CONSTRUCTION AND MONITORING OF THE UNIQUE ROOF PHOTOVOLTAIC SYSTEM IN PRAGUE

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Abstract
A photovoltaic system with a nominal output power of 449 kW_p *has been working reliably for almost 9 years on the roof of a sports stadium in Prague. We have used the monitoring system Solarmon-2.0 developed by us to monitor the data. A roof-mounted structure (RIPV) with flexible photovoltaic modules based on thin layers of amorphous silicon was chosen. These modules are located horizontally and lie flat over the roof so that they can not be seen from the street and do not interfere with the architectural concept of the city district. In this article we describe the unique design of the photovoltaic system and we present interesting results captured from the evaluated data. In the end, we discuss the comparison of the amount of electricity produced with the expected values in the given location and comparison of the data with similar photovoltaic systems.*

Key words: *solar energy; energy conversion; flexible PV module; photovoltaic system.*

INTRODUCTION

We have been designing and testing photovoltaic systems for many years and the results have been published in many previous works, see for example *(Poulek et al., 2018)*. The photovoltaic (PV) system on the roof of the sports stadium (see Fig. 1) started working in 2010, so it has already been running for almost 9 years. Flexible PV modules based on thin layers of amorphous silicon, placed horizontally, were used for its construction. Such PV system is not visible from the street and does not disturb the architectural concept of the city district. In this article we present its design and our results of long-term data monitoring. First experiences with this PV system have been published earlier in the work *(Libra et al., 2016)* including unique data during solar eclipse. At work *(Monteiro et al., 2017)*, there is an annual monitoring of a similar PV system on the roof of the Mineirão football stadium in Brazil, and other PV systems on the roofs of the sports stadiums are described. Large flat roofs are considered as very suitable for installation of PV systems.

The aim of study was following. Design of the large photovoltaic system, long-time data monitoring and data evaluation. Data comparison with the similar photovoltaic system and with the expected values according PV GIS (http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#). To monitor the data, we use the Solarmon-2.0 monitoring system developed by us, which we have described in detail in the article *(Beránek et al., 2018)*.

We have also tested the flexible PV modules used in our laboratory (see Fig. 2). Tests have confirmed that the modules are suitable for the application. The construction of PV cells based on thin layers of amorphous silicon describes in more detail, for example, work *(Foti et al., 2014)*. For example, work on thin film layers of another semiconductor (CdTe) refers to work *(Khrypunov et al., 2006)*. For example, the works *(Peng et al., 2011, Fung & Yang, 2008)* refer to other possibilities of integrating photovoltaics into building architecture (BIPV). Hybrid PV/PT systems incorporated in buildings are mentioned in the report *(Matuška & Šourek, 2017)*, and about energy self-sufficiency of buildings with integrated PV system, e.g. in report *(Luthander et al., 2015)*.

