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Operation of the photovoltaic system in Prague and data evaluation

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Abstract. The on-grid photovoltaic system was installed at the Faculty of Engineering in 2015. The monitoring system developed in our laboratory monitors data and can also detect failure and type of failure. The evaluation of the data shows that the amount of electricity produced slightly exceeds the expected values predicted by the internationally used internet application PVGIS. The effect of the aging of PV panels has so far had a minimal effect on the electricity produced. Immediate output power is affected by multiple parameters. Higher temperatures reduce the efficiency of energy conversion, so in summer the instantaneous power may be lower even at higher radiation intensity and smaller angle of incidence.

Key words: solar energy conversion, photovoltaic generators, Solar panels, data monitoring.

INTRODUCTION

The efficiency of a photovoltaic (PV) system depends on many parameters. In our previous article (Daneček et al., 2020), we compared PV systems with different constructions located in very different and distant locations in the Czech Republic in Central Europe and in Chile in South America. We compared mainly the amount of electricity produced.

In this article we will focus on only one PV system located at the Faculty of Engineering, CULS Prague and in addition to the total amount of electricity produced, we will monitor in more detail the distribution of output power during selected sunny days and we will compare measured values with expected values according to theoretical calculations. To monitor the data, we used the Solarmon (2.0) monitoring system (Beránek et al., 2018) developed in our laboratory. This monitoring system is already successfully working on a number of PV systems in the Czech Republic and abroad, and similar monitoring systems have been described in the papers (Ayompe et al., 2011, Madeti & Singh, 2017, Øgaard et al., 2020). Data monitoring can also predict failures of PV systems and the types of such failures. We have also dealt with this in previous works and for example, works (Spertino et al., 2015, Bilčík et al., 2019) also dealt with it. The cracked PV cells in the PV panel and broken contacts are the ordinary faults, but there are many types of faults. If the PV system or part of it reduces the output power, the monitoring system will report a suspected failure. The monitoring system thus helps operators with the management of the PV system.

The widely used internet application (Photovoltaic Geographical Information System, 2020) provided us with the expected values of the amount of electricity produced for a PV system of a given construction and location. We could compare the expected values with our measured values. A similar comparison of expected and measured values was performed in the work (Baena et al., 2020). During operation, a decrease in the values of the produced electricity can also be expected due to the aging of the PV system. Our observation is also given below. Similar observations have been addressed in the work (Kazem et al., 2020).

MATERIALS AND METHODS

Fig. 1 shows the PV system installed at the Faculty of Engineering in Prague (50.13° north, 14.37° east). 40 PV panels (Renesola, GmbH, type JC 260M-24/Bb, nominal nominal output power 260 W_p) based on polycrystaline silicon are divided into two independent sections. In each section, 20 PV panels are connected in a series and they are connected to the distribution network via inverters. PV panels are installed on a fixed stand, they are oriented nearly to the south with an inclination of 35°. (Azimuth 5° to the east is given by the building orientation.) The nominal output power is cca 10 kW_p. Solar conditions correspond to the temperate climate zone in Central Europe.

Figure 1. On-grid PV system installed at the Faculty of Engineering, Czech University of Life Sciences Prague (nominal output power 10 kW_p).

Fig. 2 shows the scheme of the PV system showing the angle of incidence of direct solar radiation at noon on two selected days in different seasons. Below, we will compare data from our monitoring system during two selected sunny days (1st June 2017 and 25th February 2018). Several factors affect the resulting amount of electricity produced (especially temperature of PV panels, intensity of solar radiation and angle of incidence).

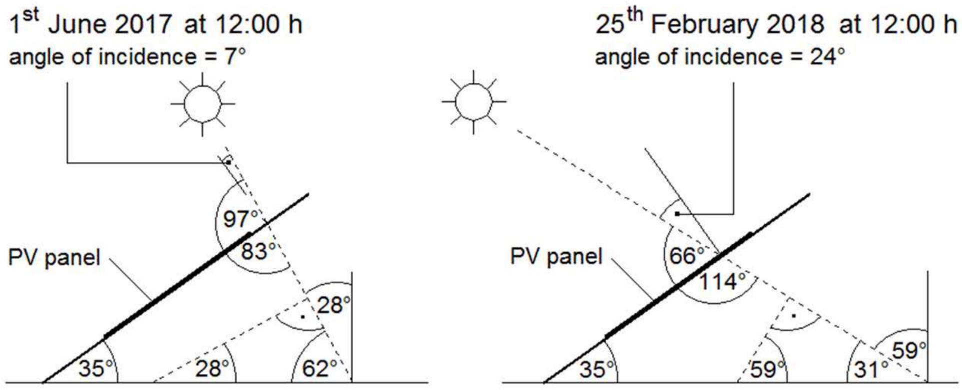

Figure 2. Scheme of the PV system showing the angle of incidence of direct solar radiation at noon on selected days.

