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EXERGY PERFORMANCE ANALYSIS OF 300 W SOLAR PHOTOVOLTAIC MODULE

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Abstract

Solar energy provides both heat and light. Solar photovoltaic systems generate electricity by utilising light of solar radiation and thermal energy content of solar radiation is lost to environment. In this paper, an experimental study has been carried out for evaluating energy and exergy output of solar photovoltaic module installed at Poornima University, Jaipur. Energy analysis was performed on the solar photovoltaic module by applying first law of thermodynamics. By applying the second law of thermodynamics, exergy analysis was performed to determine exergy losses and exergy efficiency during the photovoltaic energy conversion process. The various operating parameters of a solar photovoltaic module such as module surface temperature, ambient temperature, overall heat transfer coefficient, open-circuit voltage, short-circuit current, fill factor, global radiation etc were determined for a sunny day of March 2016 at Jaipur. The experimental data are used for the calculation of the energy and exergy efficiencies of the PV systems. Energy efficiency is varying between 9% and 14.41% during the test day. In contrast, exergy efficiency for solar photovoltaic module for electricity generation, ranging from 45.80% to 68.16%. It is noted that solar photovoltaic module temperature has a considerable amount of effect on the energy and exergy efficiencies. The energy and exergy efficiencies can be improved by removing heat from the surface of solar photovoltaic module. The heat can be removed with the help of water or air.

Keywords: Solar photovoltaic; exergy analysis; energy analysis; energy efficiency; exergy efficiency; performance analysis

INTRODUCTION

The development of renewable energy sources as a replacement of conventional energy sources had been taken into consideration in past few decades [1-2]. For the sustainable development of any country, the development of renewable energy sources is becoming necessary due to depleting fossil fuel, increasing fuel prices across the world and emission level. In India till May 2015, about 96% of villages have been electrified out of which 30% of the households get less than 12 hours of electricity supply. The demand for electricity is increased by 28% from 2009 to 2015 and is expected to increase at the rate of 1.2% per year. The amount of solar radiation reaching the earth's surface depends on the various factors such as season, weather conditions, location, and orientation of the surface but it averages about 1000 W/m2 for the absorbing surface which is perpendicular to the sun's rays and the sunny day. In India, most of the parts in a year experienced clear sunny weather for 250 to 300 days. The annual average solar radiation intensity varies between 5-7 kWh/m2day [3]. This energy is sufficient to provide adequate energy for electrical and thermal applications. If 1% of land is used to harness solar energy with an efficiency of 10%, as much as 46.7 MWh/year of electrical power can be generated.

Many theoretical and experimental studies on solar energy were carried out in last 25 years as it is easily available, cheap and environmental friendly alternative source [4]. For distributed power generation the solar PV technology is considered to be well suited technology. Solar photovoltaic systems also increase the reliability of the system to which they are connected and as they generate the electricity close to the point of consumption, they also reduce transmission and distribution losses [5].

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Solar radiation consists of both direct beam radiation and diffuse radiation. Solar photovoltaic systems uses only beam radiation and very small component of diffuse radiation. But even on clear and sunny day, the diffuse radiation contributes about 20 percent of the total solar radiation [6]. A surface normal to the direction of sun's rays received the maximum amount of solar radiation. So, the design of a solar photovoltaic system needs all the information related to the site meteorological data. The solar cell generates the electric power when solar energy incident on solar cell pushes the electrons into the p-layer and leaves holes in the n-layer. This generated electric power is extracted through an electric circuit.

Energy efficiency, based on the first law of thermodynamics, is the ratio of the power output of solar cell to the solar energy delivered to the solar panel whereas compared to exergy analysis, which is based on the second law of thermodynamics. Energy analysis is gives the quantity of energy interaction during a process whereas exergy gives the quality of energy available for converting to useful work. The efficient and effective usage of solar energy is evaluated by exergy analysis of solar energy conversion system. Exergy analysis can be used to improve the efficiency of a system by evaluating the sources and magnitude of irreversibilities.

