SZENT ISTVÁN UNIVERSITY

Energetic modelling of photovoltaic modules in grid-connected systems

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by

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NOMENCLATURE AND ABBREVATIONS

A	Area (m^2)
AM	Air mass ratio (-)
E	Solar irradiation (kWh/m^2)
$\dot{En}$	Rate of energy (W)
Ex	Exergy (J)
$\dot{Ex}$	Rate of exergy (W)
Ex_loss or Ex_{loss}	The major loss exergy (exergy destroy) as a consequence of the irreversibilities of the process (W/m^2)
$\dot{En}_{chemical}$	Available of photonic energy or Chemical potential (W)
en	Specific energy (J/kg)
ex	Specific exergy (J/kg)
FF	Fill Factor (-)
G	Solar irradiace (W/m^2)
I	Electric current (A)
I_r	Rate of exergy consumption due to irreversibilities (W)
N_{ph}	Numbers of photon falling on the Earth ($1/m^2$ s)
P	Electric power (W)
$\dot{Q}$	Heat transfer across system boundary (W)
T	Temperature (^oC) or (K)
V	Output/applied voltage (V)
v	Wind velocity (m/s)

Subscripts:

a	Ambient
arr	Array
c	Solar cell/module
dest	Destructive
en	Energy
ex	Exergy
hor	Horizontal
in	Input
mp	Maximum point
max	Maximum (theoretical) value
oc	Open circuit
out	Output
pc	Power conversion
pv	Photovoltaic
s	Sun
sc	Short circuit

Greek symbols:

β	PV plane tilt angle (^{o})
γ	PV plane azimuth angle (^{o})
η	Efficiency (%)
λ	Wavelength of spectrum the light (nm)

ABBREVIATIONS

a-Si	Amorphous silicon
pc-Si	Polycrystalline silicon (or multicrystalline silicon)
I-V-P	Current-Voltage-Power
PV	Photovoltaic
STC	Standard Test Conditions
SZIU	Szent István University

1. INTRODUCTION AND OBJECTIVES

In this chapter, the importance of the research topic is presented along with the objectives of this research.

1.1. Introduction

Developing a clean and renewable energy has become one of the most important tasks in field of modern science and engineering. Solar energy can be recognized as one of the most promising renewable energy sources. Photovoltaic (PV) systems, presently is accepted as the most important way to convert solar energy into electricity, due to pollution free and abundantly available anywhere in the world. 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, PV system performance can be evaluated in terms both energy and exergy, and in applications level, PV module is basic building block to construct PV systems.

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.

1.2. Objectives

In this research, comprehensive evaluation of two PV modules technologies will be performed based on points of view energetic and exergetic. As a subject, polycrystalline silicon, pc-Si (included wafer based crystalline silicon technology) and amorphous silicon, a-Si (included thin-film technology), as components of grid-connected PV array system at Szent István University (SZIU), are used under Gödöllő climatic conditions. It is well known that energy analysis is more suitable for energy balance when we design a system, while exergy analysis is more appropriate when we evaluate the performance of a system qualitatively.

The objectives of this research can be described as follow:

1. Evaluation of an existing grid-connected PV array system in view of macro PV model, based on theoretical and experimental.
2. Evaluation of surface orientation (tilt and surface azimuth angles) effect on the yield energy in grid-connected PV array system.

3. Elaborates the mathematical model of PV cell/module, and its correlation in the PV panel/array, in view of energetic.
4. Evaluation of *I-V-P* (current-voltage-power) characteristic of the PV modules and its correlation in the PV panel/array, using a relevant software packages, such as: NSol, RetSCreen, Homer, etc.
5. Elaborates the thermodynamic performances of PV modules in view of energetic and exergetic.
6. Evaluation of PV modules performances in view energetic and exergetic based on theoretical (mathematical model) using PV*SOL and experimental.
7. Comparing an exergetic performances based on ”thermodynamic approach for solar energy” and ”photonic energy (chemical potential) from the sun” models.
8. Study of spectral irradiations effects on energetic and exergetic PV performance.

2. MATERIAL AND METHODS

In this research, energy and exergy evaluation of two PV module technologies (from the first and second generation), as component of PV array system, will be performed, refers to installation of 10 kWp grid-connected PV array system at Szent István University, Gödöllő – Hungary.

A system description and the method of analysis in view of energy and exergy, as bases for evaluation, are presented in this chapter.

2.1. System description

The grid-connected PV array systems at Szent István University were installed on the flat roof of Dormitory building and are structured into 3 sub-systems. Sub-system 1 consists of 32 pieces of polycrystalline silicon (pc-Si), ASE-100 type (wafer based crystalline silicon as the first generation of PV technology), and sub-system 2 and 3 consists of 77 pieces of amorphous silicon (a-Si), DS-40 type (thin film as the second generation of 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. The schematic installation of grid-connected PV array at Szent István University can be seen in Fig. 2.1. The PV surface orientation of this system are 30^o for tilt angle (β), and 5^o to East for South facing (-5^o) for surface azimuth angle (γ).

