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An Approach Towards Performance Evaluation of Solar Photovoltaic Module Through Energy and Exergy Analysis

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ABSTRACT

The pressure on the agriculture sector has significantly grown due to the fast rising trend of global population growth, which is predicted to reach more than 9 billion by 2050. In the meantime, the issues related with emission of greenhouse gases (GHG) and the decreasing supply of fossil resources are eliminating traditional farming practices. The agriculture sector is looking to feed the increasing population in more sustainable way with the access of technology based on renewable energy. Solar energy is one of the most accessible types of renewable energy when applied to farm uses. Solar photovoltaic (PV) technology has been used to generate the necessary energy to operate number of equipment used in agricultural throughout the years, including drying of crop, irrigation through pumping, greenhouse and dairy farming. In present work, an attempt has been made to evaluate the performance of solar photovoltaic system. The parameters such as ambient temperature, panel temperature, open-circuit voltage, short-circuit current, energy and exergy efficiencies were determined during experiment. Energy and exergy efficiencies during the day was ranged from 10.11–13.35% and 10-13.29%, respectively. It has been found that the exergy efficiency of PV modules was significantly influenced by the temperature, and that the exergy efficiency may be increased by removing heat from the PV module surface.

Keywords Energy efficiency, Exergy efficiency, PV, Fill factor, Power, Solar intensity.

INTRODUCTION

Solar photovoltaic technology has been shown to be advantageous in the agricultural sector for number of tasks including water pumping for drip irrigation and cattle drinking, aeration for aquacultures, refrigeration of agricultural products, electric fences, illumination for poultry, and insect control. Increased productivity (including greater yields, reduced losses, and faster production) and increased natural resource management are stated as the key effects of solar power on agricultural operations.

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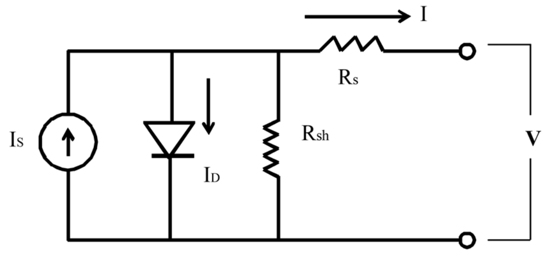

Fig. 1. Schematic of electric circuit of solar PV cell.

There is no doubt that human feed is solely produced by the agriculture sector. The demand for food and energy is anticipated to rise dramatically as a result of the estimated 25% increase in world population over the next 20 years. The majority of agricultural operations are driven, either directly or indirectly, by fossil fuels that release greenhouse gases, which result in climate change as a result of global warming. Photovoltaic systems provide a viable approach to managing agricultural operations sustainably. The PV technology is reportedly one of the energy technologies with quickest rate of growth. The agriculture industry also employs various techniques to benefit from these various solar energy properties for a number of purposes. For instance, one direct application of solar energy's thermal qualities is the drying of commodities such as meat, vegetables, crops, and other items (Tariq *et al.* 2021).

In spite of this tremendous potential, utilization of solar energies is not used on large scale, except for heating of water. It has been found that India has favorable climatic conditions to harness solar energy for many applications. A solar PV is a standout amongst the largest and fastest developing technology that converts the solar radiation into direct current electricity through semiconductors. Photovoltaic solar panel performance depends on solar cell temperature, output voltage, current, module area, ambient temperature and solar intensity (Sarhaddi *et al.* 2009). Among different renewable energy technologies, the photovoltaic is the best technology known and widely used for generating electricity. Solar PV system utilizes only beam radiation and very little diffuse component. But even on a clear day, the diffuse radiation can represent 20% of the total radiation (Wyman *et al.* 1980). The maximum quantity of radiation is always received on earth's surface which is normal to its direction. Therefore, design data such as solar radiation being intercepted by the titled surface and metrological data of the location are required for designing of PV system.

An exergy analysis has proved as powerful tool in simulation thermodynamics analyses of energy system and has wider application in the design, simulation and performance analysis of the energy system. This analysis further shows scope of improvement in term of thermodynamics and cost aspects.

Light coming from sun pushes electrons into the p-layer and leave holes in the n-layer in solar PV cell. This will generate an electric power to be extracted through means of electric circuit. The solar exergy is further converted into electrical exergy. A schematic representation of electric circuit of solar PV system is shown in Fig. 1.

