# Energy and Exergy analysis of polycrystalline PV module

**Abstract**

The present study focuses on the Energy and Exergy analysis of polycrystalline PV module. The experiment was assessed during the month April 2021. Solar PV system is very versatile technology that generates electricity when solar radiation is incident on the panel. Such solar PV system can be established on free unused surface of roof and barren land etc. The energy and exergy analysis was done in order to get better insight in performance evaluation. Different parameter of the system that was calibrated includes PV module energy efficiency, exergy efficiency, fill factor, exergy loss rate, and energy loss rate. The variation in energy efficiency and exergy efficiency with respect to module temperature, ambient temperature, and wind velocity was also done. According to the data obtained maximum energy efficiency was 23.6% and exergy efficiency was found out to be 12%. It was concluded that module temperature should be maintained at 35℃ for optimum performance of the solar PV system. It was observed that exergy analysis give a more realistic performance evaluation of solar PV system and it depends on difference between module temperature and ambient temperature. According to the obtained it was concluded that solar PV systems have high capital cost but low maintenance and low payback period and thus can be a very feasible green energy technology.

**Keywords: Polycrystalline, PV module, energy loss rate, exergy analysis,**

**1. Introduction**

An accurate observation about the importance of energy in economic development and how per capita energy consumption is a crucial indicator of a country's development scale. As conventional energy resources decline and environmental concerns rise, there is a growing need for sustainable and renewable energy sources like solar energy. Solar energy, harnessed through photovoltaic (PV) solar cells and modules, has seen significant research and development over the past three decades. However, the electricity conversion efficiency of commercial silicon solar modules still ranges from 12% to 18%, indicating room for improvement. One of the challenges faced by solar modules is that more than 80% of the incoming solar energy is either reflected or absorbed as heat energy, leading to a rise in the working temperature of the solar cells during prolonged operation. As a result, the efficiency of the cells decreases significantly at higher temperatures. To counteract this issue and improve the electricity yield, researchers have explored the concept of cooling PV modules with a fluid stream, such as air or water. By cooling the modules, the efficiency of electricity generation can be enhanced, as lower temperatures are more conducive to optimal performance. Furthermore, the heat picked up by the cooling fluid can be put to practical use, such as supporting space heating or service hot-water systems, creating an added benefit from the solar energy system. Overall, the combination of cooling PV modules and utilizing the recovered heat from the cooling process is a promising approach to enhance the efficiency and practicality of solar energy systems, making them even more valuable for sustainable economic development in the future. Indeed, the public's perception and acceptance of photovoltaics (PV) can significantly influence the adoption of solar energy technologies. As a result, researchers have been working on making PV systems more visually appealing and easier to integrate into buildings. Building-Integrated Photovoltaics (BIPV) and Building-Added Photovoltaics (BAPV) are two approaches that aim to seamlessly integrate solar panels into building structures [1, 2]. The exergy analysis was applied on solar PV system and its components and exergy flow, losses and efficiency was evaluated. It was reported that energy and exergy efficiencies vary from 7-12% and 2-8% respectively. It was also concluded that this new method of assessment and evaluation is more realistic for modeling evaluation and planning for PV cell system [3]. Overall, using a hybrid PVT collector technology with water as the coolant offers a promising solution for improving energy performance and increasing the utilization of solar energy resources [4]. The ratio of thermodynamic loss fee to capital cost is a sizeable parameter .It was reported that relative unfold in values for Ren (ratio of thermal power loss to capital price of device) is comparatively is more than Rex (ratio of exergy losses to capital value). It has additionally been determined that ratio of thermodynamic loss charge to capital value (Ren and Rex) is higher for PV module. It was concluded that in terms of electricity saving the glazed hybrid PVT module air collector offers a more capacity as compared to PV module [5]. Designing and optimizing air-type hybrid systems, such as a flat PVT (Photovoltaic-Thermal) solar air collector, can have significant benefits in increasing solar absorption and reducing infrared emittance. To achieve these goals, you might have employed computer simulations to model the behavior of the system under different conditions and configurations. These simulations allow you to test various design parameters, materials, and geometries to find the optimal combination that enhances solar absorption while minimizing heat loss through infrared radiation [6].