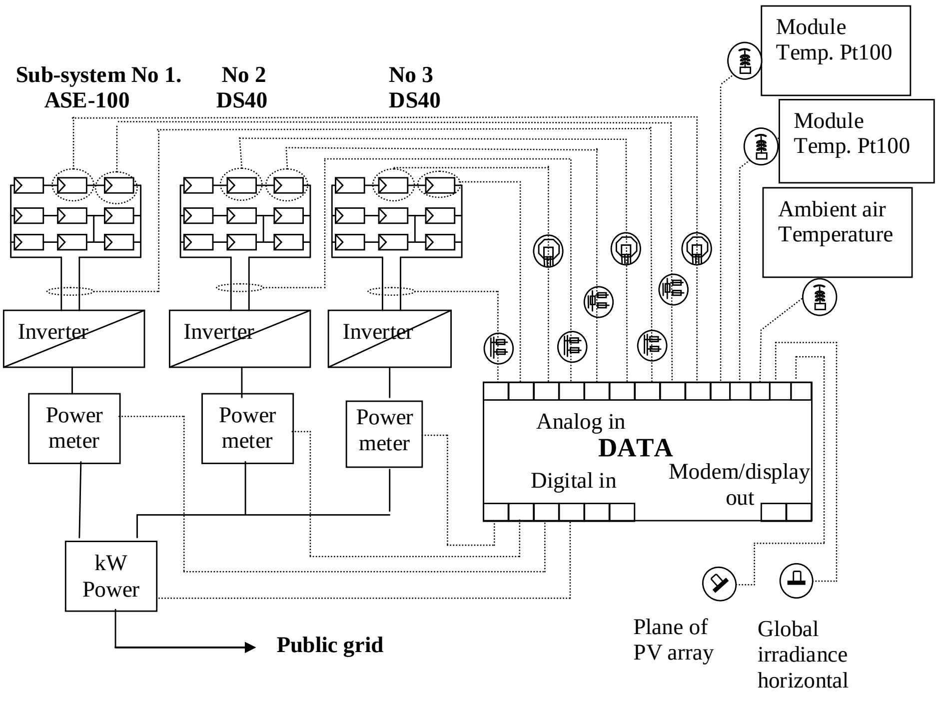


Fig. 2.1. The schematic diagrams of a 10 kWp grid-connected PV array at SZIU

The electrical parameters under Standard Test Conditions (STC), such as (short circuit current); (open circuit voltage); (current at maximum power point); (voltage at maximum power point) are provided by manufacturer sheets and shown in Table 2.1.

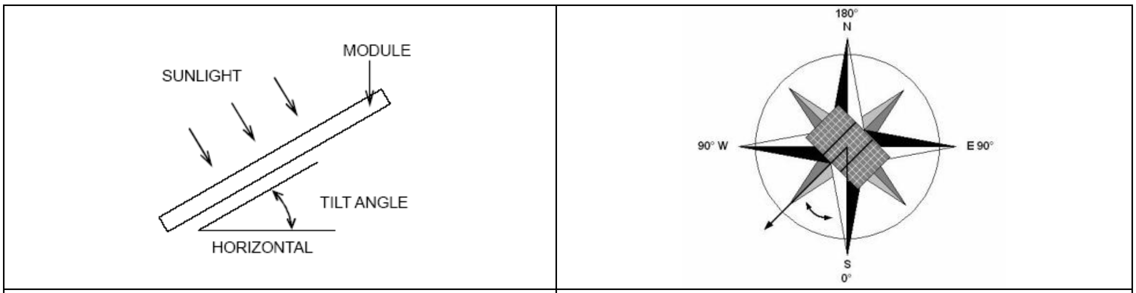
Table 2.1. PV modules specifications in SZIU grid-connected PV array system

Module parameters *Electrical Module**	pc-Si sub-sys 1	a-Si sub-sys 2	a-Si sub-sys 3
Typical peak power (W)	105	40	40
Voltage at peak power (V)	35	44.8	44.8
Current at peak power (A)	3	0.8	0.8
Short circuit current (A)	3.3	1.15	1.15
Open circuit voltage (A)	42.6	62.2	62.2
Temp. coefficient of open circuit voltage (%/^{o}C)	-0.38	-0.2797	-0.2797
Temp. coefficient of short circuit current (%/^{o}C)	0.10	0.0897	0.0897
Approximate effect of temperature on power (%/^{o}C)	-0.47	-0.190	-0.190
Nominal operating cell temperature, NOCT (^{o}C)	45	50	50
Others			
Active surface area (m^2)	0.83	0.79	0.79
Specific heat capacity (J/kg K)	920	920	920
Absorption coefficient (%)	70	70	70
Weight (kg)	8.5	13.5	13.5
Array			
No. of modules in series (per string)	16	7	7
No. of strings in parallel (per inverter)	2	11	11
Total module area (m^2)	27	61	61

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

2.2. Evaluation of electric production of the PV array system in a macro views

First of all, the production of electric energy of 10 kWp grid-connected PV array systems, as a function of surface orientation (see Fig. 2.2) will be simulated using commercial software packages as follow: RETScreen V 3.2, NSoL V4.4 and Homer 2.68 Beta.

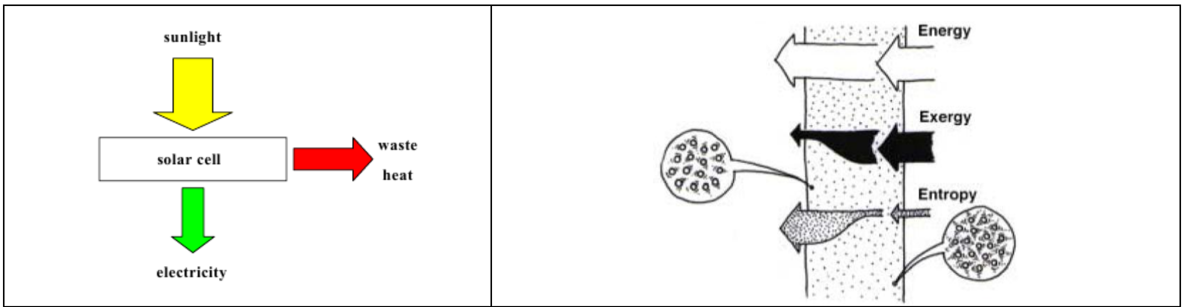


a) Tilt angle (β) | b) Surface azimuth angle (γ)

Fig. 2.2. Surface orientation of PV module

2.3. PV modules performances based on energy and exergy analysis

The energy of a PV system (cell/module/panel/array) depends on two major components namely electrical energy and thermal energy (see Fig. 2.3.a). While the electricity is generated by photovoltaic effect, the PV cells also get heated due to the thermal energy present in the solar radiation. Energy conversion process in PV module and different point of view about energy and exergy can be seen in Fig. 2.3.b.



a) Energy conversion process in the PV module | b) Energy, exergy and entropy flow in and flow out a system

Fig. 2.3. Thermodynamic point of view of the PV module

The energy efficiency of a PV system in general can be defined as the ratio of the output energy of the system to the input energy received on the photovoltaic surface, and can be expressed as:

$$\eta_{en} = \frac{\dot{E}n_{out}}{\dot{E}n_{in}} = \frac{\dot{E}n_{electrical} + \dot{E}n_{thermal}}{\dot{E}n_{in}} = \frac{V_{oc} I_{sc} + \dot{Q}}{GA}. \qquad (1)$$

Meanwhile the exergy efficiency of a system in general can be given as:

$$\eta_{ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = \frac{\dot{E}x_{electrical} + \dot{E}x_{thermal} + \dot{E}x_{dest.}}{\dot{E}x_{solar}} = \frac{\dot{E}x_{electrical} + I_r}{\dot{E}x_{solar}}, \qquad (2)$$

$$I_r = \sum \dot{E}x_{dest} = \dot{E}x_{destthermal} + \dot{E}x_{destelectrical}, \quad (3)$$

$$\eta_{ex} = \frac{V_{mp}\, I_{mp} - \left(1 - \left(\frac{T_a}{T_c}\right)\right)\left[(5.7 + (3.8v))A(T_c - T_a)\right]}{\left(1 - \left(\frac{T_a}{T_s}\right)\right) G\, A}. \quad (4)$$

2.4. Theoretical exergetic performances of PV modules

In this research, exergetic performance of PV modules will be performed by:

1. Thermodynamic approach for solar energy
2. Photonic energy (chemical potential) from the sun models.

For theoretical analysis, the climates data is taken from PV*SOL 3.0 software packages, which acquires data from MeteoSyn, Meteonorm, PVGIS, NASA SSE, SWERA.

