Exergetic Analysis of Photovoltaic Modules Based on Photonic Energy

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Abstract
In thermodynamic point of view, photovoltaic (PV) system (cell/module/panel/array) 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 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. In this paper, an exergy analysis of PV module based on photonic energy will be carried out, as a basic prerequisite to find a new method in order to increase and optimize the PV module performance.

Key words: *thermodynamic of photovoltaic, energetic and exergetic, irreversibility, optimize, photovoltaic performance*

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/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.

Testing (conducted to an experimental data) and modelling efforts are typically to quantify and then to replicate the measured phenomenon of interest. Testing and modelling of PV system performance in the outdoor environment is very complicated and influenced by a variety of interactive factors related to the environment and solar cell physics. In order to effectively design, implement, and monitor the performance of photovoltaic systems, a performance model must be able to separate and quantify the influence of all significant factors. In view of this, it is now becoming essential to look for various aspects in order to increase the PV energy conversion into electricity on its application in the field.

In thermodynamic point of view, photovoltaic (PV) system (cell/module/panel/array) performance can be evaluated in terms both energetic and exergetic. Energy analysis is based on the first law of thermodynamics meanwhile exergy analysis is based on both the First and the Second Laws of Thermodynamics.

The Earth receives solar energy (energy from the sun) by way of radiated (light) energy. Refers to quantum theory, light is made up of packets of energy, called photons (tiny particles having no mass), whose energy depends only upon the frequency or colour of the light. The energy of visible photons is sufficient to excite electrons, bound into solids, up to higher energy levels where they are relative free to move so that an electrical current can be produce (Nelson, 2003)

In this paper, an exergetic analysis of PV module, as a basic component of PV array system, will be presented based on photonic energy perspective, 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).

The grid-connected PV array system at Szent István University is installed on the flat roof of Dormitory building and is structured into 3 sub-systems. Sub-system 1 consists of 32 pieces of ASE-100 type modules (RWE Solar Gmbh) from polycrystalline PV technology, and sub-system 2 and 3 consists of 77 pieces of DS-40 type of modules (Dunasolar Ltd) from amorphous silicon PV technology, respectively. The total power of the system is 9.6 kWp with the total PV surface area 150 m^2. Every sub-system uses a separate inverter (Sun power SP3100-600 for sub-system 1 and SP2800-550 for others sub-system), that will convert the production of DC electrical energy to the 230 V AC, 50 Hz electrical grid (Farkas et al., 2008). The schematic installation of grid-connected PV array at Szent István University can be seen in Fig. 1.

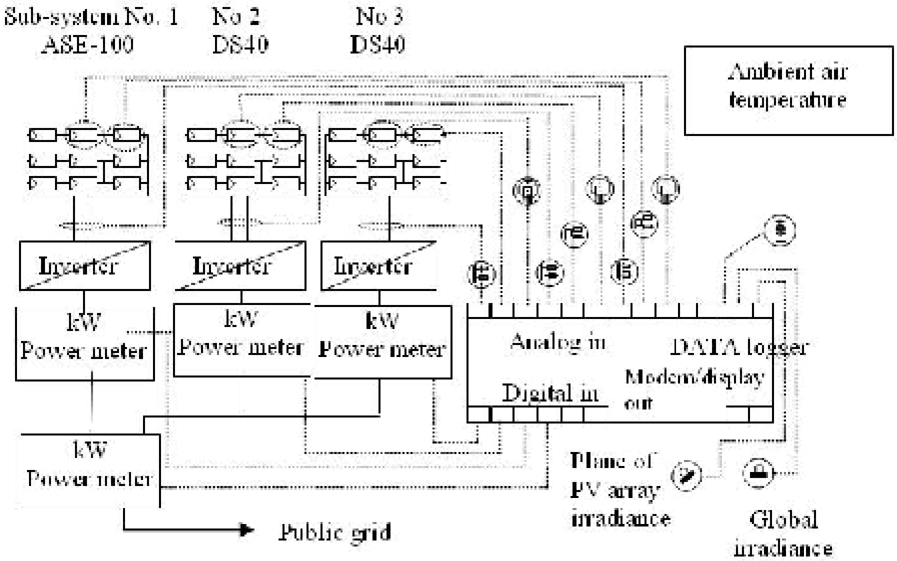

Figure 1 The schematic diagram of a 10 kWp grid-connected PV array at Szent István University, Gödöllő – Hungary.

As a long term target of this research, a new method to increase and optimize the overall performance of grid-connected PV array system at Szent István University can be found.

Characteristics of PV and exergy analysis

A PV system is non linear device and can be presented by its *I-V-P* (current-voltage-power) characteristic curve. There are several mathematical models, which can describe *I-V* characteristics curve. The general equivalent circuit of a solar cell in a single diode model is presented in Fig. 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).