The performance of a PV module, expressed in terms of its current voltage and power-voltage characteristics, principally depends on the solar radiation and module temperature. At any level of solar radiation and module temperature, a single operating voltage will result in maximum electrical power production from the module. Energy analysis simply focused at how much energy is being used and how effectively it is processed. Hence, decreases in energy potential that may be usefully utilized in other physical and/or chemical processes are ignored by energy analysis. When it comes to applications where the only factor affecting utilization effectiveness is energy amounts, energy analysis can offer reasonable management advice.

Exergy is defined as the maximum amount of work that can be done by a system. Unlike energy, exergy is not subject to a conservation law, exergy is consumed or destroyed, due to the irreversibility's present in every real process. Exergy analysis is recognized by many researchers to be a powerful technique for estimation of the thermodynamic and economic performance of thermodynamic system in general. Exergy analysis gives an option for estimating and comparing the solar PV. Exergy analysis is applied to know the energy use efficiency of an energy

Table 1. Input values used for analysis.

Input parameters	Values
Nominal operating cell temperature (NOCT)	56.62ºC
Stefan Boltzmann constant (σ)	5.67×10^{-8} W/m^2 K
Emissivity of the panel (ε)	0.9
Sun temperature	5762 K

conversion unit. Exergy analysis yields useful results because it deals with irreversibility minimization or delivery of maximum exergy. Exergy analysis has been used more often during the past few decades, partly due to its benefits over energy analysis. To perform energy and exergy analyses of the solar PV, the quantities of input and output of energy and exergy must be evaluated.

The analysis of energy and exergy were conducted to determine the performance of a solar PV system. The operating parameters of a PV cell includes normal operation cell temperature, open-circuit voltage, and short-circuit current were obtain from manufacturer data sheet. The exergy and energy efficiency ranged from 10.8% to 15.8% and 15.71% to 15.74 %, and the exergy destruction ranged from 182.8 to 352.3 W/m^2 throughout the year. It was found that, the efficiency based on first law was greater than second law efficiency (Kareem *et al.* 2019). Kibirige *et al.* (2022) investigated electrical and thermal performance analysis of a 1000 W monocrystalline solar PV power generator in Eastern Uganda in dry and rainy season. The thermal and electrical qualities of the monocrystalline PV module have been considered under various seasonal environmental conditions in order to develop energy and exergy modelling. The parameters considered for study was converted power, exergy and energy efficiencies. Also time, solar radiation, wind speed, ambient temperature and cell temperature were used as the input tool where as thermal and electrical efficiencies were the outputs in PV cell. The results of simulation indicated that the efficiency of the system was altering with respect to the dissimilarity in the solar insolation, temperature, and wind speed. It has been evidently observed that the efficiencies were higher in the months of the dry season compared to the month in the rainy season. The performance analysis of solar PV installation of the selected power plants in the utility scale of solar PV in regions of Thailand was investigated. The PV system performance was varied from 71.1% to 84.50% and their energy yields varied from 1,361 to 1,467 kWh/kWp (poly c-Si), 1,492 kWh/kWp to 1,635 kWh/kWp (a-Si), 1,381 kWh/kWp to 1,495 kWh/kWp per annum (Peerapong 2021). Aktacir *et al.* (2020) evaluated the performance of four different PV panels using their catalogue values like Nominal Operating Cell Temperature (NOCT) of 20ºC, solar radiation of 800 W/m^2, wind speed 1 m/s and air mass 1.5 at standard test conditions (STC). For this, real working conditions were simulated using previous 3 years meteorological data of Sanliurfa, Turkey. PV panel efficiency, electricity generation values and performance ratios were calculated in accordance with the temperature. According to research data, the performance ratios of the PV panels dropped by up to 0.75 during the summer. There are similar studies that indicate the performance of the PV system. A study presented a reliable mathematical method for predicting energy production of grid-connected photovoltaic systems with different technologies commercially used in different regions of India (Chakraborty *et al.* 2017). In another study (Skoplaki and Palyvos 2009),

Table 2. Technical specification of the solar PV panel.

