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Correlation analysis of tilted and horizontal photovoltaic panel's electricity generation and horizontal global radiation

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Abstract―Present paper aims at analyzing the correlation between global radiation and electricity production of photovoltaic (PV) panels. In case of high correlation, the electricity production can be estimated by the measured or predicted global radiation. Such solution can be applied for forecast purposes if global radiation data are available. On the other hand, global radiation can be measured based on the performance of a small and cheap PV system, which can be a reasonable solution if global radiation data is not available and a high precision monitoring system is too expensive.

The study is based on on-site measurements for the period of four months. At the station, seven PV panels are installed with different orientation and tilt angle and their electricity production is registered. The solar radiation is measured with a pyranometer. In the first group, there are four PV panels. One is placed horizontally and the other three are placed with a tilt angle of 45°. In the second, three-panel group the panels are placed with 90° tilt angle. The station is located in Debrecen, Hungary and the paper focuses on the Hungarian climatic conditions.

The research proves that the correlation strongly depends on the orientation and the tilt angle of the panel, and for prediction and estimation purposes the 45° tilted, south oriented surface is the most recommended option.

Key-words: PV panels, electricity production, energy performance, monitoring, global radiation, on-site monitoring, daily courses of electricity production

1. Introduction

For PV system installations it is fundamental to estimate the energy output of the systems. In most cases PV panels are placed with optimized tilt angle and orientation. A four-step optimization is described by Mehleri et al. (*Mehleri et al.*, 2010). The first step of the optimization process is to select the best performing diffuse radiation model to calculate the radiation components. As a second step, the global radiation can be calculated from the previously calculated radiation components for any tilt angle and orientation. As a third step, linear regression and RBF (radial basis-function) are applied to identify the best fitting model for the measured global radiation data. Further on, this model was used for the calculations. As a fourth step, a nonlinear programming (NLP) problem is formulated taking into account constraints and limitations of the system.

In several cases, the PV panels cannot be optimally tilted and as a result are oriented simply according to the site conditions. Several papers were published on this issue. A case study on a Korean office building was made by Hwang et al. *(Hwang et al.*, 2012). In that paper different options were examined focusing on the energy output of the BIPV (building integrated PV) arrays. The aim of the study was to determine the maximal electricity production for different tilt angles and orientations along with the effect of the installation distance to module length ratio. The study found that "it is efficient to install BIPV systems at a horizontally inclined angle of 60° and a vertically inclined angle that is smaller than 15°".

A different research was conducted in Australia, where PV production was measured at different tilt angles and orientations (*Yan et al.*, 2013). The measured electricity output was compared to calculated data, and the results showed that the chosen model was acceptable, thus further calculations and optimization were made. Based on the measurements and calculations, the yearly system efficiency and energy output for different orientations and the optimal tilt angle and orientation were determined.

Further parametric analysis was carried out by Bhattacharya et al. in Rajasthan, India (*Bhattacharya et al.*, 2014). The aim of the research was to perform PV output modeling under the climatic conditions of India. The effect of orientation, tilt angle, temperature, and humidity on the PV system efficiency and energy output was examined. The meteorological parameters were collected from five different stations, and the effect of orientation and tilt angle was examined by applying model calculations. The conducted research included determination of optimal orientation and tilt angle.

Further research was conducted by *Ding et al.* for three different stations, from which two were located in the USA and the third one in Kenya, Africa (*Ding et al.*, 2015). In the paper, different PV types and ways of their installation were examined and their effect on the PV system output and efficiency was monitored. They proved that by using the optimal orientation and tilt angle, the output of the system can be increased by 30%. As a result of PV type investigations, it was clearly visible that not optimal placement of PV panels in some cases can lead to significant drop in the system efficiency. Consequently, for such panels, imperfect installation must be avoided.

Mulcué-Nieto and Mora-López examined the effect of orientation and tilt angle of PV panels at several stations in Columbia and Spain *(Mulcué-Nieto* and *Mora-López,* 2015). As a result of the research, it was concluded, that in case of nation-wide characterization it is necessary to divide the country into appropriate zones. In case of Columbia, the zone borders were defined by longitudes. In each zone, the incoming solar energy was calculated for big cities within the region. The results were taken as an average for the given area. The results also showed that the effect of orientation is smaller in countries which are exposed to higher diffuse radiation.

