ENERGY AND EXERGY PERFORMANCE EVALUATION OF A TYPICAL SOLAR PHOTOVOLTAIC MODULE

by

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This paper presents the energy and exergy performance evaluation of heterojunction with intrinsic thin layer solar photovoltaic module for a particular day of different months of the year of a typical climatic zone of north India. The energy, exergy, and power conversion efficiencies have been calculated and plotted against time based on hourly insolation. The variation in all the efficiencies has been observed with respect to variation in solar radiation and wind speed and found that all the efficiencies are higher in morning and evening time as compared to noon time which is due to the variation in temperature of module throughout the day. Performance of solar photovoltaic module has been found to be the best in the month of February i. e. all the three efficiencies have been found to be the highest among all the months analysed and presented in the study for the month of February. The energy efficiency is found to be always higher than that power conversion and exergy efficiencies. However, exergy efficiency in some months like February, May, June, September, October, and December has been found to be higher than that of power conversion efficiency, reverse is found in rest of the months.

Keywords: *energy, exergy, solar radiation, heterojunction with intrinsic thin layer solar photovaltaic module, wind speed*

Introduction

Due to growing environmental concern, energy generation from renewable energy sources *i. e.*, clean and green energy sources are increasingly important. Solar energy is clean energy and India is very rich in solar energy having 300 sunny days throughout the year. Keeping this view in mind, Government of India, Ministry of New and Renewable Energy launches the Jawaharlal Nehru National Solar Mission (JNNSM) to promote ecologically sustainable growth while addressing India's energy security challenge. The target of solar mission is to produce 100 GW of power using solar energy by 2022 [1].

Researchers from all over the world working on high efficient, low cost solar cells are for this several approaches have been investigated. One of the options might be reduction in the amount of material for the fabrication of solar cells. Wafer slicing technology including kerf loss reduction for a thin having width less than 200 μm and the manufacturing technology for

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the same are under investigation [2]. By using the thin film technology for solar cells shortage of silicon material can be managed. Thinner active layers having width less than 100 μm are the efforts in the direction of achieving high-efficiency and low-cost solar cells [3], however before proceeding to mass production there is need of further efforts to reduce the process cost. Enhancement in the efficiency of solar cells means obtaining the more power from the same solar cells which in turn reduce the amount of materials needed to fabricate them and hence the cost of cells. Recently, lot of work from all over the world has been done in the direction of achieving low cost high efficiency solar cells. Multicrystallline silicon (mc-Si) has been found to be good option for as compared mono-crystalline silicon (c-Si). However, as far efficiency is concerned many problems have been found that in obtaining high efficiency (20%) with a practical size. The problems are crystal growth technology to control the grain quality uniformly, passivation technology for surface, light-trapping technology, crystal grains itself, and grain boundary. These technologies have been systematically and actively investigated at the laboratory level [4]. For obtaining both low cost and high efficient solar cells a different approach has been investigated, a new a-Si/c-Si heterojunction structure called heterojunction with intrinsic thin layer (HIT) has been developed [5-9]. This structure features a very thin intrinsic a-Si layer inserted between a doped amorphous silicon (a-Si) layer and a c-Si substrate. This structure has several advantages such as: it has an excellent surface passivation and *p-n* junction which results high efficiency, its low-temperature processes (<200 ºC) can prevent any degradation of bulk quality that happen with high-temperature cycling processes in low-quality silicon materials such as solar grade Czochralski Si and compared with it has much better temperature coefficient as compared to conventional diffused cells. Taguchi *et al*. [10] reported the high conversion efficiency of 21.5% in HIT cells with a size of 100.3 cm^2.

Energy efficiency is based on the first law of thermodynamics and doesn't consider the irreversibilities associated with the system therefore, represents the quantity of energy. Exergy analysis is based on the first law of thermodynamics considers the losses associated with system and hence represents the quality of energy [11-15]. Smestad [16] examined concepts of hot carrier and light converter, indicating that electrons are ejected not only as heat but also as light. Carnot factor in solar cell theory was investigated by Landsberg and Markvart [17], they obtained an expression for the open-circuit voltage which is equal to the band gap multiplied by the Carnot efficiency. Thermodynamics and reciprocity of solar energy conversion was also discussed by Markvart and Landsberg [18] by taking into consideration the photovoltaic (PV), photochemistry and photosynthesis.