Model	LUM 24330
Maximum Power (P_{max})	330 Wp
Voltage at P_{max} (V_{mp})	37.76 V
Current at P_{max} (I_{mp})	8.9 A
Short circuit current (I_{sc})	9.4 A
Open circuit voltage (V_{oc})	45.39 V
Maximum system voltage	1000 V
Cell temperature	25°C
Dimension of panel (L×B×D)	1976 × 991 × 35 mm
Weight	22.5 kg
Solar cell	72 in a 6 × 12

Table 3. Parameters measured.

Output parameters	Symbol
Ambient temperature	T_o
Cell temperature	T_{cell}
Solar intensity	I_s
Open-circuit voltage	V_{oc}
Short-circuit current	I_{ssc}
Wind velocity	V_w

PV utility and PV power models that were existent in the literature were examined, depending on temperature. The impact of rising solar cell temperature due to dust particle deposition on the PV surface was observed and reported by Jiang and Lu (2016). The main purpose of the present investigation was to evaluate efficiency of PV cell and application and challenges in agriculture.

MATERIALS AND METHODS

Experimental study

The experimental investigation was conducted in the West region (Rajasthan) of India. The latitude and longitude of the location are 24º 34' 16" N and 41º 41' 29" E. The ambient temperature fluctuates in the range of 2-46ºC during a year in Udaipur. The solar panel data tested at STC was used for the calculation and the parameters such as V_{max}, I_{max}, wind velocity, solar intensity, ambient temperature were measured at interval of one hour from 09:00 to 17:00. The wind velocity, ambient temperature and cell temperatures were measured using anemometer (accuracy: 0.2 %) and a digital thermometer (accuracy: ±1ºC). The solar intensity was measured using a portable solar radiation meter. Tables 1-3 represents the input parameter, specification of module and required parameters.

Photovoltaic efficiency

Energy efficiency

The most applicable general equation for an open system under steady-state assumption based on first law of thermodynamic which is expressed by following equations :

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

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

Above equation (2) is a general equation applied in exergy balance, Ex_{out} = Maximum power from photovoltaic system, in W, Ex_{in} = Input energy received on the photovoltaic surface, in W and Ex_{loss} is the amount of energy lost during conversion of energy. The efficiency of the solar panels, defined as the ratio of output energy (electrical energy) of the system to the input energy (the solar energy) received on the photovoltaic surface. The output power and energy efficiency of the PV system, however fluctuate depending on solar insolation, ambient and cell temperature.

The energy conversion efficiency of the solar PV is determined by following formula (Eqn. 3) cited by many researchers (Joshi *et al.* 2009, Akyuz *et al.* 2012).

$$\eta_{energy} = \frac{V_{oc} \times I_{sc} \times FF}{A_{pv} \times I_s} \quad (3)$$

Where, η_{energy} = Efficiency of PV system, in %, I_{sc} =Short circuit current, in A, FF = Fill factor, A_{pv} = Area of the photovoltaic system, in m^2 and I_s = Solar intensity, in W/m^2.

The current-voltage characteristics of the electric circuit of solar cell can be expressed in following equation (Akyuz *et al.* 2012) :

$$I = I_1 - I_0 \times \exp^{(q\times(v-IRs))/(Apv\times K\times T))} \quad (4)$$

The electric output power produced from PV is given by

$$P_{ele} = I \times V \quad (5)$$

Moreover, the maximum output power is written as

$$P_{max} = V_{oc} \times I_{sc} \times FF = V_{mp} \times I_{mp} \quad (6)$$

Where, P_{max} = Maximum power of solar PV, in W, V_{oc} = Voltage during open circuit, in V, I_{sc} = Current during short circuit, in A, FF = Fill factor, V_{mp} = Voltage produced at maximum power, in V and I_{mp} = Current at maximum power, in A.

The solar energy absorbed by the PV module is converted to electrical energy the thermal energy, which is dissipated, by convection, conduction and radiation process. The rate of heat transfer depends on the design of the solar PV system. To assess the efficiency of solar PV system, it is necessary to determine the operating temperature test condition, which may be considered as homogeneous on the plate and dependent on the surrounding environment. The solar PV efficiency may decrease due to higher surface temperature of the PV cell. Therefore, it has been proposed by several studies that the cell may be artificially cooled by flowing air or water over the back of the module, especially in the hot region, by mechanized or manually. This may leads to enhance the efficiency of the solar PV (Sudhakar and Srivastava 2014).