In case of nearly zero energy buildings (NZEB), it is important to utilize the renewable energies to a high extent. Sánchez and Izard performed a research aiming at the determination of energy yield of PV panels placed on the external walls of buildings (*Sánchez* and *Izard,* 2015). The measurement was performed on southwest facing façades. In addition, four other orientations were also modeled. It was concluded, that in the case of PV panels placed on the southwest side of the building, a more balanced and stable electricity output is produced, which better fits the electricity consumption.

The aim of this paper is to determine the electricity production of different PV panel installations under climatic conditions of Hungary. The output of PV panels is also compared to the global radiation measured on a horizontal surface. In the paper, the measurement station is described along with its limitations.

2. Measurement station

The measurement station is located in Debrecen, Hungary, in the 'Megújuló Energiapark' (4031 Debrecen, Kishegyesi út 187.). The solar radiation is measured with a KIPP & ZONEN CM-3 pyranometer, which is placed at 2 m above the ground (*Fig. 1*). The radiation measuring device is connected to a Campbell CR 1000 data logger. The sample rate of the device is 1 s, which is collected by the data logger. The data logger from the 1 s data calculates 10 min averages. The data logger is connected to a server through an Ethernet interface (NL120), and sends data every 10 minutes.

At the station the PV panels are installed in two groups (*Fig. 2*). The installed PV panels are Istar Solar® IS4000P, with 210 W peak power. The manufacturer's catalog claims a maximal efficiency of 15.4% for these panels. There are four PV panels in the first group. One is placed horizontally and the other three are placed with a tilt angle of 45°. The inclined PV panels are oriented to the east, south and west. In the second group, three panels are placed with 90° tilt angle facing towards east, south and west. The beginning of data logging was September 20, 2014. The electricity output of PV panels is measured and logged every 10 minutes.

In this paper, data from September 20, 2014 to January 18, 2015 were analyzed. The measured data were first processed in order to exclude errors, and then statistical analysis was performed for the filtered data.

Fig. 1. The KIPP & ZONEN CM-3 pyranometer at the station.

Fig. 2. The PV arrays at the station.

3. Measured data and statistical analysis

3.1. Correlation of PV electricity production and global radiation measured on a horizontal plane

The daily average of global radiation and PV output of the horizontal PV panel for the entire period of monitoring are shown in *Fig. 3*. From the figure it can be seen, that the electricity output is at least twice as high as the output in December and January.

Based on the measured output of the horizontal PV panel and the global radiation, the calculated average efficiency of the PV panel is 14%. The calculated daily maximum efficiency was 19%, whilst the lowest was nearly 0%. The actual maximal daily efficiency was higher than the PV panel's maximum efficiency of 15.4% given by the manufacturer. The reason for the higher efficiency is possibly a result of a shading obstruction on the global radiation measurement device. This resulted in a lower value of measured global radiation, while the unshaded PV panels production was not lower. The calculated correlation coefficient of the measured global radiation and PV output was 0.930.

