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# PERFORMANCE ANALYSIS OF PHOTOVOLTAIC SYSTEMS IN THE BRESTANICA THERMAL POWER PLANT

# ANALIZA UČINKOVITOSTI SONČNIH ELEKTRARN V TE BRESTANICA

Bojan Vovčko[R]

**Keywords:** performance ratio, energy yield, photovoltaic system, solar cell, temperature coefficient of efficiency, solar irradiation, inclination angle, azimuth angle, partial shading

## Abstract

This paper deals with the performance ratio and energy yield of three photovoltaic systems (MFE TEB 1-3) in the Brestanica thermal power plant (TE Brestanica). The objective of this paper is to analyse these two parameters according to the different types of solar cells (amorphous/monocrystalline silicon), non-ideal inclination, and azimuth angles of PV modules in different seasons. The analysis was made on the basis of operating data of MFE TEB 1-3 for the period from 2011 to 2016. Performance ratio is one of the most important parameters in the assessment of the quality of photovoltaic systems; it represents the ratio between the actual energy produced and the theoretical energy produced by a photovoltaic system and shows the proportion of energy that is available for transmission to the electricity network after deducting lost energy. In contrast, the energy yield represents the ratio between the actual energy produced and the nominal power of the photovoltaic system. The results show a significant influence of temperature coefficient, as well as the inclination and azimuth angles of the PV modules on the performance ratio and the energy yield.

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## Povzetek

Prispevek obravnava faktor učinkovitosti in energijski izplen treh sončnih elektrarn (MFE TEB 1-3), katere ima v lasti Termoelektrarna Brestanica. Cilj tega prispevka je narediti analizo teh dveh parametrov glede na različno vrsto sončnih celic (amorfni/monokristalni silicij), neidealnim naklonskim in azimutnim kotom sončnih modulov v različnih letnih časih. Analiza je bila narejena na osnovi obratovalnih podatkov za obdobje od 2011 do 2016. Faktor učinkovitosti je eden izmed najpomembnejših parametrov pri ocenjevanju kakovosti sončnih elektrarn in predstavlja razmerje med dejansko in predvideno proizvodnjo električne energije sončne elektrarne ter prikazuje delež energije, ki je na voljo za prenos v omrežje po odbitku izgubljene energije, energijski izplen pa predstavlja razmerje med dejansko proizvedeno električno energijo in nazivno močjo sončne elektrarne. Rezultati kažejo precejšen vpliv temperaturnega koeficienta, naklonskega in azimutnega kota sončnih modulov na faktor učinkovitosti in energijski izplen.


# 1 INTRODUCTION

In TE Brestanica, we are very much aware of the importance of environmentally friendly energy production, so we started to direct our activities to renewable energy sources (RES) almost a decade ago. We have actively participated in the construction, operation, and maintenance of hydroelectric power plants at the lower Sava River. From the start of this project in 2002, and in 2008, we also started with activities on the development and construction of photovoltaic systems. In February 2009, we had a trial run of the first photovoltaic system (MFE TEB 1), with a rated output of 38 $kW_p$. At the end of March 2010, we had a trial run of another two photovoltaic systems: MFE TEB 2 integrated in the roof of a covered parking lot with a rated output of 82 $kW_p$ and MFE TEB 3 with nominal power 50 $kW_p$, which is placed on the roof of gas turbine (GT) units PB4 and PB5. The total installed power of photovoltaic systems in TEB is 170 $kW_p$.

For the MFE TEB 2, integrated into the parking lot's roof, we obtained the status of an integrated photovoltaic system (higher feed-in tariff) from the Energy Agency in 2010. Additionally, in 2011, we received a "Bronze Award for the Best Innovations in 2010" for the covered parking lot from the Posavje Regional Chamber of Commerce and Industry of Slovenia (CCIS).

In the case of our photovoltaic system projects, we mainly pursued the vision of placement of photovoltaic systems on the TE Brestanica location in the most architecturally acceptable and useful way. Furthermore, in the design phase of photovoltaic systems, we were quite experimental, which means that we tried to use as many different materials and implementation methods as possible so that would will be able to determine the advantages and disadvantages.