Sahin *et al*. [19] investigated the thermodynamic characteristics of the solar photovoltaic (SPV) cells using exergy analysis. They developed and applied the new approach for the assessment of PV cells and found that the presented approach is realistic as it accounts for thermodynamic quantities such as enthalpy and entropy. They found that energy efficiency varies between 7-12% during the day however, exergy efficiency was found to be varying between 2-8%. Bisquert *et al*. [20] investigated the physical and chemical principles of SPV conversion systems. They found that the open-circuit voltage and chemical potential of a SPV cell is dependent on Carnot and statistical factors. Joshi *et al*. [21] investigated the performance characteristics of a PV and photovoltaic-thermal (PV/T) system using energy and exergy analysis for the New Delhi, India. They found that in the case of PV/T, the energy efficiency varies between 33-45%, while the corresponding exergy efficiency varies between 11-16%. On the other hand, for PV alone, the exergy efficiency was found to be varying in the range of 8-14% for a typical set of operating parameters. Hepbasli [22] has done a literature review on exergy analysis of several solar energy systems especially PV/T systems and gave similar expressions as given by Fujisawa and Tani [23] and Saitoh *et al*. [24].

Present study deals with the thermal performance evaluation of HIT SPV module based on energetic and exergetic analysis for different months of the year under Indian climatic condition.

Materials and methods

The experimental study of HIT SPV module has been carried out for around ten months at the typical climatic zone in north India which is located at 28º26'24" latitude and 77º1'16" longitudes. The experiments have been carried out for each day of the different months of the year in real outdoor conditions from 9 a. m. to 5 p. m. The measured parameters includes, the solar radiation, wind speed, open circuit voltage, short circuit current, voltage corresponding to maximum power point, current corresponding to maximum power point, fill factor (*FF*), ambient temperature, average temperatures at the top, middle, and the bottom of the module, minimum temperature at the top, middle, and bottom of the module and maximum temperature at the top, middle, and bottom of the module. After having data of each day of different months of the year the calculations have been made using the above measured parameters for a clear sky day of each month of the year. Due to some technical problem in the system calculation for the month March and November has not been made. In this experimental study, the comparative energetic and exergetic analysis of HIT SPV module in the different months of the year under Indian climatic conditions has been carried out for which following materials and methods has been used.

Solar radiation, spectral power distributions of illuminants, wind speed, air temperature, and humidity have been measured with the help of weather station which includes a meteorological measurement system and data acquisition system. Meteorological measurement system composed of pyranometres, spectroradiometers, wind monitor, temperature, and humidity sensors. Solar radiation has been measured with the help of two pyranometers viz. at horizontal *i. e.*, parallel to earth's surface and at tilted positions equal to the latitude of the experimental location having the wavelength range of each pyranometer is 305 nm to 2800 nm. Silicon pyranometer is a very sensitive with execution time one second. The ultraviolet pyranometer has been used for the measurement of only ultraviolet radiation having the wavelength range between 280 nm to 400 nm.

Spectral power distributions of illuminants have been measured by spectroradiometers. Two different spectoradiometers visible spectroradiometer (MS 710) and infrared spectroradiometer (MS 712) having the range of 350-1100 nm and 900-1700 nm, respectively, have been used in this experimental study. Wind monitoring is being done by high performance wind sensor which measures wind speed and wind direction in the range 0-100 m/s and 0°-360°, respectively. Then temperature and humidity are measured by air temperature and humidity sensors, respectively. The measurement range is –40 °C to 60 °C for air temperature and 0.8% to 100% relative humidity for humidity sensor, respectively. Finally the data was collected through data logger. Photographic view of the complete weather monitoring system has been shown in fig. 1.