2.5. Experimental exergetic performances of PV modules

For experimental analysis, to simplify the process of exergy evaluation, a “Sankey diagram” as can be seen in Fig. 2.4, can be implemented as guidance in order to understanding the process and to get all the required parameters. Actual operational data will be used in this analysis.

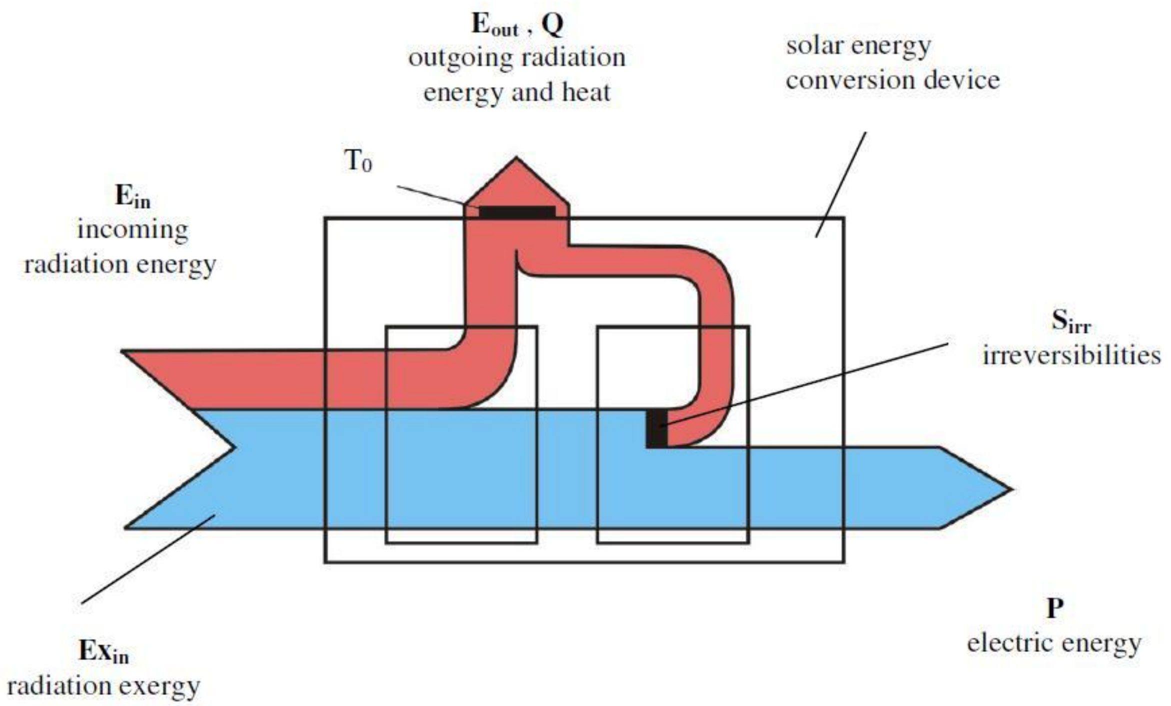


Fig. 2.4. Energy and exergy flow diagrams in solar energy conversion device

3. RESULTS

For theoretical evaluation and analysis, secondary data of annual climates of Gödöllő, Hungary, which is located at 47.4^o N lattitude and 19.3^o E, can be seen in Table 3.1.

Table 3.1. Annual climate data of Gödöllő, Hungary

Month	E_{hor}	E_{arr}	v	T_a	*Sun hours**	$G_{arr} = G$
	kWh/m^2	kWh/m^2	m/s	°C	h	W/m^2
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
Annual	1,199.00	1,344.00	2.60	11.00		

*Based on average effective sun hours in Hungary

3.1. Energy production of 10 kWp grid-connected PV array system

In simulation process, the properties of both PV modules (pc-Si and a-Si) are taken from Table 2.1 (PV modules specifications in SZIU PV system). Fig. 3.1 shows the influence of various tilt and azimuth angles on the output system.

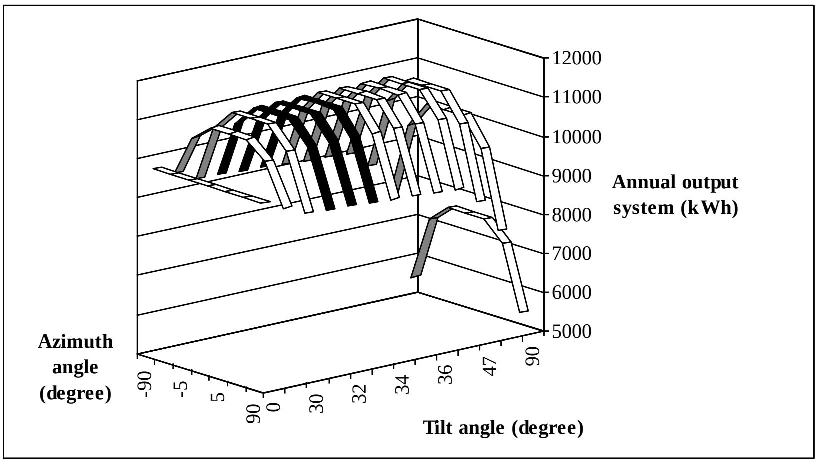


Fig. 3.1. Output system in various surface orientations (tilt and azimuth angles)

Based on this characteristic, the system could maximize annual output of the system at azimuth angle 0^o (pure facing to South) and tilt angle between $30\text{-}34^o$.

3.2. Thermodynamic performance of PV modules

The variation of energy, exergy, power conversion and maximum efficiencies of PV modules, against time are shown in Fig. 3.2 and Fig. 3.3 for pc-Si and a-Si, respectively. The energy efficiency for pc-Si varies from a minimum of 39.9% at December to a maximum of 56.4% at June, meanwhile for a-Si varies from a minimum of 34.8% at December to a maximum of 52.9 at June. The exergy efficiency for pc-Si varies from a minimum of 10.9% at June to a maximum of 12.6% at February, meanwhile for a-Si varies from a minimum of 3.5% at June to a maximum of 4.9% at December.