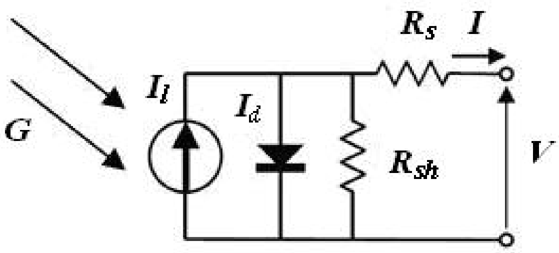

Figure 2 General model of solar cell circuit in a single diode model

The *I-V-P* characteristics both for ASE-100 and DS-40 PV modules, indicates that high temperature and low irradiation conditions will reduce the power conversion capability of PV modules (Rusirawan et al., 2011).

Exergy is defined as the maximum amount of work that can be done by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Exergy analysis is a technique that uses the conversion of mass and conversion of energy principles together with the second law of thermodynamics for the analysis, design, and improvement of energy system and other analogous system (Dincer et al., 2005).

Basically, for a steady state flow system, energy and exergy balances through a system can be expressed as follow:

$$\sum_{in} en_{in}\dot{m}_{in} - \sum_{out} en_{out}\dot{m}_{out} + \sum \dot{Q} - \dot{W} = 0\,, \tag{1}$$

$$\sum_{in} ex_{in}\dot{m}_{in} - \sum_{out} ex_{out}\dot{m}_{out} + \sum \dot{E}x^{Q} - \dot{E}x^{W} - I_r = 0\,, \tag{2}$$

$$I_r = T_a S_{gen}\,. \tag{3}$$

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; $\dot{Q}$ 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).

There are two different methods for the PV exergy analysis purpose i.e. namely based on solar energy parameter and based on photonic energy.

Methods of evaluation

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 $En_{ph}(l)$, in Joule, can be calculated as:

$$En_{ph}(l) = \frac{hc}{l}\,. \tag{4}$$

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 l is wavelength of spectrum the light (nm).

In order to evaluation of photonic parameters, the sets equations as follow can be implemented:

$$N_{ph} = G\,\frac{4.4\times 10^{21}}{1367}\,, \tag{5}$$

$$\dot{E}n_{ph}(l) = En_{ph}(l)\times N_{ph}\times A\,, \tag{6}$$

$$\dot{E}n_{chemical} = \dot{E}n_{ph}(l)\times\left(1-\frac{T_c}{T_s}\right), \tag{7}$$

$$\dot{E}x_{chemical} = \eta_{pc} \times \dot{E}n_{chemical} \,. \qquad (8)$$

where N_{ph} is the numbers of photon falling per second per unit area on 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); $\dot{E}x_{chemical}$ is exergy rate available from chemical potential (W); T_c and T_s are cell and sun temperatures, respectively (K); and η_{pc} is efficiency of power conversion (Joshi et al., 2009).

For an initial analysis, the yearly insolation and weather data (climate data) for Gödöllő - Hungary (with specific site location are 47.4^o N for lattitude and 19.3^o 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 can be seen in Table 1.

Table 1 Annual climate data for Gödöllő, Hungary site location

Month	G_{hor}	G_{arr}	v	T_a	*Sun-hours**	$G_{arr} = G$
	[kWh/m2.m]	[kWh/m2.m]	[m/s]	[°C]	(h)	[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

Meanwhile the electrical parameters under reference conditions (STC) and the others parameters of PV module are provided by manufacturer sheets and shown in Table 2.

*Table 2 Electrical parameters of ASE-100 and DS-40 module at Standard test condition (STC)**

Parameters	ASE 100	DS40
Typical peak power (W)	105	40
Voltage at peak power (V)	35	44.8
Current at peak power (A)	3	0.8
Short circuit current (A)	3.3	1.15
Open circuit voltage (A)	42.6	62.2
Active surface area (m^2)	0.83	0.79
Temp. coeff. of open circuit voltage (%/^{o}C)	-0.38	-0.2797
Temp. coeff. of short circuit current (%/^{o}C)	0.10	0.0897
Approximate effect of temp. On power (%/^{o}C)	-0.47	-0.190
Nominal operating cell temperature/NOCT (^{o}C)	45	50

* Under Standard Test Conditions (G = 1000 W/m^2, AM = 1.5 and T_c = 25^{o}C).

The values of η_{pc} is taken from previous study, with average values are 11.8 for ASE-100, and 4.3 for DS-40.

Results and Discussion

Figs. 3 and 4 show the variation of photonic energy (chemical potential) and exergy corresponding to photonic energy of a PV modules during a year (yearly). In this study, photonic energy and exergy have been calculated by varying wavelength of visible spectrum for a given range of 400 to 800 nm.

