ANALELE UNIVERSITĂȚII
"EFTIMIE MURGU" REȘIȚA
ANUL XXII, NR. 1, 2015, ISSN 1453 - 7397

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Analyzing the Energy and Exergy of Photovoltaic Array for Kerman Climate

The energy efficiency and exergy efficiency of recommended photovoltaic (PV) array are calculated for Kerman climate. Since energy efficiency and exergy efficiency of PV array is dependent on weather conditions, the recommended PV array energy and exergy have been analyzed in various months of the year to be used in Kerman climate. Also, the wind speed impact on exergy efficiency has been studied in this research. The simulated results were compared to experimental results to confirm the validity of employed relationships and a good agreement was observed between them. Since the model's results match those of experiments, the model presented in this paper can be used for various weather conditions. An important result of the research was higher accuracy of exergy efficiency calculation of present model relative to past models. Also, energy efficiency and exergy efficiency were almost identical for various months of the year and the PV array can be used to produce a part of required electric power in Kerman climate throughout the year. The annual averages of exergy, energy, and electrical efficiencies in Kerman climate are 12.03%, 16.27%, and 12.14%, respectively.

Keywords: *photovoltaic array, energy, exergy, Kerman*

1. Introduction

Renewable energies are a good substitute for fossil fuels. Among various renewable energies, PV is a major technology that is developing rapidly with huge potential for future applications. PV systems are semiconductor devices that can convert solar energy into electrical energy at 5%-20% efficiency levels [1].

PV cells as the solar energy receptor units which convert it to electrical energy are specially important to provide a power supply that tap renewable energy sources.

PV phenomena is based on absorbing light photons, creating an electron-hole pair, electron isolation, and finally embedding generated holes by an electrical converter into the semiconductor material. The current and voltage of solar cells are low but by arranging them serially or in parallel, higher currents and voltages are achievable.

The PV cell set is called a PV module. A set of modules makes a solar panel and a set of these panels is called solar array. The solar array efficiency depends on weather, working conditions, sunlight intensity, PV array temperature, heat loss coefficient, open-circuit voltage, short-circuit current, voltage at point of maximum power, current at point of maximum power, and PV array surface area [2].

PV energy efficiency is defined as the ratio of generated electrical energy to the received solar energy. Exergy efficiency is under influence of the weather, heat specifications, and chemical potential of components [3]. Ghoneim offered a computer simulation for determining heat efficiency of PV system that supplied water pump energy in Kuwait climate. He also obtained optimum amounts of angle of surface slanting for PV array [4]. Badescu checked weather and latitude impact on PV module shape based on energy analysis and also found the optimal number of cells in series and the number of strings for various weather conditions [5].

Abdolzadeh&Ameri [6] sprayed water over PV array to experimentally study PV water pump optimization in Kerman climate and showed that the water spray increased the PV array efficiency. They did not check PV array exergy.

Akyuz et al. offered an approximation to estimate PV array exergy efficiency. They used experimental average data and found that the wind speed is a main parameter in calculating PV array exergy efficiency [7].

Based on research, in most of the past studies, wind speed effect was not included in exergy efficiency calculations but in the present article, the wind speed is studied as a main parameter in calculating exergy efficiency calculations and besides extracting a mathematical model to calculate the energy/exergy efficiency.

2. Statement of the problem

2.1. Energy analysis

The electrical circuit equivalent of PV array is shown in figure 1 [8].

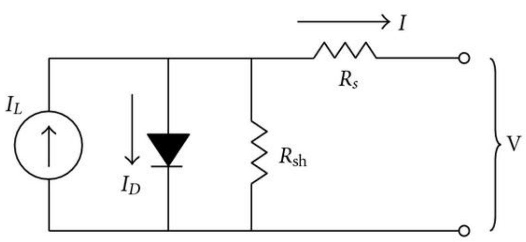

Figure 1. Equivalent electrical circuit in the five-parameter photovoltaic model

Based on nodes law where in sum of all the currents entering and leaving a node must be equal, it can be written[8]:

$$I = I_L - I_0\left[\exp\left(\frac{V + IR_s}{a}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \quad (1)$$

Where, I and V are current and voltage in the presence of the load. R_{sh}, R_s, I_0, I_L and a are equivalent parallel resistance, serial resistance, diode reverse saturation current, light factor, and ideal factor, respectively. In equation (1), the second terms on the right define diode current I_D. Below conditions are proposed to calculate the 5 reference parameters $R_{sh,ref}$, $I_{o,ref}$, $R_{s,ref}$, $I_{l,ref}$ and a_{ref}.

