideal case as unavoidable losses always arise with the operation of the PV system. High-performance PV systems can however reach a performance ratio of up to 80% (Verma and Singhal, 2015). PR can be calculated using the following equation:

$$\text{PR} = \frac{\text{Actual yield (in kWh)}}{\text{Calculated nominal yield}} \tag{2}$$

where

$$\begin{aligned} \text{Calculated nominal yield} = \text{GHI (in kWh/m}^2) \\ \times \text{Rated module efficiency} \\ \times \text{Total PV area (in m}^2) \end{aligned} \tag{3}$$

As an example, PR is calculated for October 17, 2013. Measured GHI in the day, I_{day}: 5.496 kWh/m^2.

Rated module efficiency, $\eta_{\text{rated}} = \eta_{\text{STC}} = 13.71\%$.
Daily yield, Y_{day}: 100 kWh.

Thus, an anticipated nominal yield is 109.25 kWh. This anticipated nominal yield corresponds to a performance ratio of 100%. However, the actual energy exported by the PV system to the grid is only 100 kWh. If this value and the calculated nominal plant output are fed into the formula for calculating the performance ratio, the following result is obtained:

$$\text{PR} = \frac{100\ \text{kWh}}{109.25\ \text{kWh}} \times 100 = 91.5$$

Hence, PR value of the day is 91.5%. This means that 8.5% of the incident solar energy is not converted into usable energy due to circumstances such as conduction loss, thermal loss or defects in components. Here, PR acts as an indicator and can prompt more detailed inspection of the PV system, so that the faults and losses can be avoided or debugged.

The performance of an SPV system is dependent on the actual AC energy output in a definite period of time, relative to the expected DC output. The expected output can either be based on ideal solar insolation or actual solar insolation, yielding two different metrics. CUF compares the output of the SPV system to the output of an ideal (lossless) system with identical nameplate capacity operating at STC (AM 1.5, GHI 1000 W/m^2, T_{amb} 25 °C). Whereas PR compares the system output to that of an ideal system operating at 25 °C in the same location (under same solar insolation). Also, solar power is available only during daylight hours. Hence, CUF is limited to the fraction of daylight hours. By accounting for geographical and temporal variations in solar insolation, PR isolates non-ideal module and system losses due to elevated temperatures or component failures and allows comparison of PV systems in different locations (Jean et al., 2015). Thus, PR defines the performance of an SPV system rather than CUF.

Fig. 5 shows the variation in performance ratio during the study period. Fig. 5(a) and (b) shows the variation in monthly average daily PR value, PR_{avg}, with respect to monthly average daily yield, $Y_{\text{day (avg)}}$ and monthly average module temperature, T_{mod}. As seen from Fig. 5(a), the PR_{avg} of the SPV system is comparatively lower for the months March, April, May, November and December than the other months of the year. From Fig 5(b), it is clear that there is an inverse relationship between PR_{avg} and T_{mod}. For better understanding, the study period is divided into four seasons, namely June–August (monsoon), September–November (post-monsoon), December–January (winter) and February–May (summer). Fig. 5(c) shows the variation in performance ratio of each season. The gradient in maximum and minimum PR values with reference to the average value of each season are different. For example, in monsoon, PR_{avg}, PR_{max} and PR_{min} are 87.3%, 89.3% and 79.8% respectively. In post-monsoon period, PR_{avg}, PR_{max} and PR_{min} are 85.6%, 95.0% and 77.7% respectively. The gradient in PR_{avg} with PR_{max} and PR_{min} values of post-monsoon period is larger than monsoon period. The gradient pattern in winter is also similar to post-monsoon whereas in summer, the gradient in PR_{max} and PR_{min} is highest. This indicates that the performance of the SPV system is dependent on the atmospheric parameters, which are different in various seasons. One of the prominent parameters that varies during the four seasons is the ambient temperature, which is a function of incoming solar radiation.

Delivering 100% of the rated power of a SPV module is possible if solar radiation is the only factor affecting the performance of the module. However, the major factor which does not allow the solar cells to showcase best performance is the module temperature, T_{mod} (Huld and Amillo, 2015), which is a function of ambient temperature. The SPV module undergoes heating on its exposure to the sunlight and the temperature measured at the surface of the module is directly proportional to the incident solar radiation. It is calculated that module temperature is around 1.5 times higher than ambient temperature. This proportionality is applicable only when physical parameters such as wind, rain and breeze do not exist.

