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Exergetic Performance Evaluation of a Solar Photovoltaic (PV) Array

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Abstract: In this paper, an attempt is made to investigate the exergetic performance of a solar photovoltaic (PV) array. A detailed energy and exergy analysis is carried out to evaluate the electrical performance, exergy components and exergy efficiency of a typical PV array. The exergy efficiency of a PV array obtained in this paper is a function of climatic, operating and design parameters such as ambient temperature, solar radiation intensity, PV array temperature, overall heat loss coefficient, open-circuit voltage, short-circuit current, maximum power point voltage, maximum power point current, PV array area, etc. Some corrections are done on overall heat loss coefficient. A computer simulation program is also developed to estimate the electrical and operating parameters of a PV array. The results of numerical simulation are in good agreement with the experimental measurements noted in the previous literature. Finally, parametric studies have been carried out. It is observed that the behavior of exergy efficiency with respect to the variations of climatic, operating and design parameters is so similar to the electrical efficiency of PV array. Further, it is observed that PV array temperature has a great effect on the exergy efficiency and the exergy efficiency can be improved if the heat can be removed from the PV array surface. On the other hand, design parameters such as PV array area have a little effect on the exergy efficiency.

Key words: Solar photovoltaic (PV) array, Exergy analysis, Numerical simulation

INTRODUCTION

Renewable energies are going to be a main substitute for fossil fuels in the coming years for their clean and renewable nature. A solar photovoltaic (PV) array is one of the most significant and rapidly developing renewable-energy technologies, and its potential future uses are notable.

PV array is a semiconductor device, which converts light energy directly into useful electricity. The energy payback time (EPBT) of a PV system lies between 10 and 15 years depending on insulation and the performance of it. If the performance of a PV array can be increased, the energy payback time can be reduced. Therefore, the performance evaluation of a PV array is important.

PV array performance parametrically depends on climatic, operating and design parameters such as ambient temperature, solar radiation intensity, PV array temperature, overall heat loss coefficient, open-circuit voltage, short-circuit current, maximum power point voltage, maximum power point current, PV array area, etc. It can be evaluated in terms of energy efficiency and exergy efficiency.

Its evaluation based on the first and second law of thermodynamics is known as energy efficiency and exergy efficiency, respectively. The energy analysis has some deficiencies (Petela, R., 2008; Petela, R., 2003). Fundamentally, the energy concept is not sensitive with respect to the assumed direction of the process, e.g. energy analysis does not object if heat is considered to be transferred spontaneously in the direction of increasing temperature. It also does not distinguish the quality of energy, e.g., 1 W of heat equals 1 W of work or electricity. Energy analyses on their own incorrectly interpret some processes (Petela, R., 2008; Petela, R., 2003), e.g., environmental air, when isothermally compressed, maintains its energy (e.g. enthalpy) equal to zero, whereas the exergy of the compressed air is greater than zero. However, exergy data are more practical and realistic in comparison with the respective energy values. Thus, exergy analysis usually provides a more realistic view of process than energy analysis (Petela, R., 2008; Petela, R., 2003).

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The energy conversion factor of a solar PV system sometimes is described as efficiency, but this usage sometimes leads to some difficulties such as follows Sahin *et al*. (2007). The energy efficiency of a PV array can be considered as the ratio of the electricity generated to the total, or global, solar irradiation. In this definition, only the electricity generated by a PV array is considered. The other components and properties of a PV array, such as ambient temperature, PV array temperature, chemical potential components and heat capacity of a PV array are not directly taken into account Sahin *et al*. (2007). However, the exergy efficiency of a PV array includes most of the climatic, geometric and operating parameters of a PV array and involves the thermal properties and chemical potential components of it directly Sahin *et al*. (2007).

A significant amount of theoretical as well as experimental studies on the energy or exergy performance evaluation of PV systems has been carried out in the last 35 years. Kerr and Cuevas (2003) presented a new technique, which can determine the current-voltage characteristics of a PV array as a function of solar radiation intensity.

Others (Radziemska, E. and E. Klugmann, 2002; Van Dyk, E.E., 2000; Nishioka, K., 2003) generally analyzed the effect of temperature on PV array performance. There are also some power efficiency models (Evans, D.L., 1981; Mondol, J.D., 2005; Hove, T., 2000; Stamenic, L., 2004; Jones, A.D. and C.P. Underwood, 2002), which can predict the real dynamic or average performance of a PV system under variable climatic conditions. Jones and Underwood (2001) studied the temperature heat profile of a PV module in a non-steady state condition with respect to time. They conducted experiment for cloudy as well clear day condition. They observed that PV module temperature varies in the range of 300-325 K (27-52°C) for an ambient air temperature of 297.5 K (~24.5°C).

Infield *et al*. (2004) analyzed a PV system that consisted of PV module and double glass wall (PV facades). They concluded that the temperature of PV module could be reduced by flowing air between PV module and double glass wall.

In order to increase the output power of PV array a sun-tracking design was presented by Mohamad (2004); the movement of PV array was controlled to follow the Sun's radiation using a programmable logic controller (PLC) unit. He observed that the daily output power of PV array with sun-tracking system is more than the fixed one.

Wei *et al*. (2007) proposed a simple model to predict PV array performance for engineering applications and validated it experimentally. They also obtained analytical expressions for the operating parameters of a PV array such as short-circuit current, open-circuit voltage, fill factor and maximum power-output.

Badescu (2006) studied the effect of latitude and climate on PV module shape based on energy analysis. He obtained the optimized value of PV cells number in series and strings number for various climatic conditions.

Skoplaki *et al*. (2008) suggested a simple semi-empirical correlation for PV array temperature. They investigated the effect of solar irradiance, ambient temperature, and wind speed on PV array temperature. However, they ignored free convection and radiation losses from PV array to the environment.

Abdolzadeh and Ameri (2009) investigated the possibility of improving the performance of a photovoltaic water pumping system by spraying water over the top surface of PV array experimentally. They pointed out that the efficiency of PV array can be increased due to spraying water over the front of PV array.

Joshi *et al*. (2009) developed a thermal model for the PV module integrated with solar air collector and validated it experimentally. They indicated that PV module temperature can be controlled and reduced in consequence of changing the mass flow rate of air in solar collector and the efficiency of PV module can be increased.

Yiping *et al*. (2009) studied the performance of solar cells immersed in liquids under simulated sunlight. They showed bare solar cells immersed in non-polar silicon oil have the best performance.

Ross and Hsiao (1977) investigated some theoretical thermodynamic limits of photochemical solar energy conversion efficiency.

Landsberg and Markvart (1998) studied the Carnot factor in PV cell theory and obtained an expression for open-circuit voltage, which is equal to the band-gap multiplied by the Carnot efficiency. Markvart and Landsberg (2002) also discussed the thermodynamics and reciprocity of solar energy conversion by considering PV, photochemistry and photosynthesis phenomena.

Würfel (2002) studied thermodynamic limitations of solar energy conversion, based on an entropy concept, and calculated the upper efficiency as 0.86 for maximally concentrated solar radiation.

Smestad (2004) examined the concepts of hot carrier and light converter, indicating that electrons are ejected not only as heat but also as light.