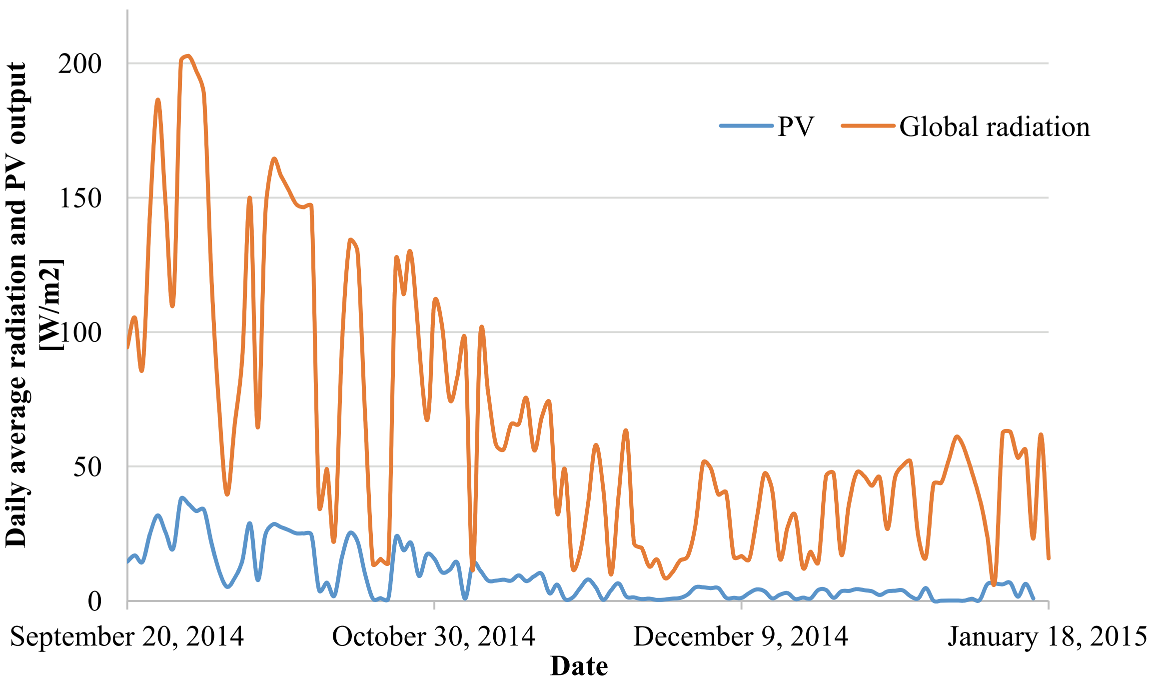

Fig. 3. Daily average of global radiation and PV output.

3.2. *Comparison of the outputs of tilted, oriented and horizontally installed PV panels*

The output of different PV panels are shown in *Table 1*. The table shows that with PV panels oriented to the south, more energy can be produced, than with a horizontally placed PV panel. The results also show that the biggest energy yield in the autumn-winter period is on a 90° tilted, south oriented panel, due to the low solar altitude. On the East oriented surface the incoming energy was nearly equal to the energy output of the horizontal panel. The east and west oriented, 45° tilted panels could produce acceptable amount of electricity, however, the 90° tilted panels oriented the same way have low energy output. Based on the values of correlation coefficients, it can be concluded that only the 45° tilted, south oriented PV panel has similar production profile to the horizontal one. The other panels show significant differences, thus they cannot be characterized by the horizontal panel.

Table 1. The produced electricity and calculated correlation coefficient for each PV panel in comparison with the horizontal panel's measurement data

	0°	**S45°**	**S90°**	**E45°**	**E90°**	**W45°**	**W90°**
Produced electricity [%]	100	119.6	136.1	101.3	47.9	72.9	39.6
Correlation [–]	1	0.930	0.818	0.853	0.556	0.758	0.300

For the measurement period, the daily average output profile was developed for every month for every panel. *Fig. 4* shows the daily average electricity output for the horizontally placed PV panel. The daily electricity production drops by 75% in the winter months compared to the daily data of September. This is due to the lower solar altitude and the higher fraction of diffuse radiation during winter.