RESULTS AND DISCUSSION

Fig. 3 shows the amount of electricity produced during 4 years of operation. Typical annual energy production in this region is about 1,100 $kWh.kW_p^{-1}$ $year^{-1}$. In 2019, production was several percent higher due to better climatic conditions. Table 1 shows the estimated amount of electricity produced per year according to an internationally used application (Photovoltaic Geographical Information System, 2020). It can be seen that our PV system has produced a little more electricity in all years than the expected value. (The year 2018 cannot be compared because there was a longer failure of the monitoring system and data are not available.) We have previously convinced that PV panels do not show significant defects by monitoring defects with a drone and we published the results (Libra et al., 2019).

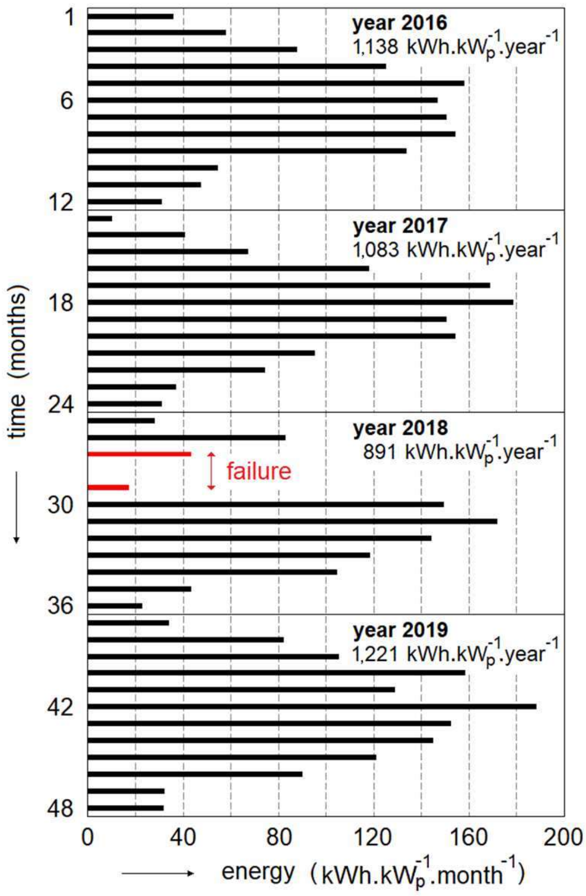

Figure 3. Monthly values of electricity produced in the years 2016–2019 calculated to 1 kW_p of installed power.

Table 1. Estimated amount of electricity produced per year

Month	Jan	Feb	Mar	Apr	Mar	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Electricity ($kWh.kW_p^{-1}.year^{-1}$)	37.4	54.9	90.8	122.2	128.8	128.4	130.4	121.4	105.2	72.6	39.3	36.3	1,067.7

Fig. 4 shows the dependence of the horizontal radiation intensity and of the instantaneous power on the time during two selected sunny days in different seasons. Fig. 5 shows the respective dependences of the temperature of PV panels and the air temperature on the time. If we focus only on the maximum values at noon, it can be seen that the measured value of instantaneous power on 25th February 2018 is about 3% higher than on 1st June 2017. This might seem strange, but the theoretical evaluation of measured data gives the following results clearly arranged in Table 2. The temperature difference of PV panels is 36°C. The energy conversion efficiency of PV panels is about 18% at 20°C and it decreases by about 0.5%/°C at increasing temperature (Libra et al., 2017). Thus, the difference in the efficiency of energy conversion due to the different temperature is 18% from 18%, that is about +3.2% (on 25th February 2018, the efficiency of energy conversion is about 3.2% higher than on 1st June 2017).

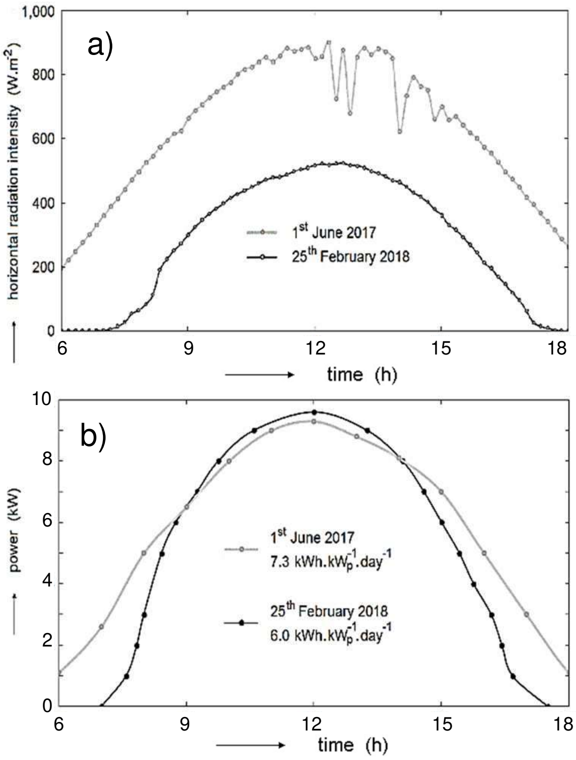

Figure 4. Dependence of (a) radiation intensity and b) instantaneous power on the time during two selected sunny days in different seasons.