At short-circuit current:

$$I = I_{sc,ref},\ V = 0 \quad (2)$$

At open-circuit voltage:

$$I = 0,\ V = V_{oc,ref} \quad (3)$$

At short-circuit current:

$$\left[\frac{dI}{dV}\right]_{sc} = -\frac{1}{R_{sh,ref}} \quad (4)$$

At the maximum power point:

$$\left[\frac{d(IV)}{dV}\right]_{mp} = 0 \quad (5)$$

$$I = I_{mp,ref},\ V = V_{mp,ref} \quad (6)$$

The reference conditions are the same as standard conditions. The solar cell temperature at reference conditions is 25ºC and the solar radiation at reference conditions is 1000(W/m^2). By substituting equations (2) to (6) in equation (1), we have:

At short-circuit current:

$$I_{sc,ref} = I_{L,ref} - I_{o,ref}\left[\exp\left(\frac{I_{sc,ref} R_{s,ref}}{a_{ref}}\right) - 1\right] - \frac{I_{sc,ref} R_{s,ref}}{R_{sh,ref}} \quad (7)$$

At open-circuit voltage:

$$I_{L,ref} - I_{o,ref}\left[\exp\left(\frac{V_{oc,ref}}{a_{ref}}\right) - 1\right] - \frac{V_{oc,ref}}{R_{sh,ref}} = 0 \quad (8)$$

$$I_{mp,ref} = I_{L,ref} - I_{o,ref}\left[\exp\left(\frac{V_{mp,ref} + I_{mp,ref}R_{s,ref}}{a_{ref}}\right) - 1\right] - \left(\frac{V_{mp,ref} + I_{mp,ref}R_{s,ref}}{R_{sh,ref}}\right) \quad (9)$$

$$\left[\frac{d(IV)}{dV}\right]_{mp} = 0 \quad (10)$$

$$\left[\frac{dI}{dV}\right]_{sc} = -\frac{1}{R_{sh,ref}} \quad (11)$$

Where, I_{mp}, I_{sc}, V_{mp} and V_{oc} are maximum power point current, short-circuit current, maximum power point voltage, and open-circuit voltage.

Equations (7) to (11) are a set of nonlinear equations that are solved by numerical methods and the result would be five parameters required in reference conditions. In this article, the PV array current and voltage parameters are calculated by PvSyst software. The below equations are used to obtain model parameters in new climate conditions [8, 9]:

$$T_{cell} = \frac{T_{amb} + (\frac{G}{G_{ref}})(\frac{U_{L,NOCT}}{U_L})(T_{cell,NOCT} - T_{amb,NOCT})}{1 - \frac{\gamma_{ref}\eta_{ref}}{(\tau\alpha)}(\frac{G}{G_{ref}})(\frac{U_{L,NOCT}}{U_L})(T_{cell,NOCT} - T_{amb,NOCT})} \quad (12)$$

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

$$\Delta T = T_{cell} - T_{cell,ref} \quad (13)$$

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

$$\Delta V = \beta\Delta T - R_s\Delta I$$

$$I_{new} = I_{ref} + \Delta I$$

$$V_{new} = V_{ref} + \Delta V \quad (14)$$

Where G_{ref}, $T_{amb,NOCT}$, T_{amb}, $T_{cell,NOCT}$, $T_{cell,ref}$ and T_{cell} are solar radiation intensity at reference conditions, solar radiation intensity, ambient temperature at operating cell temperature condition, ambient temperature, solar cell temperature at nominal operating cell temperature, solar cell temperature in reference conditions, and solar cell temperature, respectively.

