

Acta Technologica Agriculturae 1  
Nitra, Slovaca Universitas Agriculturae Nitriae, 2019, pp. 5–11

## EFFICIENCY COMPARISON OF DIFFERENT PHOTOVOLTAIC MODULES

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Solar photovoltaic power generation capacity is rising continuously as a result of various regional, sub-regional renewable energy policies and the impact of technology development, as well as the increasing environmental concerns. Characteristics of photovoltaic modules are provided by manufacturers after they have been tested indoors under standard test conditions. These parameters may vary under exterior conditions. It is thus imperative to establish the quantity of the energy produced by photovoltaic modules under real operation conditions. This study sought to assess the performance of different kinds of photovoltaic module technologies in the city of Gödöllő, Hungary, and ascertain the behaviour of the modules under real outdoor conditions. Modules include amorphous silicon (a-Si), monocrystalline silicon (mc-Si), polycrystalline silicon (pc-Si), transparent monocrystalline silicon module (mc-Si). Measurement of the module characteristics was performed and various meteorological parameters were obtained. Performance parameters such as performance ratio and efficiency are given and analysed. Module temperature was estimated and evaluated in comparison with experimental values. Energy conversion rates of the modules were determined as 9.4%, 4.4%, 10.3%, 8.2% and 10.4% for mc-Si module transparent glass (165 Wp), a-Si module (glass 40Wp), pc-Si module (105 Wp), pc-Si module (60 Wp) and mc-Si (PV-T 180 Wp), respectively. Under the given outdoor conditions, the highest average performance ratio of 85.2% was obtained for the mc-Si module (transparent glass, 165 Wp), exhibiting the best performance, while pc-Si module (60 Wp) showed the least average performance ratio of 71.8%.

**Keywords:** photovoltaic technologies; energy yield; field performance; energy conversion rate

The Sun, a silent, free and non-polluting source of energy, is responsible for all forms of life on earth. Sun's harnessable energy is endless in the nearest foreseeable time, both as a source of heat and light. Without doubt, it is one of the most promising energy source alternatives for meeting the challenges of this millennium. Sunlight, which is available everywhere on the Earth, is virtually responsible for all other energy sources. Therefore, energies from the other energy sources are virtually derived from the Sun.

Solar PV (photovoltaics) has become a ubiquitous source of renewable energy (Bilčík et al., 2018). Solar PV power market is increasing continuously as a result of the various regional, sub-regional and country renewable energy policy schemes. Other factors accounting for this expansion include the depleting status of fossils fuels caused by the increasing energy demand, impact of technology development, lower cost of technology and environmental concerns.

Data sheets of PV modules provide characteristics that are determined by manufacturers in an interior laboratory under a controlled STC (standard test conditions), which include a cell temperature of 25 °C, radiation intensity of 1,000 W·m<sup>-2</sup> and air mass AM1.5. Not only spectral reactions, temperature coefficients, voltage and current values of individual solar cells and module types differ, but their reactions to environmental factors like radiation, temperature and wind speed vary as well. However, solar spectrum varies depending on geographical location (Atsu et al., 2017).

There is an increase in the diversity of available technologies of solar cells integrated in PV modules – from thin films to crystalline silicon, which still dominates the market with nearly 90% (IEA, 2014). The most common PV module types currently available have energy efficiencies of approximately (7–11)% a-Si and (14–19)% (c-Si, single or double face). Other available module type is triple-junction PV with concentrating lenses with energy efficiency approximately (23–27)%. Future multi-junction cell structures are expected to increase the average efficiency from current 40% to over 50% (King et al., 2012). To choose a particular technology of solar module for an individual site, it is important to establish the energy yield of the module under real meteorological conditions of the specific location.

Studies by Singh (2013), Carr and Pryor (2004), Del Cueto (2002), Cañete et al. (2014) and Balaska et al. (2017) show the dependence of PV energy efficiency and final power output on conditions that deviate from STC for different mounting geometries and PV materials extending the range of useful predictions of PV cells performance.

Majority of these relationships are either theoretical or semi empirical, founded on laboratory measurements, and as a result, they do not incorporate the entire range of interdependencies between the various environmental factors. These, however, may have a pronounce effect on the actual PV efficiency and power output (Durisch et al., 2007).