The ratio of output power of the SPV module by input power, which is the incident solar radiation is defined as module efficiency, η and is given by,

$$\text{Efficiency}, \eta = \frac{\text{Power output}}{\text{Power input}} \times 100 \tag{4}$$

where power input, P_{in} is a product of incident solar radiation flux (I_{i}) in W/m^2 and total PV area. Power output, $P_{\text{out}} = V_{\text{oc}} \times I_{\text{sc}} \times \text{FF}$ with FF being the fill factor. The power output of a module is dependent on V_{oc} and I_{sc}. V_{oc} is the maximum voltage measured across the terminals of the module or cell when current is 0. The effect of T_{mod} on V_{oc} and I_{sc} are different. V_{oc} of the cell linearly decreases with increase in T_{mod}. On the other hand, the effect of T_{mod} on I_{sc} (quantified as temperature coefficient of I_{sc}, α) is comparatively smaller than the effect on V_{oc} and is around 0.6 mA per °C for silicon (PV Education, 2014). Thus, one of the factors which majorly hampers η_{i} at higher temperatures is V_{oc}. The impact of T_{mod} on V_{oc} is denoted as temperature coefficient of V_{oc}, β and is calculated using Eq. (5).

$$\text{Temperature coefficient of } V_{\text{oc}}, \beta = \frac{dV_{\text{oc}}}{dT}$$

$$= -\frac{V_{\text{GO}} - V_{\text{oc}} + \gamma\frac{kT}{q}}{T} \tag{5}$$

where V_{GO} is the zero temperature band gap voltage of silicon, $\gamma = 3$ and q is the electron charge, kT is thermal energy, which is the product of Boltzmann constant, k and temperature at STC, T_{STC}. The drop in V_{oc} per °C is found to be 2.06 mV for the SPV cells under consideration, which lies within the range of β values of polycrystalline solar cells (Bensalem et al., 2013).

For one of the hottest days of the study period (31st March, 2014), at $I_{\text{i}} = 881$ W/m^2; $T_{\text{mod}} = T_{\text{mod (max)}} = 63$ °C, the efficiency, $\eta_{\text{i (T)}}$ is calculated as 12.08%. Whereas, for a