$U_{L,NOCT}$, $\eta_{el,ref}$, $(\tau\alpha)$, ε, N_c, α, β, γ_{ref}, U_L are overall heat loss coefficient at nominal operating cell temperature, electrical efficiency at the reference conditions, the effective product of transmittance- absorptance, semiconductor band gap energy, cells number in series, current temperature coefficient, voltage temperature coefficient, efficiency correction coefficient for temperature and overall heat loss coefficient, respectively. The total heat loss coefficient includes convection loss and radiation loss obtained form equation below [3]:

$$U_L = h_{conv} + h_{rad} \quad (15)$$

Such that the convection heat transfer coefficient (h_{conv}) and radiation heat transfer coefficient (h_{rad}) are calculated from equations below:

$$h_{conv} = 2.8 + 3V_w \quad (16)$$

$$h_{rad} = \varepsilon_g \sigma (T_{sky} + T_{cell})(T_{sky}^2 + T_{cell}^2) \quad (17)$$

Where V_w, σ and ε_g are wind speed, Stefan- Boltzmann′ s constant, and PV array emissivity respectively. The sky temperature has been approximated by the experimental equation below:

$$T_{sky} = T_{amb} - 6 \quad (18)$$

The PV array manufacturer supplies total heat loss coefficient, nominal working temperature of the cell conditions, and temperature coefficient. The PV energy efficiency is defined as the ratio of system's energy output to its energy input which is captured by the PV array surface [10]:

$$\eta_{en} = \frac{V_{OC} I_{SC}}{S} \quad (19)$$

The solar heat flux is obtained by equation below:

$$S = GA_{arr} = G(N_S N_m A_{mod}) \quad (20)$$

Where, N_s, N_m and A_{arr} are the number of strings, number of modules in series per strings, and PV array area. The PV module surface is obtained by equation below:

$$A_{mod} = L_1 L_2 \quad (21)$$

Where, L_1 and L_2 are solar module's length and width, respectively.

For PV array, the energy efficiency is defined as the ability of converting solar energy into electrical energy. The output power is equal to multiplication of current in voltage of PV set. This conversion efficiency is not constant even when the sunlight is consistent. However, there is a point of maximum power where in voltage is V_{mp} which is less than open-circuit voltage and the current in the point of maximum power is I_{mp} which is less than short-circuit current.

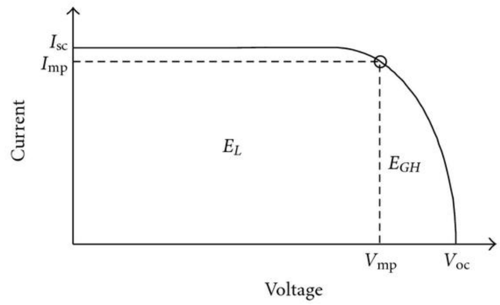

Figure 2. Representation of a general current-voltage characteristic point of maximum power O

In fig.2, E_{GH} is the highest electron energy level at highest sunlight intensity which is equal to the surface area under $\left(\int_{V=0}^{V_{oc}} I(V)dV\right) I-V$ plot and E_L is the lowest electron energy level shown with dotted line. The energy efficiency at the point of maximum power-a.k.a. electrical efficiency is defined as the ratio of electrical energy output to solar energy input:

$$\eta_{el} = \frac{V_{mp} I_{mp}}{S} \tag{22}$$

2.1. Exergy analysis

Exergy analysis is a technique that employs the laws of conservation of mass/energy and the second law of thermodynamics, to analyse, design, and develop energy systems. Exergy is defined as the maximum work performed by a system or a mass stream or an energy stream to strike a heat balance with the environment.

$$\Sigma EX_{in} - \Sigma EX_{out} = \Sigma EX_{dest} \tag{23}$$

The general equation of exergy balance for a control volume is shown below: Where, Ex_{in}, Ex_{out}, Ex_{dest} are input exergy, output exergy, and exergy loss, respectively.

The input exergy is sunlight exergy obtained by Petela theory from equation below (24), (25):

$$Ex_{in} = S\left(1 - \frac{4T_{amb}}{3T_{sun}} + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4\right) \tag{24}$$

T_{sun} is sunlight temperature in Kelvin.

The output exergy for a PV system is obtained by equation below:

$$\Sigma EX_{out} = \Sigma EX_{th} + \Sigma EX_{el} - \Sigma EX_{loss} \tag{25}$$

Where Ex_{loss}, EX_{el}, and EX_{th} are output exergy loss by wind speed, electrical exergy and thermal exergy, respectively.