The maximum useful work which can be obtained from input energy is called exergy [7-8]. Many engineers recognized exergy analysis to be a useful tool for the evaluation of the thermodynamic performance of system in general [9-11]. Exergy analysis of the solar photovoltaic system provides an alternative method of evaluating and comparing performance of the system [12]. Exergy analysis of the system is based on the separate quantification theory and accounting for the usable energy from the system, called exergy or available energy, and unavailable energy, called irreversibility [13]. The energy utilization efficiency of an energy conversion system is found out by means of exergy analysis. Useful results were obtained from exergy analysis because it deals with minimization of irreversibility and maximum exergy delivery.

Figure 1. A 300W Solar PV module at Poornima University, Jaipur

Over the last several decades the exergy analysis has been increasingly applied because of its advantages and benefits over energy analysis. To apply the energy and exergy balance on the solar photovoltaic system, the input energy and exergy and output energy and exergy of the system must be evaluated. L. Geng [14] evaluated the exergy performance analysis of solar water heating system experimentally and the energy and exergy efficiencies are compared. Review on exergetic analysis and assessment of renewable energy resources are done [15] for a sustainable future. A. S. Joshi [16] described a model of a solar photovoltaic thermal system in terms of exergy analysis. The purpose of work presented in this paper is to apply an energy and exergy balance for the solar photovoltaic module. With the help of energy and exergy analysis a realistic model was developed for predicting the performance of solar photovoltaic module.

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METHODOLOGY

2.1. Energy Efficiency of Solar Panel

By using the first law of thermodynamics the general form of the exergy balance equation for an open steady state system can be written as:

$$E_{in} = E_{out} \quad (1)$$

The general equation for the exergy balance is:

$$E_{in} - E_{out} = E_{loss} \quad (2)$$

The maximum amount of useful work obtainable during a process when system brings to equilibrium is called exergy which is combined property of system and surrounding. In equation (2) the maximum amount of work obtainable from the system undergoing process is Eout. The lower the exergy consumed, lower will be the exergy loss.

Energy conversion efficiency a solar cell connected in electrical circuit is the percentage of power converted to electricity when light falls on it. The ratio of energy output to energy input is called the energy efficiency of the solar photovoltaic cell. The output energy of solar photovoltaic cell depends on cell surface temperature and incident solar radiation on surface of solar cell. When a solar radiation incident on the panel it generate electricity and 75-80% of the absorbed radiation is dissipated in the form of heat to the surrounding after photovoltaic conversion. The electrical conversion efficiency increases with increase in solar irradiation but it also increases the temperature of panel. With increase of 1 0C in temperature there is reduction of the photoelectric conversion efficiency by 0.5%. The following equation gives the energy conversion efficiency of the solar photovoltaic [17]:

$$\eta_{energy} = \frac{V_{oc} \times I_{sc} \times FF}{A \times G} \quad (3)$$

The I-V characteristics i.e. current-voltage characteristics of the solar cell can be given by the following equation:

$$I = I_1 - I_0 \times \exp^{\left[\frac{q \times (V - IR_s)}{A \times K \times T}\right]} \quad (4)$$

The output electrical power of solar photovoltaic is given by:

Pel = I × V (5)

Moreover, the maximum electrical output power is given by:

Pmax = VOC × ISC × FF = Vmp × Imp (6)

The solar energy absorbed by the solar photovoltaic modules is converted to electrical energy and thermal energy. The thermal energy is dissipated by different modes of heat transfer such as convection, conduction, and radiation. The heat transfer rate depends on the design of the solar photovoltaic system. To calculate the efficiency of a solar photovoltaic module, its operating temperature i.e. solar cell temperature (Tcell) need to be determined. For simplicity it could be assumed homogenous on the surface of solar module and it is depend on the ambient conditions. The electrical conversion efficiency increases with increase in solar irradiation but it also increases the temperature of panel and with increase in temperature of solar cell there is reduction of the photoelectric conversion efficiency. Therefore, it is necessary that the solar cells must cooled naturally or forced by passing air or water on the rare side of the module.