**Table 1** Geographical site parameters for Gödöllő (PVsyst 6.7.0)

Period	Global irradiation (kWh·m <sup>-2</sup> ·d <sup>-1</sup> )	Diffuse irradiation (kWh·m <sup>-2</sup> ·d <sup>-1</sup> )	Temperature (°C)	Wind speed (m·s <sup>-1</sup> )
January	0.97	0.69	-0.6	2.78
February	1.84	0.94	1.1	3.00
March	2.93	1.46	5.6	3.41
April	4.41	2.08	11.7	3.10
May	5.53	2.44	17.1	2.99
June	5.99	3.00	19.6	2.89
July	5.98	2.85	21.8	3.09
August	5.00	2.22	21.3	2.71
September	3.60	1.81	15.6	2.61
October	2.31	1.19	11.3	2.6
November	1.14	0.73	5.7	3.00
December	0.81	0.51	0.2	2.49
<b>Year average</b>	<b>3.38</b>	<b>1.66</b>	<b>10.9</b>	<b>2.49</b>

Considering this area, multiple studies have been conducted in different locations to assess the impact of environmental factors on the performance of different cell technologies or numerous studies have set their goals to determine the best operation conditions for the specific sites.

Study by Ye et al. (2014) evaluates the performance of a-Si and mc-Si modules according to radiation distribution, temperature and other external environment factors – authors observed that a-Si modules were more efficient in the blue rich spectrum, whereas the mc-Si modules showed efficiency varying with changes in cell temperature. Sharma et al. (2013) evaluated different on-grid PV systems with arrays of different module technologies in India. They concluded that systems with a-Si and HIT modules showed better results than pc-Si modules.

Cañete et al. (2014) performed a comparative study under meteorological conditions in Southern Spain on four different PV module technologies: a-Si, tandem structure of a-Si/ $\mu$ c-Si, cadmium telluride (CdTe) and pc-Si module. Results of their study showed that performance of thin film modules is better than that of pc-Si modules for this location.

Basoglu et al. (2015) compared the energy performance of three different PV module technologies under Izmit, Kocaeli climatic conditions in Turkey. Module technologies were mc-Si, c-Si and CdTe. They concluded that CdTe modules are more acceptable for climatic condition in Izmit.

Aforementioned studies have shown that each of the PV technologies has unique merits and limitations in operation under various climatic conditions (Cristina et al., 2014).

The amount of usable solar radiation at any site is dependent on the angle of inclination and equipment orientation, as well as on intensity of total solar radiation. In comparison to other European countries, Hungary has more favourable conditions for PV. Annual sunshine hours range between 1,900 and 2,200 hours. Annual average global irradiation of Gödöllő is approximately 3.38 kWh·m<sup>-2</sup>·d<sup>-1</sup> and diffuse irradiation is 1.66 kWh·m<sup>-2</sup>·d<sup>-1</sup> (Table 1). This makes

Hungary an appropriate location for the utilization of solar energy for energy generation.

Our study aims to assess the performance of different kinds of PV module technologies (a-Si, mc-Si, pc-Si, transparent mc-Si) under real outdoor conditions. Performance parameters, such as performance ratio and efficiency, are given and analysed.

## Material and methods

### Experimental setup

Experimental setup was located at the Solar Energy Laboratory of the Szent István University, Gödöllő, Hungary situated at latitude 47° 35' 39" N, longitude 19° 22' 0" E. PV modules types used and their specifications under laboratory STC are summarized in Table 2. PV modules were inclined to a fixed physical support outside the lab and oriented to the south with an inclination corresponding to the site latitude. The modules' output power, voltage and current were measured automatically using the Geräte Unterricht Naturwissenschaft Technik (G.U.N.T) PV setup as shown in Fig. 1. Solar radiation was measured with a Kimo solarimeter LSL 200 at the level and inclination of the PV modules (resolution 1 W·m<sup>-2</sup>, accuracy 5%). Temperature of PV modules, ambient temperature of PV modules and ambient temperature were measured using HT-9815 Xintest Pt-100 sensors ( $\pm 0.1$  °C).

### Performance analysis

Performance of individual modules was evaluated in accordance the IEC standard (IEC 61724) describing the parameters of solar modules. Certain parameters like yield, performance ratio efficiency, were calculated.