Thermal exergy is obtained by equation below[2]:

$$Ex_{th} = \frac{m_{array}C_p}{\Delta t}\left(T_{cell} - T_{amb} - T_{amb}\ln\left(\frac{T_{cell}}{T_{amb}}\right)\right) - \left(I_{SC}V_{oc} - I_{mp}V_{mp}\right)\left(\frac{T_{cell}}{T_{sun}}\right) \tag{26}$$

Where, Δt and m_{array} are PV time interval and PV array mass. PV array mass is 66 kg and C_p is silicon's specific heat capacity in J/g/K obtained by equation below[3]:

$$C_p = 0.844 + 1.18\times10^{-4}T_{cell} - 1.55\times10^{4}T_{cell}^{-2} \tag{27}$$

Ex_{loss} is output exergy loss caused by negative impact of wind speed on exergy efficiency for its forced convection heat transfer from PV array surface; and excluding this term leads to overestimation of exergy efficiency. Therefore, in this article, wind speed heat loss was included and more accurate results were obtained relative to models that exclude such term. Ex_{loss} is calculated by equation below[11]:

$$Ex_{loss} = U_L A_{arr}(T_{cell} - T_{amb})\left(1 - \frac{T_{amb}}{T_{cell}}\right) \tag{28}$$

In equation (26) the first term on the right shows physical exergy variations and the second term shows exergy variations caused by chemical potential changes in PV array.

Electrical exergy is obtained by equation below:

$$Ex_{el} = V_{mp}I_{mp} \tag{29}$$

The exergy efficiency of PV array is defined as the ratio of output exergy to input exergy.

$$\eta_{ex} = \frac{\Sigma EX_{out}}{\Sigma EX_{in}} \tag{30}$$

3. Numerical results and discussion

3.1. Comparison between theoretical and experimental methods

To verify relationships used in this article, the experimental results of Barker & Norton [12] were compared to results of the present method. The comparison parameters included: PV array temperature, open-circuit voltage, maximum power point voltage, short-circuit current, and maximum power point current. Weather conditions and PV array design parameters are shown in table 1.

Table 1. PV array weather conditions, and design and working parameters[3]

PV module parameters	**Values**
PV module type	SM55Siemens monocrystal silicon
No. of modules in series based on strings	2
No. of strings	6
Sunlight intensity in reference conditions	$1000W/m^2$
Ambient air temperature in NOCT conditions	293.15 ºK
Solar cell temperature in reference conditions	298.15 ºK
Solar cell temperature in NOCT conditions	318.15 ºK
Temperature of the Sun	5760 ºK
Wind speed compared to experimental work	1m/s
Short-circuit current in reference conditions (whole PV array)	20.7A
Open-circuit voltage in reference conditions (whole PV array)	43.4 V
current at point of maximum power in reference conditions (whole PV array)	18.9 A
voltage at point of maximum power in reference conditions (whole PV array)	34.8V
Electrical efficiency in reference conditions	0.12
Current temperature coefficient	1.2 mA/s
Voltage temperature coefficient	0.077 - V/ºC
semiconductor band gap energy	1.12 ev
Multiplication of absorption coefficient in penetration	0.9
Emission coefficient of PV array	0.88
Solar module length	1.293 m
Solar module width	0.329 m

Since experimental work in [12] did not report wind speed, in this article, a wind speed of 1m/s was used to compare it with other experimental works. To compare simulation results with experimental results, the square root of the arithmetic mean of squares of all possible values of a function (RMS) was used [8].

$$RMS = \sqrt{\frac{\Sigma\left[100\times\frac{X_{exp,i}-X_{sim,i}}{X_{exp,i}}\right]^2}{n}} \tag{31}$$

Where n = quantity of experimental data, and exp & sim subscripts show experimental and simulated data. The sunlight variations are shown in fig.3.

In fig.4, ambient temperature and PV array temperature are shown. Fig.4 shows that there is a good agreement between simulated and experimental results with standard difference percentage: RMS=5%.

The simulated values of open-circuit voltage, voltage at point of maximum power, short-circuit current, current at point of maximum power, and experimental values are shown in fig.5 which indicate that there is a good agreement between simulation and experimental results with 4.41, 4.91, 6.89 and 1.59 percentage differences for voltage at point of maximum power, short-circuit current, current at point of maximum power, and open-circuit voltage.