Several researchers, *[1]–[7]*, have analysed the performance ratio of integrated photovoltaic system. In this paper, we will focus on the analysis of the performance ratio (*PR*) and the energy yield (*Y*), in order to verify the performance and quality of the photovoltaic system in TE Brestanica, depending on the type of solar cells, inclination and azimuth angles, partial shading, weather conditions and on the duration of the operation. The analysis will be done on the basis of operating data for a six-year period from 2011 to 2016.

## 2.1 Photovoltaic system MFE TEB 1

The first photovoltaic system in TE Brestanica, MFE TEB 1, was built as a part of the energy efficient renovation of the business building, which included the implementation of an energy efficient facade and the replacement of the asbestos roof covering. We started with renovation of the business facility in November 2008 and completed it in spring 2009. As a new roof covering, we used the Trimo SNV-3L sandwich panels with integrated thin-film PV modules Unisolar PVL 136 from amorphous silicon. The market name of the panel with a PV module, shown in Figure 1, is Trimo EcoSolar PV.

The key reasons for using thin-film PV modules from amorphous silicon are:

- Low temperature coefficient of the PV module output power (-0.21%/°C): output power decreases with increasing module surface temperature as in case of monocrystalline PV modules (-0.48%/C). This is essential in the case of Trimo EcoSolar PV modules, because module surface temperature is higher, since they are glued to a sandwich panel with insulation on the underside.
- Small weight (7.7 kg) and thickness (3 mm) of the PV module: no additional reinforcement of roof and breakthroughs and architectural appearance of the building were not changed.
- A special cell structure (three layers of silicon) that allows the exploitation of a wider spectrum of light and a lower sensitivity to partial shading (each cell has a bypass diode), which is quite pronounced in the MFE TEB 1 due to the surrounding buildings (cooling tower, stacks of GT units PB4 and PB5, etc.).

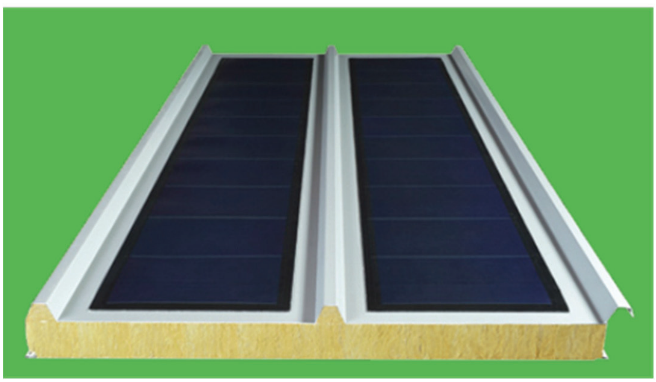

***Figure 1:*** *Trimo EcoSolar PV* sandwich panel

Basic technical data of the MFE TEB 1 are listed in Table 1. Location is shown in Figure 2a.

## 2.2 Photovoltaic system MFE TEB 2

At the end of 2009, we began the construction of a parking lot, the roof of which was made with PV modules. In this case, PV modules simultaneously perform the functions of the roof and the photovoltaic system. This is a so-called integrated photovoltaic system, named MFE TEB 2.

The parking lot's roof is designed as a metal construction made of hot zinc profiles with a roof made of monocrystalline PV modules. The roof has a distinct design, which is carried out in such a way that in case of rain, water does not pass through the slots between the PV modules. The problem of "sealing" was solved by a combination of omega profiles and channels, which form a catching rainwater catchment system under the PV modules. With this solution, we avoided the use of standard sealing solutions, which are expensive and intended for larger sloping roof angles (usually from a 22° angle forward). Another distinct feature of the parking lot's roof is that it can be upgraded during its lifetime so that electric cars could be powered.

We finished with the construction of a photovoltaic system MFE TEB 2 at the end of March 2010 and started with trial run in April 2, 2010. Basic technical data of the MFE TEB 2 are listed in Table 1. Location is shown in Figure 2b.

## 2.3 Photovoltaic system MFE TEB 3

Simultaneously to the construction of the photovoltaic system MFE TEB 2, we started with construction of the photovoltaic system MFE TEB 3, located on the roof of the GT units PB4 and PB5.

