**PERFORMANCE ASSESSMENT OF PV AND PV/T**

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**1. Energy and Exergy Analysis of PV**

The performance PV cell depends on some physical, thermo-physical and environmental parameters such as p-n structure, solar radiation intensities, climatic, operating and design parameters such as ambient temperature, PV module temperature, overall heat loss coefficient, open-circuit voltage, short-circuit current, maximum power point voltage, maximum power point current, and module area etc. All these parametes are effected on energy efficiency and exergy efficiency of PVs.

**1.2. Energy Efficiency**

The energy efficiency of a solar panel, the ratio of the power output to the energy originally delivered to the solar panel, conventionally is used to measure solar PV efficiency. Energy analysis is based primarily on the first law of thermodynamics, as compared with exergy analysis which is based on the second law of thermodynamics. Energy analysis is concerned only with quantity of energy use and efficiency of energy processes. Energy analysis thus ignores reductions of energy potential, which could be used productively in other physical and/or chemical process. Energy analysis can provide sound management guidance in those applications in which usage effectiveness depends solely on energy quantities [1].

**a) For PV Cell**

The PV cell is semiconductor device and its usually represented by the single diode model. The single diode equivalent circuit of a solar cell is shown in Figure 1.



Figure 1. A typical electrical circuit of solar PV cell

The current–voltage relation of PV cell under constant illumination intensity is given by:

 (1)

The PV cell can be characterised by two main parameters:

**i) Short circuit current (Isc)**

The solar cell generates a current, and this current varies with the cell voltage. When the voltage of this solar cell is zero described as a short-circuited solar cell and the short circuit current, Isc, proportional to irradiance on the solar cell, can be measured [2]. In other words, the short circuit current is the current for no voltage in the solar cell circuit. This can be achieved by connecting the positive and negative terminals by copper wire: The short-circuit current (Isc) and open-circuit voltage (Voc). The short-circuit current is the current through the PV cell when the voltage across the cell is zero.

**ii) Open circuit voltage (Voc)**

When the cell current is equal to zero, the solar cell is described as open-circuited. The cell voltage then becomes the open-circuit voltage (Voc): Open–circuit voltage reflects the voltage of the cell in the night and it can be mathematically expressed as:

 (2)

It is clear that the open-circuit voltage increases logarithmically with the ambient irradiation, when the short-circuit current is a linear function of the ambient irradiation. The dominant effect with increasing cells temperature is the linear decrease in the open–circuit voltage, the cell being thus less efficient. The short-circuit current slightly increases with the cell temperature [3].

**b) For PV System**

Energy efficiency of a PV system can be defined as the ratio of the output energy of the system (i.e., electrical energy) to the input energy (i.e., solar energy) received on photovoltaic surface. The energy efficiency of a PV system is given as [4-5]:

 (3)

However, this definition of energy efficiency is restricted to theoretical cases. In equation (3), G(t)is the solar energy and Acell is the surface area of the cell. So it is given as:

 (4 )

where, L1 and L2 are the length and width of solar cell, respectively. Electrical energy output:

 (5 )

For PV system in practical cases, energy efficiency measures the ability of converting solar energy into electrical energy [4-6]. The electrical power output of a PV module is the product of its voltage and current of photovoltaic device. This conversion efficiency is not constant, even under constant solar irradiation. However, there is point of maximum power, where voltage is Vmp, which is less than open-circuit voltage (Voc) but closed to it, and current is Imp, which is less than short-circuit current (Isc) but closed to it as shown in Figure 2. In Figure 2, EGH stands for the highest energy level of electron at maximum solar irradiation conditions. EGH is equivalent to area under the I–V characteristics curve. In addition, EL stands for the low energy content of electron, which is the practical case, as shown by the rectangular area in same Figure. EL is thus equivalent to ImpVmp. The maximum power point is restricted by a term called fill factor (FFcell) as follows [7]:

 (5 )

FFcell is assumed to be constant. However it varies according to solar radiation intensity and ambient temperature.