Energy and exergy analysis

The energy and exergy analysis of the data collected by using the above materials and methods have been carried out by using a set of equation.

Energy analysis

The input energy *i. e.*, energy of solar radiation is given by [21-26]:

Figure 1. Photographic view of weather monitoring system

$$Q_{in} = I_s A \tag{1}$$

where I_s is intensity of solar radiation and A – area of SPV module

Actual output of the SPV module may be defined [21-26]:

$$Q_o = V_{oc} I_{sc} FF \tag{2}$$

where V_{oc} is open circuit voltage, and I_{sc} – short circuit current.

The *FF* of the SPV system can be defined as the ratio of the product of voltage corresponding to maximum power (V_m) and the current corresponding to maximum power (I_m) to the product of open circuit voltage and short circuit current and can be expressed:

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \tag{3}$$

Using the definition (3) eq. (2) can also be expressed:

$$Q_o = V_m I_m \tag{4}$$

The energy efficiency can be defined [21-26]:

$$\eta = \frac{V_{oc} I_{sc}}{I_s A} \tag{5}$$

However, this definition is restricted to theoretical cases only.

Exergy analysis

The input exergy *i. e.*, exergy of solar radiation is given by [21-26]:

$$Ex_{solar} = Ex_{in} = \left(1 - \frac{T_a}{T_s}\right) I_s A \tag{6}$$

where T_s is the temperature of Sun which is taken as 5777 K.

The exergy output of the SPV systems can be given:

$$Ex_{out} = Ex_{elec} + Ex_{therm} + Ex_d = Ex_{elec} + I' \tag{7}$$

where $I' = \sum Ex = Ex_{d,elect} + Ex_{d,therm}$ which includes internal as well as external losses Internal losses are electrical exergy destruction *i. e.*, $Ex_{d,elect}$ and external losses are heat loss, $Ex_{d,therm}$ which is numerically equal to Ex_{therm} for PV system. For the calculation of electrical exergy of the PV system *i. e.*, Ex_{elec} it has been assumed that exergy content received by PV surface is fully utilized to generate maximum electrical exergy ($V_{oc}I_{sc}$).

$$Ex_{elec} = E_{elec} - I' = V_{oc} I_{sc} - (V_{oc} I_{sc} - V_m I_m) \tag{8}$$

where $V_{oc}I_{sc}$ represents the electrical energy and ($V_{oc}I_{sc}$ – V_mI_m) represents the electrical exergy destruction. Therefore from eq. (9) we find the electrical exergy:

$$Ex_{elec} = V_m I_m \tag{9}$$

The thermal exergy of the system (Ex_{therm}) which is defined as the heat loss from the PV surface to the ambient can be represented [21-26]:

$$Ex_{therm} = \left(1 - \frac{T_a}{T_{cell}}\right) Q \tag{10}$$

where $Q = h_{ca}A(T_{cell} - T_a)$ and $h_{ca} = 5.7 + 3.8v$ and
where h_{ca} is the convective heat transfer coefficient, and v – the wind speed. Using the equations, exergy of SPV system can be written:

$$Ex_{PV} = V_m I_m - \left(1 - \frac{T_a}{T_{cell}}\right) h_{ca} A (T_{cell} - T_a) \tag{11}$$

The solar cell power conversion efficiency (η_{pce}) can be defined as the ratio of actual electrical output to the input solar radiation ($I_s A$) on the PV surface and can be given [21-26]:

$$\eta_{pce} = \frac{V_m I_m}{I_s A} \tag{12}$$

The power conversion efficiency can also be written in the terms of FF using the equations [21-26]:

$$\eta_{pce} = \frac{FF V_{oc} I_{sc}}{I_s A} \tag{13}$$

In general the exergy efficiency (ψ) is defined as the ratio of output exergy to the input exergy. Therefore, the exergy efficiency (ψ) can be expressed [21-26]:

$$\psi = \frac{V_m I_m - \left(1 - \dfrac{T_a}{T_{cell}}\right) h_{ca} A (T_{cell} - T_a)}{\left(1 - \dfrac{T_a}{T_s}\right) I_s A} \tag{14}$$

Results and discussion

The specifications of the HIT SPV module as given by the manufacturer at standard test conditions (STC) *i. e.*, at solar radiation of 1000 W/m^2, air mass of 1.5 and ambient temperature of 25 ºC are: open circuit voltage (V_{oc}) = 73.60 V, short circuit current (I_{sc}) = 3.79 A, maximum power point voltage (V_m) = 59.7 V, maximum power point current (I_m) = 3.52 A, and maximum power point power (P_{max}) = 210 W.