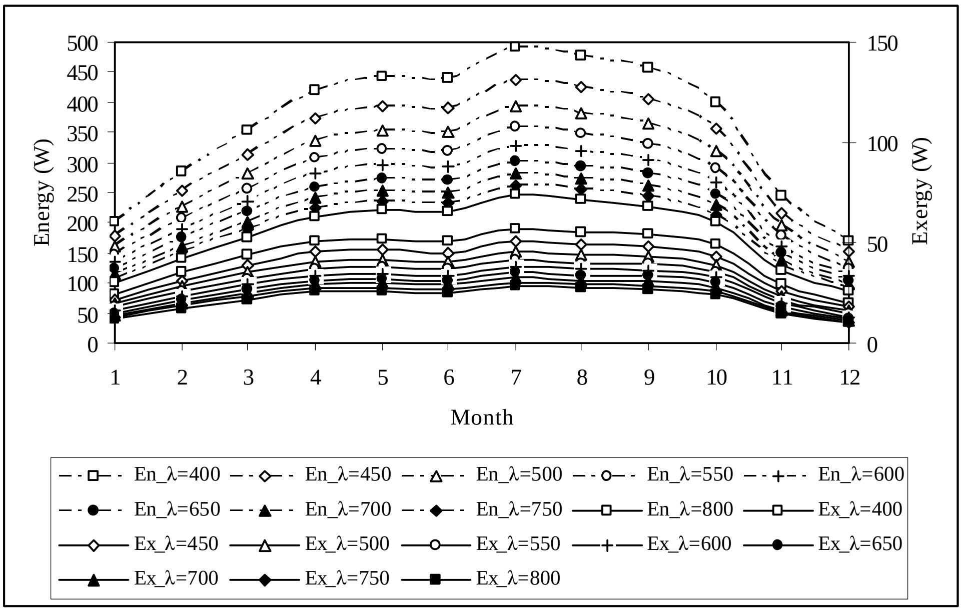

Figure 3 Yearly variation of photonic energy and exergy for polycrystalline PV module (ASE-100) at the different wavelength (λ, nm)

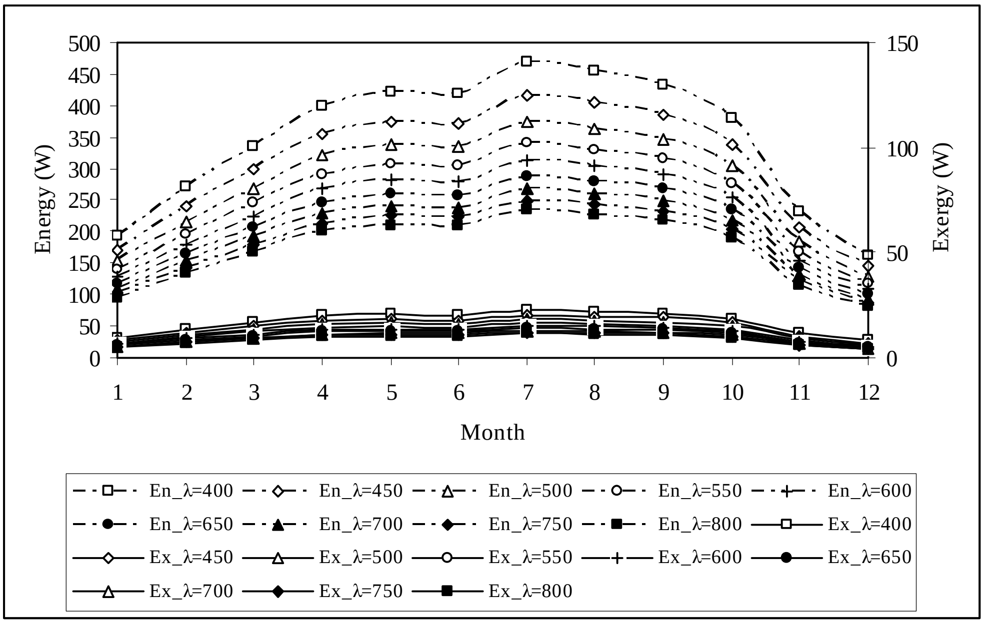

Figure 4 Yearly variation of photonic energy and exergy for amorphous silicon PV module (DS-40) at the different wavelength (λ, nm)

Based on both of figures, it can be seen that energy (or available photonic energy or chemical potential) and exergy (or exergy rate available from chemical potential) of each PV modules are higher for lower of wavelength.

Conclusion

In this study, estimation of exergy of two type PV modules, as a main part of 10 kWp grid-connected PV array system at the Szent István University, has been performed, based on photonic energy method. Based on evaluation, it can be seen that the wavelength of visible spectrum plays an important role. As a result of the irreversibilities of the process, evaluation of major loss of exergy is needed in future study.

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