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Article

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Simulation and performance analysis of 110 kW_p grid-connected photovoltaic system for residential building in India: A comparative analysis of various PV technology

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ABSTRACT

System simulation is necessary to investigate the feasibility of Solar PV system at a given location. This study is done to evaluate the feasibility of grid connected rooftop solar photovoltaic system for a residential Hostel building at MANIT, Bhopal, India (Latitude: 23° 16' N, Longitude: 77° 36' E). The study focuses on the use of Solargis PV Planner software as a tool to analyze the performance a 110 kW_p solar photovoltaic rooftop plant and also compares the performances of different PV technologies based on simulated energy yield and performance ratio. Solargis proves to easy, fast, accurate and reliable software tool for the simulation of solar PV system.

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1. Introduction

Renewable energy sources are considered as alternative energy sources due to environmental pollution, global warming and depletion of ozone layer caused by green house effect. Earth receives about 3.8×10^{24} J of solar energy on an average which is 6000 times greater than the world consumption (Aliman et al., 2007). Solar energy is most readily available source of energy. Solar energy is Non-polluting and maintenance free. Solar energy is becoming more and more attractive especially with the constant fluctuation in supply of grid electricity. Solar power plant is based on the conversion of sunlight into electricity, either directly using photovoltaic (PV), or indirectly using concentrated solar power. Concentrated solar power systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. The voltage and current both are the function of light falling on solar PV. But too much insolation on the cell causes saturation and eventually the power output is reduced because of increase in mobility of electron and increase in temperature. The other problem is tracking of the sun according to the PV module i.e. orienting the panel in such a direction so that panel receives maximum irradiance. It is anticipated that

photovoltaic (PV) systems will experience an enormous increase in the decades to come. However, a successful integration of solar energy technologies into the existing energy structure depends on detailed knowledge of the solar resource availability at a particular location. The electrical and thermal simulation of a roof-mounted BIPV system inclined at Ballymena, Northern Ireland and facing due south was performed by using TRNSYS (Mondol et al., 2005). The efficiency of the BIPV system as a shading device was examined at different months. The simulation program SOLCEL was developed to calculate the shading effect on the solar cells, PV module temperature, incident solar irradiance, BIPV output. The simulation of a BIPV system was performed to optimize its performance through parametric analysis (Yoo, 2011).

Masa-Bote and Caamaño-Martín (2014) developed a methodology to estimate BIPV electricity production under shadow. The developed methodology was validated by means of one-year experimental data obtained from two similar PV systems. The study included several weather conditions: clear, partially overcast and fully overcast sky. A performance analysis and modeling of a BIPV system in Romania was conducted by Fara et al. (2013). Forecasting tests were run by utilizing Autoregressive Integrated Moving Average models.

Kane and Verma (2013) investigated the performance enhancement of a BIPV module by using thermoelectric cooling. Thermoelectric module was attached at the back of the PV module. Mathematical modeling of individual systems was performed and then,

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Nomenclature

Abbreviation

PV:	Photovoltaic
MANIT:	Maulana Azad National Institute of Technology
STC:	Standard Test Condition
AC:	Alternating Current
PR:	Performance Ratio

Symbols

c-Si:	Crystalline silicon
a-Si:	Amorphous silicon
CdTe:	Cadmium telluride
CIS:	Copper indium selenide
G_h :	Horizontal Irradiance
G_{hm} :	Monthly sum of global irradiation
G_{hd} :	Daily sum of global irradiation
D_{hd} :	Daily sum of diffuse irradiation
T_{24} :	Daily air temperature
E_{PV} :	The annual PV electricity generated

the dynamic model of the BIPV system by considering the temperature of the PV module was developed. The results of the simulations revealed that the proposed cooling method improved PV efficiency with minimal power loss.

Mei et al. (2002) estimated the thermal parameters which describe the performance of ventilated photovoltaic façades integrated into buildings. The method allowed the heat transfer coefficients to be obtained from data measured on an operational ventilated photovoltaic façade.