Exergy efficiency

Exergy analysis includes a consideration of energy quality, which allows estimation of the most effective, not just most efficient, use of energy potential. The following equation may be used to define the total exergy balance within a solar PV system for a constant flow process over a finite time period (Wong 2000).

$$Ex_{in} = Ex_{out} + Ex_{loss} + \text{Irreversibility} \qquad (7)$$

This degradation in the quality of energy is called exergy loss or availability loss. The exergy loss sometimes also known as irreversibility (Hepbasli 2008). The solar radiation emitted by the solar cells is transformed by two ways i.e., electrical and thermal. The energy obtained in the form of electricity is termed as electrical energy, where as thermal energy is dissipated to the ambient as a heat loss and it becomes as exergy destruction.

The energy of PV module depends on two major components-electrical and thermal. The PV effect produces electricity, but the photovoltaic panels are also heated by the thermal energy of the solar radiation. The power (electrical energy) produced by a solar system is also known as "electrical exergy" since it is accessible energy that may be fully used for productive purposes. The thermal energy present on the solar surface was not put to productive use and is now thought to have been lost as heat to the surrounding environment. Therefore, due to heat loss, it becomes exergy destruction. The following formula may be used to determine the photovoltaic system's output of exergy (Kalbande and Deshmukh 2015).

$$Ex_{out} = V_m I_m - \left(1 - \frac{T_o}{T_{cell}}\right) [h_c \times A_{pv} \, (T_{cell} - T_o)]$$

Where, V_m = Maximum voltage, in V, I_m = Current of the photovoltaic system, in A, h_c = Convective heat transfer coefficient from photovoltaic cell to ambient, in W/m^2 °C, A_{pv} = Area of the photovoltaic surface, in m^2, T_{cell} = Cell temperature, in °C, T_o = Ambient temperature, in °C.

The convective heat transfer coefficient from the photovoltaic cell to ambient can be calculated by using correlation (Eqn. 9) given by Akyuz *et al.* (2012).

$$h_c = 5.7 + 3.8 \times v \qquad (9)$$

Where,
v = Wind velocity, m/s.

The module or cell temperature is used to determine the output energy of the photovoltaic module. Cell temperature is a function of ambient temperature, wind speed and total solar irradiance. The relationship shown below may be used to calculate the cell temperature :

$$T_{cell} = 0.943 T_a + 0.028 \text{ Irradiance} - 1.528 \text{ Wind speed} + 4.3 \qquad (10)$$

The exergy input of a PV system, which is the exergy of solar energy, may be calculated by formula (Eqn. 11) given by Akyuz *et al.* (2012).

$$Ex_{in} = Ex_{solar} = A_{pv} \times I_s \times \left(1 - \frac{T_o}{T_s}\right) \qquad (11)$$

Where, Ex_{solar} = Exergy of solar energy, in W, T_s = Temperature of the sun taken as 5762 K, A_{pv} = Area

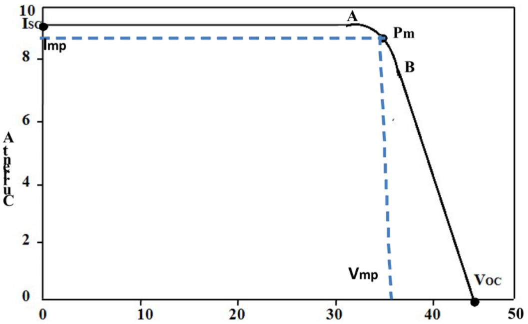

Fig. 2. I-V characteristics of the PV panel.

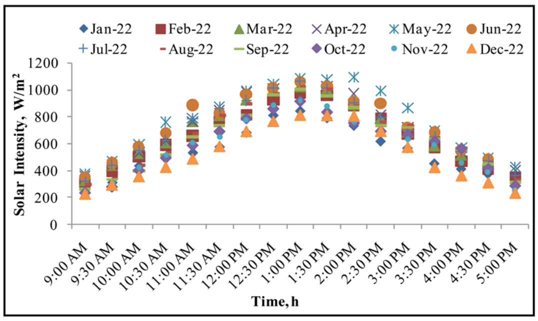

Fig. 3. Variation of solar intensity with time in different months in year 2022.