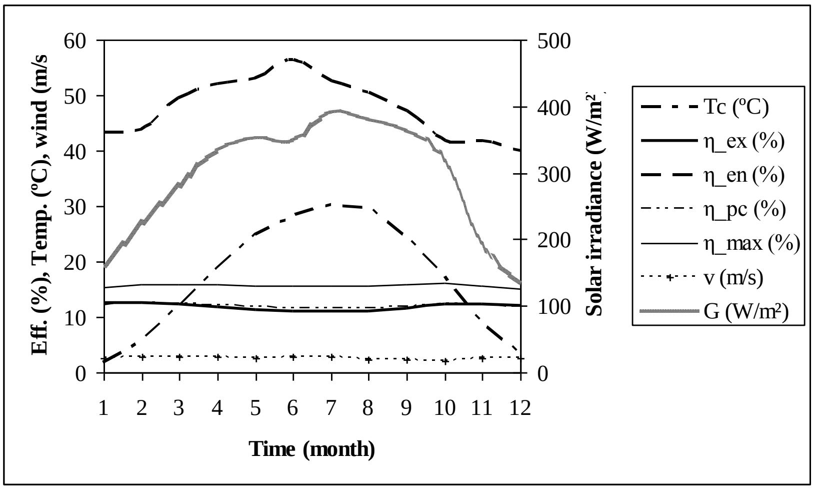


Fig. 3.2. Variation of thermodynamic efficiencies of pc-Si during a year

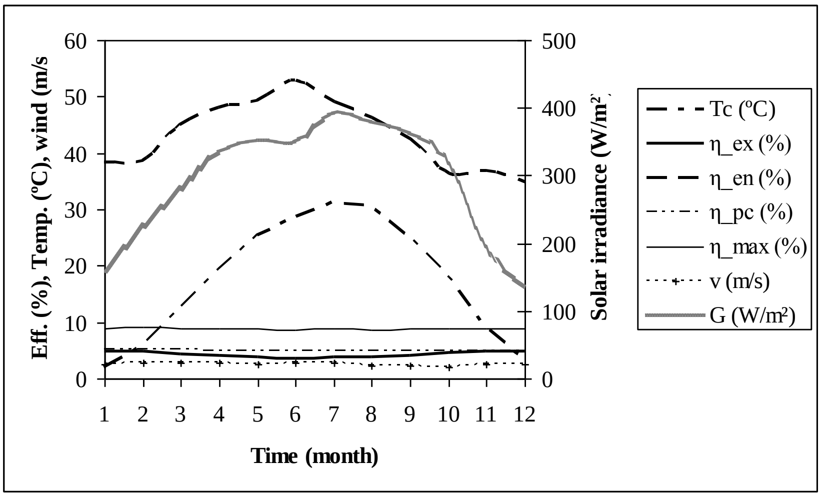


Fig. 3.3. Variation of thermodynamic efficiencies of a-Si during a year

In summary, average thermodynamic efficiencies (included energy efficiency, exergy efficiency, power conversion or electrical efficiency and electrical maximum efficiency) both PV modules during a year are shown in Table 3.2.

Table 3.2. Average thermodynamic efficiencies of PV modules during a year

Thermodynamic performances		Average in year		
		pc-Si	a-Si	a-Si
η_{en}	Efficiency of energy (%)	47.66	43.20	43.20
η_{ex}	Efficiency of exergy (%)	11.82	4.30	4.30
η_{pc}	Efficiency of power conversion (%)	11.94	4.91	4.91
η_{max}	Efficiency of electrical maximum (%)	15.72	8.88	8.88

The results showed that energy efficiency of PV modules higher than exergy efficiency, due to the energy efficiency is based on the electrical energy and the thermal energy (which available on the PV surface) as an output, meanwhile exergy efficiency considers only electrical energy as an output (the thermal energy is viewed as losses and is not taken into account as an output). Based on Figs 3.2 and 3.3, it is found that thermodynamic efficiencies of PV modules in power conversion (η_{pc}) and exergy (η_{ex}) are slight different, either for pc-Si or a-Si. The efficiency maximum (η_{max}) higher than other efficiencies, because this efficiency calculates the maximum electricity generated (as function of I_{sc} and V_{oc}). The results showed also that performance evaluations of PV modules with exergy analysis will lead us getting a realistic values rather than energy analysis, if compared to efficiency power conversion (efficiency of electric). The exergy efficiency of PV module decreases with solar irradiance in higher temperature (in June, July and August). If the temperature decreases, the trend in exergy efficiencies changed (increasing).

3.3. Actual efficiencies of exergy and power conversion of PV modules

To verify the results shown in Figs 3.2-3 and Table 3.2, hourly data based on experimental is also used in PV modules analysis. But, due to based on theoretical approach we saw that power conversion and exergy efficiencies are the most important efficiencies for evaluating of PV modules, further analysis based on experimental are just given on the two efficiencies.

Figs 3.4 and 3.5 show the variation of solar irradiance (G), exergy of solar energy (Ex_{solar}), the power supplied by the PV modules (P), exergy loss (Ex_{loss}), exergy efficiency (η_{ex}) and power conversion efficiency (η_{pc}), during the day, based on experimental.

Solar irradiance, exergy solar, electric power and exergy loss are based on active surface area of module, i.e. 0.83 m and 0.79 m, for pc-Si and a-Si, respectively.

Ex_{loss} is evaluated as a consequence of the irreversibilities of the process. Data for evaluation is based on Gödöllő climate in May, but due to actual data about temperature and wind velocity were not available, evaluation have been performed at constant temperature, i.e. average temperature in May, 16.48 ^oC (see Table 3.1). Exergy efficiency and power conversion efficiency in the experimental case are calculated based on actual electricity generated, as an output.