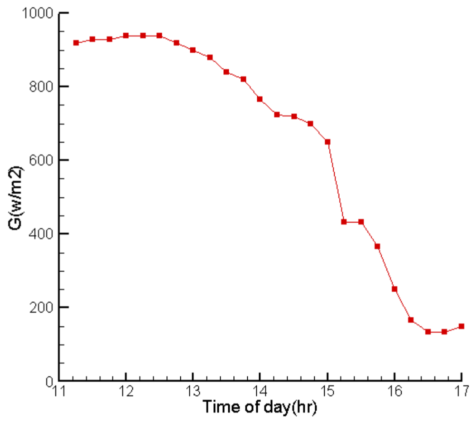

Figure 3. The variations of solar radiation intensity [12]

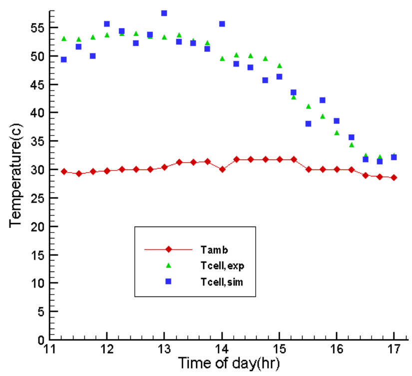

Figure 4. The ambient temperature, experimental PV array temperature and simulated PV array temperature during the test day

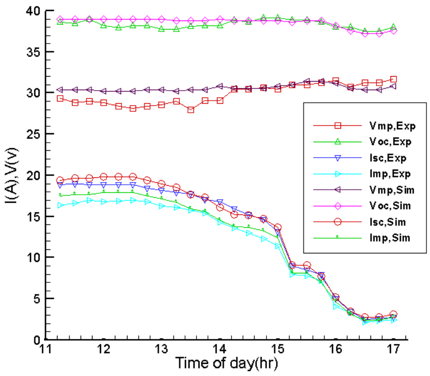

Figure 5. Comparison of current and voltage parameters in experimental and simulated situations

The simulated and experimental values for energy efficiency, exergy efficiency, and electrical efficiency are shown in fig.6. There is a good agreement between simulated and experimental results with 5.05, 5.16, and 8.71 difference percentages for energy efficiency, exergy efficiency, and electrical efficiency.

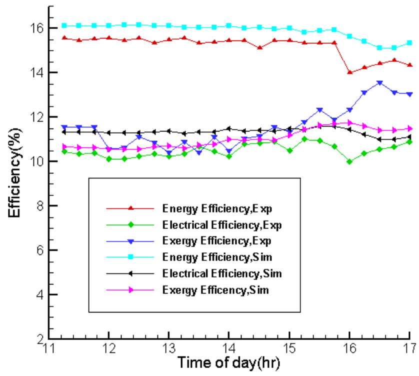

Figure 6. The simulated and experimental values for energy efficiency, exergy efficiency, and electrical efficiency during the test day.

Comparison between simulated and experimental results confirms selecting 1m/s as a logical choice for wind speed. Differences between simulated and experimental results can be sought as below:

It was assumed that temperature coefficients for current and voltage are identical, while in experimental work, changes in PV array temperature and sunlight intensity modify these coefficients. Wind speed is not fixed in experimental work, which in turn directly affects total heat loss coefficient and reduces calculation accuracy of total heat loss coefficient in computer simulation. Also, data extraction from experimental reports might be flawed.

3.2. Comparison of present model with a model without including equation (28) to calculate exergy efficiency of PV array

Figure 7 shows the results of PV array exergy efficiency calculation according to recent model and a model that excludes exergy loss term caused by wind speed:

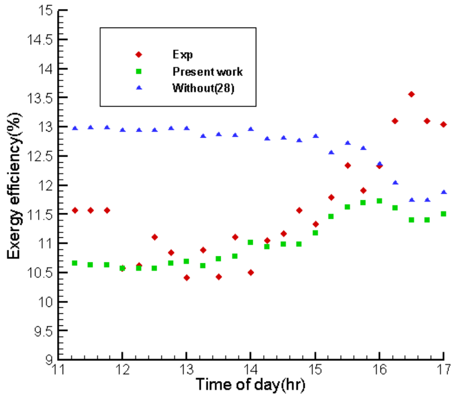

Figure 7. Comparison between exergy model of recent work with a model that excludes equation (28) relative to experimental data

Figure 7 reveals that the exclusion of wind speed loss term (eq.28) in exergy efficiency calculation leads to overestimation of it, and the model that excludes the term has 15.3419 percentage difference relative to experimental result. While the recent model that includes the wind speed loss term in calculation of exergy efficiency calculation has a 6.6577 percentage difference. Thus, wind speed loss term is effective in exergy efficiency calculation and excluding it results in its overestimation.