2.2. Exergy Efficiency of Solar Panel

The most effective use of energy potential can be evaluated by consideration of energy quality which is given by exergy analysis. The overall exergy balance of the solar PV under the steady-state flow process during a finite time interval is given as follows [18].

Exergy Input = Exergy Output + Exergy Loss + Irreversibility (7)

Exergy loss or availability loss is the quality of energy degraded when undergoing process. The loss of exergy is called irreversibility [15]. The incident solar radiation on the solar cells converted in to electrical and thermal energy. The electrical energy is utilized and the thermal energy is dissipated to the surrounding as a thermal or heat loss cause exergy destruction.

The ratio of total output exergy to total input exergy is called exergy efficiency of the solar photovoltaic module [18-20]. An exergy efficiency of the solar PV can be defined as the ratio of the output exergy by the solar photovoltaic module to the input exergy of the solar radiation [21].

$$n_{ex} = \frac{E_x \text{ output}}{E_x \text{input}} \tag{8}$$

Input exergy of a solar photovoltaic module includes only solar radiation intensity exergy which incident on solar photovoltaic module [21-22] and is given by.

$$E_x \text{ in} = AG\left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] \tag{9}$$

The output exergy of the solar photovoltaic module can be evaluated as [23] outlet exergy for a solar photovoltaic module includes thermal exergy and electrical exergy.

$$E_x\text{out} = E_x\text{thermal} + E_x\text{electrical} \tag{10}$$

Thermal Exergy is given by

$$E_X\text{Thermal} = Q\left[1 - \frac{T_a}{T_m}\right] \tag{11}$$

$$Q = UA(T_m - T_a) \tag{12}$$

Convection and radiation losses contributes overall heat loss coefficient of a solar photovoltaic module [24] and is given by:

$$U = h_{conv} + h_{rad} \tag{13}$$

Coefficient of convective heat transfer [25] is given by:

$$h_{conv} = 2.8 + 3V_w \tag{14}$$

Coefficient radiation heat transfer between solar module & surroundings [26]:

$$h_{rad} = \varepsilon\sigma(T_{sky} + T_m)(T_{sky}{}^2 + T_m{}^2) \tag{15}$$

Sky Effective temperature is given by [26]:

$$T_{sky} = T_a - 6 \tag{16}$$

Module temperature on the basis of NOCT can be calculated as.

$$T_m = T_a + (\text{NOCT} - 20).\frac{G}{800} \tag{17}$$

Electrical exergy in the output power of solar photovoltaic module [27]:

$$E_x\text{electrical} = V_{oc} \times I_{sc} \times FF \tag{18}$$

2.3. Experimental study

The experimental study was carried out in the meteorological conditions of Jaipur, India. Jaipur has the latitude of 26°91 N and longitude of 75°78 E. The fluctuation of ambient temperature during a year in Jaipur in the range of 5 to 41 ºC and has a hot and semi arid climate. The experiment was carried out on the 300W solar photovoltaic panel and the parameters such as Voc, Isc, Power, Wind velocity, solar irradiance, ambient temperature etc., needed for the analysis of the systems were measured between 8.00 and 16.00 at interval of one hour. Anemometer and temperature meter are used to measure the wind velocity and ambient temperature respectively. Solar Power meter and thermocouples are used to measure the Solar Irradiance and temperature of solar panel respectively.