With the construction of MFE TEB 3, we approached to the ideal installation of the photovoltaic system (azimuth south, inclination 7°), but there we encountered the problem of partial shading of the surrounding artificial barriers (stacks of GT units PB 1-3, lightning rod, etc.). Due to this problem, it was necessary to thoughtfully implement strings of the PV modules and choose an appropriate configuration of the inverters, which significantly eliminated the effect of partial shading.

a)  b) c)

***Figure 2:*** *Photovoltaic systems MFE TEB 1-3*

We finished the construction of the photovoltaic system MFE TEB 3 at the end of March 2010 and started the trial run in April 2, 2009. Basic technical data of the MFE TEB 3 are listed in Table 1. Location is shown in Figure 2c.

***Table 1:** Basic technical data of the photovoltaic systems MFE TEB 1-3*

<table>
<tr><th colspan="3"></th><th colspan="2">MFE TEB 1</th><th colspan="2">MFE TEB 2</th><th colspan="2">MFE TEB 3</th></tr>
<tr><td colspan="3">Nominal power [kW$_p$]</td><td colspan="2">38.08</td><td colspan="2">81.78</td><td colspan="2">49.9</td></tr>
<tr><td colspan="3">Location</td><td colspan="2">Business building</td><td colspan="2">Car parking roof</td><td colspan="2">Roof of GT unit PB 4 in 5</td></tr>
<tr><td colspan="3">Inclination angle [°]</td><td colspan="2">5 °</td><td colspan="2">5 °</td><td colspan="2">7 °</td></tr>
<tr><td colspan="3">Azimuth angle [°]</td><td colspan="2">90° (E), 180° (S), 270° (W)</td><td colspan="2">90° (E)</td><td colspan="2">180° (S)</td></tr>
<tr><td colspan="3">Year of construction</td><td colspan="2">2009</td><td colspan="2">2010</td><td colspan="2">2010</td></tr>
<tr><td rowspan="14">PV modules</td><td colspan="2">Type</td><td colspan="2">PVL 136</td><td colspan="2">Asola 290 W/72</td><td colspan="2">Solarwatt M230</td></tr>
<tr><td colspan="2">Material of solar cell</td><td colspan="2">Amorphous Si</td><td colspan="2">Monocrystall. Si</td><td colspan="2">Monocrystall. Si</td></tr>
<tr><td colspan="2">Nom. power $P_{mpp}$ [W]</td><td colspan="2">136</td><td colspan="2">290</td><td colspan="2">235</td></tr>
<tr><td colspan="2">Efficiency [%]</td><td colspan="2">6 %</td><td colspan="2">15 %</td><td colspan="2">15 %</td></tr>
<tr><td colspan="2">Manufacturer</td><td colspan="2">Unisolar (USA)</td><td colspan="2">Asola (DE)</td><td colspan="2">Solarwatt (DE)</td></tr>
<tr><td colspan="2">Dimensions [mm]</td><td colspan="2">5486×394×4</td><td colspan="2">1979×990×50</td><td colspan="2">1610×1060×50</td></tr>
<tr><td colspan="2">Weight [kg]</td><td colspan="2">7.7</td><td colspan="2">26.6</td><td colspan="2">24</td></tr>
<tr><td>$U_{mpp}$ [V]</td><td>$I_{mpp}$ [A]</td><td>33</td><td>4.1</td><td>37,44</td><td>7,83</td><td>47,8</td><td>4,9</td></tr>
<tr><td>$U_0$ [V]</td><td>$I_{sc}$ [A]</td><td>46.2</td><td>5.1</td><td>44,71</td><td>8,38</td><td>59,1</td><td>5,4</td></tr>
<tr><td colspan="2">Temper. coeff. of output power [%/°C]</td><td colspan="2">-0.21</td><td colspan="2">-0.48</td><td colspan="2">-0.50</td></tr>
<tr><td colspan="2">No. of PV modules</td><td colspan="2">280</td><td colspan="2">282</td><td colspan="2">212</td></tr>
<tr><td colspan="2">Effective surface of solar cells [m$^2$]</td><td colspan="2">524</td><td colspan="2">564</td><td colspan="2">339</td></tr>
<tr><td colspan="2">Specific power of PV module [W/m$^2$]</td><td colspan="2">73</td><td colspan="2">145</td><td colspan="2">147</td></tr>
<tr><td colspan="2"></td><td colspan="6"></td></tr>
<tr><td colspan="3">Inverters (No. x kW)</td><td colspan="2">SMA (2×3 and 6×5) 1 phase</td><td colspan="2">SMA (6×11 and 3×5) 1 phase</td><td colspan="2">SMA (1×5, 2×7 and 3×11) 1 phase</td></tr>
<tr><td colspan="3">Average annual energy produced [kWh]</td><td colspan="2">34,278</td><td colspan="2">74,290</td><td colspan="2">45,266</td></tr>
<tr><td colspan="3">Average annual energy yield [kWh/kW$_p$]</td><td colspan="2">900</td><td colspan="2">908</td><td colspan="2">906</td></tr>
</table>