### Module yield

Specific module yield ( $Y_a$ ) is defined as the ratio of the energy output from the module to a particular duration to its rated power:



Fig. 1 PV modules and experimental setup for data collection

Table 2 Technical specifications of PV modules under STC

Parameters	a-Si (Glass) (DUNA SOLAR)	mc-Si (Glass) (SOLARWATT)	pc-Si (60Wp) (SOLAREX SM2160)	pc-Si (105Wp) (RWE SCHOTT SOLAR)	PV-T glazed (mc-Si) (SOLIMPEKS)
$V_{oc}$ (V)	62.5	23.4	21.3	29.5	43.39
$I_{sc}$ (A)	1.15	9.02	3.8	4.92	5.55
$V_{mpp}$ (V)	44.0	19.2	17.1	23.5	35.15
$I_{mpp}$ (A)	0.90	8.71	3.5	4.47	5.12
$P_{mpp}$ (Wp)	40	165	60	105	180
Module area (m <sup>2</sup> )	0.791	1.62	0.564	0.826	1.427
Temp. coeff. of power	-0.47	-0.40%/°C	-0.47	-0.47%/°C	-0.45%/°C
Temp. coeff. of $V_{oc}$	-0.36%/	-0.32%/°C	-0.073%/°C	-0.38%/°C	-0.34%/°C
Temp. coeff. of $I_{sc}$	+0.04%/	0.05%/°C	0.003%/°C	+0.10%/°C	+0.06%/°C
Efficiency	5%	10.3%	10.6%	12.7%	12.6%

PV-T – photovoltaic thermal,  $V_o$  – open circuit voltage,  $I_{sc}$  – short circuit current

$$Y_a = \frac{E_{DC}}{P_{PV, rated}} \quad (1)$$

$$P_m = P_{mSTC} \times \frac{G}{G_{STC}} \times (1 - \gamma(T_c - 25)) \quad (3)$$

where:

- $P_m$  – calculated output power (W)
- $P_{mSTC}$  – maximum rated power at STC given by the manufacturer (W)
- $G$  – solar radiation intensity on the plane of the module (W·m<sup>-2</sup>)
- $G_{STC}$  – solar radiation intensity of 1,000 W·m<sup>-2</sup>
- $\gamma$  – maximum power correction factor for temperature
- $T_c$  – module temperature (°C)

### Solar module temperature

Considering the calculation of the module temperature ( $T_c$ ), following model is used:

$$T_c = T_a + \frac{G}{G_{STC}} \times (T_{NOCT} - 20) \quad (2)$$

where:

- $T_a$  – ambient temperature (°C)
- $T_{NOCT}$  – nominal operating cell temperature given by the manufacturer (°C) (NOCT – nominal operating cell temperature)
- $G$  – measured solar irradiation over the surface of the module (W·m<sup>-2</sup>) (Duffie and Beckman, 2006)

### Solar module output power

Solar module output power is calculated from the model taking into account the linear dependence of output power on the solar irradiance and cell temperature. It is given by Eq. (3):

### Solar module efficiency

Instantaneous efficiency of the module is defined as follows:

$$\eta = \frac{P}{(G \times A)} \quad (4)$$

where:

- $\eta$  – efficiency (%)
- $P$  – measured power output (W)
- $G$  – measured solar irradiation (W·m<sup>-2</sup>)
- $A$  – surface area of the module (m<sup>2</sup>) (Duffie and Beckman, 2006)

However, model given by Eq. (5) is necessary for calculation of instantaneous efficiency:

$$\eta = \eta_{Tref} (1 - \beta_{ref} (T_c - T_{ref}) + \gamma \lg G_T) \quad (5)$$

where:

- $\eta$  – instantaneous efficiency;
- $\eta_{Tref}$  – efficiency at the reference condition (%)
- $\beta_{ref}$  – temperature coefficient
- $T_{ref}$  – temperature at the reference condition (°C)
- $T_c$  – solar module temperature (°C)
- $\gamma$  – correction factor for the irradiance
- $G_T$  – solar irradiance intensity ( $W \cdot m^{-2}$ ) (Almonacid et al., 2011)

However, following module is used for the majority of c-Si modules:

$$\eta = \eta_{Tref} (1 - \beta_{ref} (T_c - T_{ref})) \quad (6)$$

where:

- $\eta$  – instantaneous efficiency
- $\eta_{Tref}$  – efficiency at the reference condition (%)
- $T_{ref}$  – temperature at the reference condition (°C)
- $\beta_{ref}$  – temperature coefficient
- $T_c$  – solar module temperature (°C)

**Performance ratio (PR)**

Performance ratio is the ratio of the PV module/system efficiency during operation to its efficiency at STC as given by Eq. (7):

$$PR = \frac{\eta_{syst}}{\eta_{STC}} \quad (7)$$

PR shows the closeness of a PV system to the ideal performance during real operation conditions and allows comparison of PV systems independently of location, tilt angle, orientation and their nominal rated power capacity (Ayompe et al., 2011).