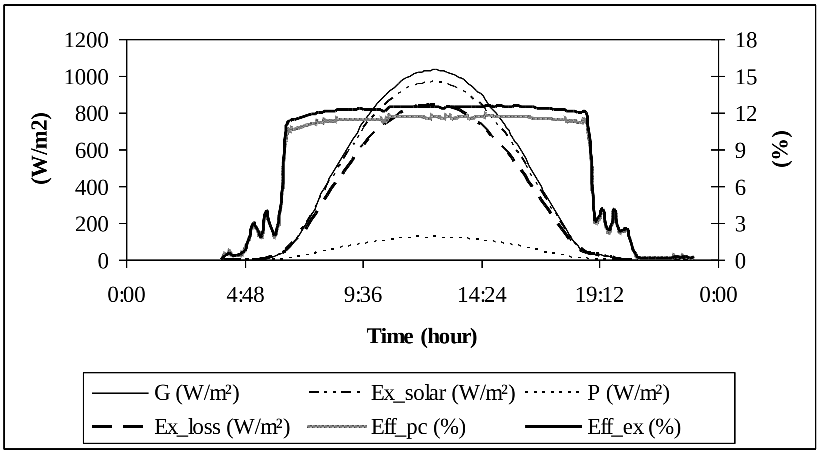


Fig. 3.4. Variation of exergy, power conversion efficiencies and other parameters of pc-Si PV module on a typical day

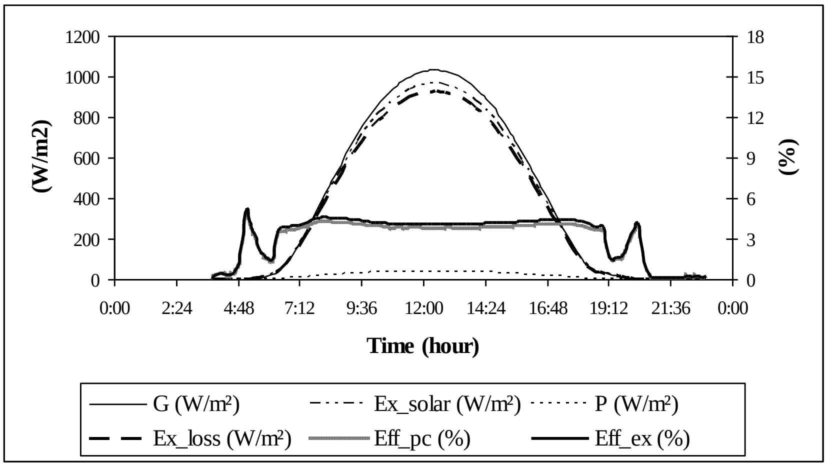


Fig. 3.5. Variation of exergy, power conversion efficiencies and other parameters of a-Si PV module on a typical day

Based on Figs 3.4 and 3.5, in view of average effective sun hour in that day, it can be seen that the average of η_{ex} and η_{pc} for pc-Si PV module are 12% and 11%, respectively, meanwhile for a-Si PV module are 4% and 3.8%, respectively. In this case, due to the solar irradiance (G) is always larger than the solar radiation exergy (Ex_{solar}), and actual electricity generated is used for both analyses, the power conversion efficiency of the PV modules is always smaller than the exergy efficiency.

As expected, the energy and exergy efficiencies of pc-Si PV module higher than a-Si PV module. It is reasonable that in order to get more realistic modelling of PV systems, application of exergy analysis are strongly encouraged. The thermodynamic characteristics showed that both the PV modules, in average, have low exergy efficiencies, i.e. 12% and 4% which equal with anergy (energy losses) of 88% and 96% for pc-Si and a-Si, respectively.

3.4. Comparison of efficiency exergy based on thermodynamic approach and photonic energy models

In section 3.2, efficiency exergy theoretically has been evaluated by using thermodynamic approach. In this section, efficiency exergy based on thermodynamic approach will be compared with efficiency exergy which calculated by using others method, i.e. photonic energy method.

In the photonic energy method, calculated are performed by varying wavelength of the visible spectrum, for a given range of 400 to 800 nm. Figs 3.6-7 show the variation of available of photonic energy (chemical potential) as an input exergy, and exergy of PV modules (as an ouput) corresponding to the available of photonic energy, during a year. If available of photonic energy is known, the exergy of PV can be determined through the following correlation:

$$\dot{E}x_{pv} = \eta_{pc}\, \dot{E}n_{chemical}\,. \tag{5}$$

As an approach, the value of η_{pc} is taken from Table 3.2.

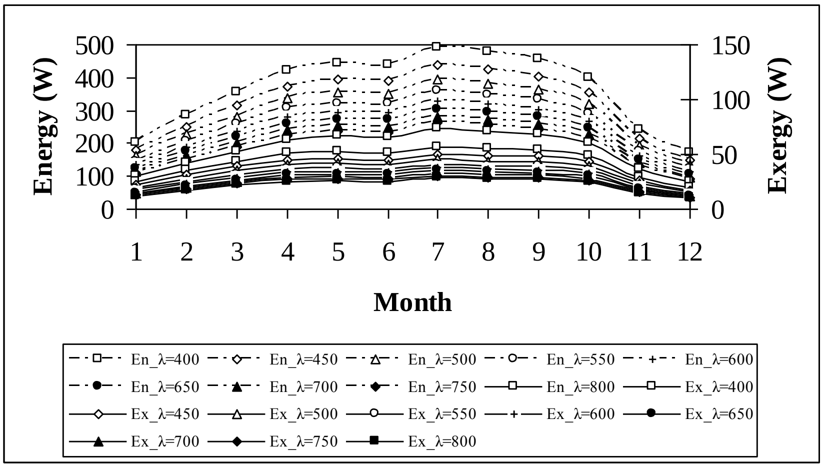


Fig. 3.6. The photonic energy and exergy of pc-Si PV module (yearly base)

All the PV modules (in this case pc-Si and a-Si) showed that the highest exergy of solar radiation (available of photonic energy) and exergy of PV modules can be generated by spectrum of solar irradiance with short wavelength, and vice versa.

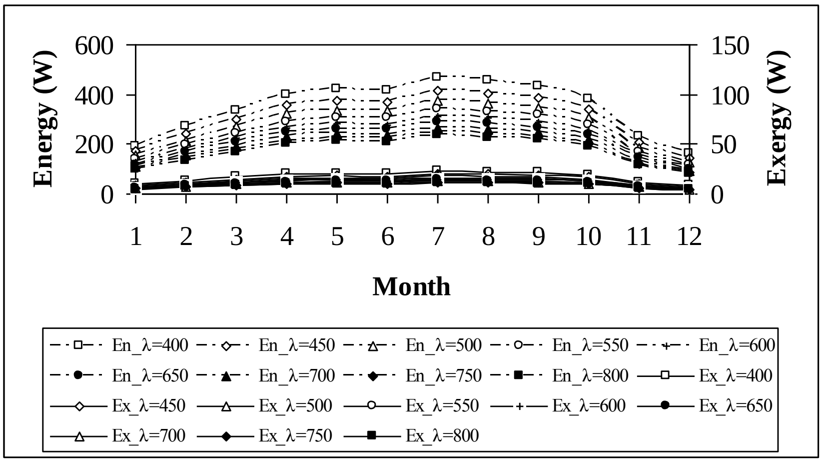


Fig. 3.7. The photonic energy and exergy of a-Si PV module (yearly base)

The rate of photons (N_{ph}) falling on the PV surface is an important factor in order to evaluate the exergy efficiency based on "photonic energy". Available of photonic energy, as an input parameter in order to evaluate the PV module performance, can be evaluated as a function of wavelength.