3.3. Extracting results for Kerman climate

For Kerman climate, the monthly averages of ambient temperature, sunny hours per day, and wind speed were obtained from the Kerman applied research meteorology office. Since sunny hours are the only long-term data whose information was measured, reliable, and accessible and can be used to estimate accurate sunlight intensity on the ground; the average sunlight intensity for various months were calculated for Kerman climate using average sunny hours per day and Angstrom Model.

3.3.1. Estimating total solar radiation on the ground

The Angstrom [13], Prescok [14] experimental formulation was the first model that estimated radiation amount on a horizontal surface based on sunny hours parameter.

$$\frac{\bar{H}}{\bar{H}_o} = a + b\left(\frac{\bar{n}}{\bar{N}}\right) \quad (32)$$

In equation above, $\bar{H}$ is average total daily radiation for a month, and $\bar{H}_o$ is the radiation measured outside of atmosphere calculated by this equation(Duffie & Beckman):

$$\bar{H}_o = \frac{24\times 3600 G_{sc}}{\pi}\left(1+\frac{0.033\cos 360n}{365}\right)\times\left[\cos\phi\cos\delta\sin\omega_s+\frac{\pi\omega_s}{180}\sin\phi\sin\delta\right] \quad (33)$$

G_{sc} is extra atmospheric radiation constant which is included in this article as 1373(W/m^2). ϕ is the latitude of the location, δ is sun's angle relative to equator in degrees ($-23.45 \le \delta \le 23.45$) that can be calculated by Cooper's approximation equation as:

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \quad (34)$$

ω_s is solar hour angle in degrees which can be calculated from the equation (35) as:

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \quad (35)$$

$\bar{n}$ is the monthly average of sunny hours per day, and $\bar{N}$ is the monthly average of max. sunny hours per day which is calculated by:

$$\bar{N} = \frac{2}{15}\omega_s \quad (36)$$

The latitude of Kerman Province is 30.29º and the experimental coefficients a and b are 0.322 and 0.421 [15].

(a) Figure 8 shows the average monthly values of sunny hours in Kerman climate.
(b) Figure 9 shows the average ambient temperature for various months of the year.
(c) Figure 10 shows the monthly averages of short-circuit currents, current at point of maximum power, open-circuit voltage, and voltage at point of maximum power.
(d) Figure 11 shows average monthly wind speed.

(e) Figure 12 shows the monthly averages of PV array exergy,energy and electrical efficiencies for Kerman climate.

It is evident that exergy efficiency variations follow electrical efficiency variations and the highest/lowest monthly energy and electrical exergy efficiencies relate to December/June. Highest average monthly exergy efficiency is observed in November. The reason why December has less exergy efficiency in spite of higher energy/electrical efficiencies relative to November, is higher wind speed in this month which lowers exergy efficiency relative to November. The reason for higher energy/electrical efficiencies in December in spite of lower average sunlight relative to warmer months is very high effect of solar cell temperature. We mentioned earlier that higher solar cell temperature lowers the efficiency and in December, when solar cell temperature is lower than warmer months, energy/electrical efficiencies are higher. Therefore, it is observed that the PV array cell temperature is very influential on energy/electrical efficiencies.

When calculating exergy efficiency, the wind speed is also important and must be included besides solar cell temperature. However, there is little difference between highest and lowest efficiencies and the PV array can be successfully employed to supply part of required power in Kerman climate. Also, the annual averages of exergy, energy, and electrical efficiencies should be 12.03%, 16.27% and 12.14%. According to better results of exergy efficiency in presented model compared to a model without wind loss term, the wind speed effect is notable on system irreversibly and if ignored- since wind speed exists in experimental work and there is loss caused by displacement heat transfer of PV array to the environment-our calculations would be rendered flawed.