The performance of PV systems is realized by comparison with a corresponding reference system. The simulations require input of the horizontal solar radiation and the ambient temperature data, both on a monthly basis, which have been obtained from PVGIS (0000).

Becker and Parker (2009) have stated that the words simulation and modeling used as synonyms, but they are not really the same thing; at least, not to those in the field bearing those words in its name. A simulation method was developed to study the temperature behavior of double façades (Von Grabe, 2002). The model accuracy was tested by using experimental data and the model accuracy was improved by modifying the flow resistance for several geometries. The performance simulation models of PV devices are also available in some existing software, such as PVsyst, PVWATTS, TRNSYS, PVFORM, INSEL, PHANTASM, P-Spice, PV-DesignPro, SolarPro, and PVcad (Ciulla et al., 2014; Lo Brano et al., 2012; Ma et al., 2014; Ishaque et al., 2011; Cameron et al., 2008; Al-Ibrahim, 1996).

Grid-connected rooftop solar PV power systems generate DC power direct from the sun's intercepted solar energy through solar PV modules. The solar PV modules are connected through a maximum power point tracker, to a grid-inverter, converting the generated DC power into AC Power, feeding the converted AC power into the public utility grid. If the grid-connected solar PV system is a roof-top system, it is often the case that the grid-connected solar PV system supplies first the power demands of the house the system is installed, selling the excess power to the local electricity provider (utility) at a defined feed-in tariff, paid by the utility company to the grid-connected solar PV system owner. Basic grid connected rooftop PV system shown in Fig. 1.

The main component for grid-connected solar PV power systems comprise of:

- Solar PV modules, connected in series and parallel, depending on the solar PV array size, to generate DC power directly from the sun's intercepted solar power.
- Maximum power point tracker (MPPT), making sure the solar PV modules generated DC power at their best power output at any given time during sunshine hours.
- Grid-connected DC/AC inverter, making sure the generated and converted AC power is safely fed into the utility grid whenever the grid is available.
- Grid connection safety equipment like DC/AC breakers fuses etc., according to the local utility's rules and regulations.

Modeling of a yield simulation requires a large quantity of input data like solar irradiation, local weather conditions and other technical parameters of the planned PV systems (Huld et al., 2008). The level of accuracy needed for the energy yield prediction depends on the stage of project development. For example, a preliminary indication of the energy yield can be carried out using solar resource data and estimates of plant losses based on nominal values seen in existing projects (Huld et al., 2008). Photovoltaic software is widely used in the design of photovoltaic systems to calculate expected energy yield. Solargis PV Planner is one of the software that has the capability of Modeling Solar PV system (Kenny et al., 2006).

The present analysis is aimed:

- To describe and assess the solar resource potential at the given site.
- To perform simulation of 110 kW_p grid connected rooftop solar power plant using solargis PV Planner software.
- To determine annual energy yield and performance ratio of the PV system.
- To determine the best PV technologies for the building based on the simulation results.
- To provide a baseline information for energy and economic assessment of the PV generated electricity.

2. System description

The site selected for the study is based on institution campus located 10 km north of Bhopal, Madhya Pradesh India. The institution (MANIT, Bhopal) obtains its power from Madhya Pradesh electricity board public grid which is shared with other residential and industrial consumer. The site selected for the study is a residential Hostel Building with large space available on rooftop area (roughly 1065 m²). The location and other site specific information are shown in Figs. 2, 3 and Table 2. The system description is given in Table 3 and total load consumption of Hostel building is listed in Table 1.

3. System modeling and performance evaluation

In PV Planner, photovoltaic power production is simulated using numerical models developed or implemented by Geo Model using aggregated data based on 15-min time series of solar radiation and air temperature data as inputs. The simulation itself is quite complex process. Fig. 4 shows the main steps involved in simulation.

Two parameters must be set before performing the PV simulation on the preselected site (Perez et al., 1992).