|  |  |
| --- | --- |
| **Nomenclatures** | |
| A area of module (m2) | air mass flow rate (kg/s) |
| b  width of module (m) | T temperature (K) |
| specific heat of air (J/kg K) | useful heat (W) |
| dx elemental length (m) | U overall heat transfer coefficient (W/m2 K) |
| **e** root mean square percent deviation (%) | estimation of internal uncertainty |
| heat removal factor | convective heat transfer coefficient through the  tedlar (W/m2 K) |
| penalty factor due to tedlar of PV module | overall heat transfer coefficient from flowing  fluid to ambient (W/m2 K) |
| penalty factor due to glass of PV module | overall heat transfer coefficient between solar  cell to ambient through glass cover (W/m2 K) |
| L length of module (m) | convective heat transfer coefficient from the  tedlar back surface to the working fluid, i.e. air  (W/m2 K) |
| thermodynamic loss (kW h) |  |
| **Greek letters** | |
| packing factor | () eff product of effective absorptivity and transmittivity |
| 0 temperature coefficient of efficiency (1/K) | absorptivity |
| σ standard deviation | transmittivity |
| 𝝶0 efficiency of solar cell at standard test condition  (%) | 𝝶 Temperature dependent efficiency (%) |
| density (kg/m3) |  |
| **Subscripts** | |
| a ambient | bs base |
| c solar cell | eff effective |
| f fluid (air) | inlet fluid |
| fo outgoing fluid | g glass |
| T tedlar | tc tedlar to cell |

The study examined the impact of air mass flow rate, air channel depth, length, and the fraction of absorber plate area covered by solar cells on the system's performance. Based on their research, the authors concluded that the solar cell efficiency showed some improvement. Regarding the thermal efficiency of the system, the study found that the average thermal efficiency for water heating ranged from 50% to 70%, while for air heating, it varied from 17% to 51%. This means that the system was more effective in heating water compared to heating air [7, 8]. It was concluded that increasing solar radiation intensity the exergy efficiency increases initially and then decrease after attaining maximum threshold. And also reported that PV array temperature had great effect on exergy efficiency and exergy efficiency can be improved if heat is removed from the PV array surface. They also found out that design parameter such as PV array area had a little effect on the exergy efficiency [9]. He assessed exergoeconomics analysis of photovoltaic thermal mixed mode greenhouse solar dryer. They calculated payback period and carbon credit earned with help of embodied energy and thermal energy gained throughout the year. It was concluded that energy payback time to be 1.23 years and 10 years on the basis of energy and exergy analysis respectively; which is less comparative to other existing systems. Also CO2 mitigation and carbon credit earn for 25 years of solar dryer found to be 81.75 tons and $ 817.50 respectively which is useful for environment sustainability [10]. He investigated the variation in efficiencies due to irregular manner of solar radiation and wind speed. From the obtained results of different experiment it was concluded that efficiencies were higher in the month of February whereas they are lost in the month of August [11]. In this research study that assessed the performance of a hybrid photovoltaic thermal (PVT) system under the climatic conditions of New Delhi. The study utilized both exergy and energy analysis to evaluate the system's efficiency. This system combines photovoltaic (PV) panels with thermal collectors to capture both electricity and heat from sunlight. The combination aims to enhance overall energy utilization and efficiency. Exergy analysis evaluates the quality of energy in a system, considering factors like temperature and pressure, while energy analysis focuses on the quantity of energy. These analyses help assess the system's efficiency and performance from different perspectives. The energy efficiency of the PVT system was reported to vary between 33% and 45%. This means that the system converted a portion of the absorbed solar energy into usable electrical energy within this efficiency range. Exergy efficiency, which considers the quality of energy, varied between 11% and 16% for the PVT system. Exergy efficiency provides insight into how effectively the system converts available energy into useful work, accounting for factors like temperature differences. The study highlighted that fill factor plays a significant role in the exergy efficiency of the PVT system. The fill factor is a parameter that indicates the quality of a PV module's power output and its voltage and current characteristics. It suggests that optimizing the fill factor can improve exergy efficiency [12]. The exergy analysis of carried using the second law of thermodynamic and energy analysis was done. The operating parameters included were PV module temperature, overall heat loss coefficient, open circuit voltage, short circuit current, fill factor etc. The data obtained was used for the calculation of energy and exergy efficiencies of the PV system. Energy efficiency was observed to vary between 6% to 9%, the efficiency was during the afternoon then the morning and evening period. Exergy efficiency varied from 8% to 10% following similar trend as energy efficiencies. It was also observed that temperature had a great impact on result and concluded that the exergy losses increased with increase in module temperature [13].