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Figure 2. I-V characteristic

The fill factor is defined as follows:

 (6)

or

 (7)

where Imax and Vmax are the current and voltage for maximum power, corresponding to solar intensity, G(t).

**c) The electrical circuit of PV**

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Figure 3. Expermental PV circuit

1. To determine the energy efficiency of PV, experimentally, please set up the experimental PV curcuit.
2. To determine Imp and Vmp the according to P=IV profile of I-V characteristic of PV cell. For this purpose:
3. According to the test apparatus of Fig.1, please hold constant the distance between the light source and the solar cell.
4. Measure the current (I) and voltage (V) values changing the value of the potentiometer at 7-8 times.
5. Draw a graph of light intensity versus Voc and Isc
6. According the the graft; find the maximum power volttage and maximum power current.
7. Calculate the fill factor (FFcell) of the PV;
8. Determine the value of Rsh and Rs resistance.
9. Find the efficiency of the solar cell.

**1.3. Exergy Efficiency**

Exergy is the maximum work potential which can be obtained from energy [8-9]. Exergy analysis is recognised by many engineers to be a powerful tool for the evaluation of the thermodynamics and economic performance of system in general [10]. Exergy analysis provides an alternative means of evaluating and comparing the solar PV. Exergy analysis is based on the separate quantification and accounting for usable energy, called exergy or availability and unusable energy, called irreversibility [11]. Exergy analysis is used to find out the energy utilisation efficiency of an energy conversion system. Exergy analyses yields useful results because it deals with irreversibility minimisation or maximum exergy delivery. The exergy analysis has been increasingly applied over the last several decades largely because of its advantages over energy analysis. Exergy analysis evaluates the efficient usage of solar energy employed in different fields of solar heating devices, solar air conditioning, and refrigeration systems [12]. Some researchers are carried out the performance analysis of a solar drying process, solar power generation and solar-assisted heat pump system. Reduction of heat loss from the collector to ambient air can enhance the maximum exergy [9, 13-14]. Tiwari et al. performed an exergetic analysis for passive and active solar distillation systems[15].

A significant amount of theoretical as well as experimental studies on the energy or exergy performance of PV systems has been carried out by several researchers [16-18] studied the performance characteristics of a photovoltaic (PV) and photovoltaic-thermal (PV/T) system based on energy and exergy efficiencies, respectively. Energy, power conversion (electrical), and exergy efficiency of a PV system are estimated based on experimental data. Sahin et al. carried out the thermodynamic analysis of a PV array based on chemical potential components. They also obtained exergy components and PV array exergy efficiency [5]. Finally, they compared exergy efficiency with energy and electrical efficiency, respectively under given experimental operating condition. To perform energy and exergy analysis of the solar PV, the quantities of input and output of energy and exergy must be evaluated. In this work, a detailed energy and exergy analysis is carried out to evaluate the electrical performances, exergy, and energy efficiencies of amorphous and polycrystalline PV modules.

The most general formulation of the exergy equation for an open system under steady-state assumption, using the first law of thermodynamics can be written as:

 (8)

a general exergy balance equation is given as:

 (9)

where Ėxin is equal to Ėxsolar and Ėxout is the maximum amount of exergy that can be obtained from a system whose supplying exergy is Ėxin. The smaller the exergy consumed, the smaller the exergy loss. Exergy efficiency of the photovoltaic module is also defined as the ratio of total output exergy to total input exergy[19-20]. An exergy efficiency of the solar PV can be defined as the ratio of the exergy gained by the solar PV (exergy output) to the exergy of the solar radiation (exergy input) [21].

 (10)

where Exin Exout and Icv are the inlet exergy, outlet exergy, and irreversibility in control volume, respectively.

The inlet exergy includes only solar radiation intensity exergy.

 (11)

where Tamb and Tsun are the ambient temperature and Sun’s temperature in Kelvin. The irreversibility in control volume includes external exergy losses from control volume and internal exergy losses (exergy destruction) in control volume [8].