**Results and discussion**

This part explains the measured data obtained during the experiment in detail and compares measured data for the individual modules with the characteristics given by manufacturer.

Incident radiation onto the modules was quite stable throughout the period of the experiment. Maximum value observed was  $965 W \cdot m^{-2}$  and minimum value recorded was  $915 W \cdot m^{-2}$  with an average radiation of  $935 W \cdot m^{-2}$  as shown in Fig. 2. Ambient temperature and module temperature measured are shown in Fig. 3. Results indicate a maximum ambient temperature of 37 °C and an average temperature of 35 °C for the experiment duration.

The pc-Si (105Wp) module had the highest recorded temperature (61 °C) during the experiment. Minimum temperature of 54.7 °C was observed in the mc-Si (165Wp) glass module. Average temperatures of the various modules were 57.7 °C, 58.9 °C, 58.7 °C, and 58.0 °C for mc-Si 165Wp

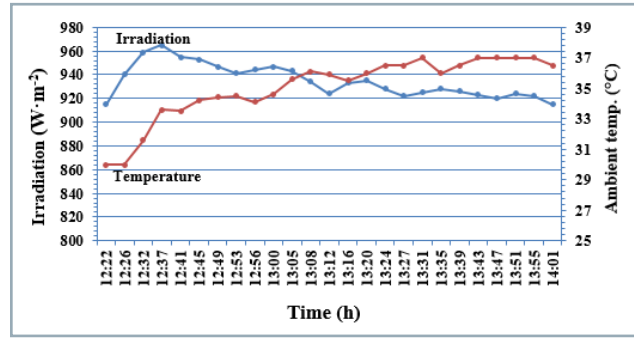


Fig. 2 Variation in ambient temperature with irradiation

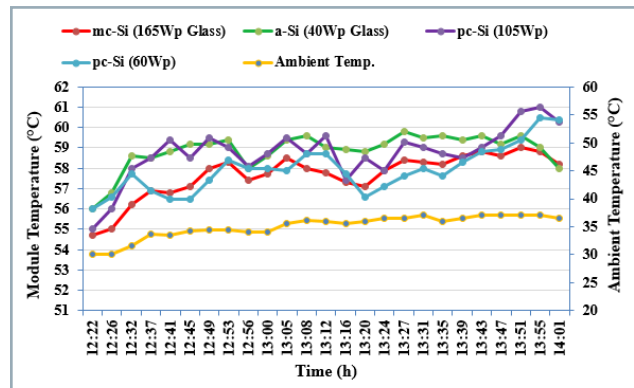


Fig. 3 Trends in module and ambient temperatures

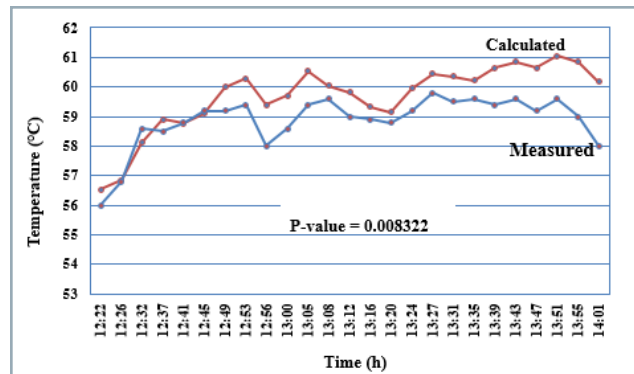


Fig. 4 Comparison between calculated and measured module temp. a-Si (40 Wp Glass)

