THE PHOTOVOLTAIC MODULES PERFORMANCE BASED ON EXERGY ASSESSMENT

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Introduction

Presently, the direct conversion of solar energy into electricity is being accepted as an important form of power generation. This electricity generated by a process known as the photovoltaic effect using photovoltaic (PV) system (cells/modules/panels or array), which are made from semiconductor materials. It is well known that most of the radiation (solar energy) absorbed by a PV system is not converted into electricity (electrical energy) but contributes also to increase the temperature of the module (thermal energy), thus reducing the electrical efficiency.

In thermodynamic point of view, photovoltaic (PV) system performance can be evaluated in terms both energy and exergy. Unlike energy, exergy is not subject to a conversion law (except for ideal or reversible processes).

Exergy is defined as the maximum amount of work (or electricity) that can be done by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Exergy is consumed or destroyed, due to irreversibility in any real processes. The exergy consumption during a process is proportional to the entropy created due to irreversibility associated with the process. Exergy analysis is a methodology that uses the conservation of energy principle (embodied in the "First Law of Thermodynamics") together with non-conservation of entropy principle (embodied in the" Second Law of Thermodynamics") for the analysis, design and improvement of energy and other systems (Rosen et al., 2009). A different conceptual about energy and exergy analysis is shown in Figure 1 (Shukuya et al., 2002). .

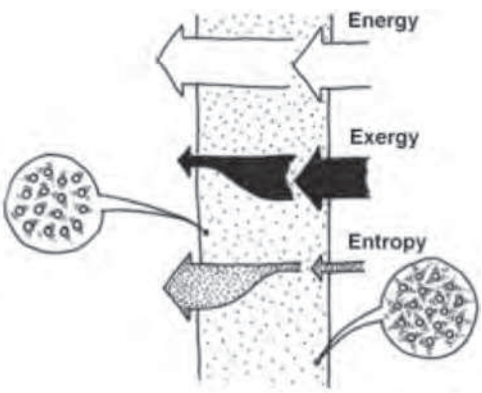

Figure 1. Energy, exergy, and entropy flow in and flow out of a system.

In this research, an exergy evaluation of PV module, as a basic component of PV array system, will be applied and elaborated, refers to a 10 kWp grid-connected PV array system at Szent István University, Gödöllő - Hungary, which uses two different of PV technology i.e. polycrystalline PV technology (ASE-100) and amorphous silicon PV technology (DS-40) (Farkas et al., 2008). Amorphous silicon is a non–crystalline form of silicon i.e. its silicon atoms are disorder in structure. As a results, comparison of two exergy evaluation methods of PV, i.e. "solar energy parameters" and "photonic energy" will be presented in this paper.

As a long term target of this research, the other possibility to optimize and increase the overall performance of grid-connected PV array system at Szent István University, can be studied, observed and proposed.

Methods of Evaluation

For a steady state flow system, energy and exergy balances through a system can be expressed as follow (Dincer et al., 2005):

$$\sum_i en_i \dot{m}_i - \sum_e en_e \dot{m}_e + \sum \dot{Q} - \dot{W} = 0 \qquad 1$$

$$\sum_i ex_i \dot{m}_i - \sum_e ex_e \dot{m}_e + \sum \dot{E}x^Q - \dot{E}x^W - I_r = 0 \qquad 2$$

$$I_r = T_a S_{gen} \qquad 3$$

where $\dot{m}$ is mass flow rate across the boundary system [kg/s]; *en* and *ex* are specific energy [J/kg] and specific exergy [J/kg], respectively; Q is the heat transfer across the boundary system [W]; $\dot{E}x^Q$ is the exergy transfer associated with $\dot{Q}$ [W]; $\dot{W}$ is the work (including shaft work, electricity, etc.) transferred out of the system [W]; $\dot{E}x^W$ is the exergy transfer associated with $\dot{W}$ [W]; I_r is the system exergy consumption due to irreversibility during a process [W]; T_a is ambient temperature [K]; and S_{gen} is entropy generated by the system [W/K].

In exergy analysis, the characteristics of a reference environment need to be specified, and in this study the temperature is used as reference.

To evaluate the exergy efficiency of PV system (η_{ex}), the exergy of the total solar radiation is needed, and in general η_{ex} could be represented as:

$$\eta_{ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} \qquad 4$$

where $\dot{E}x_{in}$ equal with exergy total solar radiation.

Exergetic PV assessment using solar energy parameters method

A PV array is non linear device and can be presented by its I-V-P (current-voltage-power) characteristic curve. The general equivalent circuit of a solar cell in a single diode model is presented in Figure 2, and consists of a photocurrent source, a diode, a parallel resistor expressing a leakage current and a series resistor describing internal resistance to the current flow (Wenham, 2007).