2.4 Input parameter and Specification of the module

Table 1: Input parameter used for analysis

Input parameter	Value
Nominal operating cell temperature (NOCT)	45 ºC
Stefan Boltzmann constant (σ)	5.67×10^{-8} W/m^2-K
Emissivity of the panel (ε)	0.9
Sun temperature	5780 K

Table 2: Specification of the PV module

Model	ELDORA 300P
Maximum power	300 W
Open circuit voltage	45.1 V
Short circuit current	8.74 A
Dimensions	1955x982x36 mm
Fill factor	0.761

RESULTS AND DISCUSSIONS

The experiments were carried out at Poornima University, Jaipur (latitude of 26°91 N and longitude of 75°78E) India. The effect of the ambient conditions on the performance of the solar photovoltaic module was investigated by applying the experimental data obtained for a sunny day in March 2016 respectively for Jaipur. The measured average annual ambient temperature was taken as 305K and 311K for March and April respectively. The exergy efficiency of solar PV System is the ratio of output exergy to input exergy and has been calculated by taking exergy of sun radiation on the basis of second law of thermodynamics. An energy balance and exergy balance for the 300 W solar photovoltaic module was carried out. By performing the exergy balance and exergy balance, it is found that for evaluating the efficiency of the solar photovoltaic panel exergy analysis is more predictable. On the basis of this experimental study it is concluded that for evaluating the performance analysis of the solar photovoltaic panel, the most effective and efficient tools is exergy analysis.

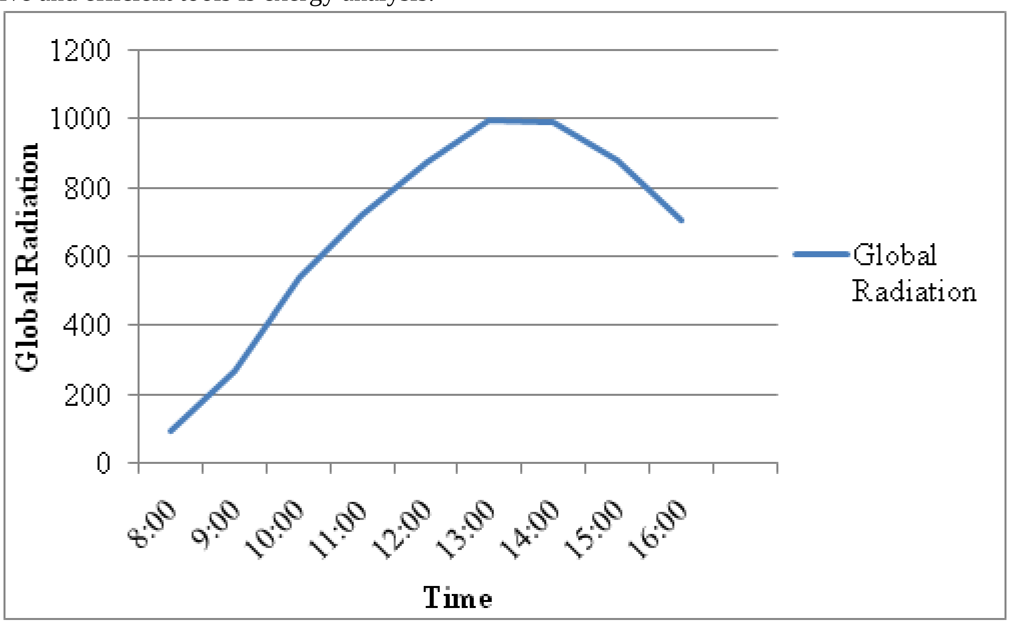

Figure 2. Variation of Solar radiation intensity on 29 March 2016 at Jaipur, India

The variation of global radiation during the test day is shown in Figure 2. The global solar radiation intensity varies between maximum 997 W/m2 and minimum 94 W/m2 with an average value of 674.33 W/m2. The power output of solar module increases with increase in solar intensity but increase in solar intensity also increases the temperature of solar cell which limits its efficiency.

