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The efficiency of different orientations of photovoltaic systems

Abstract. *This paper compares the efficiency of different orientations of photovoltaic systems under outdoor conditions over the five-year period in Slovenia. The four different photovoltaic systems were analysed with the same mono-crystalline silicon solar modules. The impact of orientation and inclination on efficiency are evaluated. The analysis of the data obtained shows that the efficiency of the photovoltaic systems depends on the solar irradiation and temperature of solar modules. Based on the analysis and measurements for different photovoltaic systems, the optimal orientation and inclination are presented.*

Streszczenie. *W artykule porównano wydajność systemów fotowoltaicznych o różnej orientacji w warunkach pracy zewnętrznej podczas pięcioletniej ich aktywności na terenie Słowenii. Badano cztery różne systemy fotowoltaiczne z tym samym monokrystalicznym modułem krzemowym. Wpływ orientacji i odchylenia na wydajność tych systemów zostały poddane ewaluacji. Analiza otrzymanych danych pokazuje, że wydajność systemów fotowoltaicznych zależy od promieniowania słonecznego i temperatury modułów. Bazując na analizie i pomiarach czterech systemów fotowoltaicznych wyznaczono optymalną orientację i odchylenie. (**Wydajność systemów fotowoltaicznych w różnych ukierunkowaniach**)*

Keywords: photovoltaic system, orientation, inclination
Słowa kluczowe:system fotowoltaiczny, ukierunkowanie, odchylenie

Introduction

Generally photovoltaic systems are divided into fixed and tracking systems [1]. Fixed systems are often used for small photovoltaic systems installed on the roof of a building, while tracking systems are often usedfor large photovoltaic systems installed to maximize the solar radiation that reaches the surface of the solar modules. When using tracking systems compared to fixed the increase of energy production is expected to be up to 40 % [2 - 4].

There are very few published works that deal with different types and orientations of photovoltaic systems, which are installed near to each other [5 – 7]. Authors in [5] demonstrate the correlation of clearness index with energy gain and efficiency of dual-axis solar tracker over static solar system based on experimental setup. Authors in [8] use different models to determine the optimal orientation and inclination of the photovoltaic systems. Some authors [9 – 11] define energy production of photovoltaic systems using different methods for predicting solar radiation. Other authors [12 – 14] compare different solar module technologies at the same orientation or different converter schemes [15]. The crack tip opening displacement test has been become a common method of measuring the real mechanical properties of used base materials [16].

This paper compares the efficiency of different orientation of the photovoltaic systems. Different orientations of photovoltaic systems are compared on the actual data measured in the five-year period. The following photovoltaic systems were analysed: the fixed photovoltaic system oriented to the south tilted at 30 º, the fixed photovoltaic system oriented to the east tilted at 30 º, the single axis photovoltaic tracking system tilted at 30 º and the fixed photovoltaic system oriented to the south tilted at 15 º. Since the discussed photovoltaic systems use the same mono-crystalline silicon (mc-Si) solar modules within a radius of 20 m the data analysis are even more authentic. The results show that the maximum energy is produced by the single axis tracking system. The fixed photovoltaic system oriented to the south tilted at 15 º produces 4 % less energy than the fixed photovoltaic system oriented to the south tilted at 30 º.

Photovoltaic systems

Four different orientations of photovoltaic systems were used for this paper, which are independent of each other. The three of photovoltaic systems are the same area and installed power. They differ according to the orientation and inclination. The largest photovoltaic system differs according to the area and installed power. All the photovoltaic systems are described in subchapters 2.1 to 2.4.

The fixed photovoltaic system oriented to the south tilted at 30 º

The first photovoltaic system consists of a fixed field of solar modules oriented to the south tilted at 30 º, as shown in figure 1. The photovoltaic system consists of six consecutively connected mc-Si solar modules, named Solar World SW175. Solar modules are fixed to the roof by metal-made construction, which allows the change in inclination of the modules. The maximum peak power of each module is 175 Wp, which gives a total installed power of 1.05 kWp. The field of solar modules is connected to the inverter SB1100, which is installed in the control room. The inverter is connected to the distribution network.