- Site Parameters: Provided by Solar GIS database (solar radiation parameters, air temperature parameters) and formulas implemented in Solar GIS system (sun path geometry).
- Technical Parameters: Provided by PV Planner user, otherwise default values are taken into consideration.

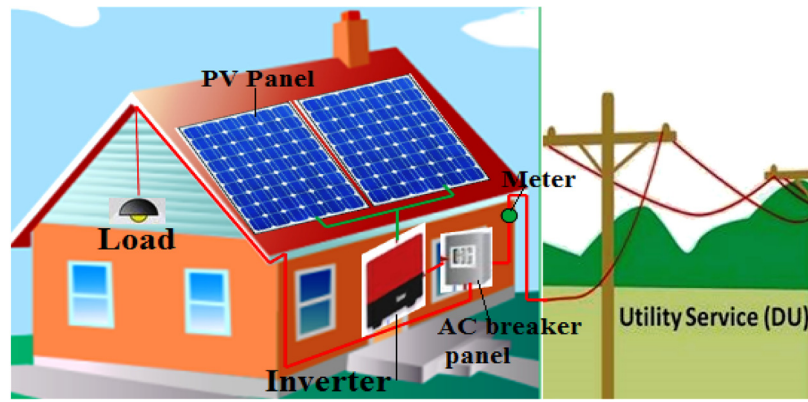


Fig. 1. Basic grid connected rooftop PV system.



Fig. 2. Photograph of Hostel No. 1, MANIT Bhopal, Madhya Pradesh.

Table 1

Load consumption in hostel building.

Electrical load and capacity (W)	Quantity	Total capacity in Watt (kW)	Hours of operation per day (h)	Energy consumptions in kWh
Tube light: 40 W	200	8	10	80
Fan: 40 W	180	7.2	10	72
Water pump: 746 W	3	2.24	5	11.2
Water geyser: 1500 W	6	9	5	45
Refrigerator: 1000 W	1	1	22	22
Water cooler: 700 W	6	4.2	20	84
Total energy consumption per day				314.2 kWh

Table 2

Site information.

Site name	Hostel No.1, MANIT Bhopal, India
Coordinates	23°12'45.29" N, 77°24'32.62" E
Elevation a.s.l	532 m
Slope inclination	1°
Slope azimuth	340° north
Annual global in-plane irradiation	2067 kWh/m ²
Annual air temperature at 2 m	24.8 °C

Table 3

System description.

Installed power	110.0 kW _p
Type of modules	c-Si/a-Si/CdTe/CSI
Mounting system	Fixed mounting, free standing
Azimuth/inclination	180° (south)/23°
Inverter Euro eff.	96.0%
DC/AC losses	5.0%/2.0%
Availability	95.0%

These parameters are implemented in the Computation process in eight steps (Perez et al., 2002, 1987).

Step 1: Global irradiation on in-plane surface

Initially, the 100% conversion of global in-plane irradiation at STC conditions is assumed. Global irradiation impinging on a tilted plane of PV modules is calculated from Global Horizontal Irradiance (G_h), DNI, terrain albedo, and instantaneous sun position within 15 min time interval.

Step 2: Losses due to terrain shading

Reduction of global in-plane irradiation is calculated assuming obstruction horizon of terrain and PV modules. Shading by terrain features is calculated by disaggregation using SRTM-3 DEM and horizon height. Shading of local features such as from nearby building, structures or vegetation is not considered:

Step 3: Losses due to angular reflectivity

The resulting irradiation is subjected to losses from angular reflectivity on the surface of PV modules, and the magnitude of effects depends on relative position of the sun and plane of the module. The accuracy of calculations of angular reflectivity losses depends on cleanness and specific properties of the module surface.