The specifications of the HIT SPV module at STC as obtained through the Sun simulator in the laboratory are: open circuit voltage (V_{oc}) = 68.7 V, short circuit current (I_{sc}) = 3.829 A, maximum power point voltage (V_m) = 56.8 V, maximum power point current (I_m) = 3.672 A, maximum power point power (P_{max}) = 209 W, cell efficiency = 19.9%, and module efficiency = 17.4%.

These mentioned parameters have been recorded through the data loggers, based on the recorded data the energy, power conversion, and exergy efficiencies for HIT SPV module have been calculated and plotted against the operating time from 9 a. m. to 5 p. m. for a typical set of operating parameters at the experimental and the discussion of results are given;

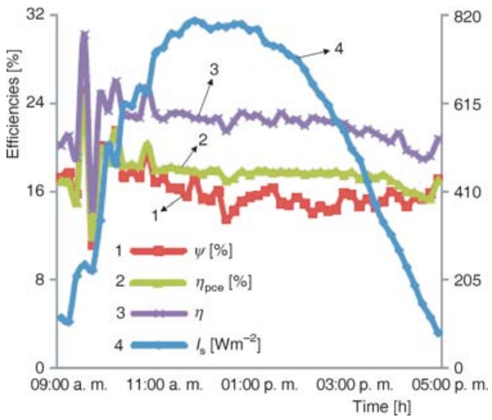

Figure 2. Variation in efficiencies and solar radiation w. r. t. time of HIT SPV module in the month of January

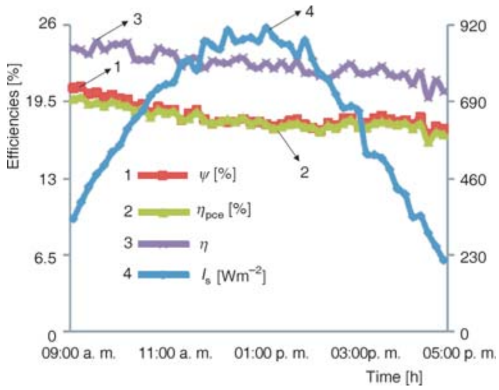

Figure 3. Variation in efficiencies and solar radiation w. r. t. time of HIT SPV module in the month of February

The variation of energy, power conversion, and exergy efficiencies of HIT SPV module along with solar radiation against time for the month of January and February has been illustrated in figs. 2 and 3, respectively, at a typical set of operating and designed conditions as mentioned. From fig. 2 it is observed that the initially solar radiation increases, attains its peak near the middle of the day and goes down sharply towards the end of the day, while fluctuating throughout the entire day which is an obvious case in practice. It has also been found that all the three efficiencies viz. energy, power conversion and exergy fluctuate with time which is due to the intermittent nature of solar radiation which also fluctuates with time. Also, initially all the efficiencies are very much fluctuating in nature *i. e*., small change in radiation causes a sharp change in efficiencies which may be explained in the terms of temperature of module in the morning time. It also observed from fig. 2 that all the three efficiencies are initially high and increases as the time increases and then decreases slowly then remains almost constant for over a long time period *i. e*., approximately between 10 a. m. to 4 p. m. and again increases. This variation in efficiencies is due to variation in solar radiation and variation in module temperature throughout the day.