**2. Material and methods**

**2.1 Description of study area**

The research work was conducted at well-equipped lab of Department of Renewable Energy Engineering, College of Technology and Engineering, MPUAT, Udaipur. The study area situated at 24° 35' 35.01 " North Latitude and 73° 44' 18.09 " East Longitude and at altitude of 582.17m (1909 feet) above the sea level. The experiment was conducted in April 2021 in real atmospheric conditions with an effective area of 0.36 m2 of one PV module.

#### 2.2 Photovoltaic effect

In 1839 a French physicist Edmund Bequerrel found out that some material when exposed to sunlight produces a small amount of current. Later in 1905 Albert Einstein described photovoltaic effect as a nature of light. The first photovoltaic module was built in 1954 by Bell laborites. Some semiconductors like Si and Ge exhibits such kind of photovoltaic effect.

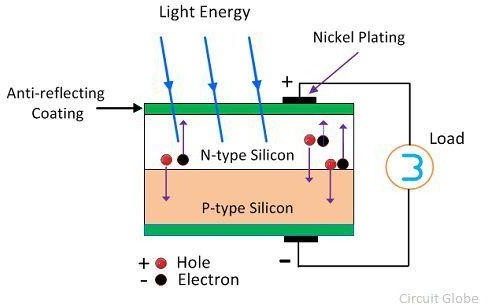


Fig. 1 Basic principle of photovoltaic effect

From figure 1 when light falls on solar cell the electrons gets excited thus they travel from p region to n region of semiconductor, also holes are generated which travels from n region to p region. Thus due to the electron hole pair generation electric field is generated. When such solar cells are connected with each other and mounted on a frame, they form a PV module. And when such modules a connected they form a solar array.



Fig. 2 Representation of solar array



Fig. 3 Equivalent circuit of solar cell

In order to know the electric behavior of the solar cell, an equivalent circuit with discrete electrical component is used. In practice no solar cell is ideal thus a shunt resistance and a series resistance is added to the model.

**2.3 Basic specification of PV module used for research work.**

**Table 1:** Technical specification of module used

|  |  |  |
| --- | --- | --- |
| **Sr no** | **Parameters** | **Values** |
| 1 | Model No. | GOLDI050PM |
| 2 | Rated Power (Pmax) | 50W |
| 3 | Open Circuit Voltage (Voc) | 21.5V |
| 4 | Short Circuit Current(Isc) | 3.14A |
| 5 | Voltage at Maximum Power(Vm) | 17.7V |
| 6 | Current at Maximum Power(Im) | 2.85A |
| 7 | Maximum System Voltage | 1000V |

**Table: 2 Input parameters used in research work**

|  |  |  |
| --- | --- | --- |
| **Sr no.** | **Input Parameters** | **Values** |
| 1 | Ambient temperature (Ta) | 308 ± 5 K |
| 2 | Temperature of the sun (Ts) | 5777 K |
| 3 | Cell temperature (Tcell) | 320 ± 10 K |
| 4 | Effective area (A) | 0.36 m2 |
| 5 | Fill factor | 0.85 |