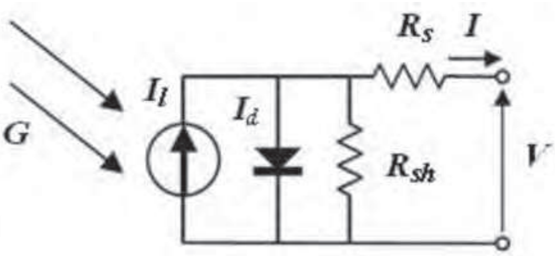

Figure 2. General model of solar cell circuit in a single diode model

The current-voltage characteristic equation for a PV system is given as:

$$I = I_l - I_o \left[\exp\left(\frac{V + IR_s}{\left(\frac{nkTc}{q} \right)} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad 5$$

where I is the current produced by the solar cell [A], I_l is a light-generated current or photocurrent [A], I_o is the dark saturation current (the diode leakage current density in the absence of light) [A], V is the output voltage/applied voltage [V], q is an electron charge [1.602 x 10-19 C], k is the Boltzmann's constant [1.381 x 10-23 J/K], T_c is the cell working temperature [K], n is an ideality factor (a number between 1 and 2 that typically increases as the current decreases), R_{sh} is shunt resistance of the cell [Ω] and R_s is a series resistance of the cell [Ω].

Based on equation (4), the exergy efficiency of a PV system in this method can be expressed as:

$$\eta_{ex} = \frac{\dot{E}x_{elect} + \dot{E}x_{thermal} + \dot{E}x_{dest.}}{\dot{E}x_{solar}} \quad 6$$

$$\eta_{ex} = \frac{\dot{E}x_{elect} + I_r}{\dot{E}x_{solar}} = \frac{\dot{E}x_{elect} + \sum \dot{E}x_{dest.}}{\dot{E}x_{solar}} \quad 7$$

$$\sum \dot{E}x_{dest.} = \dot{E}x_{dest.thermal} + \dot{E}x_{dest.elect} \quad 8$$

I_r contains both internal and external losses. Internal losses are electrical destruction, $\dot{E}x_{dest.elect}$, and external losses are heat losses, $\dot{E}x_{dest.therm}$, which is numerically equal to $\dot{E}x_{thermal}$ (Joshi et al., 2009).

$$\dot{E}x_{elect} = V_{mp} \times I_{mp} \quad 9$$

where V_{mp} is voltage at maximum power point and I_{mp} is current at maximum power point.

$$\dot{E}x_{thermal} = \left(1 - \left(\frac{T_a}{T_c} \right) \right) \times \dot{Q} \quad 10$$

$$T_c = T_a + \frac{G}{G_{ref}} \left(NOCT - T_{a,ref} \right) \quad 11$$

Based on equations (6), (9) and (10), $\dot{E}x_{out}$ from the PV can be expressed as:

$$\dot{E}x_{out} = V_{mp} \times I_{mp} - \left(1 - \frac{T_a}{T_c} \right) \times \dot{Q} \quad 12$$

meanwhile,

$$\dot{E}x_{in} = \dot{E}x_{solar} = \left(1 - \frac{T_a}{T_s} \right) \times G \times A \quad 13$$

where $T_{a,ref}$ is the reference of ambient temperature [K]; $NOCT$ is Nominal Operating Cell Temperature [K]; G and G_{ref} are the actual and reference solar radiation [W/m^2], respectively.

Exergetic PV assessment using photonic energy method

Solar energy can be termed as photonic energy from the sun and this energy travels in the form of photons. The energy of a photon, $En_{ph}(\lambda)$[J], can be calculated as:

$$En_{ph}(\lambda) = \frac{hc}{\lambda} \quad 14$$

where h and c are physical constants; h is Planck's constant [≈ 6.626 x 10^{-34} J.s]; c is speed of light in vacuum [2.998 x 10^8 m/s]; and λ is wavelength of spectrum the light [nm].

In order to evaluation of photonic energy parameters, the sets equations as follow can be implemented (Joshi et al., 2009):

$$N_{ph} = G \frac{4.4 \times 10^{21}}{1367} \quad 15$$

$$\dot{E}n_{ph}(\lambda) = En_{ph}(\lambda) \times N_{ph} \times A \quad 16$$

$$\dot{E}n_{chemical} = \dot{E}n_{ph}(\lambda) \times \left(1 - \frac{T_c}{T_s} \right) \quad 17$$

where N_{ph} is the numbers of photon falling per second per unit area on the Earth [1/m^2.s]; $\dot{E}n_{ph}(\lambda)$ is the photonic energy falling on the PV system [W]; $\dot{E}n_{chemical}$ is available photonic energy or Chemical potential [W] and T_s is the sun temperature [5777 K] (Joshi et al., 2009).