The fixed photovoltaic system oriented to the east tilted at 30 º

The second photovoltaic system also consists of a fixed field of solar modules oriented to the east tilted at 30 º, as shown in figure 1.

Fig. 1: From left to right: the fixed photovoltaic systems oriented to the east tilted 30 º and the fixed photovoltaic systems oriented to the south tilted 30 º.

The photovoltaic system consists of six consecutively connected mc-Si solar modules, named Solar World SW175. Solar modules are fixed to the roof by metal-made construction, which allows the change in inclination of the modules. The maximum peak power of each module is 175 Wp, which gives a total installed power of 1.05 kWp. The field of solar modules is connected to the inverter SB1100, which is installed in the control room. The inverter is connected to the distribution network.

The photovoltaic tracking system

The third photovoltaic system is a single axis photovoltaic tracking system tilted at 30 °, as shown in figure 2. Single axis trackers have one degree of freedom that acts as an axis of rotation. The discussed system is a vertical single axis tracker (VSAT). The axis of rotation for VSAT is vertical with respect to the ground. These trackers rotate from east to west over the course of the day [1]. The photovoltaic system consists of six consecutively connected mc-Si solar modules (World SW175), which gives a total installed power of 1.05 kWp. The single axis tracking system is built in such a way that its zero point facing south tilted at 30 °. They have installed an electrical drive for changing the azimuth angle (east - west). The modules of tracking system are connected to the inverter SB1100, which is installed in the control room. The inverter is connected to the distribution network. Electrical drive is supplied by the energy from distribution network with an average daily energy consumption of 120 Wh.

Fig. 2: The single axis photovoltaic tracking system tilted at 30 °.

The fixed photovoltaic system oriented to the south tilted at 15 °

The fourth photovoltaic system consists of a fixed field of solar modules oriented to the south tilted at 15 °, as shown in figure 3.

Fig. 3: The fixed photovoltaic system oriented to the south tilted at 15 °.

The photovoltaic system consists of 72 mc-Si solar modules (Solar World SW175) and gives a total installed power of 12.6 kWp. The modules of the field are divided into 9 sets of 8 consecutively connected modules. They are fixed to the roof by aluminium construction which is 10 cm deviated from the roof. There are 3 sets connected in parallel to each inverter SB3800, this includes 24 modules. The total installed power of modules, which are connected to each inverter, is 4.2 kWp. The entire field of solar modules is connected to the three inverters SB3800, each of them is connected to its phase of three phase distribution network.

Operating devices and visual presentation of the photovoltaic systems

In addition to the above-described systems the photovoltaic systems includes other power operating devices, which are shown in Figure 4 - inverters, safety systems, a control unit and a power supply for the tracking field of photovoltaic modules.

Fig. 4: Inverters and other operating devices in the control room and visual presentation of the photovoltaic systems.

Data from individual inverters and embedded sensors are then displayed on the ten clearly positioned monitors as shown in Figure 4. They show: temperature of the module; intensity of solar radiation; DC voltage, current and power on the module; wind speed; ambient temperature; AC voltage, current and power; total energy transmitted to the grid;

Analysis of the photovoltaic systems

The analysis of performance and comparison between the individual photovoltaic systems was done on the basis of measured data during the last five years. Table 1 shows the amount of energy generated by the photovoltaic systems throughout their period of operation. It is evident that the highest amount of energy is obtained from the fixed photovoltaic system oriented to the south tilted at 15 °. Which was expected, since it is also the largest system considering the installed power. The last column gives a percentage of energy generation per kWp of installed power in comparison with the system oriented to the south tilted at 30 °. It can be concluded from the results that the system oriented to the east tilted at 30 ° is inferior by 20 %, the tracking system is better by 13 % and the system oriented to the south tilted at 15 ° is inferior by 4%.