It can also be observed from fig. 2 that all the three efficiencies are high in the morning and evening time as compared to noon time which is due to the fact that in the morning time module is cool and as the time increases temperature of the module also increases and again in the evening time temperature of the module is less as compared to noon time. As the temperature of the module increases voltage decreases due to negative temperature coefficient of module and current increases but not in the ratio of voltage so that ultimate product of voltage and current *i. e*. output energy decreases. Therefore, product of voltage and current is high in the morning and evening time as compared to noon time hence, output to input ratio *i. e*. efficiencies are high in the morning and evening time as compared to noon time. The exergy efficiency fluctuates more frequent than that of energy efficiency which is due to variation in wind speed throughout the day as exergy efficiency is strongly dependent on the wind speed.

The energy efficiency is found to be always higher than those of exergy efficiency throughout the day. As exergy efficiency deals with the evaluation of losses associated with the system from second law of thermodynamics and represent the quality of energy. However, energy efficiency is based on the first law of thermodynamics and represents the quantity of energy rather than quality of energy and doesn't incorporate the losses/irreversibilities due to various parameters associated with the system. The average energy, power conversion and exergy efficiencies are found to be 22.16%, 17.65%, and 16.12%, respectively in the month of January.

It is seen from fig. 3 that it shows almost the same pattern of variation in all the parameters *i. e*., energy, power conversion and exergy efficiencies and solar radiation against time as that of fig. 2. Figure 3 shows that the average exergetic efficiency is higher than that of power conversion or actual efficiency which is reverse in the case of crystalline technology based modules. Higher exergy efficiency than that of power conversion efficiency in HIT based modules shows that losses are less as compared to crystalline based technology due to its internal structure which combination of both *a*-Si and *c*-Si. From fig. 3 it is also found that the fluctuation in all the three efficiencies for the month of February is found to be less then in January which is due to the variation in solar radiation and wind speed throughout the month and day. All the efficiencies have been found to be high in the morning and evening time as compared to noon time same as in the month of January but all the efficiencies in the morning time are higher than that of evening time. This is due to the fact that, in the night time there is no availability of solar radiation and hence ambient temperature is low as compared to day time. Therefore, module temperature is relatively cool as compared to evening time. Also average energy, power conversion and exergy efficiencies for the month of February are found to be 22.53%, 18.03%, and 18.35%, respectively. From figs. 2 and 3 it is also found that all the efficiencies for the month of February is found to be higher than those in January.

The energy, power conversion and exergy efficiencies and the solar radiation for HIT module are plotted against time for the months of April and May as can be seen in figs. 4 and 5, respectively. From fig. 4 it is seen that the energy and power conversion efficiencies are almost constant in nature throughout the day this is due to the fact that the fluctuation in solar radiation is not much. However, exergy efficiency fluctuates due to the reason as explained before. Average energy, power conversion, and exergy efficiencies are found to be 20.52%, 16.04%, and 15.77%, respectively, for the month of April. Figure 5 also shows almost the same pattern of variation as that of figs. 2-4 and due to the same reason as explained before. Average energy, power conversion, and exergy efficiencies are found to be 19.54%, 15.40%, and 15.50%, respectively, for the month of May. From figs. 4 and 5 it also found that all the efficiencies for the month of April are found to be higher than that in May.

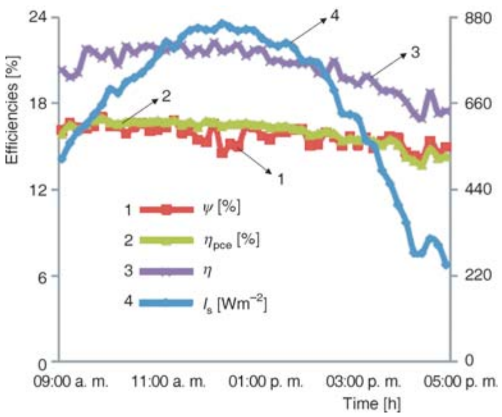

Figure 4. Variation in efficiencies and solar radiation w. r. t. time of HIT SPV module in the month of April