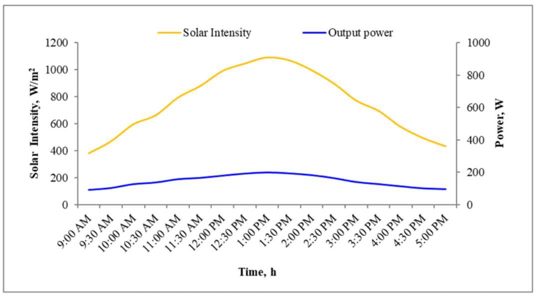

Fig. 4. Variations in PV output power and solar intensity with time.

of the photovoltaic surface, in m², I_s = Solar radiation intensity, in W/m², T_o = Ambient temperature, in K.

Exergy efficiency of the PV system is the ratio of total output exergy (recovered) to total input exergy (supplied). It was calculated by following correlation (Eqn. 12) given by Akyuz *et al.* (2012).

$$\psi_{pv} = \frac{Ex_{out}}{Ex_{in}} \qquad (12)$$

Where, ψPV = Exergy efficiency of the photovoltaic system, in % , Ex_{out} = Total output exergy (recovered), in W, Ex_{in} = Total input exergy (supplied), in W.

I-V characteristics of solar panel

The I-V characteristic of the solar PV panel at standard test conditions in which PV panels are tested at solar intensity of 1000 W/m², air mass of 1.5, and a cell temperature of 25ºC. The short circuit current is the maximum value of current that the solar PV panel could generate and it is produced during the short circuit condition when voltage is equal to zero. The open circuit voltage is the maximum voltage that the solar PV panel provides when the terminals are not connected to any load. Nominal maximum power (P_m) denotes the point where the power supplied to the load is maximum. It is calculated by multiplying the maximum voltage (V_{mp}) and maximum current (I_{mp}) values. In real time application, the power supplied from the PV panels will often vary between the points A and B as presented in Fig. 2 depending on the load.

RESULTS AND DISCUSSION

The data recorded for typical months in a year (2022), for Udaipur were used to determine the effect of the ambient condition on the working performance of the panel. The intensity of solar radiations falling on the solar panel throughout the day depends on the geographical location of that place. The solar intensity at Udaipur district of Rajasthan, India was recorded from morning 9 AM to evening 5 PM throughout the year (Jan 2022 to Dec 2022). The average value of solar intensity throughout the year ranged from 228 to 1089 W/m² in prescribed time of the day and presented in Fig. 3. The average lowest value of 228 W/m² was recorded in month of Dec 2022, whereas highest value of 1089 W/m² in the month of May 2022. The recorded data indicated that the solar intensity (S) was low in the morning and rose up to 11.00 h and thereafter slightly increased at it approached to 13.00 h and it decreased during the afternoon period. Fig. 3 represents the relationship between intensity of solar radiation and time of the day in different months, and

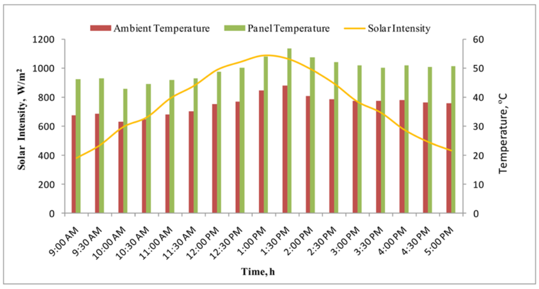

Fig. 5. Variation of solar intensity, module and ambient temperature with time.

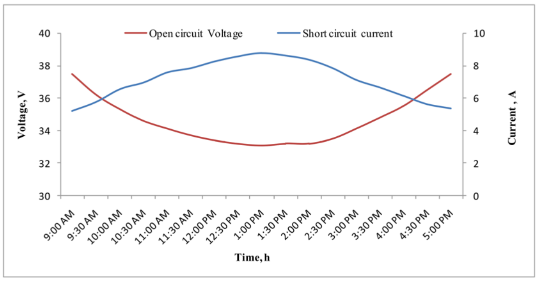

Fig. 6. Variation in short circuit current and open circuit voltage with time.