Bisquert *et al*. (2004) presented some physical and chemical principles of PV conversion and found the relation between chemical potential and open-circuit voltage of PV cell to be dependent on Carnot and statistical factors.

Sahin *et al*. (2007) carried out the thermodynamic analysis of a PV array based on chemical potential components. They also obtained exergy components and PV array exergy efficiency. Finally, they compared exergy efficiency with energy and electrical efficiency, respectively under given experimental operating conditions.

Joshi *et al*. (2009) studied the performance characteristics of a photovoltaic (PV) and photovoltaic-thermal (PV/T) system based on energy and exergy efficiencies, respectively. They proposed equations for the energy, power conversion (electrical) and exegry efficiency of a PV system. Finally, they compared the energy, power conversion (electrical) and exegry efficiencies using experimental data and gave useful results.

Dubey *et al*. (2009) evaluated the energetic and exergetic performance of a PV/T air collector with air duct above the absorber plate and the one with air duct below the absorber plate. They investigated the effect of design and operating parameters and four weather conditions on the performance of above-mentioned PV/T air collectors for five different cities of India and found that the latter one gives better results in terms of thermal energy, electrical energy and exergy gain.

Tiwari *et al*. (2009) carried out the energy and exergy analysis of an integrated photovoltaic thermal solar (IPVTS) water heater. They reported that the overall exergy and thermal efficiency of an IPVTS system is maximum at the hot water withdrawal flow rate of 0.006 kg/s.

Agrawal and Tiwari (2009) carried out an energy analysis in order to select an appropriate building integrated photovoltaic thermal (BIPVT) system suitable for the cold climatic conditions of India. They reported that for a constant mass flow rate of air the system connected in series gives a better performance whereas for a constant velocity of air flow the system connected in parallel gives a better performance.

Sarhaddi, Farahat and Ajam have optimized solar collector systems based on exergy analysis (Sarhaddi, F., 2008; Farahat, S., 2009; Ajam, H., 2005).

In this paper, the exergetic performance of a PV array will be evaluated. A detailed energy and exergy analysis will be carried out to calculate the operating and electrical parameters, exergy components and exergy efficiency of a typical PV array. The operating and electrical parameters of a PV array include PV array temperature, overall heat loss coefficient, open-circuit voltage, short-circuit current, maximum power point voltage, maximum power point current, etc. Further, an equation for the exergy efficiency of a PV array will be derived in terms of climatic, design and operating parameters. A computer simulation program will be developed to calculate the operating and electrical parameters of a PV array. Finally, parametric studies will be carried out; also, the effect of climatic, design and operating parameters on exergy efficiency will be studied.

PV array exergy analysis is parametrically dependent on its energy analysis. Hence, firstly PV array energy analysis will be carried out. Then the exergy components and exergy efficiency of a PV array will be computed and studied.

Energy Analysis:

The proof of governing equations on PV array energy analysis is not included in order to have a brief note. A PV array is nonlinear device and can be represented by its current-voltage (I-V) characteristic curve. There are several mathematical models, which can describe I-V characteristic curve. Five-parameter photovoltaic model (Fig. 1) for I-V characteristic curve is defined as (De Soto, W., 2004)

$$I=I_L-I_o\left[\exp\left(\frac{V+IR_S}{a}\right)-1\right]-\frac{(V+IR_S)}{R_{sh}} \quad (1)$$

$$a=\frac{\gamma k T_{cell}}{q} \quad (2)$$

where, I and V represent current and voltage at load, q, k, γ , a, I_L, I_o, R_s and R_{sh} are electron charge, the Boltzmann constant, dimensionless diode curve-fitting factor, ideality factor, light current, diode reverse saturation current, series resistance and shunt resistance, respectively.

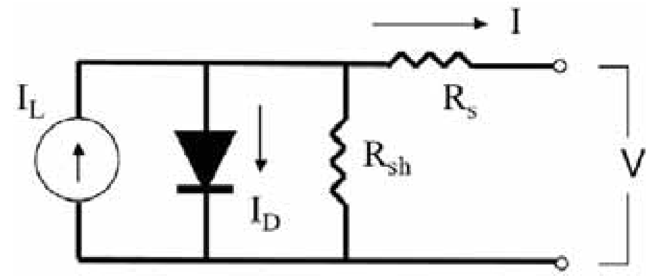

Fig. 1: Equivalent electrical circuit in the five–parameter photovoltaic model (De Soto, W., 2004).

The second terms on the right hand side of Eq. (1) indicate diode current (I_D). In order to calculate five reference parameters (a_{ref} , $I_{L,ref}$, $I_{o,ref}$, $R_{s,ref}$ and $R_{sh,ref}$), five pieces of information are needed at reference conditions. These five pieces of information are defined as follows (De Soto, W., 2004):

At short circuit current:	$I=I_{sc,\ ref}$, V=0.
At open circuit voltage:	I=0, $V=V_{oc,\ ref}$
At the maximum power point:	$I=I_{mp,\ ref}$, $V=V_{mp,\ ref}$
At the maximum power point:	$[d(IV)\ dV]_{mp}=0$.
At short circuit:	$[dIdV]_{sc} = 1/R_{sh,\ ref}$

Reference conditions or standard rating conditions (SRC) are defined as follows (Siemens Company, 2009):

The solar cell temperature at reference conditions:	$T_{cell,ref}$ =25°C
The solar radiation intensity at reference conditions:	G_{ref} = 1000W/ m^2.

Substituting the above five pieces of information into Eq. (1), the following equations are obtained

$$I_{sc,ref}=I_{L,ref}-I_{o,ref}\left[\exp\left(\frac{I_{sc,ref}R_{S,ref}}{a_{ref}}\right)-1\right]-\frac{\left(I_{sc,ref}R_{S,ref}\right)}{R_{sh,ref}} \tag{3}$$

$$0=I_{L,ref}-I_{o,ref}\left[\exp\left(\frac{V_{oc,ref}}{a_{ref}}\right)-1\right]-\frac{\left(V_{oc,ref}\right)}{R_{sh,ref}} \tag{4}$$

$$I_{mp,ref}=I_{L,ref}-I_{o,ref}\left[\exp\left(\frac{V_{mp,ref}+I_{mp,ref}R_{S,ref}}{a_{ref}}\right)-1\right]-\frac{\left(V_{mp,ref}+I_{mp,ref}R_{S,ref}\right)}{R_{sh,ref}} \tag{5}$$

$$[d(IV)dV]_{mp} =0. \tag{6}$$

$$[dIdV]_{sc} = -1/ R_{sh,ref} \tag{7}$$

where V_{oc} , V_{mp} , I_{sc} and I_{mp} are open-circuit voltage, maximum power point voltage, short-circuit current and maximum power point current, respectively. The subscript "ref" indicates the value of parameters at the reference conditions.