Step 4: Losses due to performance of PV module outside of STC conditions

The conversion efficiency is non-linear and depends on the distribution of pair of values of irradiance and temperature. Relative change of produced energy from this stage of conversion depends on modules technology and mounting type. Crystalline silicon is the technology with the lowest uncertainty of performance prediction among the three most commonly used technologies: crystalline silicon, copper indium gallium selenide, and cadmium telluride. Typically, loss at this step is higher for crystalline silicon modules than thin films due to higher negative thermal power coefficient of crystalline silicon and higher conversion efficiency of thin films at low light levels.



Fig. 3. Site location—Hostel No.1, MANIT Bhopal, Madhya Pradesh.
Source: <https://earth.google.com>.

Step 5: DC losses

A number of effects cause DC power losses:

- Mismatch due to different MPP operating point of modules connected into an inverter, heat losses in interconnections and cables; these losses depend on the design and components of the PV power plant
- Dirt and dust, snow, icing, soiling, bird droppings.
- Inter-row shading.

- Losses in the DC section are to be inserted by a user. The total magnitude of DC losses typically ranges from 5% to 9% or more, depending on the site and system configuration.

Step 6: Inverter losses from conversion of DC to AC

Due to inverter specification an inverter euro efficiency approximating average losses gives good information on the inverter performance. The inverter Euro efficiency typically ranges from 93.5% to 97.5%.

Step 7: AC and transformer losses

Losses in AC section and transformer depend on the system architecture. The inverter output is connected to the grid through the transformer. These losses usually range from 1.5% to 2.5%.

Step 8: Availability

Availability can be assumed that 0.5% to 2% of yearly PV power production may be lost due to various disruptive events.

Solar GIS PV Planner

PVGIS is Energy Capacity Assessment Tool which is used to quickly assess the feasibility of potential solar sites for Installation of roof or ground-mounted PV System. It determines the likely yield and revenue from roof-mounted plant using various PV technologies (a-Si, c-Si, CdTe, CIS) modules.

Key technical assumptions (Skoczek et al., 2008, 2009)