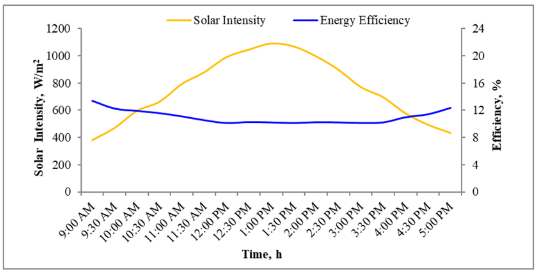

Fig. 7. Variation of solar intensity and energy efficiency with time.

it closely follows the sine curve. This is consistent with the widely held belief that the fluctuation in solar radiation intensity with time throughout the day is a sinusoidal function.

The positions of the sun have a direct effect on the intensity of solar radiation. The angle at which the sun's rays impact the surface of the planet greatly influences the strength of solar radiation. The incoming insolation hits the surface of the earth at a straight angle and is most powerful when the sun is directly above or 90° from the horizon. If the sun is 45° above the horizon, the incoming insolation strikes the earth's surface at an angle. This causes the rays to be spread out over a larger surface area reducing the intensity of the radiation (Carg 1982). This is the cause of the greater levels of solar radiation during midday compared to the beginning of the day or late afternoon. The sun is high in the sky during the middle of the day, shortening its rays' travel through the atmosphere. As a result, less solar energy is dispersed or absorbed, allowing more solar energy to reach the earth's surface. (Bhattacharya and Bhoumick 2012).

Solanki (2013) reported the similar values of intensity with maximum intensity of 900 W/m^2 at 13.00 h during the day. Kumar *et al.* (2013) also found that the intensity ranged from 400 W/m^2 and 903 W/m^2 during 09.30 to 16.30 h at NIT, Kurukshetra, India with highest value at 12.30 h. It was also reported that solar intensity increased from morning to about 12.30 h and declined during afternoon. The trend of increase in solar intensity from morning to noon time and subsequent decline in the intensity was also reported by Singh *et al.* (2010). The similar trends of solar intensity was reported by Akyuz *et al.* (2012),Kareem *et al.* (2019), Aktacir *et al.* (2020).

Effect of solar intensity and ambient temperature on power output

Fig. 4 indicates that the power output of solar module changed significantly with variation in solar intensity and ambient temperature during the no load test day in month on may 2022 which may be due to increase of clearness index. The average output power start increasing as solar intensity increases and reaches to its minimum and maximum value of 95.12 W and 211.94 W corresponding to solar intensity values ranged from 379 to 1089 W/m^2. The corresponding temperature of ambient also increased with rise in solar intensity. The wind speed was found to be varied between 0.17 – 0.5 m/s. This affected the convective heat transfer coefficient between the PV array surface and the ambient air. The ambient temperature varied from 33.6 to 56.6°C at its lowest and highest points. This increase of ambient temperature caused the heating of module and cool down in afternoon as solar intensity declined as shown in Fig. 5. The continuous gap in curves of average solar intensity and output power denotes the constant power loss in the solar photovoltaic system. The P_{max} changed significantly with ambient temperature (T_{amb}) which indirectly affected the module temperature. These results are in agreement with results reported by Onyegegbu (1989), Sudhakar and Srivastava (2014).

Higher sunlight heating, low wind speed, which results in less heat being transferred from the cell to the ambient, and a high atmospheric temperature

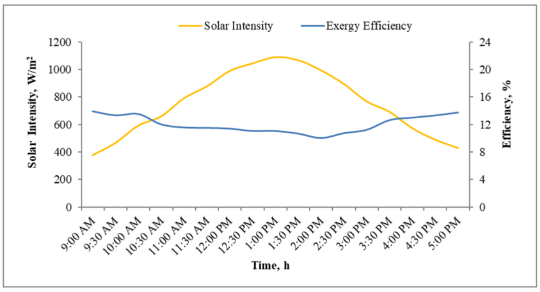

Fig. 8. Variation of solar intensity and exergy efficiency with time.