The Eqs. (3)-(7) are a set of nonlinear equations that can be solved with numerical methods. Solving Eqs. (3)-(7) gives the value of five parameters (a_{ref} , $I_{L,ref}$, $I_{o,ref}$, $R_{s,ref}$ and $R_{sh,ref}$) at the reference conditions ($T_{cell,\ ref}$ 25 °C, G_{ref} 1000 W/ m^2). In order to calculate the model parameters at new climatic and operating conditions (G_{new} , $T_{cell,\ new}$), a set of translation equations is used such as follows (Skoplaki, E., 2008; De Soto, W., 2004; Luque, A. and S. Hegedus, 2003)

$$T_{cell} = \frac{T_{amb} + \left(\frac{G}{G_{ref}}\right)\left(\frac{U_{L,NOCT}}{U_L}\right)(T_{cell,NOCT} - T_{amb,NOCT})\left[1 - \frac{\eta_{el,ref}}{(\tau\alpha)}(1 + \lambda_{ref} T_{cell,ref})\right]}{1 - \frac{\lambda_{ref}\eta_{el,ref}}{(\tau\alpha)}\left(\frac{G}{G_{ref}}\right)\left(\frac{U_{L,NOCT}}{U_L}\right)(T_{cell,NOCT} - T_{amb,NOCT})}, \tag{8}$$

$$\frac{a}{a_{ref}} = \frac{T_{cell}}{T_{cell,ref}}, \tag{9}$$

$$\frac{I_o}{I_{o,ref}} = \left(\frac{T_{cell}}{T_{cell,ref}}\right)^3 \exp\left(\frac{\varepsilon N_c}{a_{ref}}\left(1 - \frac{T_{cell,ref}}{T_{cell}}\right)\right), \tag{10}$$

$$I_L = \left(\frac{G}{G_{ref}}\right)[I_{L,ref} + \alpha(T_{cell} - T_{cell,ref})], \tag{11}$$

$$\Delta T = T_{cell} - T_{cell,ref}, \tag{12}$$

$$\Delta I = \alpha\left(\frac{G}{G_{ref}}\right)\Delta T + \left(\frac{G}{G_{ref}} - 1\right)I_{sc,ref}, \tag{13}$$

$$\Delta V = \beta\Delta T - R_s\Delta I, \tag{14}$$

$$I_{new} = I_{ref} + \Delta I, \tag{15}$$

$$V_{new} = V_{ref} + \Delta V. \tag{16}$$

Where T_{cell}, $T_{cell,ref}$, $T_{cell,NOCT}$, T_{amb}, $T_{amb,NOCT}$, G and G_{ref} are solar cell temperature, solar cell temperature at the reference condition, nominal cell temperature, ambient temperature, ambient temperature at NOCT conditions, solar radiation intensity and solar radiation intensity at the reference conditions, respectively. Further, parameters U_L, $U_{L,NOCT}$, $\eta_{el,ref}$ $(\tau\alpha)$ ε, N_c, α, β and λ_{ref} are overall heat loss coefficient, overall heat loss coefficient at NOCT conditions, electrical efficiency at the reference conditions, the effective product of transmittance-absorptance, semiconductor band gap energy (1.12eV for silicon solar cell), cells number in series, current temperature coefficient, voltage temperature coefficient and efficiency correction coefficient for temperature (0.004 $°C^{-1}$ for silicon solar cell), respectively.

PV module manufacturers usually give temperature coefficients and NOCT conditions (Siemens Company, 2009). The new values of maximum power point voltage and maximum power point current are obtained from solved I-V characteristic curve (Fig. (2)) and Eq. (6) simultaneously at new climatic and operating conditions (Boyle, G., 2004).

In the previous studies, PV array overall loss coefficient (U_L) has been assumed as a constant factor or a variable with little effect, whereas it is not constant. The overall heat loss coefficient of a PV array includes convection and radiation losses.

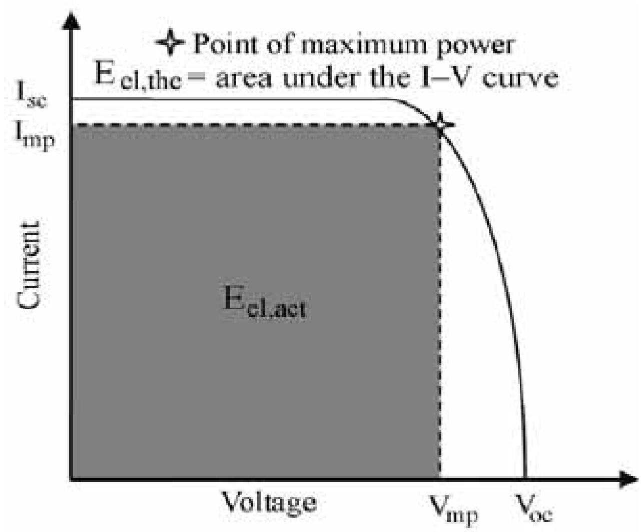

Fig. 2: Representation of a general current–voltage characteristic curve and its parameters (Boyle, G., 2004).

$$U_L = h_{conv} + h_{rad} \tag{17}$$

The convective heat transfer coefficient is given by (Watmuff, J.H., 1977)

$$h_{conv} = 2.8 + 3V_w \tag{18}$$

Where V_w is wind speed. The radiative heat transfer coefficient between PV array and surroundings is obtained from (Sukhatme, S.P., 1993)

$$h_{rad} = \varepsilon_g \sigma (T_{sky} + T_{cell})(T_{sky}^2 + T_{cell}^2) \tag{19}$$

Where ε_g and σ are PV array emissivity and the Stefan-Boltzmann's constant, respectively and the effective temperature of the sky (T_{sky}) is calculated from the following empirical relation (Sukhatme, S.P., 1993).

$$T_{sky} = T_{amb} - 6 \tag{20}$$

The 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 maximum energy efficiency of a PV system is given by (Joshi, A.S., I. Dincer, 2009; Sahin, A.D., 2007)

$$\eta_{en} = \frac{V_{oc} I_{sc}}{S} = \frac{E_{el,the}}{S} \tag{21}$$

where $E_{el,the}$ is the theoretical output electrical power of a PV array. However, this definition of energy efficiency is restricted to theoretical cases. In Eq. (21), S is solar absorbed flux and it is given by

$$S = GA_{arr} = G(N_s N_m A_{mod}) \tag{22}$$

where A_{arr} , N_m and N_s are PV array area, number of modules in series per string and number of strings, respectively. PV module area (A_{mod}) is given by

$$A_{mod} = L_1 L_2 \tag{23}$$

where L_1 and L_2 are the length of solar module and the width of solar module, respectively.

For PV systems in practical cases, energy efficiency measures the ability of converting solar energy into electrical energy (Joshi, A.S., I. Dincer, 2009; Sahin, A.D., 2007; Boyle, G., 2004). The output electrical power of a PV array is the product of its voltage and current. According to Fig. 2, Eel,the is the theoretical output electrical power of a PV array. $E_{el,the}$ is equivalent to area under the I-V characteristic curve $\left(\int_{V=0}^{V_{oc}} I(V)dV\right)$. In practical cases, there is a point of maximum power, where voltage is V_{mp}, which is less than open-circuit voltage (V_{oc}) but close to it, and current is I_{mp}, which is less than short-circuit current (I_{sc}) but close to it (Fig. 2).

the rectangular area under the I-V characteristic curve (Fig. 2).Thus, $E_{el,act}$ is equivalent to I_{mp} V_{mp}.