In this method, $\dot{E}n_{chemical} = \dot{E}x_{in}$ and $\dot{E}x_{out}$ equal with power generated by the PV modules, and can be calculated as the product of their output current (I) and the voltage across their terminals (V) or as shown in equation (9).

Table 1 Monthly variation of climate data for Gödöllő, Hungary.

Month	G_{hor} [kWh/m2.m]	G_{arr} [kWh/m2.m]	v [m/s]	T_a [°C]	*Sun-hours** (h)	$G_{arr} = G$ [W/m2]
January	29.79	44.57	2.65	-0.94	9	159.75
February	46.35	62.82	2.70	1.70	10	224.34
March	86.25	104.16	2.82	6.20	12	279.99
April	127.23	140.31	2.91	11.54	14	334.07
May	162.17	163.76	2.67	16.48	15	352.16
June	172.06	167.49	2.76	19.30	16	348.93
July	182.90	182.05	2.75	21.42	15	391.51
August	153.71	164.99	2.38	20.82	14	380.16
September	109.33	130.47	2.29	16.54	12	362.42
October	70.55	98.39	2.12	11.37	10	317.39
November	35.31	52.03	2.49	5.30	9	192.71
December	23.06	33.38	2.64	1.14	8	134.60

* Based on sun - path diagram.

Results and discussion

For analysis, the yearly (monthly variation) of climate data for Gödöllő - Hungary (specific site location: 47.4° N for lattitude and 19.3° E for longitude) are taken from PV*SOL 3.0 software packages, which acquires data from MeteoSyn, Meteonorm, PVGIS, NASA SSE, SWERA (Klise et al., 2009). The following data such as solar radiation (both in horizontal, G_{hor} and tilt array position, G_{arr}), ambient temperature and wind velocity (v) are shown in Table 1. Meanwhile the electrical parameters under reference conditions (STC), such as I_{SC} (short circuit current); V_{OC} (open circuit voltage); I_{mp} (current at maximum power point); V_{mp} (voltage at maximum power point), are provided by manufacturer sheets.

The calculated results of the modules performance in exergy efficiency is shown in Figure 3.

Figure 3 (a)-(b) shows the exergy efficiency for both methods, refers to preceding sets equation. The values of I and V is taken from *I-V-P* characteristics which obtained from previous research (Rusirawan et al., 2011).

For the photonic method purpose, calculated are performed by varying wavelength of the visible spectrum, for a given range of 400 to 800 nm. Comparison between exergy efficiency based on photonic, exergy efficiency based on solar energy parameter and energy efficiency is shown in Figure 3 (c)-(d).

Based in Figure 3(a)-(b), it can be seen that for the same case, exergy efficiency based on "solar energy parameter" is spread between exergy efficiency values based on "photonic energy" in the varying wavelength of the visible spectrum. Both of methods results an average of exergy efficiencies 11-12 % for ASE-100 and 4-5 % for DS-40. On the other hand, the actual PV efficiencies (electrical efficiency) average based on operational results are 13 % and 4 % respectively for ASE-100 module and DS-40 module.

Figure 3(c)-(d), shown that energy efficiency of PV higher than exergy efficiency, because in the energy efficiency terminology, the thermal energy and electrical energy are taken into account as an output of energy of the PV system. Meanwhile, in the exergy efficiency terminology, the thermal energy is viewed as losses and is not taken into account as an output.

Conclusion

In this study, exergy efficiency characteristics of two type of PV modules, i.e. polycrystalline silicon (ASE-100) and amorphous silicon (DS-40), as a main part of 10 kWp grid-connected PV array systems at the Szent István University, have been performed, based on "solar energy parameter" method and "photonic energy" method. It is observed that both methods of PV exergy assessment gives the realistic values than the PV energy assessment (if compares to an actual electrical efficiency). It also has been found that in the photonic energy method the wavelength of visible spectrum plays an important role on the exergy efficiency characteristics. As expected, the efficiency characteristics of ASE-100 module (which included crystalline materials type) are higher than DS-40 module (which included thin film materials type). Further parametric studies are still needed, in order to obtain a deep correlation between climatic and operating parameter, and finally other possibility to optimize and increase the PV module performance can be found.