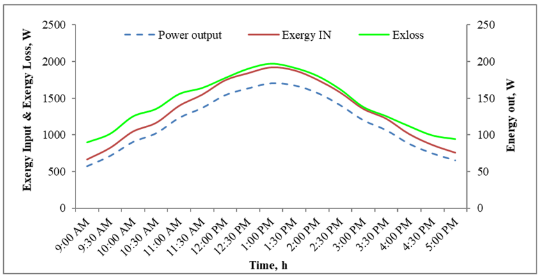

Fig. 9. Variation in Exergy loss, exergy in and power out through solar PV.

would all contribute to this rise in cell temperature. Due to this, maximum open circuit voltages were seen in the morning when the module temperature was low. The higher I_{sc} and lower V_{oc} were observed during the afternoon time (Fig. 6). The higher module temperature (T_{cell}) causes a decrease in peak power. From Fig. 6 it is found that V_{oc} decreased with increase in T_{cell}, while I_{sc} increased significantly as slightly increase in temperature. This result was in agreement with result obtained by Eltawil and Samuel (2007), Baimel *et al*. (2019).

Photovoltaic efficiency

The hourly variation in the energy efficiency of the investigated PV system with respect to the solar radiation is presented in Fig. 7. It is clear from the Fig. 7 that the efficiency of the PV system was slightly increased in the morning and afternoon of the day as compared to midday which was due to thermal effects. The conversion efficiency is inversely proportional to the module temperature. The energy efficiency of PV panel for the month of May 2022 was found in the range of 10.11–13.35%. This result was in agreement with result obtained by Sudhakar and Srivastava (2014).

Based on the second law of thermodynamics and using the exergy of solar radiation, the energy efficiency of the PV system has been calculated and presented in Fig. 8. From Fig. 8 it is found that the PV exergy efficiency was low and it was ranged from 10.0–13.29% for the month of May 2022, which was far from the ideal 100% reversible process (Sudhakar and Srivastava 2014). This low exergy was due to the irreversibility of the PV conversion process. Exergy analysis was more convenient than the energy analysis for predicting the efficiency of the solar panel. The relative loss of exergy exceeds 89% throughout the day as seen from Fig. 9. It is evident from Fig. 9 that the maximum exergy loss of 1706 W was observed in the afternoon. This huge amount of useful exergy is being lost and this show that today's silicon module takes little advantage of the high exergy content of the solar radiation. The exergy efficiency of the conventional silicon cell solar panel is small as the output is of low quality. The exergy losses occurs inside the solar panel was high. This result was in agreement with result obtained by Sudhakar and Srivastava (2014).

Increasing PV array temperature determines the sensible decrease of the energy efficiency. The temperature of the PV array should be kept close to the ambient temperature or in other words, it should be managed, in order to have the highest energy efficiency possible. There are various practical ways to regulate the temperature of PV panel, like spraying water on the top surface of the photovoltaic modules or combining PV modules with other materials to create photovoltaic/thermal (PV/T) collectors.

CONCLUSION

An extensive energy and exergy analysis of the solar PV panel utilizsed for cooling in this work was carried out experimentally. To determine the performance of solar PV panel, a parametric analysis was conducted. The use of renewable energy sources in farming communities is essential in view of the significant increase in energy consumption and associated increased carbon footprint in agricultural operations.

Following is a summary of the present investigation on the application of PV technology in agriculture.

The maximum and minimum weekly average solar radiation intensity was observed to be 1025 W/m^2 at 1 PM and 649 W/m^2 at 5 PM, respectively.

PV technology has a wide range of applications in agricultural fields, all of which have great potential to reduce carbon emissions and boost corporate profitability.

The development of numerous hybrid technologies has increased creativity and flexibility in the use of PV technologies on farms, particularly PVT systems for dairy farms, water heating, crop drying, greenhouses, and desalination systems.

PV cells warm up when they convert energy and as a result of solar radiation. They become less effective as a result, necessitating effective cooling solutions.

In dry regions, water is already in short supply and is needed for maintenance problems, particularly washing PV panels.

Usually used in small-scale applications. Major areas of research at the present include operation control and optimization.

Based on these data it can be concluded that PV panel may be better alternative to substitute electricity to perform various operations in agriculture such as crop drying, storage, chilling, irrigation, fencing . The cost of producing power from solar energy might be considerably reduced with advancement and low-cost semiconductor materials.

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