**Table: 3** Hourly variation of electrical parameter: voltage, current for a typical day in summer month (April, 2021).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Sr.no | Time (h) | Intensity (W/m2) | Open circuit voltage (Voc) | Short circuit current (A) | Load voltage (V) | Load current (A) |
| 1 | 9:00 | 300.9 | 19.39 | 1.68 | 16.49 | 1.552 |
| 2 | 9:30 | 690.3 | 20.02 | 1.996 | 16.33 | 1.857 |
| 3 | 10:00 | 705.6 | 19.39 | 2.31 | 16.53 | 2.08 |
| 4 | 10:30 | 770.2 | 19.32 | 2.46 | 15.83 | 2.39 |
| 5 | 11:00 | 827.5 | 19.29 | 2.175 | 16.39 | 2.01 |
| 6 | 11:30 | 863.6 | 19.5 | 3 | 16.669 | 2.77 |
| 7 | 12:00 | 897.4 | 19.36 | 3.005 | 16.29 | 2.74 |
| 8 | 12:30 | 898.3 | 19.46 | 2.938 | 16.02 | 2.59 |
| 9 | 1:00 | 891.56 | 19.46 | 2.915 | 16.94 | 2.41 |
| 10 | 1:30 | 886.2 | 19.36 | 2.826 | 16.54 | 2.23 |
| 11 | 2:00 | 887.9 | 19.93 | 2.646 | 16.33 | 2.01 |
| 12 | 2:30 | 812.3 | 19.29 | 2.42 | 16.06 | 1.98 |
| 13 | 3:00 | 754.9 | 19.48 | 2.175 | 16.37 | 2.01 |
| 14 | 3:30 | 661.12 | 19.32 | 2.2 | 16.38 | 1.56 |
| 15 | 4:00 | 480.3 | 18.92 | 2.15 | 15.82 | 1.07 |
| 16 | 4:30 | 350.2 | 19.39 | 1.832 | 15.02 | 0.89 |
| 17 | 5:00 | 213.2 | 18.5 | 1.6 | 13.3 | 0.8 |

**2.4 Instrument used in research**

Luxmeter is an instrument used for measuring illuminance of the sun or other light. Unit of measurement is lux which is lumen/m2. Luxmeter uses silicon photo diode and is proved to be a good substitute of pyranometer shown in fig. (4a).

**Fig 4** (a) Luxmeter (b) Anemometer (c) Infrared thermometer

(d) Multimeter (e) Compact hygro thermometer

Anemometer is a device used for measuring the wind speed of the surrounding in which research is conducted. It is a simple device consisting of a fan rotating perpendicular with respect to direction of wind. Operating temperature 0℃ to 50℃ was used for the experiment shown in fig. (4b). Infrared thermometer is a device which helps in calculating the temperature of any object with making contact which the object. It works on the principle of black body radiation. By knowing the amount of infrared energy emitted by the object the temperature of the object can be determined which is close to its actual temperature. Infrared thermometer was used to measure the temperature of solar module. An infrared thermometer model made by Raytec MT4 was used for the experiment with temperature range of 50℃ to 70℃ shown in fig. (4c). A multimeter is a versatile instrument used for measuring voltage, resistance and current. A digital multimeter with three ports was used for the measurement of maximum voltage and maximum current generated by the solar module during load condition shown in fig. (4d). A compact hygro thermometer was used for measuring the ambient temperature. A typical thermometer manufactured by templab with temperature range of 50℃ to 70℃ was used shown in fig. (4e).

**2.5 Experimental setup:**

From figure 5 the setup consists of given module attached with two wires in the circuit hub. In order to get the reading of open circuit voltage and short circuit current the wire are attached to the millimeter. The reading was obtained in no load condition.



Fig.5 Experimental setup in no load condition

In order to get maximum voltage (Vm) and maximum current (Im) a rheostat was used to provide a constant load. The rheostat circuit used is shown in figure 6.



Fig.6 Rheostat used during load condition

From figure 7 the reading was taken every hour from 10 am to 5 pm. A proper resistance must be set in order to get proper difference in load and no load condition. Similarly ambient temperature, wind velocity, solar radiation was measured in each consecutive hour of the day.