Table 1: Energy production of discussed photovoltaic systems.

System	Size [m^2]	Direction and angle	Nominal power [kWp]	Generated energy [kWh]	Energy [kWh/kWp]	Proportion compared to south 30°
South 30 °	8,02	South 30 °	1,05	4.823	4.593,3	-
East 30 °	8,02	East 30 °	1,05	3.827	3.644,8	- 20 %
Tracking system	8,02	South 30 ° east-west	1,05	5.459	5.199,0	+ 13 %
South 15 °	96,2	South 15 °	12,6	55.565	4.409,9	- 4 %

Efficiency of the photovoltaic modules

To determine the performance of different orientations of photovoltaic systems, efficiency were calculated, in accordance with standard IEC 61724. The maximum power value was measured at the input $P_{DC\text{-}MPP}$ and output $P_{AC\text{-}MPP}$ of inverters for each photovoltaic system. The measurements were recorded in 15-minute intervals. The solar module efficiency is the ratio of the output power of module $P_{DC\text{-}MPP}$ [W] to the irradiance G [W/m^2] and surface area [m^2]. By using the measured data, the efficiency of modules $\eta_{PV\text{-}M}$ can be calculated by (1):

(1) $$\eta_{\text{PV-M}} = P_{\text{DC-MPP}} / \left(\text{Area} \cdot G\right) \cdot 100 \ [\%]$$

Figure 5 shows the efficiency of the modules depending on the solar irradiation at a constant temperature.

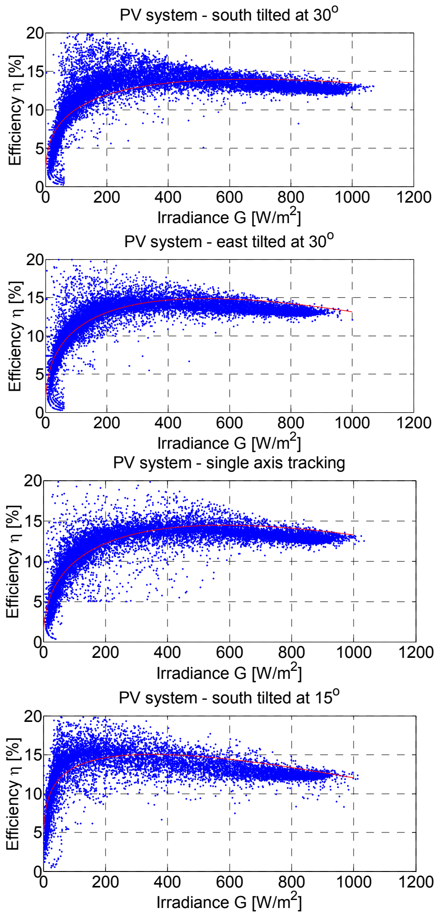

Fig. 5: Efficiency of the modules depending on the solar irradiation

Since all the systems use the same solar modules, is expected the same efficiency characteristics as a function of the irradiance. The figure 5 shows minor differences between the characteristics.

Figure 6 shows the efficiency values as a function of the module temperature for different types of photovoltaic systems. This kind of test would give an indication on the temperature coefficient of module efficiency.