Comparison between efficiency exergy based on photonic energy (in various wavelengths), exergy efficiency based on thermodynamic approach and energy efficiency is shown in Figs 3.8-9.

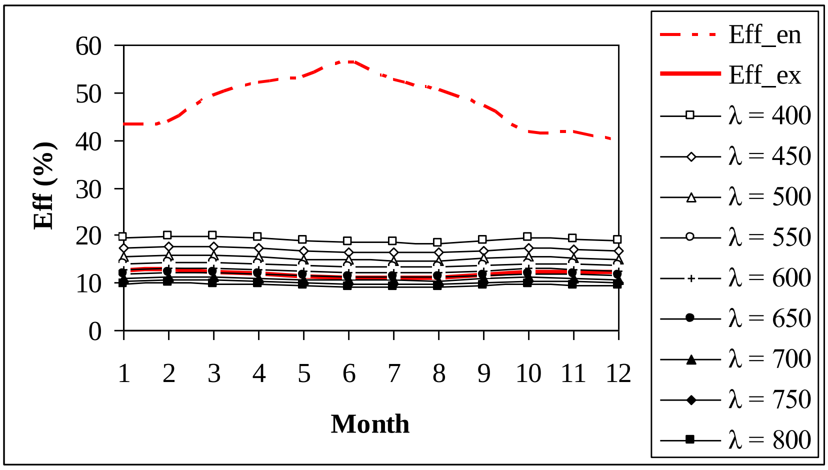


Fig. 3.8. Pc-Si module energy and exergy efficiencies based on two approaches

Based on Figs 3.8-9, it can be seen that energy efficiency of PV higher than exergy efficiency of PV, 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.

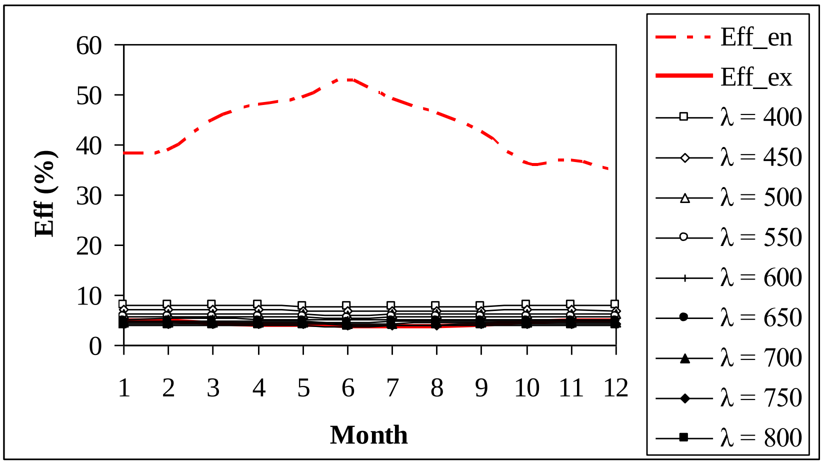


Fig. 3.9. A-Si module energy and exergy efficiencies based on two approaches

Based on Figs 3.8-9, it also can be seen that for the same case, exergy efficiency based on "thermodynamic approach" is spread between exergy efficiency values based on "photonic energy" in the varying wavelength of the visible spectrum.

3.5. Fill factor effects on exergetic performances of PV modules

The Fill Factor (*FF*) measures of quality of the PV cell. It is evaluated by comparing the maximum power (P_{max}) to the theoretical power that would be output at both the V_{oc} and I_{sc} together. A larger fill factor is desirable, and typical fill factors range from 0.5 to 0.85.

Variability of fill factor (*FF*) on exergy performance of pc-Si and a-Si PV modules have been evaluated, and the results are shown in Figs 3.10-11.

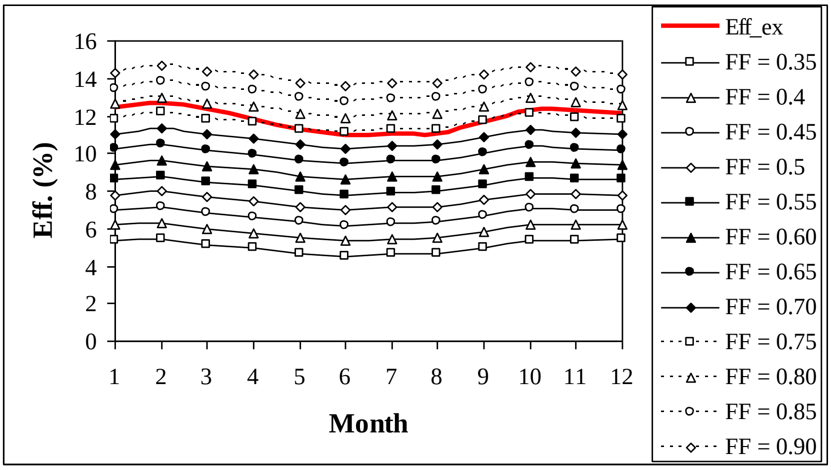


Fig. 3.10. Effect of fill factor (*FF*) on the exergy performance (pc-Si)

In Laboratory scales, generally the *FF* values of PV cell are around 0.80 for pc-Si and 0.74 for a-Si.