## 3 PERFORMANCE RATIO AND ENERGY YIELD

Performance ratio is the ratio between the actual energy and theoretical energy produced by a photovoltaic system. It is defined in IEC 61724, *[8]*, and shows the proportion of energy that is available for transmission to the network after deducting lost energy (due to thermal losses, conductivity losses, inverter losses, mismatch between components, dustiness of PV modules, shading losses, system degradation, snow on modules, system failure, etc.). Performance ratio is calculated by (3.1):

$$PR = \frac{E}{E_{sim}} = \frac{E}{\sum \eta_{STC} \cdot H_c \cdot \Delta t \cdot A} \tag{3.1}$$

Where *PR* is performance ratio, *E* [kWh] is the actual energy produced, $E_{sim}$ [kWh] theoretical energy produced, $\eta_{STC}$ [%] efficiency of PV modules at standard test conditions (STC), $H_c$ [kW/m$^2$] solar radiation on tilted surface, $\Delta t$ [h] time of operation and *A* [m$^2$] effective surface of PV modules.

Energy yield describes the relationship between the energy produced and the nominal power of a photovoltaic system and is calculated by (3.2):

$$Y = \frac{E}{P_{STC}} \tag{3.2}$$

Where *Y* [kWh/kW$_p$] is the energy yield, *E* [kWh] actual energy produced, and $P_{STC}$ [kW] is the nominal power of the photovoltaic system. Energy yield represents the number of hours that the photovoltaic system would need to operate at its nominal power to provide the same energy. The unit of *Y* could be also kWh/kWp. Energy yield depends on solar radiation and temperature.

# 4 RESULTS

The analysis of the performance ratio and the energy yield is calculated based on the operating data of the photovoltaic systems MFE TEB 1-3 for a six-year period (2011–2016). During this time, photovoltaic systems operated steadily, stable and without long interruptions or failures.

Energy production data were obtained from distribution network operator database (SODO). In these data, the losses on the AC side (such as losses in the connecting cable between the AC switch block and the connection measuring block (PMO)) are taken into account. Solar radiation data were obtained from local communication units (SMA Sunny Webbox), which are part of every photovoltaic system. Each communication unit has its own solar irradiation sensor, surface temperature sensor and ambient temperature gauge. The values of solar irradiation enabled us to calculate the performance ratio for each photovoltaic system. The following analyses were carried out:

- Analysis of the PR according to (3.1) for the average of six years in the period from 2011 to 2016.
- Analysis of the Y according to (3.2) for the average of six years in the period from 2011 to 2016.
- Analysis of the PR according to (3.1) for each year in the period from 2011 to 2016.
- Analysis of the Y according to (3.2) for each year in the period from 2011 to 2016.

In Table 2, average monthly values of PR and Y are presented for photovoltaic systems MFE TEB 1-3 during the period from 2011 to 2016. In Table 3, average annual values of PR and Y values are presented for photovoltaic systems MFE TEB 1-3 for each year, during the period from 2011 to 2016.