Fig. 1 PV system on the roof of the sports stadium in Prague

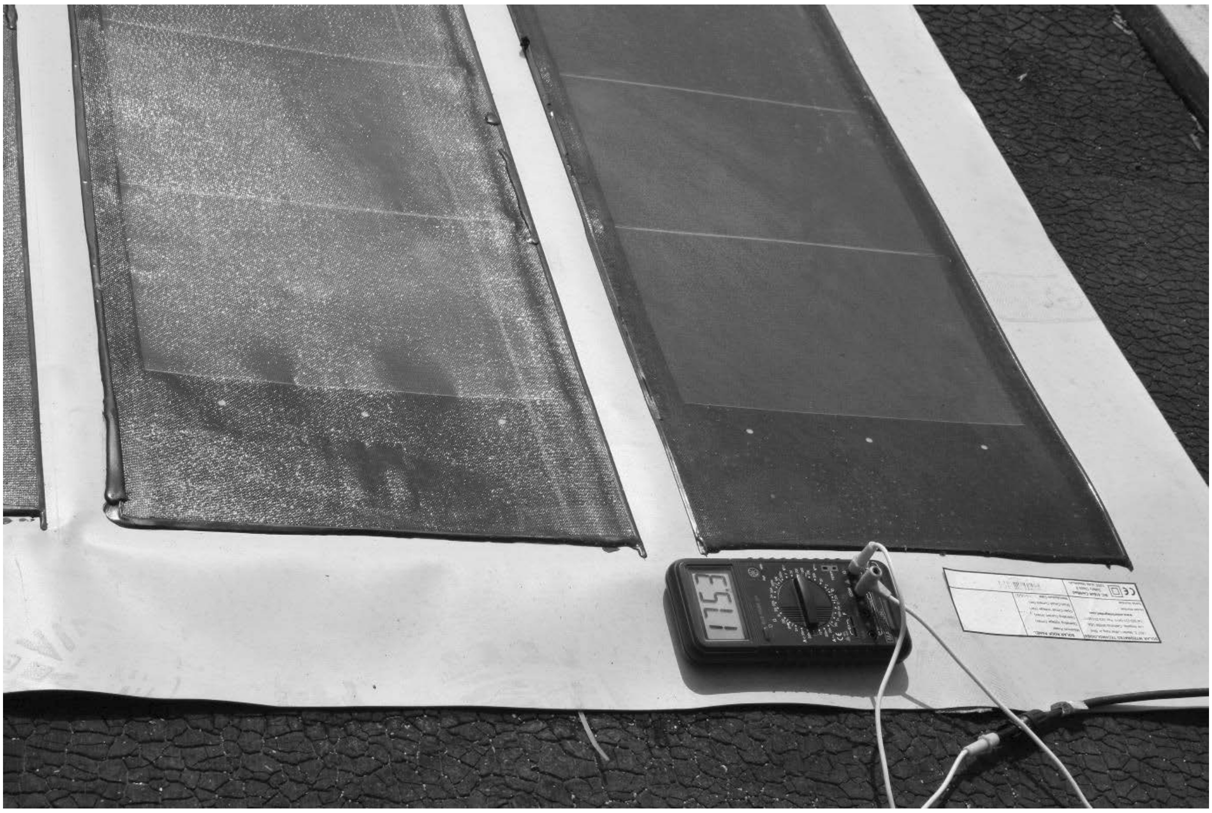

Fig. 2 Flexible PV module during testing in our laboratory

MATERIALS AND METHODS

The PV system was integrated into a flat roof with slight rounding. The flexible VAEPLAN V Solar 432 solar modules used in the experiment are shown in Fig. 1. They are oriented horizontally. They cannot be seen from the street and cannot disturb the architectural concept of the city district. Each module has a nominal output power of 432 W_p. The PV system has 8 identical independent sections. There is a merging switchboard in each section and 26 strings are connected to it. In each string there are 5 PV modules connected in series. Switchboards are equipped with fuse disconnecters, overvoltage arresters and ABB OT160E4 DC disconnecters, from which output power goes to the inputs of the electronic inverters. The total number of PV modules is 1040 and the total nominal power of the PV system is approximately 449 kW_p on the DC voltage side.

For connection of the PV system to a three-phase AC network, two inverters from Aurora Power-One (type PVI-CENTRAL-220.0-CZ) with three-phase alternating voltage are used. Each inverter consists of four blocks of 55 kW_p of maximum power. Each block has an output on the central bus which leads the power to the transformer. The eight sections are therefore connected to two inverters and the maximum power on the AC side is 440 kW_p.

RESULTS AND DISCUSSION

Fig. 3 summarizes the results of the monitoring of the PV system within 8 years of operation. For better comparison, the values are converted to 1 kW_p of installed power. The low values of the electricity produced in October and November 2014 are related to the failure of the PV system caused by the storm. If we calculated the electricity produced in these months as in previous years, we would have a value of around 715 $kWh.kW_p^{-1}.year^{-1}$ in 2014.