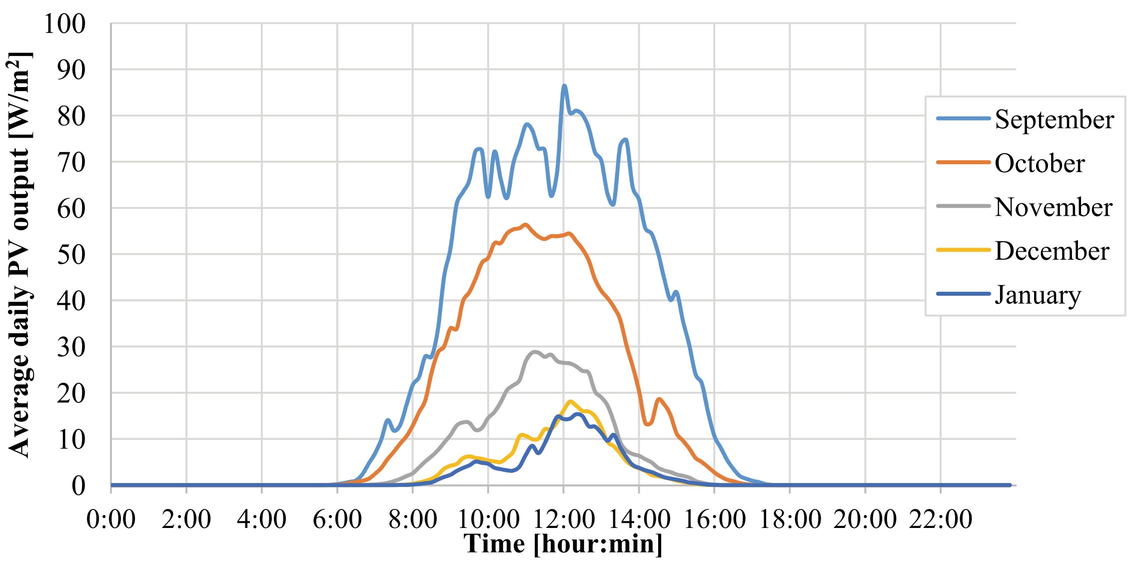

Fig. 4. Daily average electricity output of the horizontal PV panel.

The electricity output of the south oriented PV panels is shown in *Fig. 5* and *Fig. 6*. From the figures it can be seen that in case of south oriented panels, the daily electricity output is nearly symmetrical. In *Fig. 6* it is presented that in December and January in the morning and afternoon, small peaks occur at the low solar altitude. These small peaks can be results of a shading object, as in case of the 45° tilted surface, these peaks do not occur.

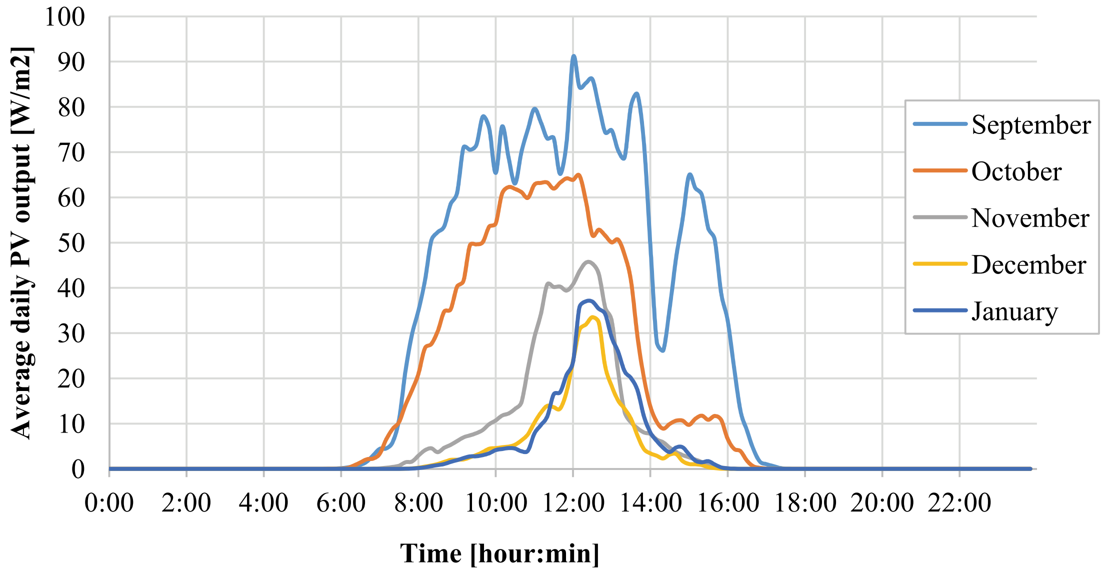

Fig. 5. Daily average electricity output of the 45° tilted, south oriented PV panel.