The maximum power point is restricted by a term called ''fill factor" and it is defined as follows

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \tag{24}$$

The energy efficiency of a PV system at maximum power is defined as the ratio of actual electrical output to input solar energy incident on PV surface area and it is given by (Sahin, A.D., I. Di, 2007; Joshi, A.S., I. Dincer, 2009; Joshi, A.S., A. Tiwari, 2009):

$$\eta_{el} = \frac{V_{mp} I_{mp}}{S} = \frac{E_{el,act}}{S} \tag{25}$$

This efficiency is also called actual electrical efficiency. The electrical efficiency of a PV array can also be defined in terms of fill factor (FF) as follows:

$$\eta_{el} = \frac{FF \times V_{oc} I_{sc}}{S} \tag{26}$$

Exergy Analysis:

Exergy analysis is a technique that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy and other systems. Exergy is defined as the maximum amount of work that can be produced by a system or a flow of mass or energy as it comes to equilibrium with a reference environment (Kotas, T.J., 1995). The general form of exergy balance equation for a control volume is written as (Kotas, T.J., 1995; Wong, K.F.V., 2000; Bejan, A., 1998)

$$\sum EX_{in} - \sum EX_{out} = \sum EX_{dest} \tag{27}$$

where Ex_{in}, Ex_{out} and Ex_{dest} are inlet exergy, outlet exergy and exergy destruction in control volume, respectively.

The inlet exergy for a PV system includes only solar radiation intensity exergy. According to the Petela theorem, it is given by (Petela, R., 2008; Petela, R., 2003)

$$\sum Ex_{in} = Ex_{Q,sun} = S\left(1 - \frac{4}{3}\frac{T_{amb}}{T_{sun}} + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4\right), \tag{28}$$

According to the same figure, $E_{el,act}$ is the actual output electrical power of a PV array and it is given by where, T_{sun} is the sun's temperature in Kelvin.

The outlet exergy for a PV system includes thermal exergy and electrical exergy.

$$\sum EX_{out} = \sum EX_{th} + \sum EX_{el} \quad (29)$$

Where Ex_{th} and Ex_{el} are thermal exergy and electrical exergy, respectively. The thermal exergy (Ex_{th}) is given by

$$Ex_{th} = \frac{m_{cell}C_p}{\Delta t}\left(T_{cell} - T_{amb} - T_{amb}\ln\left(\frac{T_{cell}}{T_{amb}}\right)\right) - (I_{sc}V_{oc} - I_{mp}V_{mp})\left(\frac{T_{cell}}{T_{sun}}\right). \quad (30)$$

Where m_{cell} and Δt are PV array mass and time interval, respectively. The first terms on the right hand side of Eq. (30) indicate physical exergy changes and the second terms show exergy changes due to the variations of chemical potential in PV array (Sahin, A.D., I. Dincer, 2007; Landsberg, P.T. and T. Markvart, 1998; Bisquert, J., D. Cahen, 2004; Joshi, A.S., I. Dincer, 2009).

The specific heat capacity of silicon solar cell (C_p) is calculated from (Regel, A.R. and V.M. Glazov, 1980)

$$C_p = 0.844 + 1.18 \times 10^{-4} T_{cell} - 1.55 \times 10^{4} T_{cell}^{-2} \quad (31)$$

The electrical exergy (Ex_{el}) includes the outlet electrical power of PV array (Joshi, A.S., I. Dincer, 2009; Sahin, A.D., 2007):

$$EX_{el} = V_{mp} I_{mp} \quad (32)$$

The Exergy Eficiency of PV Array:

Exergy efficiency is defined as the ratio of total output exergy (recovered) to total input exergy (supplied) (Kotas, T.J., 1995; Wong, K.F.V., 2000; Bejan, A., 1998):

$$\eta_{ex} = \frac{\sum EX_{out}}{\sum EX_{in}} = 1 - \frac{\sum EX_{dest}}{\sum EX_{in}} \quad (33)$$

Substituting Eqs. (28)-(32) into Eq. (33), the exergy efficiency of a PV array is obtained:

$$\eta_{ex} = \frac{\frac{m_{cell}C_p}{\Delta t}\left(T_{cell} - T_{amb} - T_{amb}\ln\left(\frac{T_{cell}}{T_{amb}}\right)\right) - (I_{sc}V_{oc} - I_{mp}V_{mp})\left(\frac{T_{cell}}{T_{sun}}\right) + I_{mp}V_{mp}}{S\left(1 - \frac{4}{3}\frac{T_{amb}}{T_{sun}} + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4\right)}. \quad (34)$$

Eq. (34) is an equation for the exergy efficiency of a PV array in terms of operating, electrical, design parameters and climatic conditions. It includes all of the exergy components of a PV array.

RESULTS AND DISCUSSION

Experimental Validation:

The experimental results of Barker and Norton (2003) for a rack-mounted PV array make it possible to verify the results obtained by our computer simulation. The measured data in Ref. Barker and Norton (2003) include the solar radiation intensity, ambient temperature, PV array temperature, open-circuit voltage, maximum power point voltage, short-circuit current and maximum power point current. Additional information about the experiment method and its conditions are found in Barker and Norton (2003). The experimental values of the above-mentioned parameters have been obtained from Fig. 8 and Fig. 9 of Barker and Norton (2003). The simulated values of PV array temperature, open-circuit voltage, maximum power point voltage, short-circuit current, maximum power point current in present work have been validated by their corresponding experimental values in Barker and Norton (2003).

The climatic, operating and design parameters of PV array during validation process are described in Table 1. They correspond to the experimental system described by Barker and Norton (2003), except that they did not report the wind speed observed over the course of their tests. This affects the convective heat transfer coefficient between PV array surface and the ambient air Table 1.

In Table 1, a wind speed of 0.5 m/s is assumed to have a comparison with the experimental data. On the other hand additionally performed calculations for different wind speeds are also reported in the next section.

In order to compare the simulated results with the experimental measurements, a root mean square percentage deviation (RMS) has been evaluated by following equation (Joshi, A.S., A. Tiwari, 2009; De Soto, W., 2004)

Table 1: The values of climatic, operating and design parameters during validation process and parametric studies of PV array (Siemens Company, 2009; Barker, G. and P. Norton, 2003)