Fig.7 Experimental setup in load condition

**Table 4 Description of various instruments**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sr.no | Instrument | Operating range | Least count | Particular |
| 1 | Copper-constantan thermocouple | oC | 0.1 oC | Calibrated against zeal thermometer in temperature controlled bath circulator |
| 2 | Solarimeter | 0 to 1000 W/m2 | 20 W/m2 | Calibrated against pyranometer |
| 3 | Infrared thermometer | oC | 0.1 oC | Emmissivity setting = 0.95 |
| 4 | Clamp meter | (1–1000) V DC/AC (1–1000) A  DC/AC | 0.001 V  0.1 A | Calibrated using measurement standard traceable to ERTL  (north) |
| 5 | Anemometer | 0.4 to 30 m/s | 0.1 m/s | Low friction ball-bearing vane |

**3. Thermal Modeling**

In order to write the energy balance equation of photovoltaic modules, the same assumptions and methodology have been considered as stated by Agrawal and Tiwari (2011a) [14].

**(i) For solar cells of PV module**

The energy balance equation for solar cell of PV module can be written as

……(1a)

[The rate of solar energy available on PV module] = [The rate of overall heat loss from top surface of the cell to ambient]

+ [The rate of overall heat transfer from cell to back surface of tedlar]

+ [The rate of electrical energy produced]

From eq. (1a), the expression for cell temperature is

**……(**1b**)**

**(ii) For the back surface of the tedlar**

…..(2a)

[The rate of heat transfer from cell to back surface of tedlar] = [The rate of heat transfer from back surface of the tedlar to flowing fluid]

Using equations (1b) and (2a), an expression for back the surface face temperature of PV module can be obtained as

(2b)

**(iii) For the air flowing below the tedlar**

…(3)

[The rate of heat gain by flowing fluid in duct] + [An overall heat transfer from flowing fluid to ambient]

= [The rate of heat transfer from back surface of the tedlar to flowing fluid]

The outlet air temperature (), useful heat gain (), temperature dependent electrical efficiency (g) from Nth hybrid PVT module air collectors connected in series is derived as, [14].

……… (4)

……. (5)

Where,

… (6)

**3.1 Instantaneous thermal efficiency**

An instantaneous thermal efficiency of flat plate collector can be obtained as, Agrawal and Tiwari (2002a).

…… (7)

……. (8)

Where,

FR and UL are the heat removal factor and overall heat loss coefficient.

Eq. (8) is known as the Hottel–Whiller– Bliss equation of flat plate collector.

**3.2. Exergoeconomic analysis**

The exergy analysis is based on second law of thermodynamics. The exergy analysis gives the idea of actual feasibility of system. Also it helps in knowing the quality of work done by the system. Consequently, the general balance equation can be written as (Rosen and Dincer, 2003) [15].

….. (9)

……(10)

The output terms in Eqs. (9) and (10) can be separated into product and waste components, That is

……. (11)

and

…….. (12)

Cost is an increasing, nonconserved quantity. The general balance equation can be written for cost as (Rosen and Dincer, 2003) [15].

….. (13)

…. (14)

For convenience, the energy loss for a system is denoted as Len (loss based on energy) and Lex (loss based on exergy) are calculated.

…..(15)

….. (16)

The energy and exergy loss can be obtained through the following equations (Rosen and Dincer, 2003):

Where, the summations are over all inputs and all products out.

Exergoeconomic parameter R is the ratio of the thermodynamic loss rate (L) to the net capital cost (K).

…..(19)

The value of R mainly depends on energetic Ren and exergetic Rex considerations the parameter equation is given by.