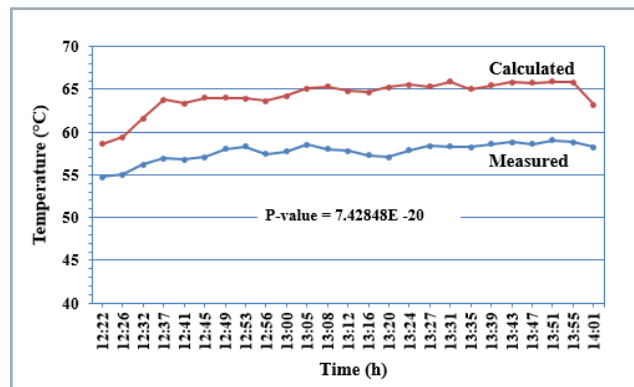


Fig. 5 Comparison between calculated and measured module temp. (mc-Si -165 Wp Glass)

glass, a-Si 40Wp Glass, pc-Si, 105Wp, pc-Si 60Wp respectively. Maximum average value of 58.87 °C was observed in the a-Si 40Wp glass module and minimum average temperature of 57.77 °C was observed in mc-Si 165 Wp glass module.

As Figs. 4, 5, 6, and 7 show, calculated average module temperature was 58.76 °C. Subsequently, minimum and maximum values were 55.64 °C and 60.16 °C respectively.

Measured temperatures for mc-Si (165 Wp Glass) were lower than the calculated module temperatures throughout the entire experiment as shown in Fig. 5. Mc-Si (165 Wp Glass) also showed the highest significant deviation between the measured and calculated values. With the exception of the pc-Si (105 Wp), which showed no significant difference between the measured and calculated temperatures, the mc-Si (165 Wp glass), a-Si (40 Wp) and pc-Si (60 Wp) had significant deviations as shown by their *P*-values. The greatest deviation was observed in the mc-Si -165 Wp module.

Measured average temperatures for the modules were 57.66; 58.87; 58.74 and 57.93 °C for mc-Si (165 Wp glass), a-Si (40 Wp), pc-Si (105 Wp) and pc-Si (60 Wp) respectively. Each module showed a different trend of measured temperatures corresponding with the calculated module temperatures as shown in Figs. 4, 5, 6, and 7.

Fig. 8 demonstrates the module efficiencies with variation in irradiation levels – initial high efficiency values of all modules are as a result of increasing irradiation (for initial 20 minutes). Subsequently, after this point, there is a gradual decrease in irradiation with corresponding decrease in efficiency for all the modules.

Figs. 9, 10, 11 and 12 present the relationships between the efficiencies and module temperatures. Results show a corresponding decrease in efficiency for all studied modules with increases in the module temperatures.

However, this trend of efficiency decreasing is not smoothly continuous. Corresponding effect of change in temperature of the module, whether increasing or decreasing, can be seen in the varying efficiency of the modules. However, for the pc-Si (105 Wp) module, the efficiency of the module began to increase with increase in module temperature at module temperature  $\geq 58$  °C.

Table 3 compares the efficiencies determined by experimental data with manufacturer’s values.

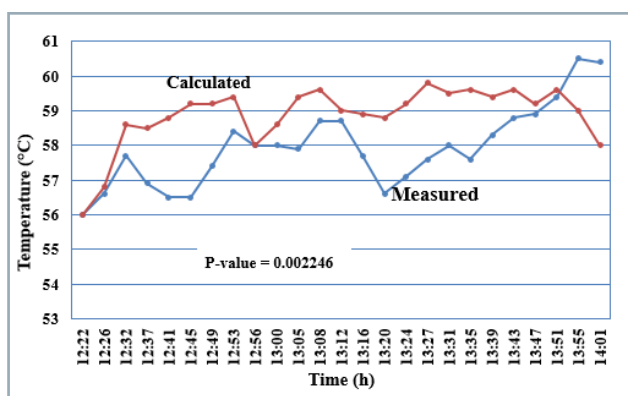


Fig. 6 Comparison between calculated and measured module temp. pc-Si (60Wp)

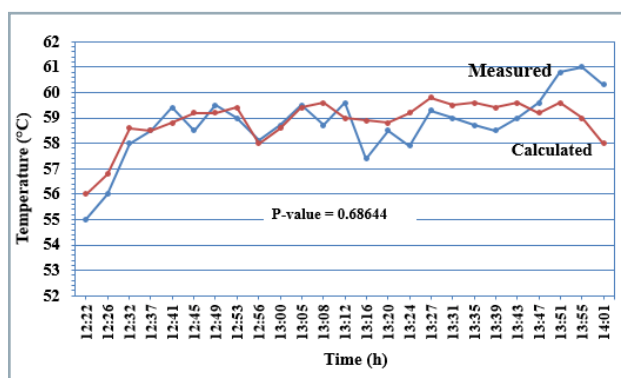


Fig. 7 Comparison between calculated and measured module temp. pc-Si (105Wp)