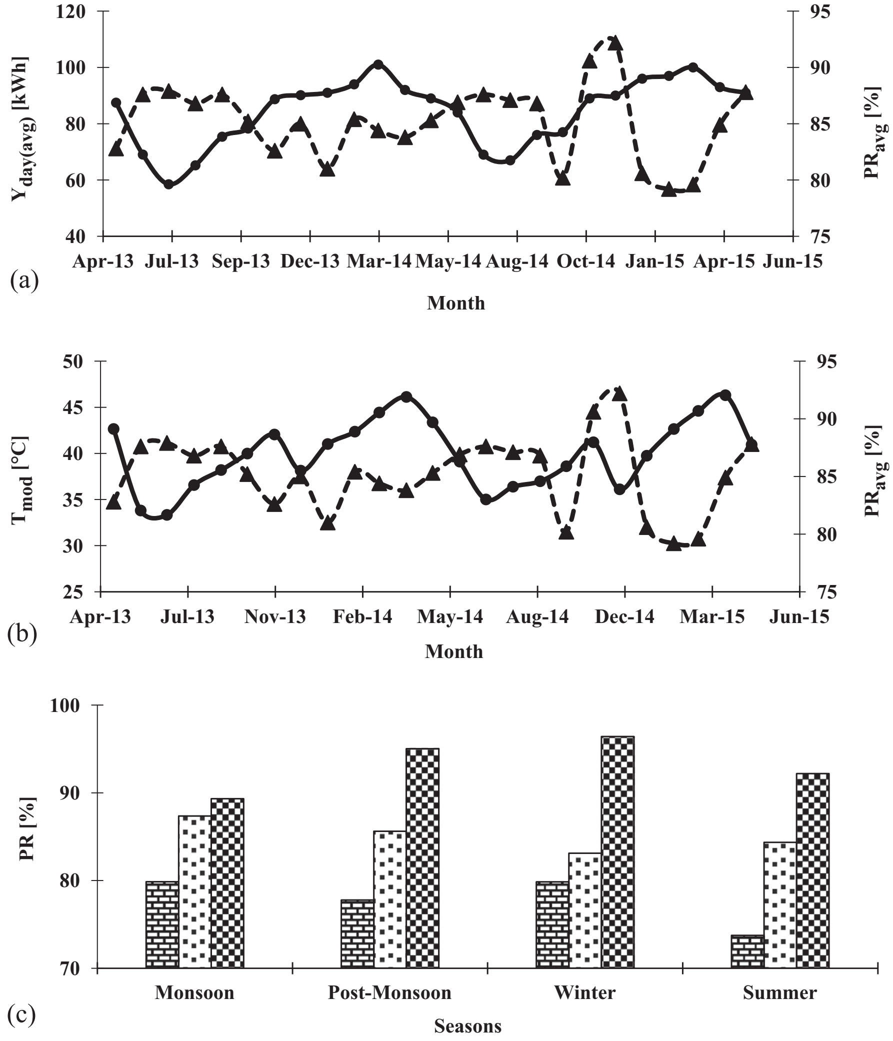

Fig. 5. Variation in performance ratio, PR in different months of the study period. (a) Variation in monthly average daily performance ratio, PR_{avg} corresponding to monthly average daily yield, $Y_{day\ (avg)}$. The circles represent $Y_{day\ (avg)}$ and triangles represent PR_{avg}. (b) Variation in monthly average daily performance ratio, PR_{avg} corresponding to monthly average module temperature, T_{mod}. The circles represent T_{mod} and triangles represent PR_{avg}. (c) Variation in seasonal average daily PR (PR_{avg}), seasonal maximum PR (PR_{max}) and seasonal minimum PR (PR_{min}) in different seasons. Brick bars represent PR_{min}, dotted bars represent PR_{avg} and checker bars represent PR_{max}.

day with moderate weather (18th June, 2013), at $I_i = 841\ W/m^2$; $T_{mod} = T_{mod\ (max)} = 46\ °C$, $\eta_{i\ (T)}$ is 13.01%. It is clear that $\eta_{i\ (63\ °C)} < \eta_{i\ (46\ °C)} < \eta_{i\ (STC)}$, which is mainly due to decrease in V_{oc} at higher T_{mod} (Radziemska, 2003).

However, the variation in the module efficiencies of clear days of different seasons are different. Module temperatures, T_{mod} attained by the SPV modules in different seasons of the study period is one of the key reasons for varying patterns of η, thereby affecting performance ratio. The gradient in I_i is dissimilar for different seasons of the study period and so are the corresponding module temperatures. For better understanding, the seasonal average of η_i and I_i for $T_{mod} > T_{mod\ (M)}$ are calculated and plotted as shown in Fig. 6. The unique variation in the performance of the SPV system during the four seasons are discussed below.

2.2. Summer

It is seen that the highest module efficiency, η_{max} during summer is 13.28% at T_{mod} of 45 °C, which is 96.8% of η_{rated}. For $T_{mod} > T_{mod\ (M)}$ (T_{mod} at η_{max}), η_i reduces by 0.085% per degree rise in T_{mod}. In peak summer months, T_{mod} and T_{amb} are quite high, thus leading to low PR values. PR_{avg} value during summer months is 83.7%, which is significantly lower compared to monsoon and post-monsoon, but higher than winter. PR_{max} value is comparatively less than that of post-monsoon and winter.

2.3. Monsoon

T_{mod} during the monsoon period are in the range of 21 °C and 56 °C, with η_{max} of 13.18% at $T_{mod\ (M)}$ of 39 °C, which is 96.13% of η_{rated}. The average rate of rise

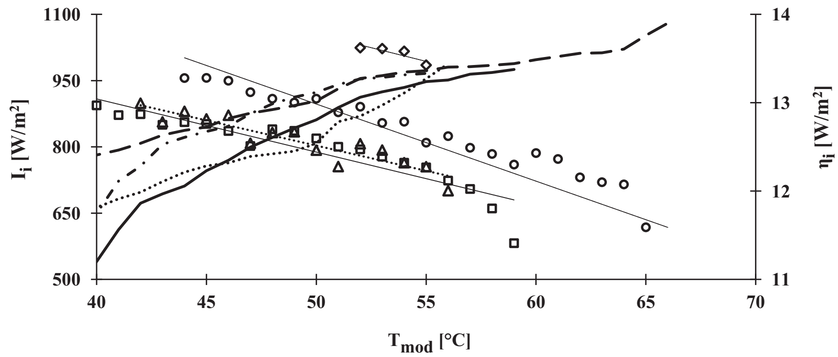

Fig. 6. Variation of module efficiency, η_i and GHI, I_i in different seasons as a function of module temperature, T_{mod}. Circles, triangles, squares and rhombuses represent η_i during summer, monsoon, post-monsoon and winter, respectively. Bold lines denote I_i and normal lines denote trend line for η_i. Broken lines, dotted lines, solid lines and dash-dotted lines represent summer, monsoon, post-monsoon and winter, respectively.