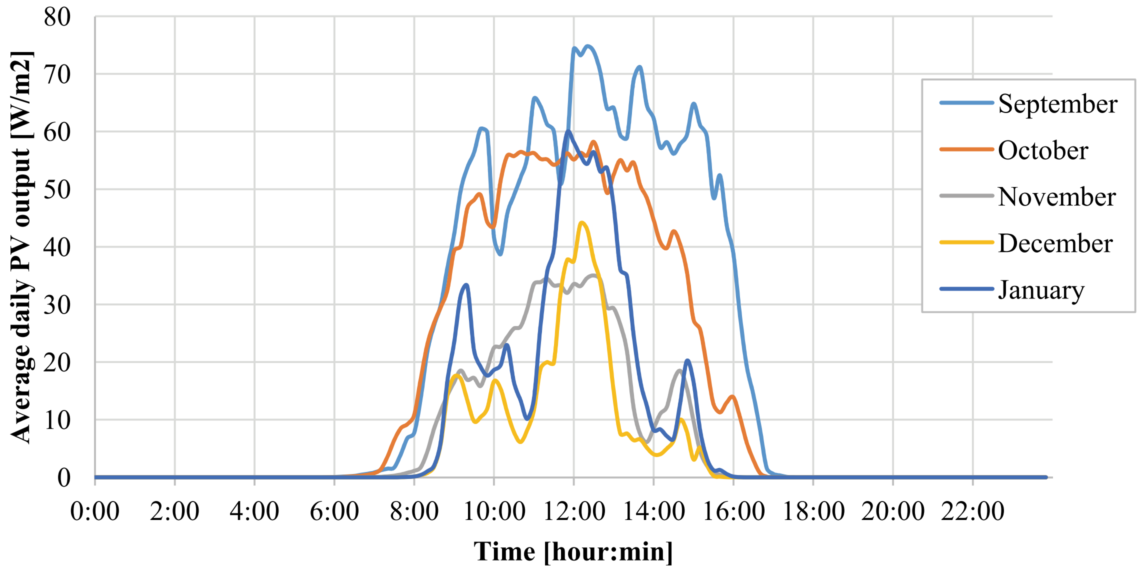

Fig. 6. Daily average electricity output of the 90° tilted, south oriented PV panel.

For east oriented PV panels, the daily electricity profiles are shown on *Fig. 7* and *Fig. 8*. On the 45° tilted panel, the highest energy output can be seen before 14:00, in case of the 90° tilted panel, the peak of the output can be found around 10:00. In case of the 45° tilted panel, a setback occurs in every month except October, this can be a result of shading objects. For the 90° tilted panel, the peak of electricity production is in the morning, when the panel is receiving direct sunlight, whilst in the afternoon the panel can not utilize the incoming diffuse radiation.

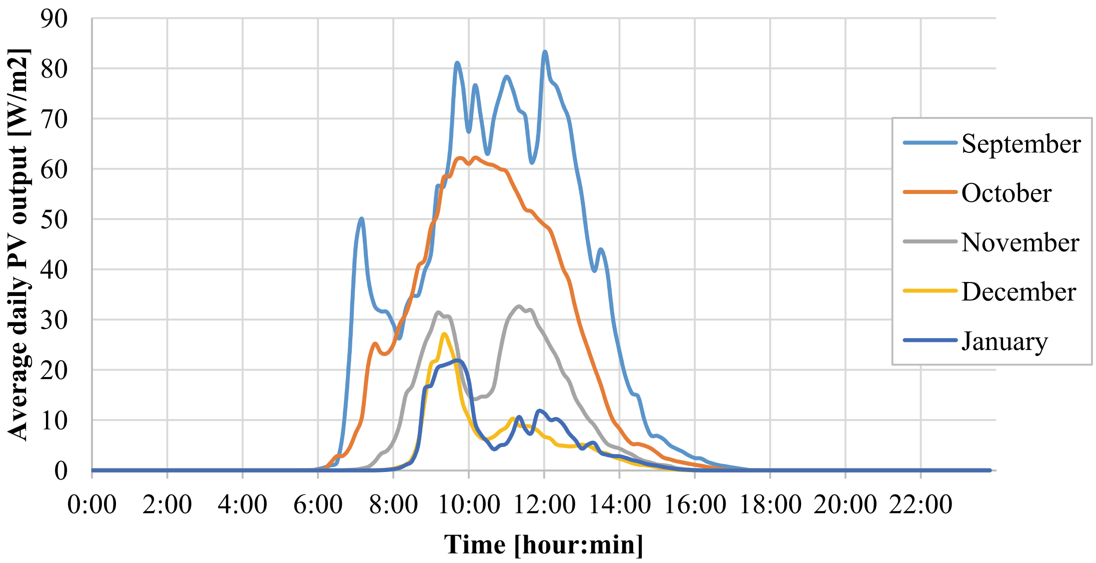

Fig. 7. Daily average electricity output of the 45° tilted, east oriented PV panel.