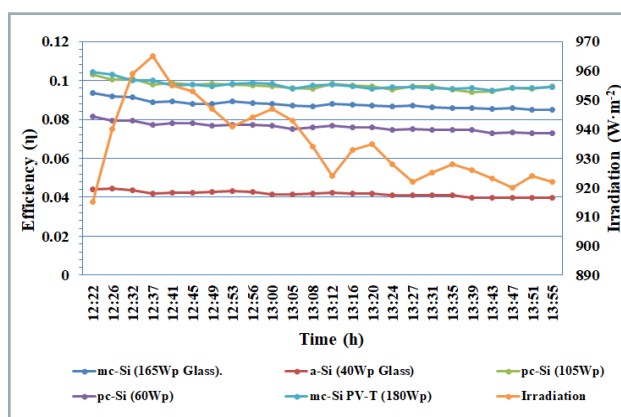


Fig. 8 Variation of efficiency of modules with irradiation

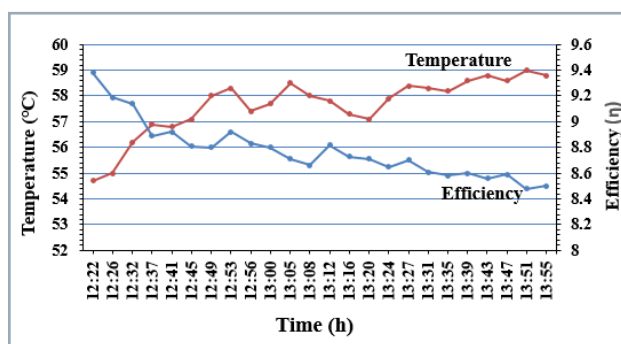


Fig. 9 Relationship between efficiency and temperature of module mc-Si (165 Wp Glass)

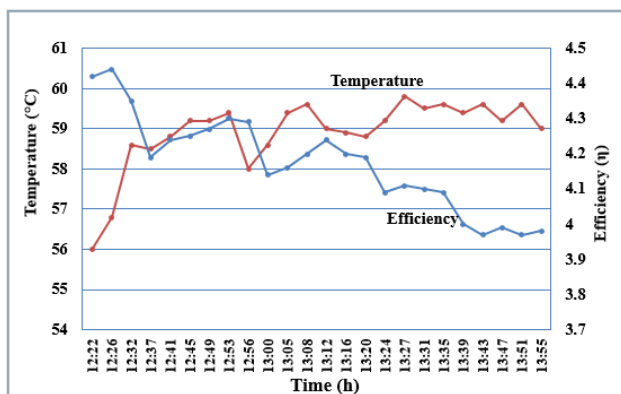
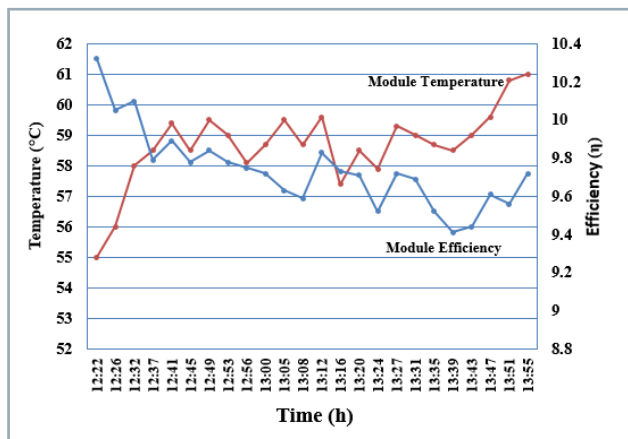
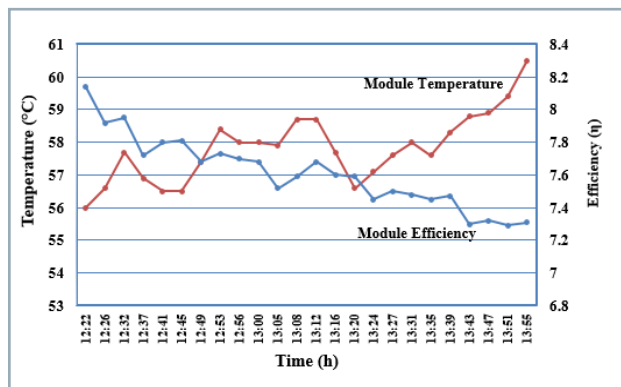