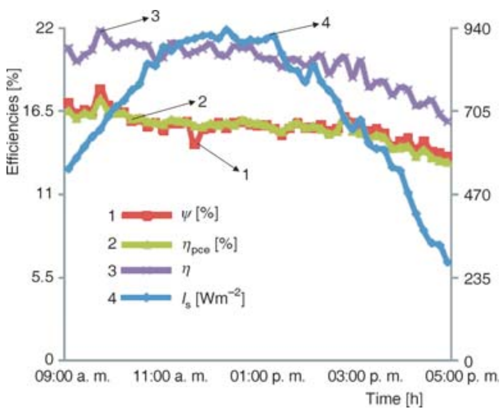

Figure 5. Variation in efficiencies and solar radiation w. r. t. time of HIT SPV module in the month of May

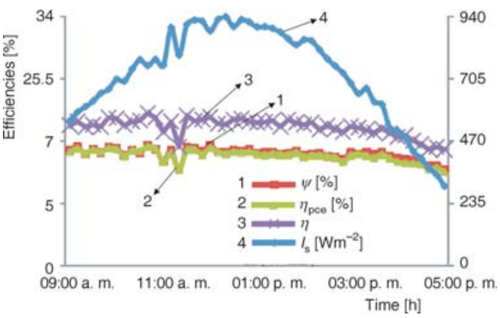

Figure 6. Variation in efficiencies and solar radiation w. r. t. time of HIT SPV module in the month of June

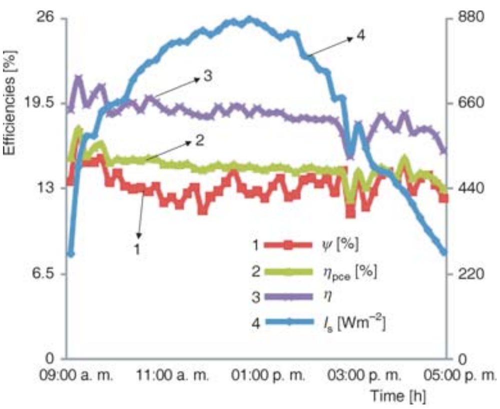

Figure 7. Variation in efficiencies and solar radiation w. r. t. time of HIT SPV module in the month of July

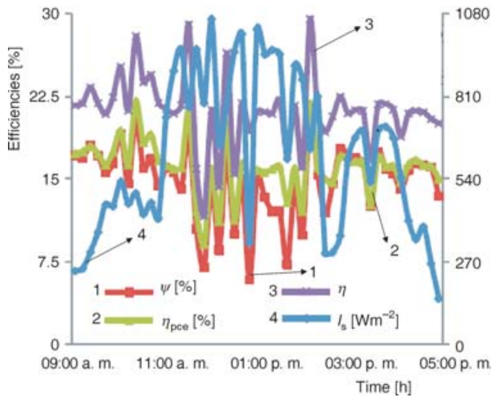

Figure 8. Variation in efficiencies and solar radiation w. r. t. time of HIT SPV module in the month of August

Variation of efficiencies and solar radiation against time of HIT SPV module in the months of June and July can be seen from figs. 6 and 7. From fig. 6, it is found that there is a sharp dip in all the three efficiencies at 11.20 a. m. and sharp increase at 11.30 a. m. This dip in the efficiencies are due to sharp fall in the solar radiation at that particular instant and therefore output to input ratio decreases sharply and as a result we got the lower instantaneous efficiency and increase in efficiencies is due to corresponding increase in solar radiation. The average energy, power conversion, and exergy efficiencies are found to be 19.52%, 15.50%, and 15.72%, respectively, for the month of June and 18.53%, 14.66%, and 13.28%, respectively, for the month of July. From figs. 6 and 7 it also found that the all efficiencies for the month of June are found to be higher than that in July.