***Table 2:*** *Average monthly values of PR and Y for photovoltaic systems MFE TEB 1-3 in the period from 2011-2016*

| | MFE TEB 1 | | MFE TEB 2 | | MFE TEB 3 | |
|---|---|---|---|---|---|---|
| **Month** | **PR [%]** | **Y [kWh/kW$_p$]** | **PR [%]** | **Y [kWh/ kW$_p$]** | **PR [%]** | **Y [kWh/ kW$_p$]** |
| **Jan** | 0.64 | 18.66 | 0.74 | 20.84 | 0.58 | 20.64 |
| **Feb** | 0.62 | 22.83 | 0.74 | 27.87 | 0.58 | 25.03 |
| **Mar** | 0.92 | 70.52 | 0.84 | 74.95 | 0.72 | 75.79 |
| **Apr** | 0.99 | 100.77 | 0.85 | 102.80 | 0.74 | 101.12 |
| **May** | 0.92 | 122.05 | 0.78 | 120.89 | 0.70 | 120.96 |
| **Jun** | 0.94 | 129.68 | 0.78 | 128.13 | 0.71 | 129.97 |
| **Jul** | 0.86 | 130.10 | 0.76 | 134.30 | 0.67 | 132.85 |
| **Aug** | 0.90 | 126.80 | 0.73 | 120.68 | 0.66 | 121.63 |
| **Sep** | 0.97 | 84.35 | 0.76 | 82.05 | 0.66 | 79.87 |
| **Oct** | 0.92 | 50.99 | 0.77 | 50.28 | 0.68 | 50.92 |
| **Nov** | 0.89 | 24.62 | 0.79 | 25.69 | 0.69 | 25.50 |
| **Dec** | 0.75 | 18.77 | 0.71 | 19.94 | 0.63 | 21.23 |
| Average | **0.86** | **75.01** | **0.77** | **75.70** | **0.67** | **75.46** |
| Sum | | **900** | | **908** | | **906** |

***Table 3:*** *Average annual values of PR and Y for photovoltaic systems MFE TEB 1-3 in the period from 2011-2016*

| | 2011 | | 2012 | | 2013 | |
|---|---|---|---|---|---|---|
| | **PR [%]** | **Y [kWh/kW$_p$]** | **PR [%]** | **Y [kWh/kW$_p$]** | **PR [%]** | **Y [kWh/kW$_p$]** |
| **MFE TEB 1** | 0.93 | 999.42 | 0.84 | 1000.58 | 0.75 | 829.12 |
| **MFE TEB 2** | 0.77 | 1012.21 | 0.76 | 968.94 | 0.81 | 855.86 |
| **MFE TEB 3** | 0.72 | 990.28 | 0.68 | 986.27 | 0.67 | 841.23 |
| | **2014** | | **2015** | | **2016** | |
| | **PR [%]** | **Y [kWh/kW$_p$]** | **PR [%]** | **Y [kWh/kW$_p$]** | **PR [%]** | **Y [kWh/kW$_p$]** |
| **MFE TEB 1** | 0.81 | 764.08 | 0.84 | 897.40 | 0.97 | 910.32 |
| **MFE TEB 2** | 0.83 | 904.44 | 0.78 | 864.06 | 0.71 | 844.97 |
| **MFE TEB 3** | 0.67 | 857.65 | 0.62 | 887.14 | 0.63 | 870.47 |

The data in Tables 2 and 3 are graphically shown in Figures 3 to 6.

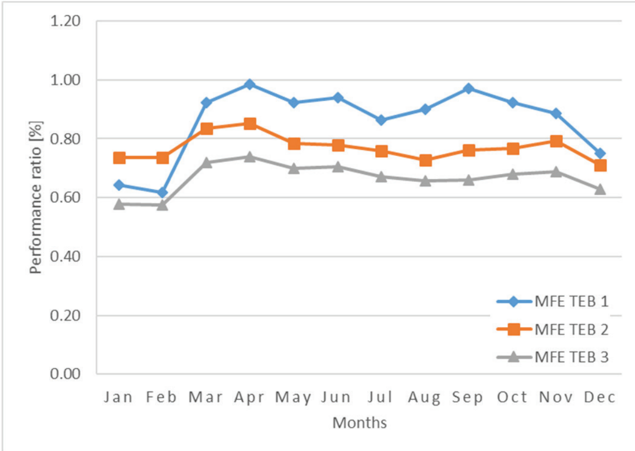


***Figure 3:** Average monthly values of PR for photovoltaic systems MFE TEB 1-3 in the period from 2011-2016*

Figure 3 shows that PR of photovoltaic systems MFE TEB 1, 2 and 3 in January, February and March is significantly lower in comparison to the summer months. The lower values of the PR in these months are the result of the accumulation of snow on PV modules, due to the low inclination angles of the PV modules of all three photovoltaic systems.