Fig. 10 Relationship between efficiency and temperature of module a-Si (40Wp Glass)



**Fig. 11** Relationship between efficiency and temperature of module pc-Si (105 Wp)



**Fig. 12** Relationship between efficiency and temperature of module pc-Si (60 Wp)

Results show varying deviations depending on the technology. As shown in Table 3, the highest deviation from the manufacturer’s values was 2.4, obtained for pc-Si module (60 Wp), while the lowest deviation from the given manufacturer’s efficiencies was 0.6, obtained for a-Si module (40 Wp). It is worth mentioning that this module has already been in operation for approximately 20 years. However, the highest percentage deviation of -22.6% was recorded for the pc-Si module (60 Wp), while the minimum percentage deviation of -8.7% was obtained for the mc-165 Wp transparent module as shown in Table 3. In literature, results by Balaska et al. (2017) indicated daily mean efficiencies of 8.38% and 12.63% for m-Si<sub>μ</sub>c-Si, and mc-Si, respectively. Cañete et al. (2014) also recorded an efficiency of 9.3% for CdTe, 6.3% for a-Si, 13.2% for pc-Si and 8.0% for a-Si/ $\mu$ mc-Si. Determining the percentage deviation between the manufacturer’s values and the experimentally obtained efficiency, Cañete et al. (2014) recorded -4.1% deviation for CdTe, -4.8% for a-Si, -5.9% for a-Si/ $\mu$ mc-Si and -1.5% for pc-Si.

The performance ratios for the modules are presented in Table 4. The mc-Si transparent glass module (165 Wp)

showed the highest average performance ratio PR of 85.2%. The lowest average PR of 71.8% was obtained for pc-Si module (60 Wp).

Average PR of 82.6%, 77.5%, and 76.7% were recorded for a-Si module (glass 40 Wp), PV-T (180 Wp) and pc-Si module (105 Wp), respectively. Cañete et al. (2014), however, observed an annual average PR of 94.8% for a-Si, 92.9% for pc-Si, and 93.9% for a-Si/ $\mu$ mc-Si.

**Conclusions**

Performance analyses were carried out for five different modules under the same outdoor conditions. Modules were exposed to an average irradiation of 935 W·m<sup>-2</sup> and average ambient temperature of 35 °C. Energy conversion rates of the modules were determined as 9.4%, 4.4%, 10.3%, 8.2% and 10.4% for mc-Si glass module (165Wp), a-Si glass module (40Wp), pc-Si module (105 Wp), pc-Si module (60 Wp) and PV-T (180 Wp) respectively. Under the given outdoor conditions, the highest average PR of 85.2% was obtained for the mc-Si glass module (165Wp) exhibiting the best performance; the lowest average PR of 71.8 was observed in case of pc-Si module (60 Wp).

**Table 3** Comparison between experimental and manufacturer’s module efficiency

Module technology	mc-Si module glass (165 Wp)	a-Si module glass (40 Wp)	pc-Si module (105Wp)	pc-Si module (60Wp)	PV-T glazed mc-Si (180 Wp)
Datasheet efficiency (DE) (%)	10.3	5	12.7	10.6	12.6
Measured efficiency (ME) (%)	9.4	4.4	10.3	8.2	10.4
(DE-ME)/DE	-8.7%	-12%	-18.9%	-22.6%	-17.5%

**Table 4** Performance ratios (PR) of modules

Performance ratios (PR) of modules	mc-Si (glass) (165 Wp)	a-Si (glass) (40 Wp)	pc-Si (105 Wp)	pc-Si (60 Wp)	PV-T glazed mc-Si (180 Wp)
Minimum	0.83	0.79	0.74	0.69	0.75
Maximum	0.91	0.89	0.81	0.77	0.83
Average	85.2%	82.6%	76.7%	71.8%	77.5%

### Acknowledgement

This work was supported by the Stipendium Hungaricum Programme and the Mechanical Engineering Doctoral School, Szent István University, Gödöllő, Hungary.

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