….. (20)

……(21)

**4. Result and discussion**

**4.1 Exergy and energy analysis of 50 W polycrystalline PV modules.**

Figure 8 shows that the variation in solar radiation and ambient temperature. Figure 9 shows the variation in solar radiation and module temperature. It was revealed that solar radiation was low during the morning and increased gradually during the afternoon reaching its peak at 13:00 h. The maximum solar radiation was recorded 890 W/m2 was recorded at 13:10 h. The ambient temperature and module temperature was 38.5℃ and 60℃ respectively at 15:00 h. Module temperature followed a complimentary trend with ambient temperature. Wind velocity followed a very non uniform trend but variation in ambient temperature lightly affected the wind velocity which can be seen in figure 10.

Fig.8 Variation in solar radiation and ambient temperature with respect to time (12 April)

Fig.9 Variation in solar radiation and module temperature with respect to time (12 April)

Fig.10 Variation in wind velocity and temperature with respect to time (12 April)

Fig.11 Variation in Energy Efficiency with respect to time

Figure 11 shows that highest energy efficiency was observed in the morning of 23.62 % on 12 April as there is less module temperature and enough solar radiation but declined over the period of time due to increase in module temperature the variation in energy efficiency and module temperature with respect to time. It is clear from the figure there is in verse. Furthermore the lowest of efficiency was achieved at 5:00 pm on 16th April of 8.3%.

Fig.12 variation in energy efficiency and module temperature with respect to time

Figure 12 shows that the module temperature increases, energy efficiency decreases and the main factor responsible for the decrease is thermal resistances offered due to increase module temperature. From the figure it is also seen as there is steep decrease in efficiency as temperature increase by 6 degree and declined as the module temperature increased. From the figure it is also concluded that module temperature should be maintained at 35℃ for satisfactory efficiency.

Fig.13 Variation in exergy efficiency with respect to time.

Fig.14 Variation in exergy efficiency with respect to module temperature

From figure 13 the highest exergy is achieved at morning of 12% and decrease consistently over the duration of day. From figure 14 during morning period there is some overlapping of the data is achieved but during the afternoon period there exist a huge gap between the two parameters which means that exergy does not depend on module temperature as whole but the difference between module temperature and ambient temperature. In order to get more clear insight on the behavior of energy and exergy efficiency the variation in energy and exergy efficiency with respect to module temperature is discussed in figure 15.

Fig.15 Variation in energy and exergy efficiency with respect to module temperature

**4.2 Exergeoeconomics analysis of PV module.**

**4.2.1 Exergy loss rate obtained during the experiment**

Fig.16 Exergy loss rate with respect to time

Figure 16 shows that the lowest exergy loss was achieved at the morning of 83.7 W and highest are achieved at the afternoon of 312 W. From the acquired data it is also clear that exergy losses are more as compared to energy losses due to the fact that exergy losses are based on second law of thermodynamics.

**4.2.2. Energy loss rate obtained during the experiment**

Fig.17 Energy loss rate with respect to time

From figure 17 the lowest energy loss rate was achieved at morning of about 79.3W and highest energy loss rate was achieved at afternoon of 16 April of 289 W. This is due to fact that as there more thermal resistance achieved during the afternoon period as there is high module temperature as compared to morning and evenings.

**Conclusion**

* The lowest energy efficiency was found out to be 8.3% on 16th of April. And the highest energy efficiency of 23.62% was observed at April 12th.
* It was observed that ambient temperature and module temperature play an important role in energy efficiency. As the thermal resistance offered by the module due to increase in temperature.
* Similarly highest exergy of 12% was observed at April 12th. And lowest of 5.19% on the same day. It was also observed that exergy efficiency followed a linear trend with module temperature and ambient temperature.
* Both the efficiencies were observed to be higher in the morning and decrease gradually till evening. As both the efficiencies are affected by module temperature, ambient temperature and solar radiation.
* The fill factor play an important role during both energy and exergy analysis and it was observed that fill factor is directly proportional to both the efficiencies.
* Exergy efficiency was observed to be always lower than energy efficiency and is more realistic approach is evaluation of PV module performance.
* Wind velocity was very less significant parameter and didn’t affect the energy and exergy efficiency.
* The exergy losses were observed to be more than energy losses as they are based on second law of thermodynamics.

**Ethics declarations: Consent for publication**

* Not applicable.

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