Solar PV module parameters	Value
Module type	Siemens SM55, monocrystalline silicon
Number of modules in series per string, N_m	2
Number of strings, N_s	6
The solar radiation intensity at the reference conditions, G_{ref}	$1000 W/m^2$
The solar radiation intensity, G	From experimental data
The ambient temperature, T_{amb}	From experimental data
The ambient temperature at NOCT conditions, $T_{amb, NOCT}$	293.15 K
The cell temperature at the reference conditions, $T_{cell,ref}$	K 298.15
The nominal operating cell temperature, $T_{cell,NOCT}$	318.15 K
The PV array temperature, T_{cell}	Eq. (8)
The sun temperature, T_{sun}	K 5760
Wind speed, V_w	0.5 m/s
The short-circuit current at the reference conditions, $I_{sc, ref}$	$N_s \times 3.45A$ (for total array)
The open-circuit voltage at the reference conditions, $V_{co,ref}$	$N_m \times 2.17V$ (for total array)
Maximum power point current at the reference conditions, $I_{mp,ref}$	$N_s \times 3.15A$ (for total array)
Maximum power point voltage at the reference conditions, $V_{mp,ref}$	$N_m \times 17.4V$ (for total array)
The electrical efficiency at the reference conditions, $\eta_{el,ref}$	0.12
The current temperature coefficient, α	1.2mA/°C
The voltage temperature coefficient, β	- 0.077V/°C
The efficiency correction coefficient for temperature, λ_{ref}	0. 004°C^{-1}
The semiconductor band gap energy, ε	1.12 eV
The effective product of transmittance–absorptance, $(\tau\alpha)$	0.9
The PV array emissivity, ε_g	0.88
The length of solar module, L_1	1.293m
The width of solar module, L_2	0.329 m
Time interval, Δt	900 second

$$RMS = \sqrt{\frac{\sum [100 \times (X_{\exp,i} - X_{sim,i}) / X_{\exp,i}]^2}{n}} \tag{35}$$

where n is the number of the experiments carried out.

The variations of solar radiation intensity, ambient temperature and PV array temperature during the test day are shown in Fig. 3. The simulated values of PV array temperature are also shown in the same figure for comparison. It is observed that there is a good agreement between the simulated and experimental values of PV array temperature with root mean square percentage deviation (RMS) = 4.82% Fig. 3.

The simulated values of open-circuit voltage, maximum power point voltage, short-circuit current, maximum power point current and the corresponding experimentally measured data during the test day are shown in Fig. 4. It is observed from this figure that there is a good agreement between the experimental and simulated values of these parameters. Further, the root mean square percentage deviations of these parameters are 2.4%, 2.28%, 4.6% and 2.98%, respectively Fig. 4.

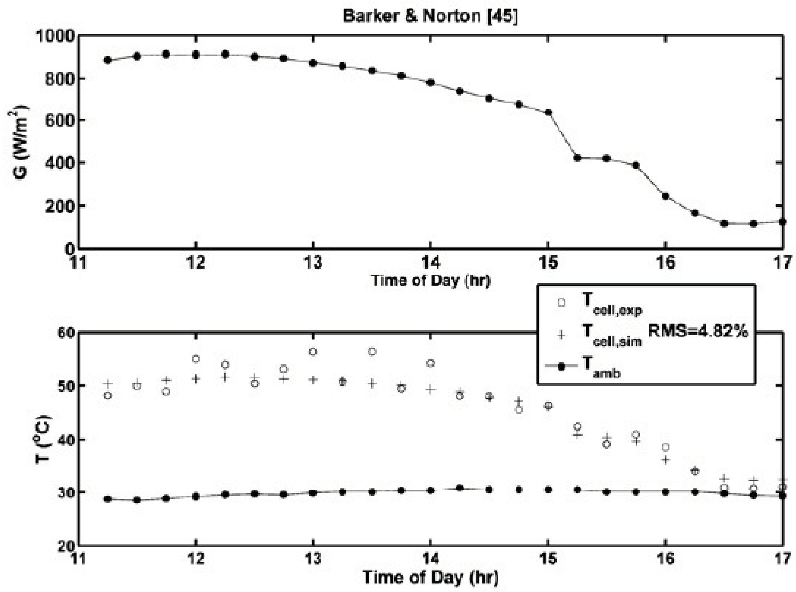

Fig. 3: The variations of solar radiation intensity, ambient temperature, experimental PV array temperature and simulated PV array temperature during the test day.

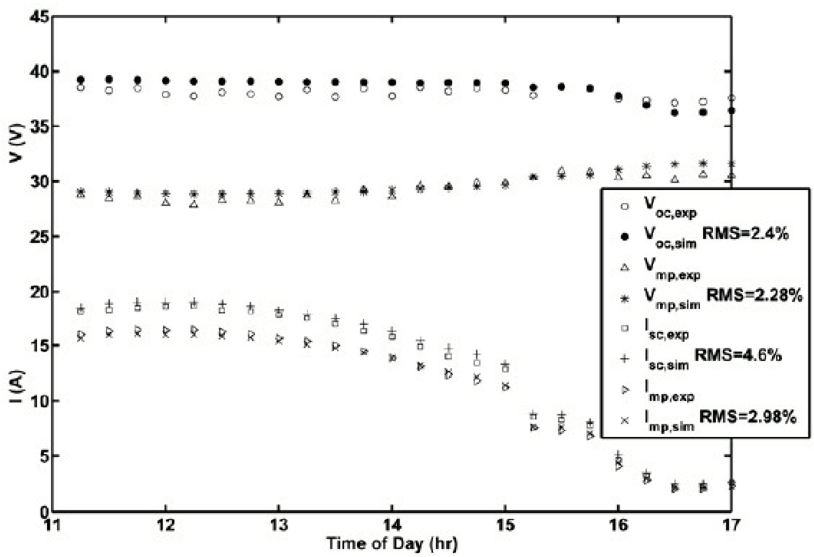

Fig. 4: The simulated values of open-circuit voltage, maximum power point voltage, short-circuit current, maximum power point current and the corresponding experimentally measured data during the test day.

The simulated and experimental values of energy efficiency, exergy efficiency and electrical efficiency during the test day are shown in Fig. 5. The respective values of root mean square percent deviation are 5.88%, 3.59% and 3.58%, respectively. It is observed from this figure that there is a good agreement between the simulated and experimental values of the above-mentioned efficiencies Fig. 5.

The good agreement between experiment and simulation that are shown in the previous figures (Figs. 3-5) indicates that the assumption of a wind speed as 0.5 m/s in the calculations is reasonable.

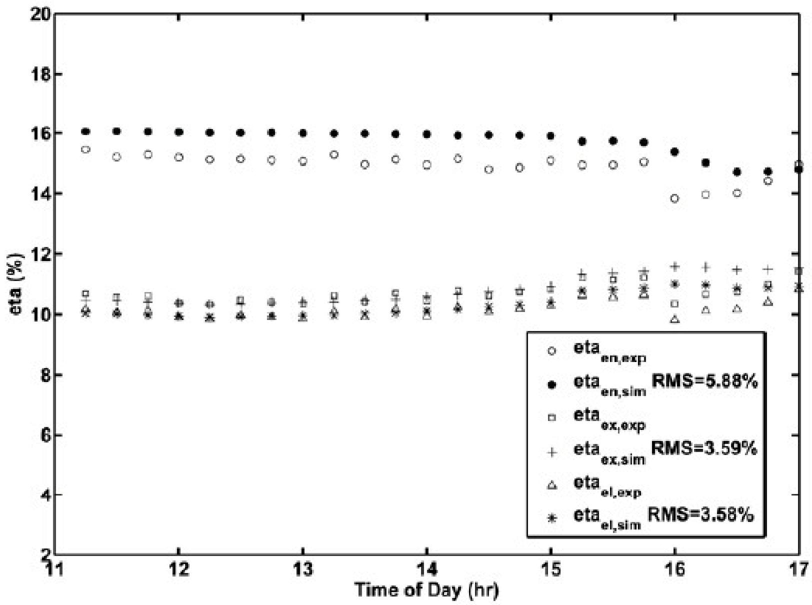

Fig. 5: The simulated and experimental values of energy efficiency, exergy efficiency and electrical efficiency during the test day.