1. Modules degrade over the time due to aging of components and stress due to weather cycles.

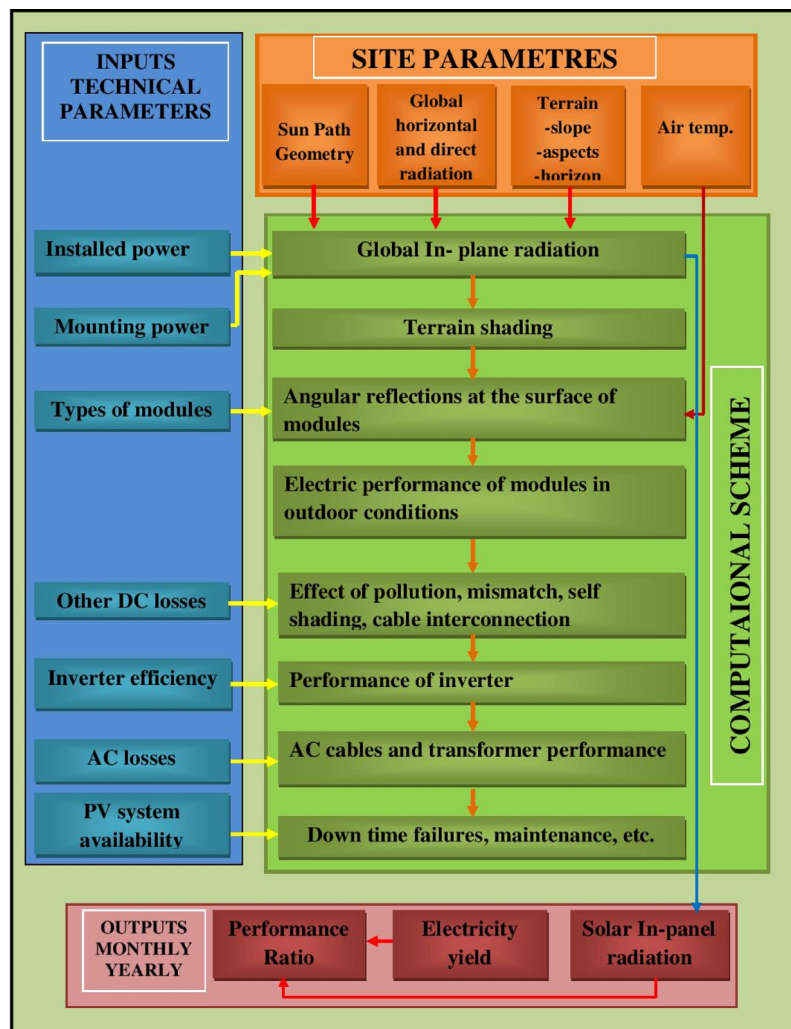


Fig. 4. Simulation methodology.
Source: <http://solargis.info>.

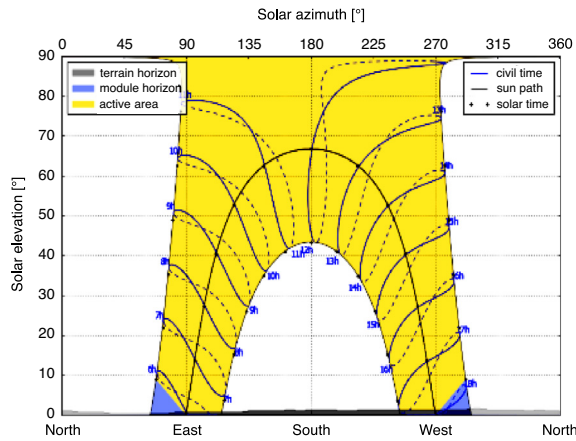


Fig. 5. Path of the Sun over a year.

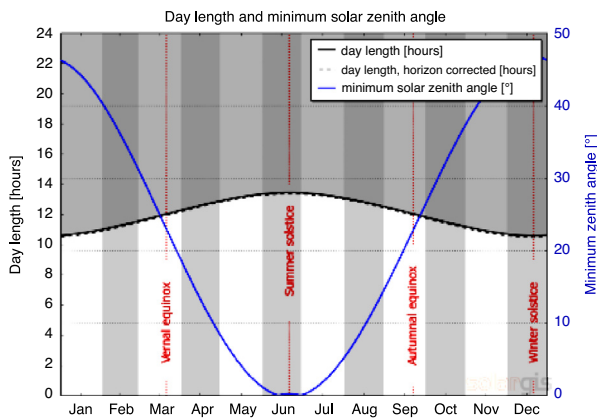


Fig. 6. Variation of the day length and solar zenith angle.

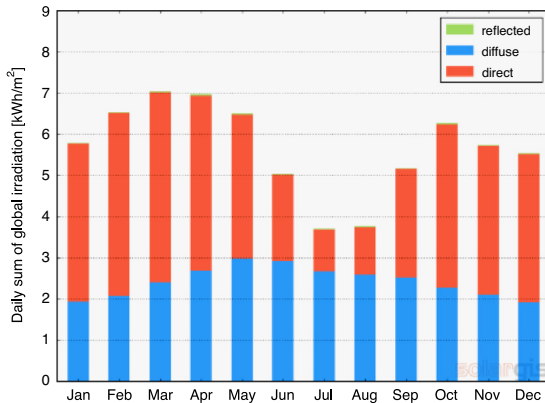


Fig. 7. Variation of global in-plane irradiation and air temperature.

2. Degradation process of PV is considered for a period of 25 years.
3. Linear annual degradation rate is considered.
4. Low level of annual degradation rate (1%–0.5%) is taken.
5. Fixed module tilt angle of 23 is taken to maximize the irradiation received by the PV module.
6. Installed module capacity: 110 kW_p.
7. Standard test conditions are assumed for performance assessment.

Performance indices (Ma et al., 2014; Kumar and Sudhakar, 2015)

The performance of a PV system depends on its solar radiation input and energy output under the operating conditions. According to IEC standard, two important parameters, e.g. system energy

Table 4

Global horizontal irradiation and air temperature.