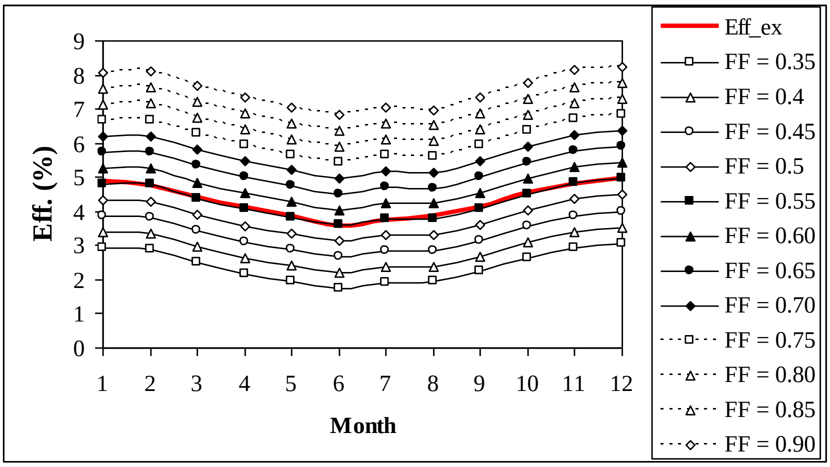


Fig. 3.11. Effect of fill factor (*FF*) on the exergy performance (a-Si)

Based on simulation it is found that yearly average of *FF* for pc-Si, in range between 0.75 – 0.80, and for a-Si in range 0.50 – 0.60.

3.6. Spectral irradiance effects on performances of PV module

The performance of photovoltaic (PV) systems is influenced by spectrum of solar irradiance even under the same solar irradiance conditions. In term of wavelength, the spectrum (light) of solar irradiance can be divided into three main regions i.e. ultraviolet region with λ < 0.4 μm (~ 5% of the irradiance), visible region with 0.4 μm < λ < 0.7 μm (~ 43% of the irradiance) and infrared region with λ > 0.7 μm (~ 52% of the irradiance).

In order to get real phenomena and correlation about effects spectral on the PV performance in term of exergetic, as an initial study, the characteristic of spectral solar irradiance in Gödöllő climates, as presented in Fig. 3.12 will be interpreted.

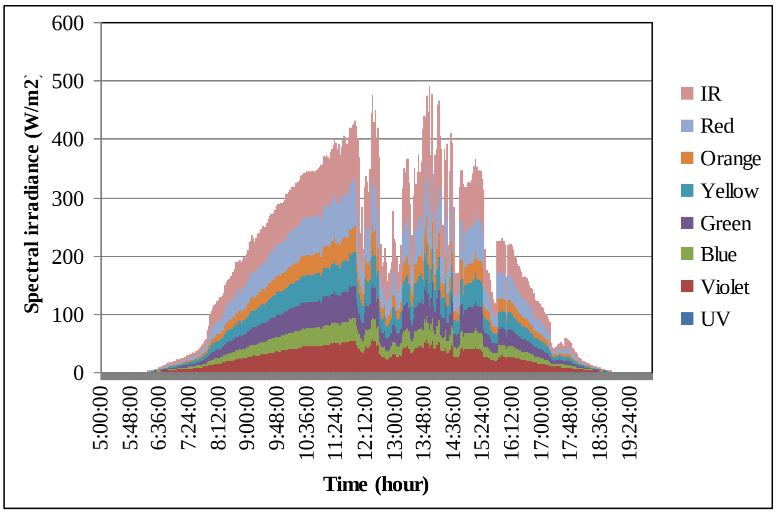


Fig. 3.12. Spectral irradiance characteristics

Based on Fig. 3.12, it clear that although the red spectral irradiation (in visible region) and infra red (in invisible region) have the lower energy (and exergy), as a consequences of high wavelength, nevertheless both are more important than the rest due to their give big distribution on the whole day (not just in solar peak hours).

Physically, light with energy too high or low is not usable by a PV systems to produce electricity (called as optical losses: thermalization and non-absorption).

4. NEW SCIENTIFIC RESULTS

The new scientific results of my PhD work can be summarized as follow:

1. I have proven that the maximum annual output of the small scale (up to 10 kWp) capacity of grid-connected PV array system, can be obtained at the tilt angle in the range of 30° to 34°. Various values of tilt angle in this range, will affect on the annual output (an electric energy production) between 1-6%.

   The overall array performance for a different surface azimuth angle less than 5° either to East or to West, in case of facing to South, will affect on the annual output less than 1%.

2. I have evaluated the yearly thermodynamics performances of two most frequently applied photovoltaic modules theoretically, i.e. polycrystalline silicon, pc-Si (which included wafer based crystalline silicon technology), and amorphous silicon, a-Si (which included thin film technology), in view of energy and exergy.

   It is found that energy efficiency (η_{en}) of PV modules 75% and 90% higher than exergy efficiency (η_{ex}), respectively for pc-Si and a-Si, due to the energy efficiency is based on the electrical energy and the thermal energy (which available on the PV surface) as an output, meanwhile exergy efficiency considers only electrical energy as an output.

   It is also found that thermodynamic efficiencies of PV modules in power conversion (η_{pc}) and exergy there are differences, specifically 1% and 12%, respectively for pc-Si and a-Si.

   The efficiency maximum (η_{max}) are 25% and 52% higher than η_{ex}, 24% and 45% higher than η_{pc}, respectively for pc-Si and a-Si, because η_{max} is calculated based on I_{sc} and V_{oc}, as ideal values.

   The results showed that performance evaluations of PV modules with exergy analysis will lead us getting a realistic values rather than energy analysis, if compared to efficiency power conversion (efficiency of electric).

3. I have evaluated exergy efficiency and power conversion efficiency based on operational data.

   Compared to theoretical evaluation, in case of η_{ex} it is found that difference the theoretical and experimental efficiencies are 1.5% and 7%, respectively for pc-Si and a-Si, meanwhile in case of η_{pc} it is found that the difference between theoretical and experimental efficiencies are 8% and 22%, respectively for pc-Si and a-Si.

In general, it can be stated that the difference of values between theoretically and experimentally in terminology of efficiencies exergy and power conversion are less than 25%.

4. I have compared two exergetic methods for evaluating of PV modules performance based on “thermodynamic approach for solar energy” and “photonic energy”, theoretically. Performance evaluation by photonic energy method was performed in the range of wavelength 400-800 nm.

   It is found that exergy efficiency based on “thermodynamic approach for solar energy” is spread on the exergy efficiency based on ”photonic energy” in the range of wavelength 550-650 nm and 600-800 nm, respectively for pc-Si and a-Si.

   It is also proving that both methods of the PV exergy assessment give more realistic values rather than the PV energy assessment.

5. I have investigated of the fill factor effect (*FF*) on the exergetic efficiency of PV modules, theoretically. Based on evaluation, it was found that yearly average of *FF* for pc-Si PV module is in range between 0.75-0.80, and for a-Si PV module, in range between 0.50-0.60.