The simulated parameters errors compared with those obtained by the experimental measurement is explained as follows:

- the temperature coefficients of current and voltage have been assumed constant. In practical cases, they have slight fluctuation due to the solar radiation intensity and PV array temperature variations;
- the experimental measurements have been obtained from the figures of Barker and Norton (2003) by interpolation and curve fitting methods. This subject decreases the precision of measured data;
- wind speed is not constant and has a direct effect on the overall heat loss coefficient that can decrease the precision of calculated overall heat loss coefficient in the computer simulation;
- the effective product of transmittance-absorptance, $(\tau\alpha)$, has been assumed constant while it is changing during the day with the change of solar incidence angle on PV array surface.

Parametric Studies:

The values of climatic, operating and design parameters in the parametric studies of PV array are described in Table 1.

In order to plot the following figures some parameters are assumed which are mentioned above each figure. The rest of parameters needed to plot the following figures are used from Table 1.

The computer simulation program gives the following results under the sample conditions of Table 1,

$$T_{amb} = 300\,\mathrm{K},\ V_w = 0.5\,\mathrm{m/s},\ G = 700\,\mathrm{W/m^2}\ \text{and}\ N_s = N_m = 1:$$

$$\eta_{ex} = 11.53\%,\quad \eta_{en} = 16.12\%,\quad \eta_{el} = 10.97\%,\quad T_{cell} = 317.39\,\mathrm{K},\quad V_{oc} = 19.74\,\mathrm{V},$$

$$I_{sc} = 2.43\,\mathrm{A},\quad I_{mp} = 2.18\,\mathrm{A},\quad V_{mp} = 14.96\,\mathrm{V},\quad I_o = 5.21\times10^{-6}\,\mathrm{A},\quad I_L = 2.43\,\mathrm{A},$$

$$R_{sh} = 483.6\,\Omega,\ R_s = 0.21\,\Omega,\ C_p = 0.72\,\mathrm{J/g.K},\ U_L = 10.01\,\mathrm{W/m^2.K},\ S = 297.78\,\mathrm{W},$$

$$a = 1.51\,\mathrm{eV},\ FF = 0.68.$$

The variations of energy efficiency, exergy efficiency and electrical efficiency with respect to PV array temperature are plotted in Fig. 6. Increasing PV array temperature from 300 to 350 K determines the sensible decrease of these efficiencies from ~1 7.1% to ~14.2%, ~12.6% to ~9.6% and ~12% to ~9%, respectively. In order to have maximum exergy efficiency, PV array temperature should be kept near the ambient temperature or in other words, PV array temperature should be controlled. In order to control PV array temperature, there are some practical methods such as spraying water on the top surface of photovoltaic modules (Abdolzadeh, M. and M. Ameri, 2009) or combining of PV modules in photovoltaic/thermal (PV/T) collectors (Joshi, A.S., A. Tiwari, 2009) Fig. 6.

Fig. 7 shows the variations of energy efficiency, exergy efficiency and electrical efficiency with respect to the solar radiation intensity Fig. 7.

It is observed that the exergy efficiency and electrical efficiency increase initially and then after attaining the solar radiation intensity of about $G \approx 200$ W/m^2, they decrease.

This indicates the optimum value of solar radiation intensity for given climatic and design parameters (Table 1). On the other hand, the energy efficiency increases from ~12.1 to ~16.1 while the solar radiation intensity is increasing from 10 to 1000 W/m^2. Since this parameter varies during the day, the design of PV array should be based on the daily or monthly average of this parameter.

Fig. 8 shows the effect of ambient temperature on energy efficiency, exergy efficiency and electrical efficiency Fig. 8. Increasing the ambient temperature from 300 to 320 K determines the sensible decrease of these efficiencies from ~16.1% to ~15.1%, ~11.5% to ~10.5% and ~11% to ~10%, respectively. Since the ambient temperature changes during the day, PV array design should be based on the daily average of this parameter.

Fig. 9 shows the variations of energy efficiency, exergy efficiency and electrical efficiency versus the changes of wind speed Fig. 9.

The energy efficiency, exergy efficiency and electrical efficiency increase from ~1 6% to ~16.8%, ~11.3% to ~12.2% and ~10.8% to ~11.7%, respectively while wind speed is increasing from 0 to 10 m/s. The increase of wind speed increases overall heat loss coefficient, therefore PV array temperature decreases and these efficiencies increase.

According to Fig. 10, energy efficiency, exergy efficiency and electrical efficiency have a slight variation (~16.1%, ~1 1.5% and 11%, respectively) with respect to the changes of PV array area (0.425 $2A_{arr} \leq 6.8$ m_2) Fig. 10.

It is observed from Figs. (5)-(10) that the behavior of exergy efficiency with respect to the variations of climatic, operating and design parameters is so similar to electrical efficiency. Moreover, the exergy efficiency of PV array is always greater than electrical efficiency. Since the solar radiation energy (S) is always larger than the solar radiation exergy ($Ex_{Q,\,sun}$) and electrical exergy and electrical energy are almost equal, thus, the electrical efficiency of PV array is always smaller than exergy efficiency.

Conclusion:

On the basis of theoretical results obtained in the present study, the following conclusions have been drawn:

- The electrical and exergetic model of PV array presented in this study are in good agreement with the experimental results of Barker and Norton (2003) (Figs. 3-5).
- The PV array temperature has a great effect on the exergy efficiency (Fig. 6). The exergy efficiency of a PV array can be improved if the heat can be removed from the PV array surface. In order to remove heat from the PV array surface, there are some practical methods such as spraying water on the top surface of photovoltaic modules (Abdolzadeh, M. and M. Ameri, 2009) or combining of PV modules in photovoltaic/thermal (PV/T) collectors (Joshi, A.S., A. Tiwari, 2009).
- The behavior of exergy efficiency with respect to the variations of climatic, operating and design parameters is so similar to the electrical efficiency of PV array (Figs. 5-10).
- The exergy efficiency of PV array is always greater than electrical efficiency. (Figs. 5-10).
- Increasing the solar radiation intensity, the exergy efficiency of PV array increases initially and then decreases after attaining the solar radiation intensity of about a maximum point (Fig. 7)
- While the ambient temperature is increasing, the exergy efficiency of PV array decreases (Fig. 8).
- While wind speed is increasing, the exergy efficiency increases (Fig. 9).
- The design parameters such as PV array area have a little effect on the exergy efficiency (Fig. 10).