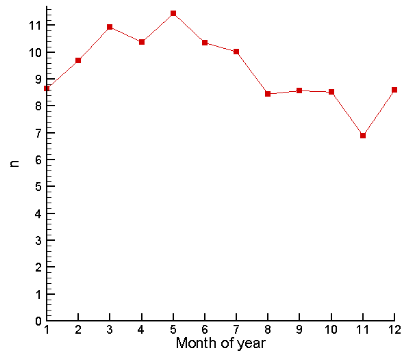

Figure 8. Avergae monthly values of sunny hours in Kerman climate

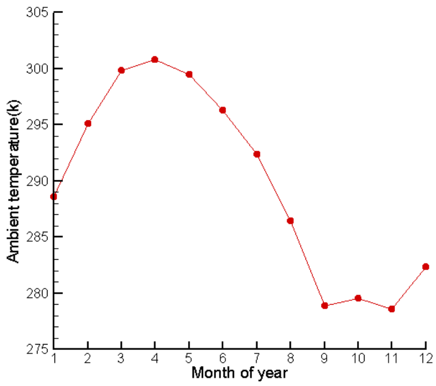

Figure 9. Average monthly ambient temperature for Kerman climate

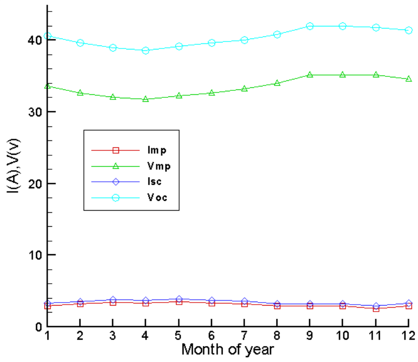

Figure 10. Monthly averages of PV array current and voltage parameters recommended for Kerman climate

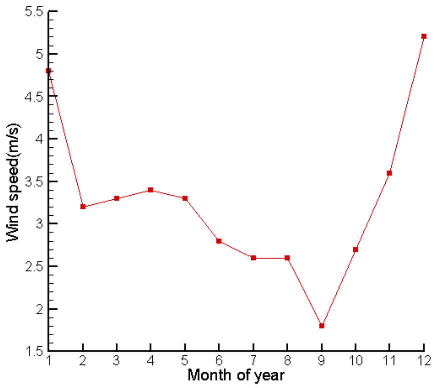

Figure 11. Average monthly wind speed for Kerman climate

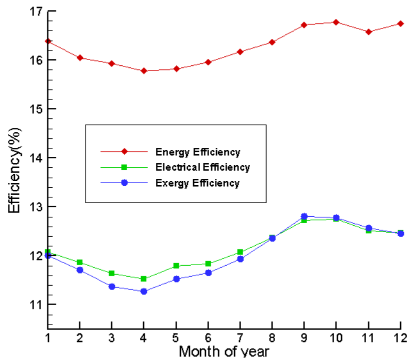

Figure 12. Monthly averages of PV array exergy/energy/electrical efficiencies for Kerman climate

4. Conclusion

The electric and exergy models introduced in present research agree reasonably with Barker & Norton[12] experimental study and thus, the presented model can be used in various climates. By increasing ambient temperature, solar sell temperature soars and energy,exergy and electrical efficiencies drop. Removing PV array surface heat to increase its electrical efficiency has been studied in several experimental works such as Abdolzadeh & Ameri [6] who sprayed water over PV array and achieved higher electrical efficiency.

Since wind speed is crucial in exergy efficiency and its exclusion leads to flawed PV array efficiency calculation, in this article, the wind speed effect on exergy efficiency was studied and more accurate results were achieved relative to a model without wind loss term. Following that, by using models presented in recent article, the average exergy/energy/electrical efficiencies for various months in Kerman climate were calculated and since the efficiency is almost fixed throughout the year, PV array can be employed to supply part of power required for buildings in the city of Kerman.

In spite of common perceptions about low efficiency of solar array in colder months, the PV array efficiency is notable in these months due to lower temperature of solar cells. So, utilization of PV array for electrical power generation is feasible in Kerman climate regardless of being used in warm or cold seasons.

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