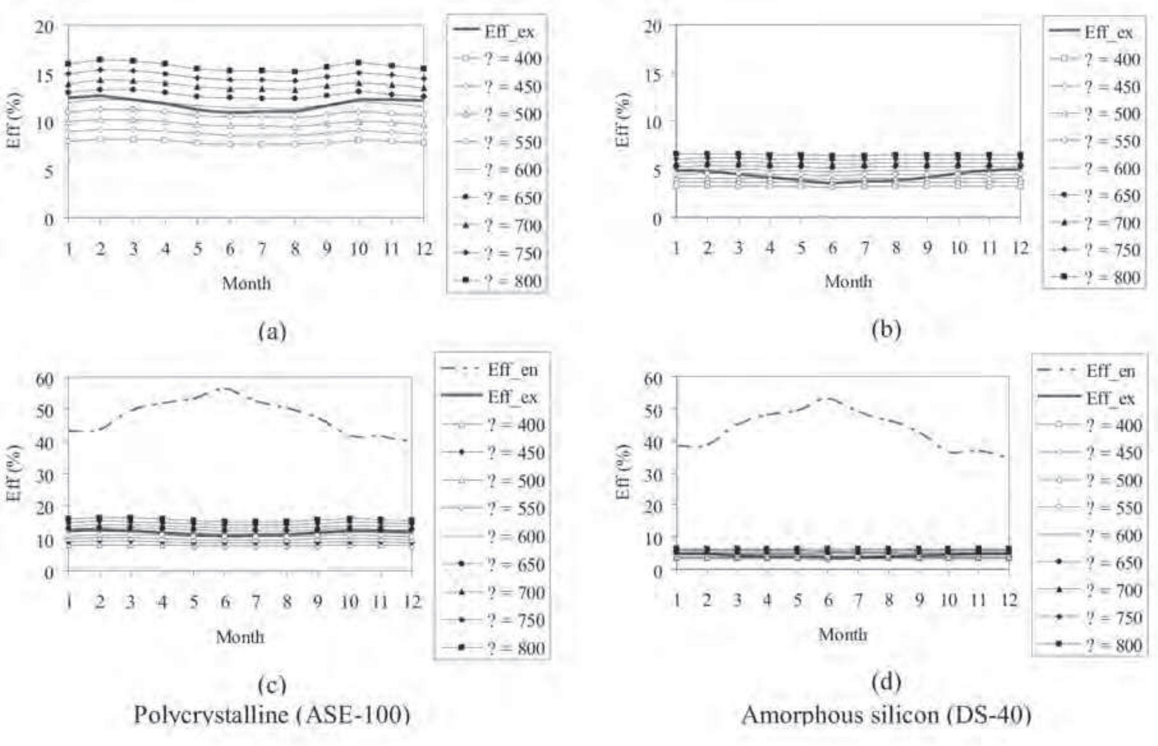

Figure 3 PV exergy efficiency at different wavelength (λ, nm) and its comparisons with exergy efficiency based on solar energy parameter (Eff_ex) and energy efficiency (Eff_en).

Acknowledgments

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References

1. Dincer, I and Rosen, M. A. (2005), Thermodynamic aspects of renewables and sustainable development, Renewable and Sustainable Energy Reviews 9, pp. 169-189.

2. Farkas, I. and Seres, I. (2008), Operational experiences with small-scale grid-connected PV system, Szent István University Faculty of Mechanical Engineering, R&D in Mechanical Engineering Letters, Gödöllő, Hungary, Vol. 1, pp. 64-72.
3. Joshi, A. S., Dincer, I and Reddy, B. V. (2009), Thermodynamic assessment of photovoltaic systems, Solar Energy 83, pp. 1139-1149.
4. Klise, G.T., and Stein, J. S. (2009), Models used to assess the performance of photovoltaic systems, Sandia report: SAND2009-8258. Available from:
<http://photovoltaics.sandia.gov/Pubs_2010/PV%20Website%20Publications%20Folder_09/Klise%20and%20Stein_SAND09-8258.pdf>, accessed on March 19, 2011.
5. Rosen, M. A. and Bulucea, C. A. (2009), Using exergy to understand and improve the efficiency of electrical power technologies, Entropy 2009, 11, pp820-835; doi: 10.3390/e11040820.
6. Rusirawan, D. and Farkas, I. (2011), Simulation of electrical characteristics of polycrystalline and amorphous PV modules, Electrotehnica, Electronica, Automatica, Vol. 59, No. 2, pp. 9-15.
7. Shukuya, M. and Hammache, A. (2002), Introduction to the concept of exergy, VTT Research notes 2158, Julkaisija–Utgivare-Publisher. Available from:
<http://www.vtt.fi/inf/pdf/tiedotteet/2002/T2158.pdf>, accessed on March 19, 2011.