Figures 8 and 9 show the variation of efficiencies and solar radiation against time of HIT SPV module for the months of August and September, respectively. Figure 8 shows that the all the efficiencies for this particular day of the month August is very much fluctuating which is due to the fact that corresponding solar radiation also fluctuates due to rainy reason in India. As all the three efficiencies are directly proportional to the solar radiation and which in turn completely dependent on the nature of weather. Therefore, due to rainy season performance of the SPV module gets affected. Average energy, power conversion, and exergy efficiencies are found to be 21.16%, 16.18%, and 14.81%, respectively, for the month of August. Figure 9 shows that this particular day of the month September is clear sky day *i. e*. Very much shiny and therefore we got the solar radiation most of the time above 500 W/m^2 also variation in wind speed is very less. Therefore, all the efficiencies also don't fluctuate much. Average energy, power conversion, and exergy efficiencies are found to be 21.95%, 16.80%, and 16.94%, respectively, for the month September. In view of the before, it is found that the all the efficiencies in the month of September is higher than that in August. However, it is also seen that change in energy and power conversion efficiencies is not much but exergy efficiency changes approximately 2%. This is due to the fact that in the month of September insolation is good and also wind speed is not varying therefore, losses are also less hence we got the better exergy efficiency in the month of September than those in August.

The energy, power conversion and exergy efficiencies and the solar radiation are plotted against time for the months of October and December as can be seen in figs.10 and 11, respectively. From figs. 10 and 11 it is found that the intensity of solar radiation is very good as that in month September. Therefore efficiencies don't fluctuate much in these months also. Average energy, power conversion, and exergy efficiencies are found to be 22.37%, 17.09%, and 17.31%, respectively, for the month of October and 21.15%, 16.54%, and 16.98%, respectively, for the month of December. From figs. 10 and 11 it also found that the all efficiencies for the month October are found to be higher than that in December.

Comparative monthly variation of all the efficiencies *i. e*., energy, power conversion, and exergy for the complete year (10 months) is shown in fig. 12. From fig. 12 it can be seen that the energy, power conversion, and exergy efficiencies for the month of February are highest among all the months analysed and presented in the study. Energy efficiency has been found to be higher than those of power conversion and exergy efficiencies in all the months analysed and presented in this paper. However, a mixed response has been found in the case of exergy efficiency and power conversion efficiency *i. e*. in some month's exergy efficiency has been found to be higher than that of power conversion efficiency such as in the months of February, May, June, September, October, and December and in rest of the months power conversion efficiency has been found to be higher than those of exergy efficiency. This is unlike c-Si technology based SPV modules [17] where power conversion ef-

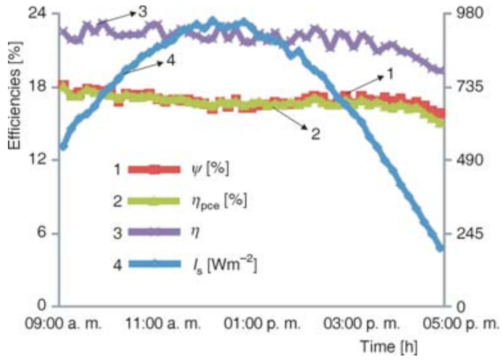

Figure 9. Variation in efficiencies and solar radiation w. r. t. time of HIT SPV module in the month of September

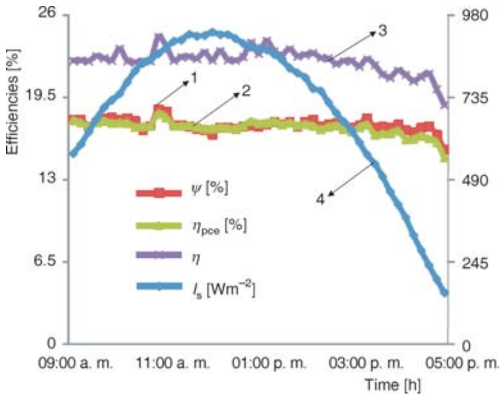

Figure 10. Variation in efficiencies and solar radiation w. r. t. time of HIT SPV module in the month of October