Month	Gh _m	Gh _d	Dh _d	T ₂₄
January	139	4.50	1.68	17.0
February	151	5.40	1.82	20.3
March	199	6.40	2.24	26.0
April	208	6.94	2.66	31.3
May	214	6.92	3.10	34.5
June	164	5.48	3.09	31.6
July	123	3.96	2.84	26.2
August	121	3.89	2.69	24.5
September	149	4.96	2.46	24.8
October	168	5.42	2.06	23.7
November	138	4.59	1.86	20.5
December	131	4.22	1.66	17.4

Table 5

Average yearly sum of global irradiation for different types of surface.

Types of surface	kWh/m ²	Relative to inclined
Horizontal	1905	92.1%
Inclined (25°)	2067	100.0%
2-axis tracking	2543	123.0%

yield and system performance ratio (PR), are implemented to evaluate and compare the performances of PV systems.

The energy yield is defined as the energy output divided to the nameplate power of the photovoltaic generator in Standard test conditions (Ma et al., 2014, 2013).

$$\text{Energy Yield} = \frac{E_{PV,AC}}{P_{\max G,STC}}. \quad (1)$$

The performance ratio (PR) is defined as the energy output E_{AC} divided by the nameplate D.C. power E_{DC} obtained in Standard test condition.

$$\text{Performance Ratio (PR)} = \frac{E_{AC,kWh}}{(E_{DC,STC} \times \text{Irradiation})}. \quad (2)$$

4. Results and discussion

4.1. Detailed solar assessment

Solar irradiation data represent some of the most important inputs for an expert assessment of energy yield. The analysis factored in site-specific meteorological data, including temperature and humidity, across the selected sites. Fig. 5 shows that the path of the Sun over a year and variation of the day length and solar zenith angle as shown in Fig. 6. The plant has more global irradiation in the month of May (214 kWh/m²) correspondingly more daily sum of global irradiation is recorded. The plant has more global in-plane irradiation in the month of May (214 kWh/m²) correspondingly more daily sum of global in-plane irradiation was recorded (Fig. 7).

Monthly global horizontal and air temperature as shown in Table 4 and Average yearly sum of global irradiation for different types of surface is given in Table 5. The modules receive 123% more solar radiation in a two axis tracking configuration over inclined configuration of 25 and as much as 92.1% solar radiation in the horizontal surface relative to the fixed titled system. Using two-axis trackers, solar modules were assessed to deliver more energy than fixed tilt and horizontally placed panels.

4.2. Energy yield and performance ratio

The performance of each PV system is depicted by its energy yield and performance ratio (PR) that are defined in (1) and (2) respectively. The energy yields and PRs of four PV