 (12)

The external energy loss caused by heat leakage is numerically equal to Ėxth for PV system.

 (13)

where Uis the overall heat loss coefficient of PV module which has been assumed as a constant factor or variable with little effect, whereas, it is not constant than it includes convection and radiation losses:

 (14)

The convective heat transfer coefficient (hconvect) is given by:

 (15)

where Vwis wind speed. The radiative heat transfer coefficient between PV module and surrounding is obtained from:

 (16)

where ε and σare emissivity and Stefan Boltzmann’s constant, respectively, and the effective temperature of the sky (Tsky) is calculated from the following empirical relation:

 (17)

The internal exergy losses (exergy destruction) includes four terms, one is caused by optical losses in PV module surface.

 (18)

where, ταis the effective product of transmittance–absorptance. The second term is caused by the temperature difference between PV module surface and the sun temperature [22].

 (19)

The third term is caused by the temperature variation of PV module with respect to the reference environmental state.

 (20)

where, mcell and Δtare PV module mass and time interval, respectively. The interval is chosen according to the time step of experiment course [5]. The specific heat capacity of silicon solar cell Cp,cellis calculated as [23].

 (21)

The fourth term is electrical exergy destruction [18].

 (22)

Exergy efficiency is given as:

 (23)

Destructive components of the input solar energy (i.e., Exdest,optic, Exdest,solar and Exdest,cell) which are not utilised to generate electrical energy, so they should be ignored. Therefore, exergy efficiency,

 (24)

Electrical exergy;

 (25)

 (26)

 (27)

In here, for the calculation of exergy efficiency (ηex), Equation (24) is used for the

sake of simplicity and ease of calculations. As seen in the figs, curves of the PV panel for different irradience values [24].



Figure 1. I-V curve [24].

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Fig. 2. P-V curve [24].

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Fig. 3. P-I curve [24].



Fig. 3. I-V and P-I curve [24].



Fig. 5. I-V curve at different temperatures [24].

As seen in the figs. Curves of the PV panel for different temperature values

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Fig. 6. P-V curve at different temperatures [24].



Fig. 7. P-I curve at different temperatures[24].

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Fig. 8. P-I curve at different temperatures [24].

**2. ENERGY AND EXERGY ANALYSIS OF PV/T**

Thermal energy also plays an important role in human life as it can generally be utilized in either high-grade (high-temperature) or low-grade (low-temperature) form. Solar PV and thermal applications appear to be potential solutions for current energy needs and to combat greenhouse gas emissions. Jones and Underwood [25] have studied the temperature profile of a PV module in a non-steady state condition with respect to time. They performed experiments for clear- as well cloudy-day conditions and observed that the PV module temperature varies between 300 and 325 K (27–52 ºC) for an ambient air temperature of 297.5 K (24.5 ºC). The thermal energy associated with the PV module may be removed (carried away) either by air or water. When a thermal energy requirement is integrated with the PV module, it is referred to as a hybrid photovoltaic/thermal (PV/T) system. Hybrid PV/T systems may find applications for:

1. air heating [e.g. 26–34]
2. water heating [e.g. 33, 35–41].

Chow has done the analysis of a PV/T water collector with single glazing in a transient condition [38]. The tube below the flat plate with a metallic bond collector was used. He observed that PV conversion efficiency is increased by 2% at a mass flow rate of 0.01 kg/s for a 10000 W/m2K plate to bond heat transfer coefficient. An additional thermal efficiency of 60% was also observed. For water heating under a natural mode of operation, Huang et al. [42] have studied experimentally the unglazed integrated photovoltaic and thermal solar system (IPVTS). They observed that the primary energy saving efficiency of IPVTS exceeds 0.60, which is higher than for a conventional solar water heater or pure PV system. Kalogirou [40] has studied the monthly performance of an unglazed hybrid PV/T system under a forced mode of operation for the climatic conditions of Cyprus and observed an increase of the mean annual efficiency of the PV solar system from 2.8 to 7.7% with a thermal efficiency of 49%, respectively. A similar study has also been carried out by Zondag et al. [41]. They have referred hybrid PV/T as a combipanel that converts solar energy into both electrical and thermal energy. The electrical and thermal efficiencies of the combi-panel were reported as 6.7 and 33%, respectively.