Figure 3 shows that the PR of the MFE TEB 1 is significantly higher in spring, summer, and the early autumn months than the PR of MFE TEB 2 and MFE TEB 3. This can be explained due to the better solar cells on MFE TEB 1 (amorphous silicon) than on MFE TEB 2 and 3 (monocrystalline silicon). Monocrystalline silicon solar cells have a significantly higher temperature coefficient of efficiency or output power than amorphous silicon solar cells do, which can be seen in Table 1.
Figure 3 shows that the PR of MFE TEB 2 is significantly higher than that of MFE TEB 3, although MFE TEB 3 has a better inclination and azimuth angle (7°, 180° - south) than MFE TEB 2 (5 °,90° - east). This can be explained by the significantly larger partial shading at MFE TEB 3 throughout the year (stacks of GT units PB1-3, lightning rods, discharge pipes on the roof of the GT units PB4, 5) and poor cooling of PV modules. Partial shading is also present at MFE TEB 1 but, due to the by-pass diode on each cell, the effect is not noticeable.

Table 2 and Figure 4 show the average monthly values of *Y* for photovoltaic systems MFE TEB1, 2 and 3 in the period from 2011-2016. The results show that due to low inclination angles, inconvenient azimuths angles, and the presence of partial shading, the energy yield is lower than in the case of optimal conditions. The Y of all three photovoltaic systems is almost the same throughout all months, which can also be seen in Figure 4.

Photovoltaic system MFE TEB 2 reaches the maximum average value of Y in the period from 2011-2016, due to the relatively low presence of partial shading (compared with MFE TEB 1 and MFE TEB 3) and good cooling conditions of PV modules.

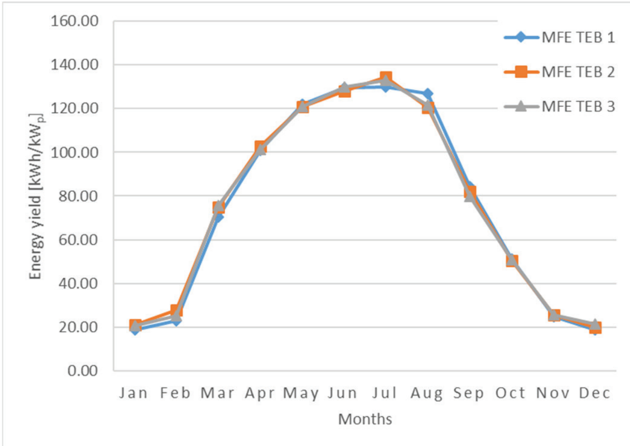


***Figure 4:** Average monthly values of Y for photovoltaic systems MFE TEB 1-3 in the period from 2011-2016*

Figure 5 shows the average annual values of the PR for solar photovoltaic systems MFE TEB 1-3 and the average annual value of solar irradiation for the period from 2011 to 2016. Figure 5 shows that in the case of higher solar irradiance (2011, 2012, 2015, and 2016), photovoltaic system MFE TEB 1 reaches higher values of PR than photovoltaic systems MFE TEB 2 and MFE TEB 3, due to lower temperature coefficient of efficiency or output power of solar cells but in the case of lower solar irradiance (2013, 2014) the impact of the temperature coefficient is not so great.

Figure 5 shows that the annual PR of the photovoltaic system MFE TEB 3 shows slightly lower values in the observed period, than that from photovoltaic system MFE TEB 2, due to the presence of partial shading. Photovoltaic systems MFE TEB 2 and 3 show no major deviations. The presence of partial shading at the MFE TEB 3 reflected in the course of the annual PR, which is slightly lower than that of the MFE TEB 2 within complete observed period. In contrast, in the course of MFE TEB 2 and 3 there are no major deviations.