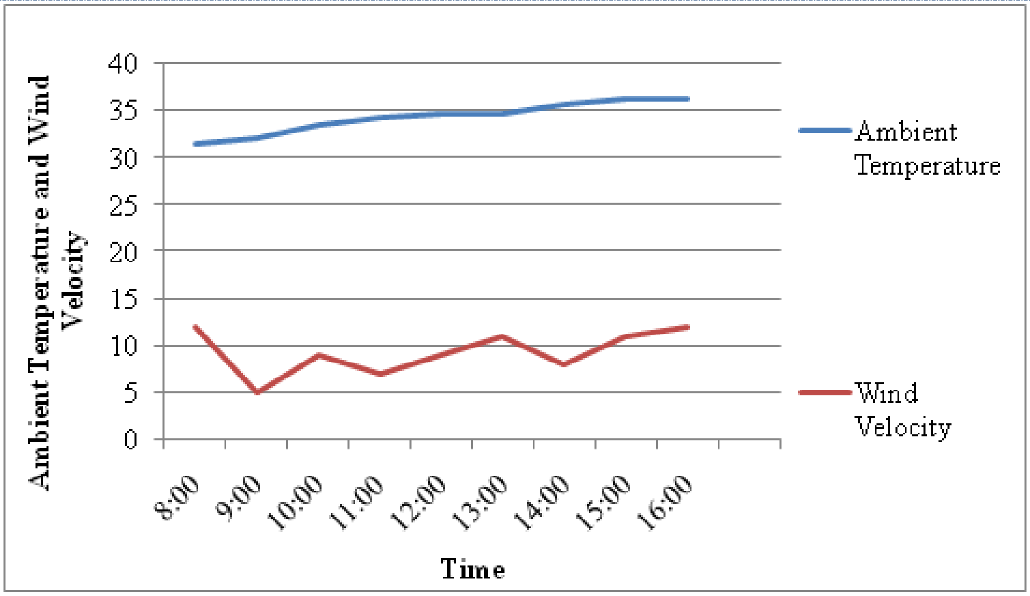

Figure 3. Ambient temperature and wind velocity on 29 March 2016 at Jaipur, India

Figure 3 shows the variation of ambient temperature and wind velocity for a sunny day 29 March 2016. The wind speed was found to vary between 1.39 to 3.33 m/sec. This variation of wind speed also affects the convective heat transfer between the solar photovoltaic module surface and the surroundings. On the test day the minimum and maximum temperature was found to be 304.6 to 309.4 K.

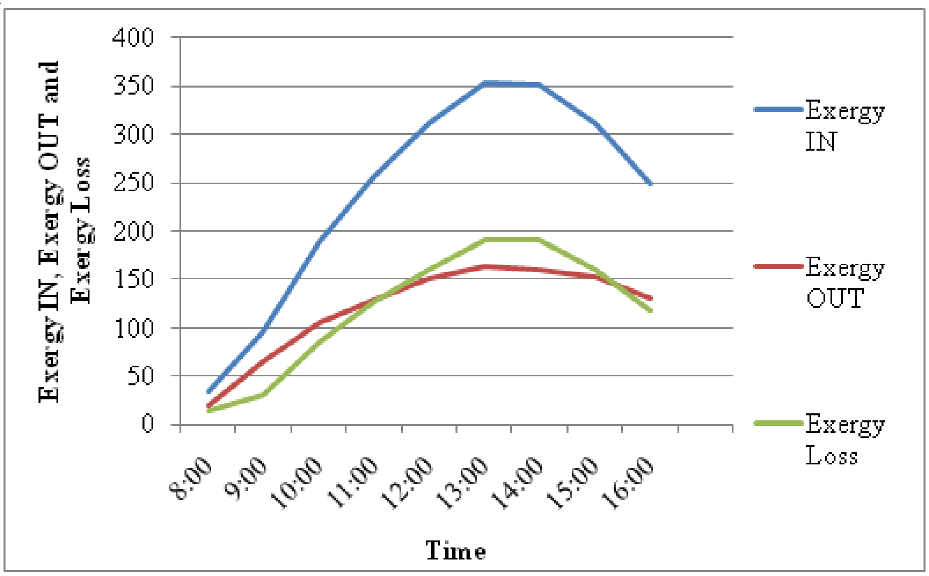

Figure 4. Exergy input, exergy output and exergy loss on 29 March 2016 at Jaipur, India

Figure 4 shows the variation of input exergy, output exergy and exergy loss of the PV module for the whole test day. It is clearly visible from the figure that output exergy from the solar photovoltaic module is much less, because of loss of exergy is large as a result of irreversibility. The average exergy loss for the day was 119 W/m2. The average exergy in and exergy out for the test day was found to be 238.91 W/m2 and 119.80 W/m2 respectively.