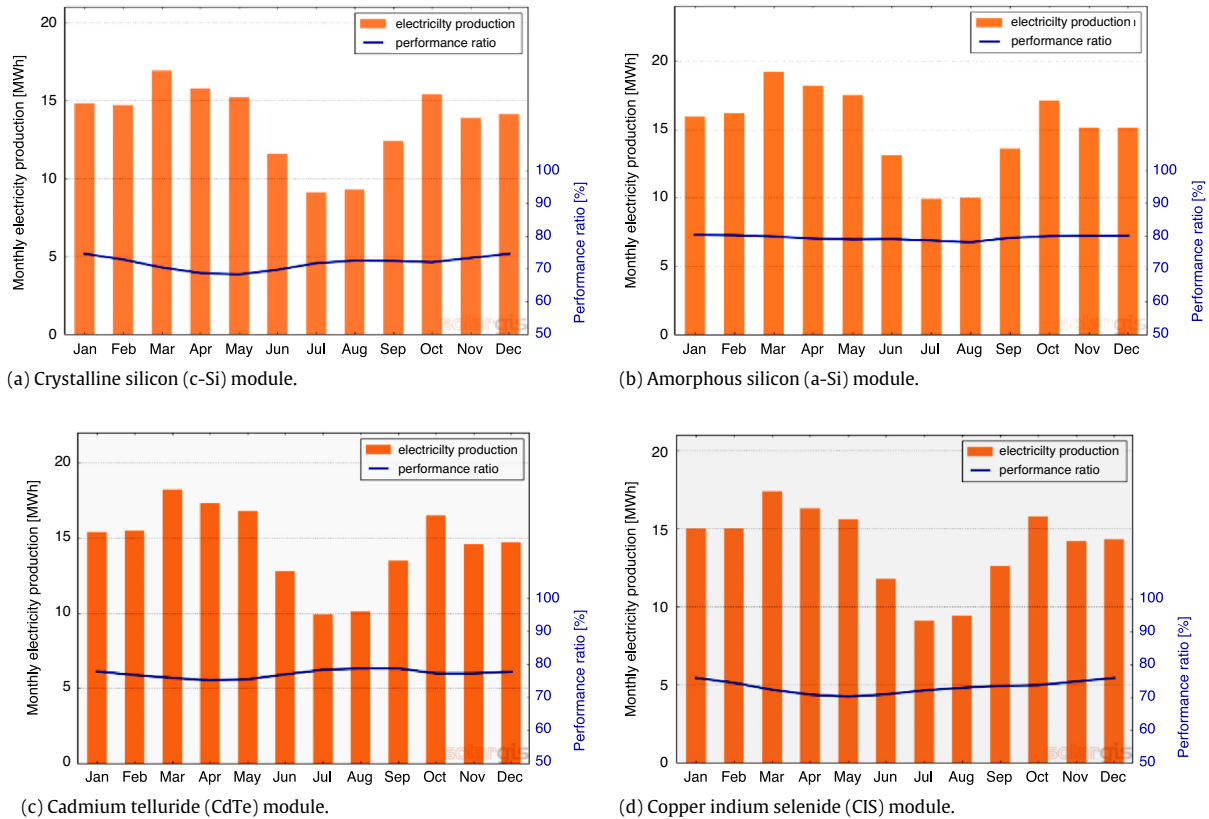


Fig. 8. Variation of PV electricity production and performance ratio.

Table 6

Annual average electricity production and average performance ratio.

PV technologies	Annual average electricity production (MWh)	Energy output (kWh/kW _p)	Average performance ratio (%)
Crystalline silicon (c-Si)	163.1	1483	71.6
Amorphous silicon (a-Si)	181.1	1646	79.5
Cadmium telluride (CdTe)	175.3	1593	77.0
Copper indium selenide (CIS)	166.5	1513	73.1

technologies are calculated and presented in Fig. 8. Annual average electricity production and average performance ratio are shown in Table 6. It is noticeable that system energy yields varies from 1483 kWh/kW_p (c-Si module) to 1646 kWh/kW_p (a-Si module) and the system PRs range from 71.6% (c-Si module) to 79.5% (a-Si module). Performance ratio above 0.8 is always desirable, as high performance directly constitutes an economic gain. Amorphous PV technology shows better performance in terms of higher annual average electricity production (181.1 MWh) and energy yield than the other three technology. This may be due to lower temperature coefficient and capture losses of these technologies, but their efficiencies may be lower under standard test conditions.

5. Conclusion

This paper has evaluated the technical performance of a 110 kW_p grid connected roof top solar PV-system to supply electricity and energy for the Hostel building. Four types of PV modules have been simulated to determine performance ratios and Energy yield. The following conclusions are drawn from the study:

- The PR of the PV systems varies from 70% to 88% and their energy yields range from 2.67 kWh/kW_p to 3.36 kWh/kW_p.
- Among the four types of PV systems considered here, two PV systems a-Si and CdTe PV system have their PRs higher than 75%.

- From the annual energy yield of the PV systems, it is observed that all the four technology perform satisfactory under the tropical weather conditions.
- The electricity generated by PV systems can be used to power the water pumps, lighting and other electrical appliances of the Hostel building.

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