in T_{mod} in the months of south-west monsoon is much low compared to summer, mainly due to partly cloudy weather. Hence, η_{max} is achieved at comparatively lower values of T_{mod} than the other months of the year. For $T_{mod} > T_{mod\ (M)}$, η_i reduces by 0.044% per degree rise in T_{mod}. PR_{avg} value of this period is 87.3%. PR_{avg} value of this season is quite high compared to PR_{avg} of other seasons, though Y_{day} is lower than other seasons. This is mainly because T_{amb} and T_{mod} values are lower than that of summer and post-monsoon period, though not as low as winter.

2.4. Post-monsoon

The range of T_{mod} during post-monsoon period is similar to the monsoon. At $T_{mod\ (M)}$ of 38 °C, η_{max} is 13.15%, which is 95.91% of η_{rated}. The rate of rise in T_{mod} during this period is higher than monsoon, thus reducing η_i by 0.061% per degree rise in T_{mod}. In this period, the sky is clear due to the rainfall of monsoon. PR_{avg} value of this period is 85.6%, which is lesser than monsoon, but greater than summer and winter. In this season, random variation in PR_{day} is observed due to erratic variation in T_{amb} and T_{mod}.

2.5. Winter

Best performance of the system is observed during winter. η_{max} during this period is 13.62% at $T_{mod\ (M)}$ of 55 °C, which is 99.34% of η_{rated}. This is mainly due to the intermittent cooling that takes place at the module surface due to the cold winds and lower values of T_{amb}, without allowing the surface of module to reach high temperatures as in summers. Hence, the values of $T_{mod\ (M)}$ during this period is comparatively lower than other seasons. PR_{avg} value during winter months is 83.1%, which is lower than monsoon and post-monsoon but higher than summer. However, PR_{max} value is highest in winter is the highest among the PR_{max} values of other seasons, though the I_{day} and t_s are lower. This indicates that T_{mod} and T_{amb} majorly influence PR.

3. Conclusion

The performance of the 20 kW_p grid-interactive SPV system is studied and the variation of the daily and monthly yields during the study period is analysed. The annual yield of the system is around 28.9 MWh. Performance evaluation of the SPV system is carried out using the popular grading systems – CUF and PR. The CUF of the SPV system is 16.5%, which lies within the range of CUF of well-performing solar plants located in India. Average PR of the SPV system is around 85% indicating that performance of the SPV system is at par with the solar plants showcasing good performance.

T_{mod} plays a key role in the energy output of the system. The annual average $T_{mod\ (M)}$ is calculated as 45 °C. However, η_i is attained at different T_{mod} for the four seasons considered. In summer, $T_{mod\ (M)}$ is 45 °C, but in winter, it is 55 °C. It is also observed that η is comparatively low in summer and post-monsoon months though the average Y_{day} were high, mainly due long sunshine period and high GHI. In summer, for $T_{mod} > 45$ °C, η_i decreases by 0.08% per degree rise in T_{mod}. In monsoon, for $T_{mod} > 35$ °C, η_i reduces by 0.04% per degree rise in T_{mod}. In post-monsoon period, for $T_{mod} > 38$ °C, η_i reduces by 0.06% per degree rise in T_{mod}. However, in winters, $T_{mod\ (M)}$ is 55 °C and doesn't exhibit much drop in η_i. This is because of intermittent natural cooling that takes places at the surface of the modules due to cool breeze and low ambient temperatures.

It is clear from the study that PR_{avg} is inversely proportional to T_{mod}. Values of PR_{max} are higher in winter and post-monsoon than summer and monsoon. This is mainly because of lower T_{mod} and T_{amb} in winter and high GHI in post-monsoon. However, PR_{avg} in monsoon and post-monsoon period are higher than winter and summer. This is because of intermittent rainfall during monsoon, which maintain module surfaces at low temperatures and higher number of clear days in post-monsoon period. It is inferred from this study that the major factors influencing the performance ratio of any SPV system is the module efficiency and one of the major factor affecting module efficiency is module temperature. Hence, to reap maximum benefit from roof-top SPV installations, it is very essential to maintain the surface of the modules at low temperatures, especially during summers and similar weather conditions of the year.

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