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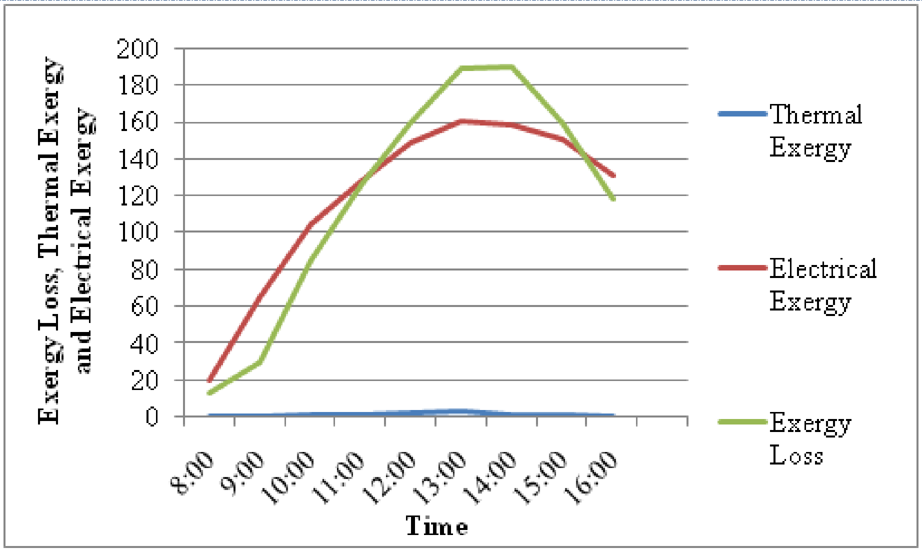

Figure 5. Exergy Loss, Thermal Exergy and Electrical Exergy on 29 March 2016 at Jaipur, India

Figure 5 shows the variation of exergy loss, thermal exergy and electrical exergy for the whole test day. The average thermal and electrical exergy was found to be 1.118 W/m2 and 118.63 W/m2 respectively. This lower value exergy is due to the irreversibility associated with the photoelectric conversion process. The photoelectric conversion process of solar cell with conventionally available silicon modules implies an enormous amount of exergy loss, despite their advantage and availability. The average exergy loss for the day was found to be 119.09 W/m2. This loss of useful exergy show that today's available silicon photovoltaic module takes little advantage of the exergy content of the incoming solar exergy.

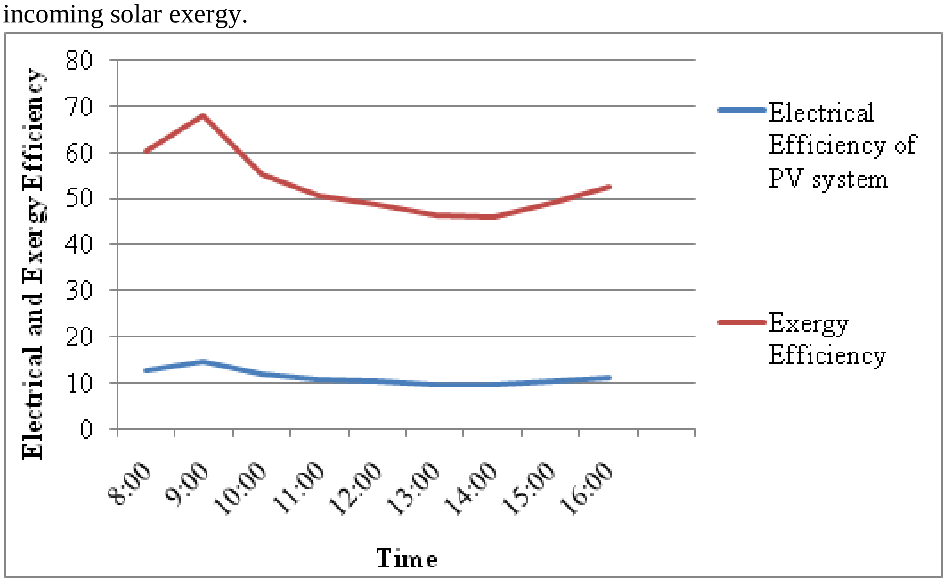

Figure 6. Electrical efficiency and exergy efficiency on 29 March 2016 at Jaipur, India