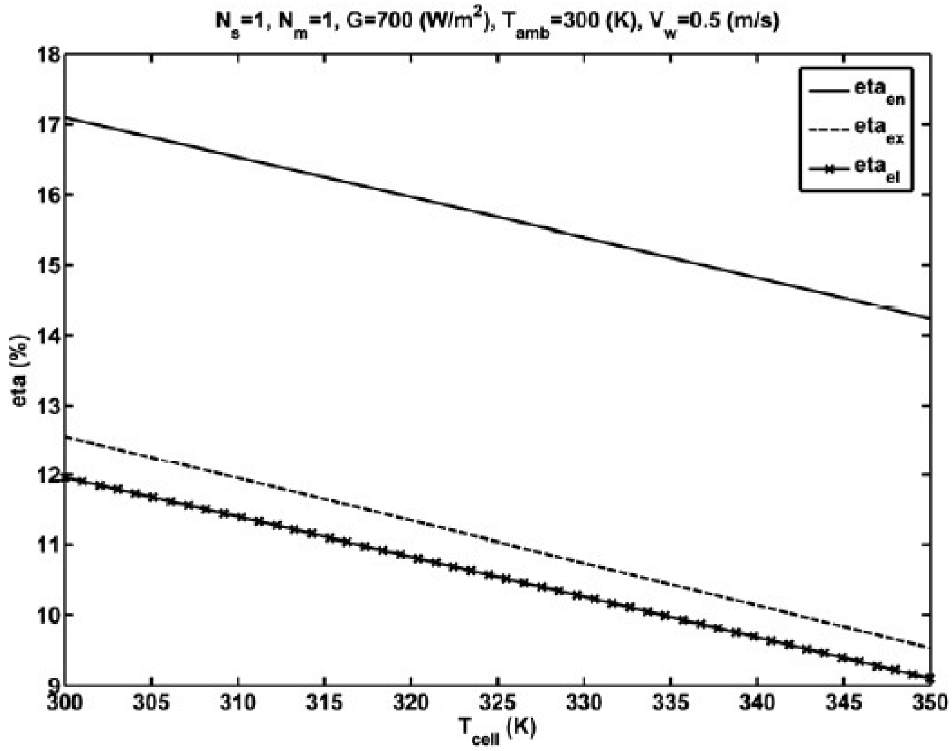

Fig. 6: The variations of the energy efficiency, exergy efficiency and electrical efficiency with respect to the PV array temperature.

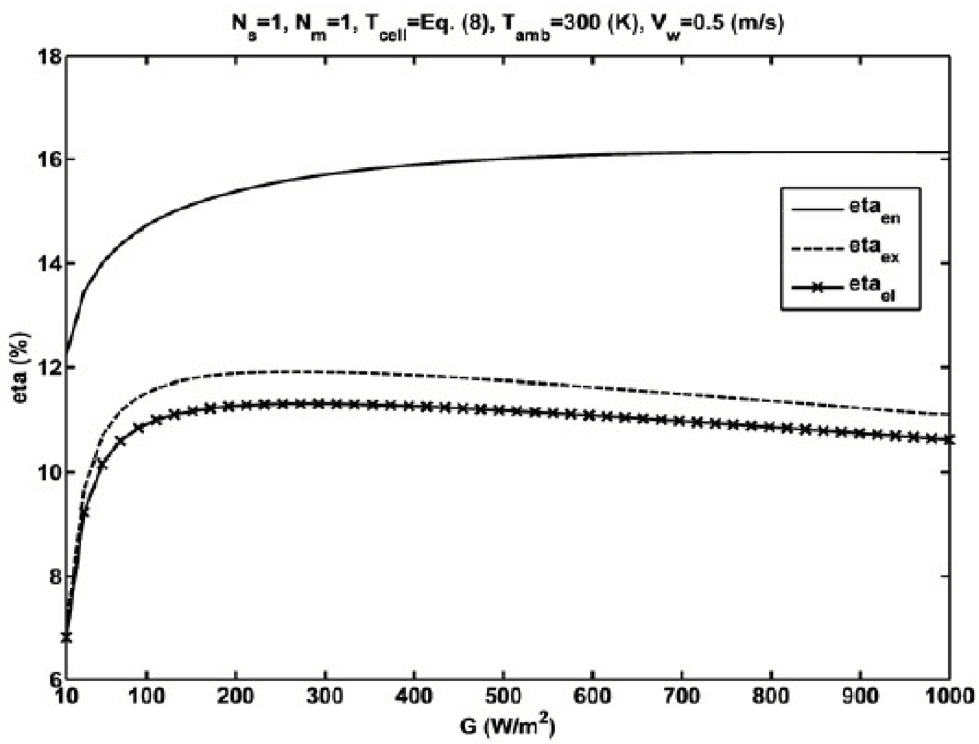

Fig. 7: The variations of the energy efficiency, exergy efficiency and electrical efficiency with respect to the solar radiation intensity.

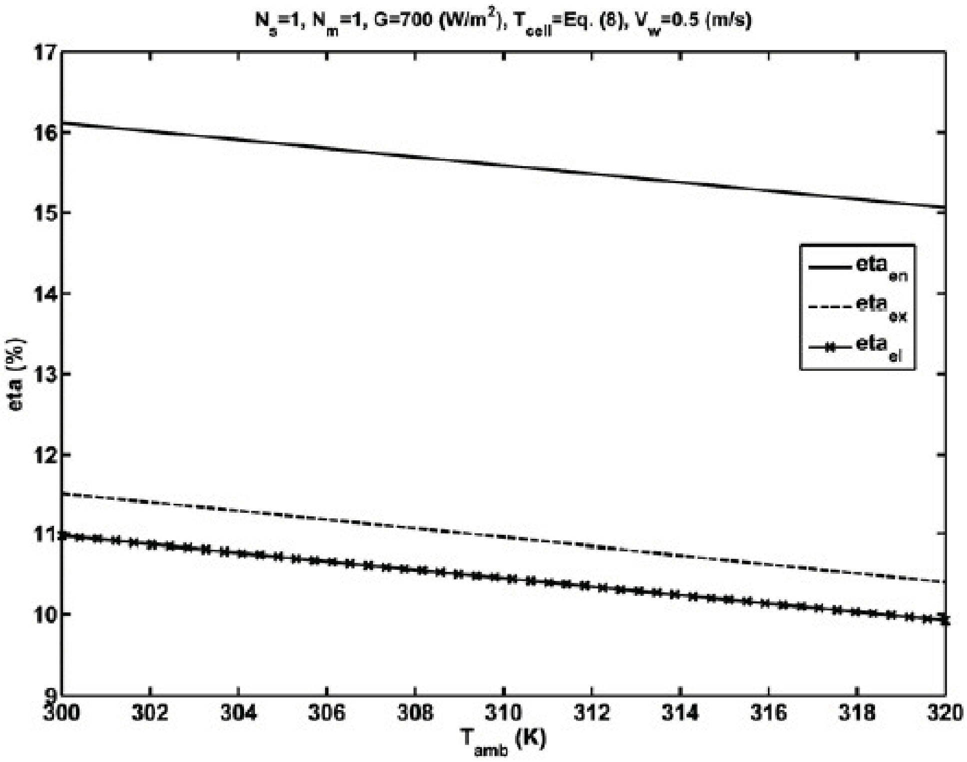

Fig. 8: The effect of ambient temperature on the energy efficiency, exergy efficiency and electrical efficiency.