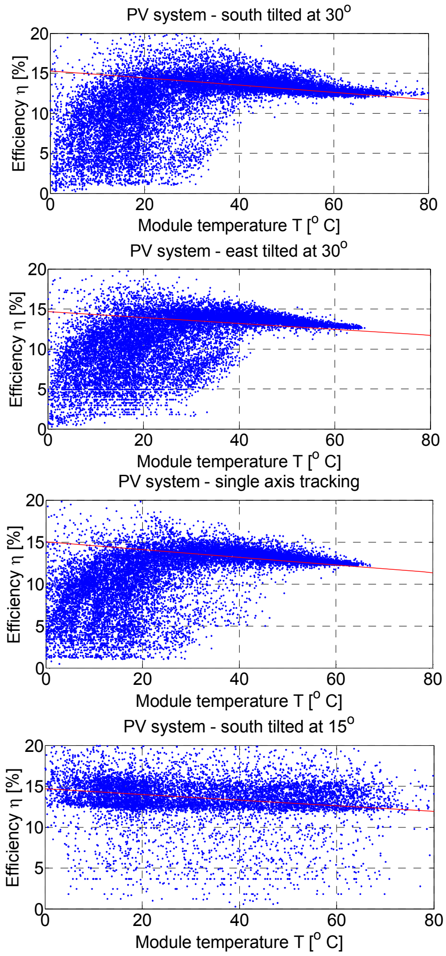

Fig. 6: Efficiency of the modules depending on the temperature.

The characteristic of solar module efficiency as a function of temperature shows that the efficiency of module decreases linearly by the increasing temperature. The efficiency of mc-Si is approximately 13.75 – 14.17 %, at a temperature of 25 °C, while it is only 12.27 – 12.62 % at a temperature of 60 °C, as shown in figure 6. The consequence of the increasing temperature is the decreasing output power whereby losses range from 0.3 to 0.5 %/°C. Which means that the output power can decrease by more than 10 % at increasing temperature for 30 °C. However, the efficiency may vary at low temperatures and may reach even higher values than expected.

Inverters efficiency

The efficiency of inverters is an important parameter that shows the efficiency conversion of power. The efficiency has a direct impact on the output power of the inverter and thus on the efficiency of the entire systems. The efficiency of inverter $\eta_{DC/AC}$ (2) is the ratio between the output $P_{AC\text{-}MPP}$ and input $P_{DC\text{-}MPP}$ power.

(2) $\eta_{DC/AC} = P_{AC\text{-}MPP} / P_{DC\text{-}MPP} \cdot 100 \; [\%]$

Figure 7 shows the efficiency of the inverters depending on the solar irradiance.

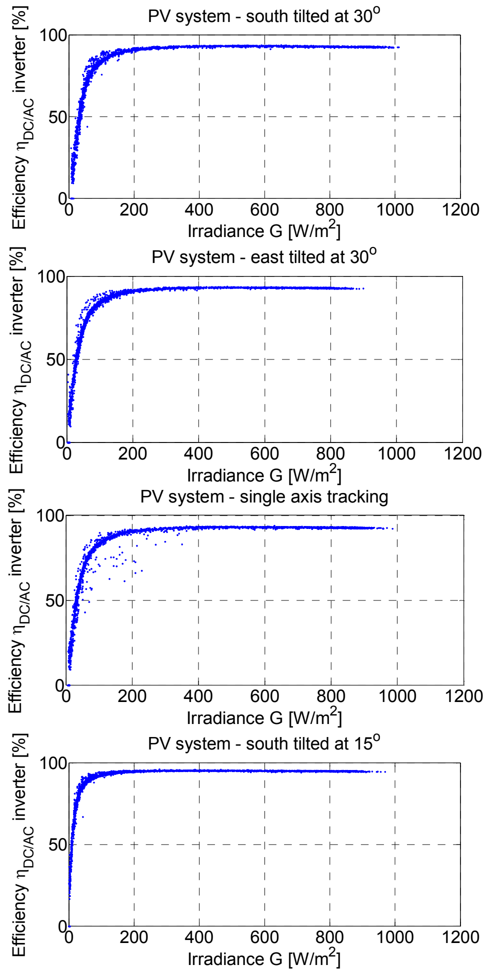

Fig. 7: Efficiency of the inverters depending on the solar irradiance.

Conclusion

In this work four photovoltaic systems were discussed. The energy production, the efficiency of modules and inverters were studied. All discussed systems are installed near to each other. The results show that the single axis tracking system produces the maximum yield of the energy (Table 1). This is 13 % more compared to a fixed system.

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