   Compared to *FF* values in Laboratory scale, it is found that existing *FFs* are equal for pc-Si and lower 19-32% for a-Si.

6. I have investigated a spectral irradiance characteristic, as initial stage in order to find the effect of spectral irradiance on the exergetic of PV modules performances.

   It has been concluded that the red spectral (in visible region) and infra red spectral (in invisible region) are more important than the rest, due to their distribution on the whole day (not just in solar peak hours). Nevertheless, both have lower energy (and also exergy), as a consequences of a high wavelength.

   As an important irradiance element in visible region, the red spectral have an average irradiance 200 W/m^2, in between time 08:00-16:00. Meanwhile, as an irradiance element with highest energy, the violet spectral have an average irradiance 25 W/m^2, in the same time interval. Difference of solar irradiance between red and violet spectral in that time interval is 87.5%.

5. CONCLUSIONS AND SUGGESTIONS

Based on the recent work, all the relevant parameters, conducted to the photovoltaic (PV) modules performances have been identified and elaborated. The existing of 10 kWp grid-connected PV array system, which used two PV modules technologies i.e. wafer based crystalline silicon (pc-Si type) and thin film (a-Si) as main components, have been evaluated. It is clear that the installation having the right position, conducted to surface orientation in order to maximize the yield of electric energy.

The thermodynamics performances of PV modules have been evaluated either theoretically or experimentally, in view of energetic (involves only the First Law Thermodynamic) or exergetic (involves both the First and Second Law of Thermodynamics). Based on theoretical evaluation, it is found that average energy and exergy efficiencies during a year were 47.66% and 11.82% for pc-Si, and 43.20% and 4.30 for a-Si. Meanwhile based on experimental in specific day, it is found that an average exergy efficieny during effective sun hours were 12% and 4%, for polycrystalline silicon and amorphous silicon.

As an expected, the energy and exergy efficiencies of pc-Si PV module was higher than a-Si PV module. Finally, in order to get more realistic modelling of PV systems, application of exergy analysis are strongly encouraged.

Beside as a comparison purpose, further outcome of this research is trying to find a possibility to increase the performances both solar PV modules, in PV array system at Szent István University.

As a follow up of this research, sequences activities below needs to be implemented, in order to achieve further research outcome:

- Further parametric studies, 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.
- Collect comprehensive operational data of a 10 kWp grid-connected PV array system at Szent István University.
- Conduct an available spectral measurements data to the concept exergetic performances based on photonic energy.
- Develop/integrate correlation about the energy - exergy mathematical model of PV system into the block oriented solution algorithm on the MATLAB/Simulink block libraries.
- Develop the real time and transient software for exergy analysis based on calculations method that have been elaborated in this research.
- Make a colaboration and synergy with Institute of material, in order to perform comprehensive research, included in view of material aspects.

6. SUMMARY

In this research comprehensive evaluation of two photovoltaic (PV) modules technologies i.e. polycrystalline silicon (pc-Si) included wafer based crystalline silicon technology, and amorphous silicon (a-Si) included thin-film technology, as components of grid-connected PV array at Szent István University (SZIU), have been performed in view energetic and exergetic. It is well known that energy evaluation is more suitable for energy balance when we design a system, while exergy evaluation is more appropriate when we evaluate the performance of a system qualitatively.

First of all, evaluation on the existing grid-connected PV array system in view of macro model has been performed in order to find the best surface orientation of PV module, which maximize the yield of electric energy.

Furthermore, thermodynamic performance of polycrystalline silicon and amorphous silicon PV modules are evaluated in term of efficiencies of energy (η_{en}), exergy (η_{ex}), power conversion (η_{pc}) and maximum/theoretical (η_{max}). Based on this evaluation, we will know which the most important of efficiencies, conducted to PV modules performance.

Exergy efficiency (η_{ex}) and power conversion efficiency (η_{pc}) of PV modules are simulated (yearly base) by two methods i.e. "thermodynamic approach method" and "photonic energy method", and after that are evaluated based on operational data for a specific day. Sensitivity of fill factor (*FF*) on exergetic performance have been evaluated also in this research.

As one of an important aspect in the utilization of solar energy, effect of spectral irradiance on the PV modules performance has been initialized also in this research.

Based on study and discussion of the results, in general it can be concluded that the energy efficiency is higher than theoretical, power conversion and exergy efficiencies throughout the year. Based on exergy analysis, it clear that there is an opportunities to increase the real of PV modules performances (in this case pc-Si and a-Si), until close to the theoretical efficiency (as an ideal value), which can be performed through various field of research and methods. Currently, one of a method i.e. tandem cells method (multi junction method) has been offered and used widely in the world, in order to increase the power conversion efficiency of PV systems (solar cells/module).

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Refereed papers in foreign languages:

1. **Rusirawan, D.** and Farkas, I. (2012): Spectral irradiance effects on exergetic performances of photovoltaic module: initial study, Mechanical Engineering Letter, Szent István University, Vol. 8 (submitted).
2. **Rusirawan, D.** and Farkas, I. (2012): Thermodynamic efficiencies of solar photovoltaic modules, Environmental Engineering Management Journal (accepted for publication). (IF: 1.004*).
3. **Rusirawan, D.** and Farkas, I. (2012): Availability of the photovoltaic modules in view of photonic energy, Scientific Monograph: Applications of Physical Research in Engineering, Part 1, pp. 42-61.
4. **Rusirawan, D.** and Farkas, I. (2011): Characterizations based an experimental of two photovoltaic module technologies, Mechanical Engineering Letter, Szent István University, Vol. 6, pp. 112-122.
5. **Rusirawan, D.** and Farkas, I. (2011): The photovoltaic modules performance based on exergy assessment, Hungarian Agricultural Engineering No. 23, pp. 53-56.
6. **Rusirawan, D.** and Farkas, I. (2011): Simulation of electrical characteristics of polycrystalline and amorphous PV modules, Electrotechnics, Electronics Automatics, Vol. 59, No. 2, pp. 9-15.

Refereed papers in Hungarian:

7. **Rusirawan D.**, Farkas I. (2012): Napelem modulok teljesítmény növelése érdekében kidolgozott technológiák, Mezőgazdasági Technika, LIII. Evfolyam, július 2012, 5-7. o.
8. Farkas I., **Rusirawan D.**,Galambos E. (2012): Hálózatra kapcsolt napelem mező cella/modul alapú modellezése, Magyar Energetika, XIX évfolyam, 2. sz., 6-9. o.