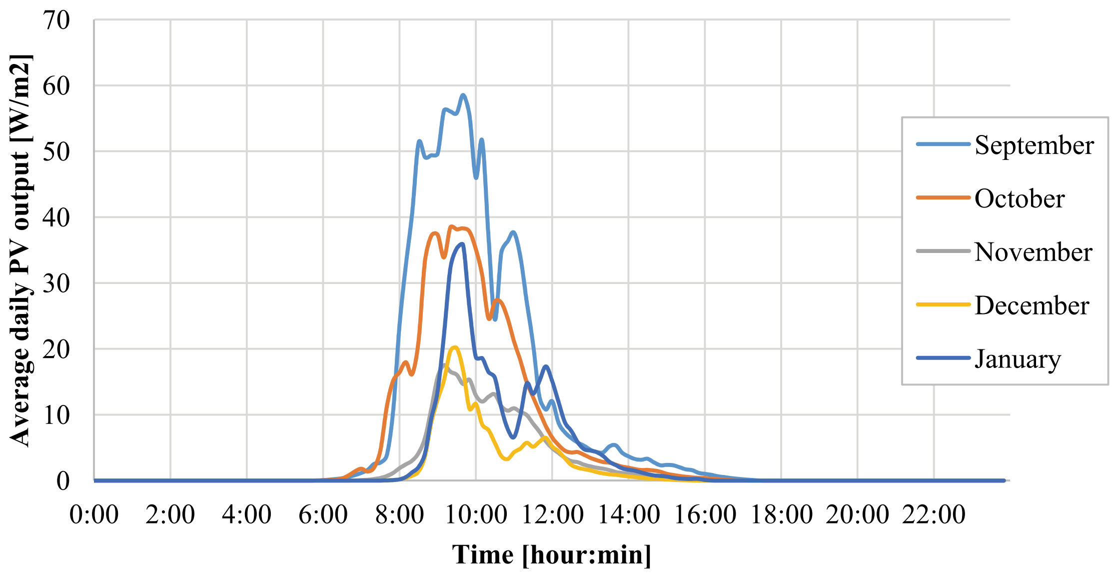

Fig. 8. Daily average electricity output of the 90° tilted, east oriented PV panel.

The average daily electricity output of west oriented surfaces are shown in *Fig. 8* and *Fig. 9*. For the west oriented surfaces nearly the same conclusions can be made as for the east oriented surfaces. The only significant difference is the time of the highest production, which, in case of west oriented surfaces, occurs in the afternoon. In *Fig. 8* it is visible, that after 12:00, the output of the panel experiences a setback which could be a result of a shading object. This problem in September is not occurring, possibly due to higher solar altitude. In *Fig. 9*, for the 90° tilted panel this setback is not visible, which also proofs the theory of the shading object.