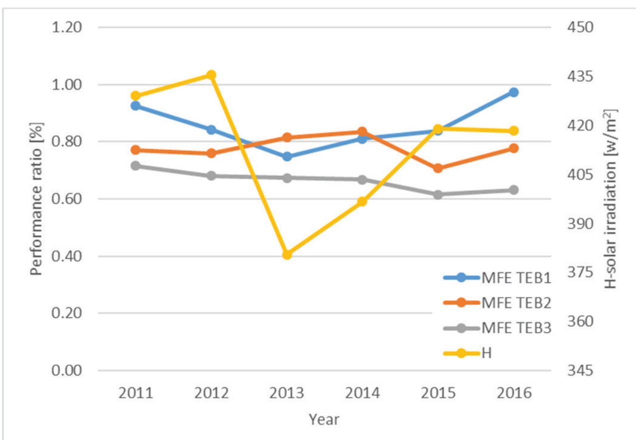


***Figure 5:** Average annual values of PR for photovoltaic systems MFE TEB 1-3*

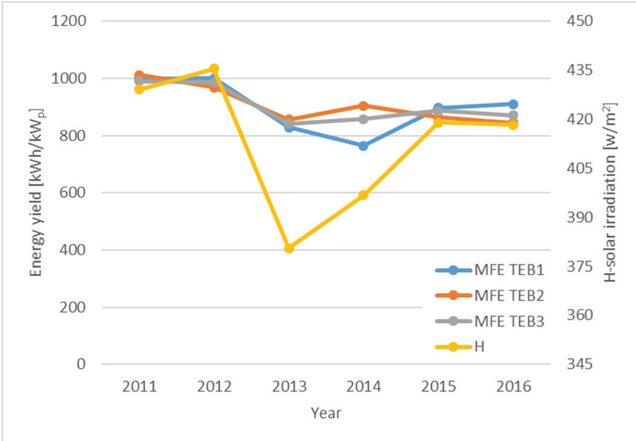


***Figure 6:*** *Average annual values of Y for photovoltaic systems MFE TEB 1-3*

Figure 6 shows the average annual values of Y for photovoltaic system MFE TEB 1-3 and the average annual value of solar irradiation for the period from 2011 to 2016. Figure 6 shows that photovoltaic system MFE TEB 1 has the lowest Y in 2013 and 2014, due to lower solar irradiation. This confirms the fact that the lower temperature coefficient of efficiency or output power at lower values of solar irradiation no longer contribute to a higher Y.

## 5 CONCLUSION

In this paper, the analysis of the PR and Y of photovoltaic systems MFE TEB 1-3 is presented, based on operational and meteorological data for the period from 2011 to 2016. The results show that values of PR and Y are lower than in the case of optimal conditions, due to inconvenient inclination and azimuth angles, the presence of partial shadings and snow barriers.

The results confirm the fact that the efficiency factors for amorphous silicon solar cells have lower temperature coefficients of efficiency or output power than monocrystalline silicon solar cells do; in the summer months or the periods of higher intensity of solar irradiation these levels are higher in comparison to those of monocrystalline silicon solar cells. Based on the results of the fourth chapter, we conclude that this applies to the average annual values of solar irradiation, which exceed 410 $W/m^2$.

PV modules of MFE TEB 1 are glued on thermally insulated roof sandwich panels, which reduces the heat exchange and causes significantly higher surface temperature of the PV module, even at lower solar irradiation. The effect of lower temperature coefficient is most pronounced at higher values of solar irradiation and higher ambient temperature.

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## Nomenclature

| | |
|---|---|
| **TEB** | Thermal power plant Brestanica |
| **PV module** | Photovoltaic module |
| **RES** | Renewable energy sources |
| **MFE** | Mala fotovoltaična elektrarna – small photovoltaic power plant |
| **CCIS** | Chamber of Commerce and Industry of Slovenia |
| **GT** | Gas turbine |
| **PB** | Plinski blok – gas turbine unit |
| **PR** | Performance ratio |
| $Y$ | Energy yield |
| **STC** | Standard test conditions |
| $E$ | Actual energy produced |
| $E_{sim}$ | Simulated energy produces |
| $\eta_{STC}$ | Efficiency of solar module at STC |
| $H_c$ | Solar irradiation |
| **Δt** | Operating time of photovoltaic system |
| **A** | Active surface of solar module |
| $P_{STC}$ | Nominal power of solar module at STC |