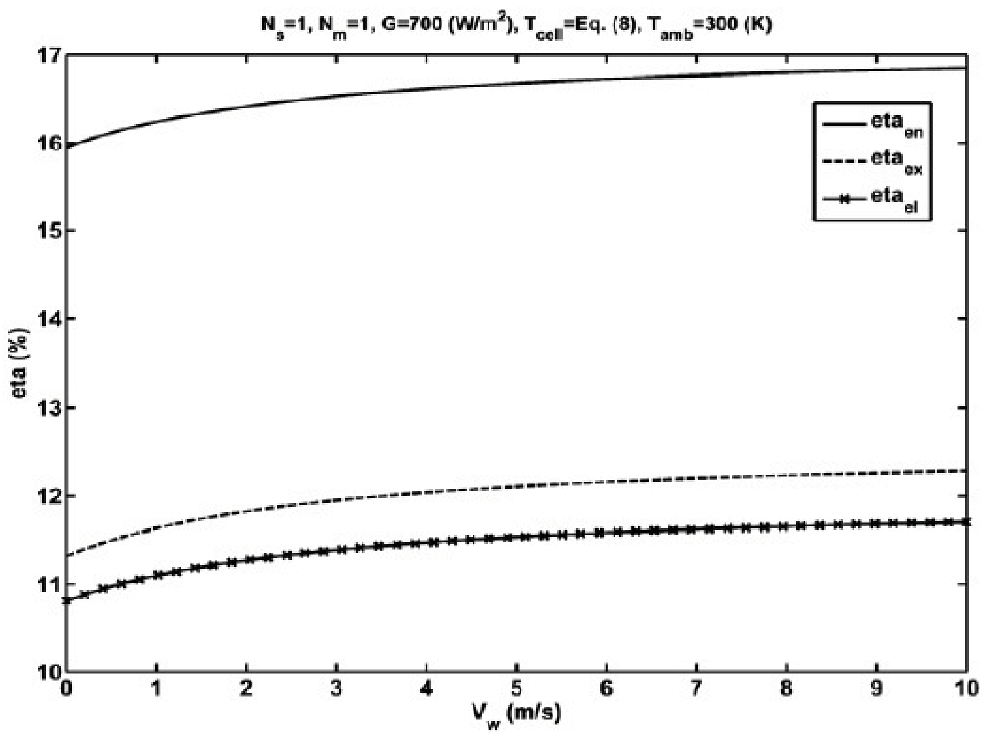

Fig. 9: The variations of the energy efficiency, exergy efficiency and electrical efficiency versus the changes of wind speed.

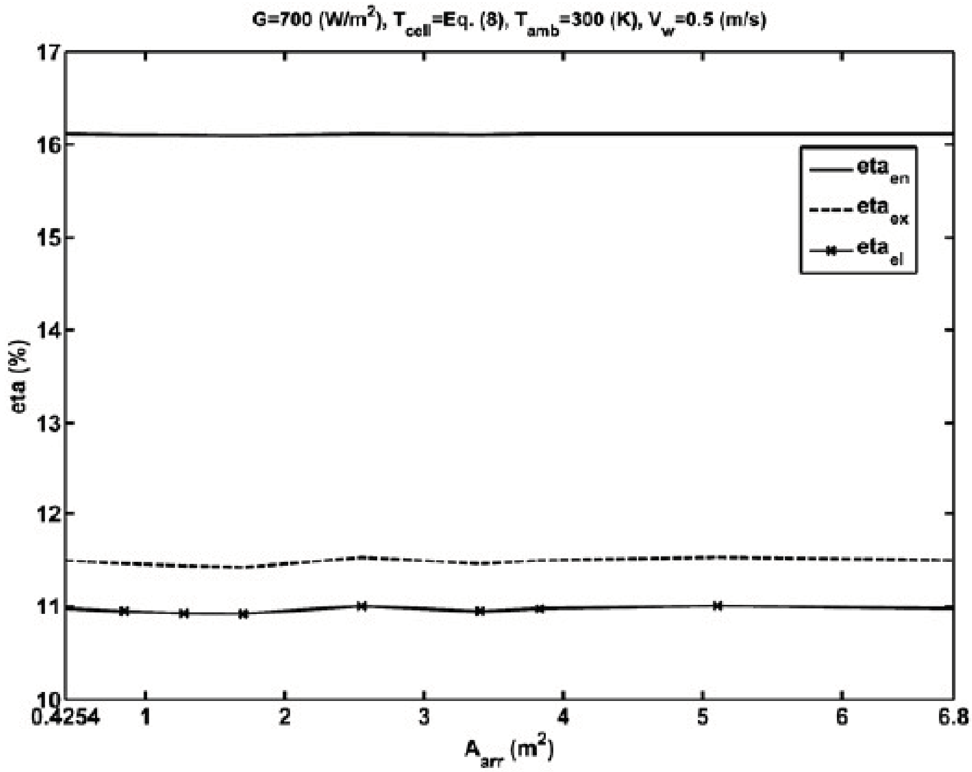

Fig. 10: The variations of the energy efficiency, exergy efficiency and electrical efficiency with respect to the changes of the PV array area.

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Nomenclature

a ideality factor (eV)
A area (m^2)
BIPVT Building Integrated Photovoltaic Thermal
C_p heat capacity of the silicon material (J/g. K)
electrical power (W) EPBT energy payback time
Ex exergy (W)
FF fill factor
solar radiation intensity (W/m^2)
heat transfer coefficient ($W/m^2.K$) I circuit current (A)
IPVTS integrated photovoltaic thermal solar
I-V current-voltage
k the Boltzmann constant (J/K)
L dimensions of solar module (m)
m mass of PV array (g)
n number of the experiments carried out
N_c number of cells in PV module
N_m number of modules in series per string
N_s number of string
NOCT nominal operating cell temperature conditions
PLC programmable logic controller

PV photovoltaic
PV/T photovoltaic/thermal collector
q electron charge (C)
resistance (:) RMS root mean square percentage deviation (%)
solar absorbed flux (W)
SRC standard rating conditions
t time interval (second)
T temperature (K)
U_L overall heat loss coefficient from the PV array to the environment ($W/m^2.K$)
V circuit voltage (V), wind speed (m/s)
X experimental or simulated value of parameter

Greek Symbols
α current temperature coefficient (mA/°C)
β voltage temperature coefficient (V/°C)
γ dimensionless diode curve-fitting factor
Δ difference in current, temperature, time, voltage
ε emissivity, semiconductor band gap energy (eV)
η efficiency (%)
λ efficiency correction coefficient for temperature ($°C^{-1}$)
σ Stefan-Boltzmann's constant (W/ m^2K^4)
(τα) the effective product of transmittance-absorptance
Subscripts
1 length
2 width
act actual
arr array
amb ambient cell cell, array conv convection
dest destroyed
D diode
el electrical
en energy
ex exergy
exp experimental
g glass
i i-th parameter
in inlet
L light current
mod module
mp maximum power point new new
NOCT at NOCT conditions
o reverse saturation
oc open-circuit
out outlet
Q heat transfer
rad radiative
ref reference
s series
sc short-circuit
sh shunt
sim simulated
sky sky
sun sun
th thermal
the theoretical
w wind

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