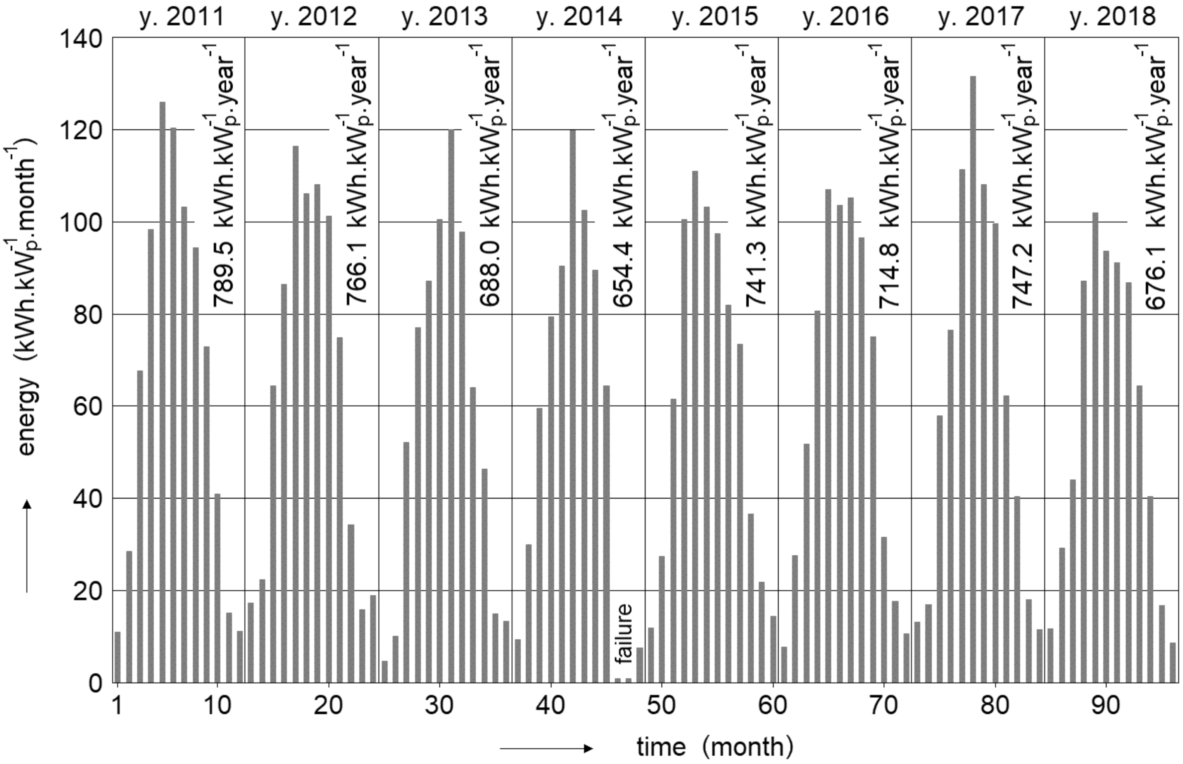

Fig. 3 Summarized results of monitoring of the PV system within 8 years of operation

According to the internationally used photovoltaic geographic information system forecast (http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#), the expected amount of electricity produced per 1 kW_p of installed power output should be around 788 $kWh.kW_p^{-1}.year^{-1}$. Because the PV system is located on a flat roof, the "free-standing" module was used for the calculation and not "building integrated". It is clear from Fig. 3 that this value reached the PV system only in the first year of operation. But we have to take into account the above-mentioned slight rounding of the roof and the slope of some PV modules slightly northwards. In addition, the PV system is in a dusty environment. The railway line is in close proximity. From horizontal PV modules, the dust is not washed away by rain. Although the PV system operator is occasionally cleaning it, the settled dust reduces electricity production. Nevertheless, the fall in electricity production over the past eight years is not dramatic, yet by 2015 and 2017 it has dropped by about 5% compared to the start of operation. In 2018, however, this drop was 14%, but the fall in one year may be in line with the natural fluctuation of meteorological conditions, and it does not mean degradation of the PV system parameters. Real output power will show next years of data monitoring.