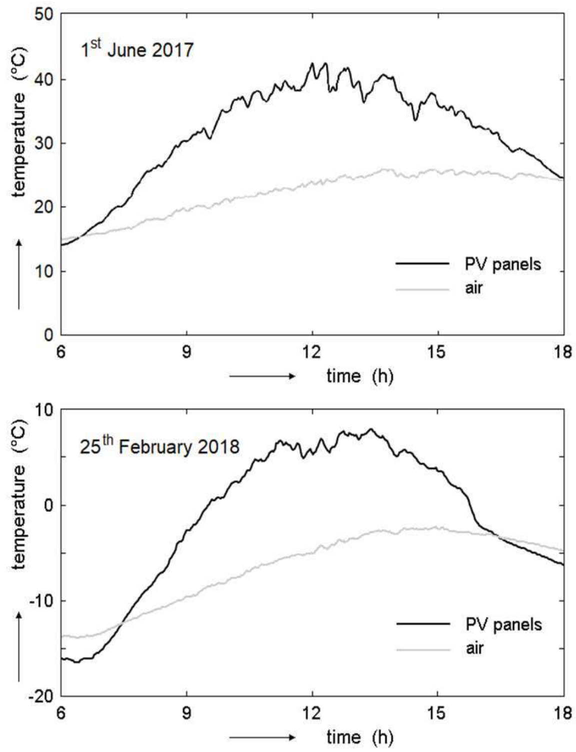

Figure 5. Dependence of PV panels temperature and air temperature on the time during two selected sunny days in different seasons.

The situation with the intensity of incident direct sunlight is the different. Table 2 shows the angles of incidence of direct solar radiation on PV panels (see Fig. 2) and the measured values of the horizontal intensity of the direct solar radiation. The calculation of the values of the intensities of direct solar radiation on the planes perpendicular to the direction of the radiation and on the planes of the PV panels was performed by a simple solution of right triangles and by using of trigonometric functions. Thus, the difference in the intensity of direct sunlight incident on PV panels is about -1.1% (on 25th February 2018 the value is about 1.1% lower than on 1st June 2017).

Table 2. Measured and calculated values of important parameters and final calculated difference of output power at noon sunny day

Quantity	1st June 2017		25th February 2018
Temperature of PV panels (°C)	42		6
Difference of energy conversion efficiency due to the temperature difference (%)		+3.2	
Angle of incidence (°) (see Fig. 2)	7		24
Horizontal direct radiation intensity ($W.m^{-2}$)	830		520
Calculated perpendicular radiation intensity ($W.m^{-2}$)	940		1,010
Calculated radiation intensity on PV panels ($W.m^{-2}$)	933		923
Difference of radiation intensity on PV panels ($W.m^{-2}$)		-10	
Difference of direct radiation intensity (%)		-1.1	
Distance Earth-Sun (AU)	1.01396		0.98992
Air humidity (%)	46		45
Final calculated difference of output power (%) 25th February compared to 1st June		+2.1	

The radiation intensity on the plane perpendicular to the direction of radiation can be discussed. The difference caused by the different angle of incidence and by the influence of the atmosphere should be about 15% (higher value in June). However, due to the greater distance of the Earth from the Sun, the radiation intensity should decrease by about 5% in June, because the radiation intensity is inversely proportional to the square of the distance. The expected value should therefore be higher in June on a very clear day, but Figure 4a shows fluctuations in the instantaneous power around noon on 1st June. Fluctuations are probably caused by clouds of steam, which the human eye does not even register, but they affect the output power of the PV system. Thus, the day was not completely clear and if the values of the instantaneous power corresponded to a smooth curve, they could supplement the missing 10%. These effects thus approximately equalized.

The resulting calculated difference of the instantaneous output power is therefore about +2.1% (calculation +3.2% -1.1% = 2.1%) and this is in good agreement with the measured difference of +3%.

CONCLUSIONS

The PV system at the Faculty of Engineering has been operating without problems for almost 5 years and the amount of electricity produced is slightly higher than the expected value according to the internationally used PV GIS application. This indicates a good quality PV system.

Even in winter season, at a higher angle of incidence, the instantaneous output power of the PV system can be few higher than in summer season, because the amount of electricity produced depends on more parameters. Only the most important parameters were included in our theoretical data evaluation. The output power of the PV system is certainly a little affected by the dusting of the PV panels, by the inclination or orientation of PV panels, etc.

The total amount of electricity produced is higher in the summer season, mainly due to the longer stay of the Sun above the horizon (see Fig. 4). But we must compare sunny days only.

The amount of electricity produced could be increased by cooling the PV panels especially in summer season, because at lower temperatures the efficiency of photovoltaic energy conversion is higher (Libra et al., 2017). However, this would require a more complicated design of hybrid photovoltaic-photothermal panels and cooling water circulation. This problem has already been studied and such hybrid panels exist, see for example (Zagorska et al., 2012, Matuška et al., 2015).

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