Sandnes and Rekstad [36] have observed the behavior of a combined PV/T collector which was constructed by pasting single-crystal silicon cells onto a black plastic solar heat absorber (unglazed PV/T system). They recommended that the combined PV/T concept must be used for low-temperature thermal applications for increasing the electrical efficiency of the PV system, e.g. space heating of a building. Zakharchenko et al. [37] have also studied an unglazed hybrid PV/T system with a suitable thermal contact between the panel and the collector. They have proved that the areas of PV panel and collector in the PV/T system need not be equal for higher overall efficiency. To operate the PV module at low temperature, the PV module should cover the low-temperature part of the collector (at the cold water inlet portion). Further, an unglazed hybrid PV/T system with booster diffuse reflector was integrated with the horizontal roof of a building by Tripanagnostopoulos et al. [33]. They suggested that a PV/T system with reflectors gives clearly higher electrical and thermal output. They have also studied the performance characteristic of PV/water and PV/air systems. Infield et al. [32] have derived an overall heat loss coefficient (U) and thermal energy gain factor (g) for a ventilated vertical PV module and a double glazed window (PV facades). The steady state analysis was used to determine ventilation gains and transmission losses in terms of irradiation (solar radiation) and various heat transfer processes involved in facades. He observed that the ventilated facades ensure that the electrical efficiency of the PV module is improved due to low temperature (generally below 45 ºC). Hagazy [31] and Sopian et al. [43] investigated glazed PV/T air systems for single and double pass air heaters for space heating and drying purposes. They have also developed a thermal model for each system. They observed that thermal energy for glazed PV/T systems increased with lower electrical efficiency due to high operating temperature. Further, Coventry [44] has studied the performance of a concentrating PV/T solar collector and concluded that overall thermal and electrical efficiency of a PV/T concentrating system are 58 and 11%, respectively. This gives a total efficiency of the system as 69%. Joshi and Tiwari [18] observed that the instantaneous energy and exergy efficiency of the PV/T system varies between 55 –65 and 12 –15%, respectively, for cold climatic conditions of Srinagar, India. They have also done the experiments on the PV/T air collector for climatic conditions of New Delhi, India and found an overall thermal energy and exergy efficiency about 50 and 14%, respectively.

In this paper, we undertake a study to investigate the performance of the hybrid PV/T air collector system through energy and exergy efficiencies and improvement potential factors and compare them for practical purposes. A case study is presented to highlight the importance of efficiency modelings and compare them using some actual data. It is also aimed to find if there is room for improvement.

**2.2. Energy efficiency**

Following Joshi et al. [4], the energy efficiency of a PV/T system can be defined as a ratio of total (thermal and electrical) energy to the solar energy falling on the PV surface and can be given as:

 (28)

where En\_ is the rate of energy (W) from the PV system which comprises electrical (VocIsc) and thermal energy produced by the PV/T system:

 (29)

 (30)

G(t) is the hourly global solar radiation (W/m2), Acell is the area of the solar panel (m2 ).

 (31)

Here, hca, Tcell and Tamb are the convective (and radiative) heat transfer coefficient (W/m2K) from PV cell to ambient, cell temperature and ambient temperature, respectively. The convective heat transfer coefficient from the PV cell to ambient, can be calculated by considering wind velocity (*v*), density of the air and the surrounding conditions [45].

**2.3. Exergy efficiency**

The exergy efficiency is critical to define the real performance of PV/T systems and it can define by:

 (32)

where Exsys is exergy from the PV/T system and Exsolar is exergy from the solar radiation falling on the PV surface. The exergy from the system and the exergy from the solar radiation can be given as:

 (33)

where Vmp is the actual voltage (V), Imp is the actual current (A) generated by PV/T system and Tsolar is temperature of the sun (5777 K).

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