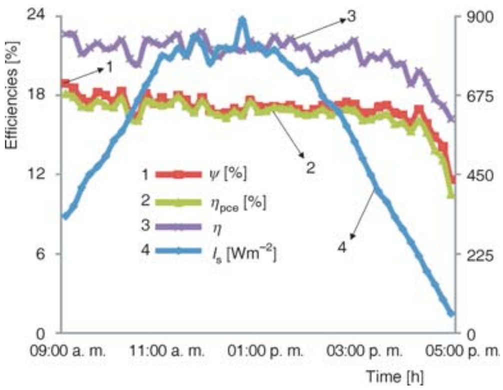

Figure 11. Variation in efficiencies and solar radiation w. r. t. time of HIT SPV module in the month of December

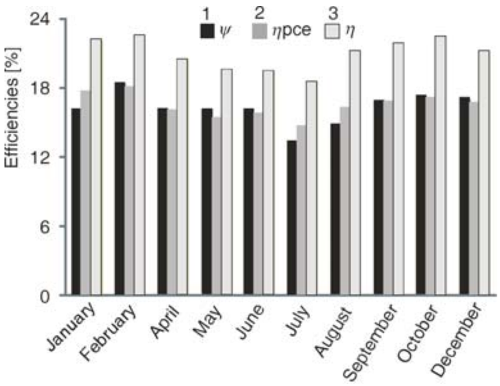

Figure 12. Monthly variations of energy and exergy efficiencies of HIT solar module

ficiency is always higher than those of exergy efficiency. This variation is due to internal structure of HIT SPV module where both a-Si and c-Si has been used for the HIT solar cell fabrication and therefore losses were found to be lees in this type of SPV module. All the efficiencies of the month October is found to be the second best. However, all the efficiencies were found to be least in the month of July. Therefore, performance of HIT module in the month of July has been found to be the least and in the month of February best.

Conclusions

Performance analysis of HIT SPV module in the different months of the year for the typical Indian climatic condition based on exergetic and energetic analysis has been done in the present experimental study. Three different efficiencies viz. energy, power conversion, and exergy efficiencies have been evaluated and the comprehensive discussion has been given. From the discussion previous it is found that the all three efficiencies show the different nature of variations in the efficiencies for different months of the year due to intermittent nature of solar radiation and variation in wind speed. Based on the experimental study and the discussions of results following conclusions have been drawn:

- All the efficiencies *i. e.* energy, power conversion, and exergy efficiencies for the month of February has been found to be the highest among all the months analysed and presented in the study under the climatic condition of north India. However, all the efficiencies have been found to be least in the month of July. Therefore, performance of HIT SPV module has been found to be best in the month of February.
- All the efficiencies have been found to be higher in the morning and evening time as compared to noon time. Also, all the efficiencies in the morning time are higher than that of evening time which is due to temperature variation in the module throughout the day.
- Energy efficiency is found to be always higher than that of power conversion and exergy efficiencies. A mixed response has been found in the case of exergy efficiency *i. e.* in some months like February, May, June, September, October, and December exergy efficiency has been found to be higher than those of power conversion efficiency however, reverse is found in rest of the months analyzed and presented in this paper.
- From the study it is also found that the *FF* plays an important role in improvement of exergy and power conversion efficiencies. The *FF* is directly proportional to both the efficiencies, higher the *FF*, higher will be exergetic and power conversion efficiency.

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Nomenclature

A	–	area of module, [m^2]
Ex	–	exergy, [W]
FF	–	fill factor
h_{ca}	–	convective (radiative) heat transfer coefficient
I_s	–	solar radiation, [Wm^{-2}]
I_{sc}	–	short circuit current, [A]
I_m	–	current corresponding to maximum power point, [A]
SPV	–	solar photovoltaic
T	–	temperature, [K]
v	–	wind speed, [ms^{-1}]
V_{oc}	–	open circuit voltage, [V]
V_m	–	voltage corresponding to maximum power point, [V]

Greek letters

η	–	energy efficiency, [%]
ψ	–	exergy efficiency, [%]
η_{pce}	–	power conversion efficiency, [%]

Subscripts

a	–	ambient
cell	–	cell
d	–	destroyed
elec	–	electrical
therm	–	thermal
in	–	input
oc	–	open circuit
out	–	output
sc	–	short circuit

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