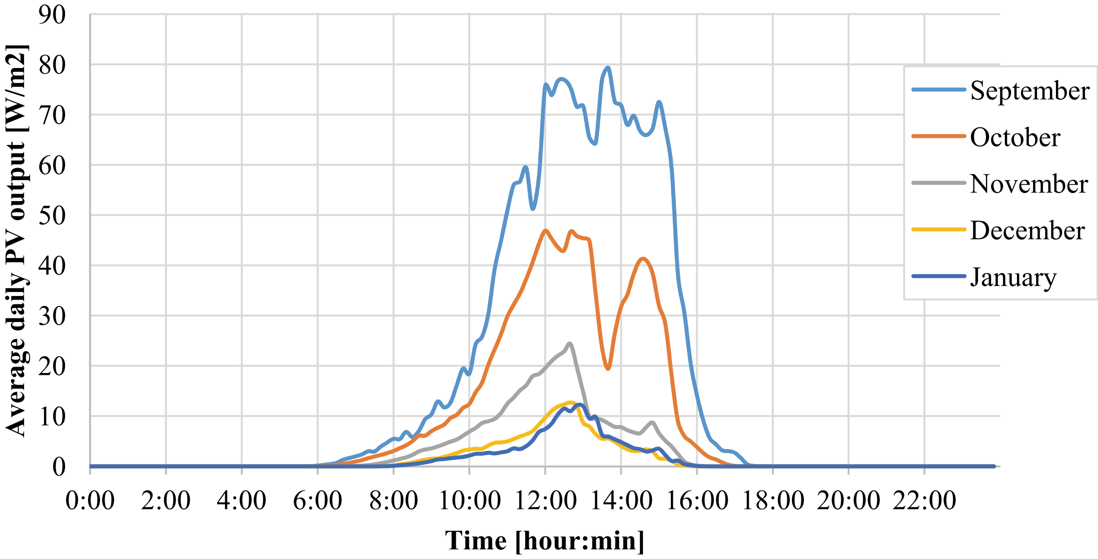

Fig. 8. Daily average electricity output of the 45° tilted, west oriented PV panel.

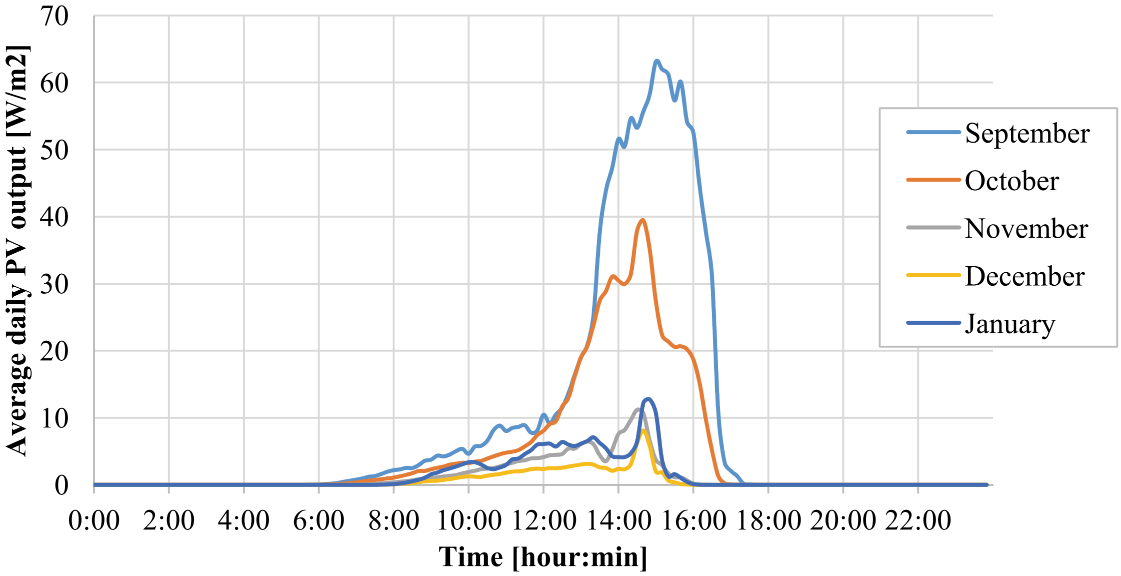

Fig. 9. Daily average electricity output of the 90° tilted, west oriented PV panel.

4. Summary

In this paper, a PV panel measurement station was described and the measured data from this station was statistically analyzed. The Hungarian station is unique due to the fact that at this station the outputs from differently oriented and tilted PV panels and global radiation are measured at the same time.

From the data measured it was concluded that, in case of the horizontally installed PV panel, the average efficiency is 14%. The correlation coefficient of the horizontal PV output and the measured global radiation is 0.930. This correlation coefficient proves linear correlation between the two datasets.

In the paper the measured PV outputs were compared. According to the measurement, in the autumn-winter period the highest energy yield is on the vertical, south oriented PV panel. Compared to the horizontal PV panel, only the south oriented panels have higher energy output in the measurement period.

Based on the values of correlation coefficients, it can be concluded that only the 45° tilted, south oriented PV panel has similar production profile to the horizontal one. The other panels show significant differences, thus they cannot be characterized by the horizontal panel.

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