Figure 6 shows the variations of electrical efficiency and exergy efficiency for the whole day. The maximum electrical efficiency of the solar photovoltaic module is 14.41% corresponding to the PV module temperature of 310.5 K at 9:00 am. The maximum exergy efficiency of the solar photovoltaic module is 68.16% corresponding to the solar photovoltaic module temperature of 310.5K. With increase in temperature the exergy and electrical efficiency decreases. The maximum exergy efficiency of solar photovoltaic module will be achieved when the module temperature should be kept near solar cell operating temperature. This can be achieved by controlling the solar photovoltaic module temperature by surface cooling using water or air.

CONCLUSION
In this comprehensive study, an energy and exergy analysis of the 300W solar photovoltaic module at Poornima University, Jaipur, India is conducted. An experimental study has been carried out to investigate the performance of a 300W solar photovoltaic module. The experimental data was obtained through measurement of various parameters during a sunny day in March 2016. The data obtained were analyzed to find the optimum temperature, which leads to the maximum electrical and exergy efficiency. The following are the conclusions drawn from this experimental study:

1. The results showed the photovoltaic modules have a low exergy efficiency of 45.80%. With respect to the solar photovoltaic module, the exergy analysis showed that today's available silicon photovoltaic module takes little advantage of the exergy content of the incoming solar exergy.
2. The average values of electrical and exergy efficiencies for the 300W solar photovoltaic module are found to be 11.15% and 52.93% respectively. The solar photovoltaic module electrical efficiency decreases as the solar radiation and ambient temperature increases due to increasing in solar cell temperature and irreversibility.
3. Research and development directed toward improving the efficiency of the solar module and low cost semiconductor material significantly reduce the cost of solar photovoltaic electricity. Future studies should focus on the efficiency modelling of the solar panel. More experimental investigation and studies are required to define the optimum efficiency of the solar module.
4. The design optimisation of the solar panel can be made by means of the exergy analysis considering both design and operational parameters.

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NOMENCLATURE

η_{energy}	Energy Efficiency	
V_{oc}	Open circuit voltage	V
V	Voltage	V
V_{mp}	Voltage at maximum power point	V
I_{mp}	Current at maximum power point	A
I_{sc}	Short circuit current	A
I	Current	A
I_1	light generated current	A
I_o	saturation current density	A
FF	Fill factor	
q	Charge of the electron	ev

R_s	Series resistance	Ohm
A	Surface area of the module	m^2
G	Global irradiance	W/m^2
K	Boltzmann constant	J/K
P_{el}	Electrical power	W
P_{max}	Maximum power	W
Ex_{in}	Input exergy	W
Ex_{loss}	Exergy loss	W
Ex_{out}	Output exergy	W
$Ex_{thermal}$	Thermal exergy	W
$Ex_{electrical}$	Electrical exergy	W
T	Temperature	K
T_a	Ambient temperature	K
T_s	Surface temperature of the sun	K
T_m	Module temperature	K
T_{sky}	Sky temperature	K
Q	Heat emitted to the surrounding	W
U	Overall heat loss coefficient	W/m^2-K
h_{conv}	Convective heat transfer coefficient	W/m^2-K
h_{rad}	Radiative heat transfer coefficient	W/m^2-K
V_w	Wind velocity	m/sec
σ	Stefan Boltzmann's constant	W/m^2-K^4
ε	Emissivity of the module	
NOCT	Nominal operating cell temperature	^oC

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