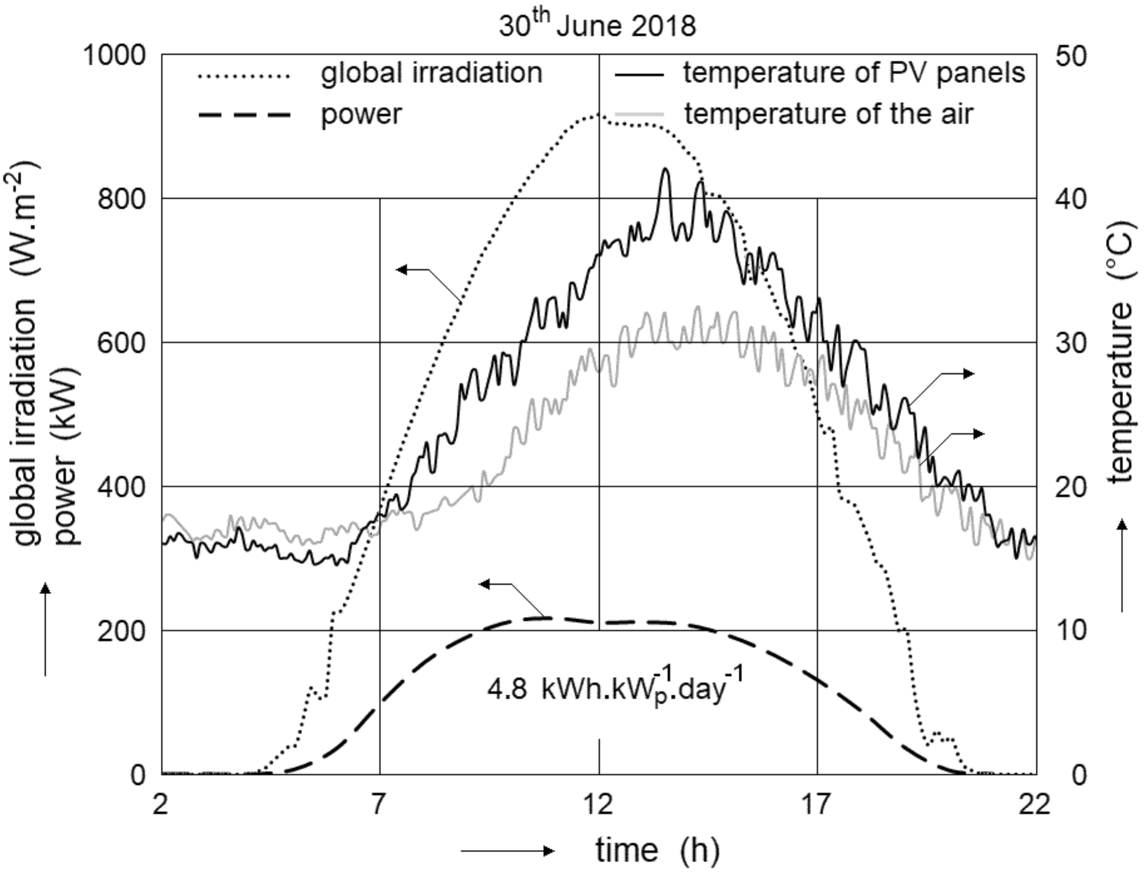

Fig. 4 Time dependence of instantaneous power, global radiation intensity, PV module temperatures and air temperatures for a sunny summer day

Fig. 4 is the time dependence of instantaneous power, global radiation intensity, PV module temperatures and air temperatures for a sunny summer day. Fig. 5 is the same dependence on a sunny winter day. The daily value of the produced electrical energy converted to 1 kW_p of nominal power is also given. However, the air temperature is measured near PV modules and is therefore slightly distorted and is not an exact meteorological value. Moreover, the instantaneous wind influences temperature fluctuations. It is easy to see the alternation of the morning temperature minima and afternoon temperature peaks, during sunny days the temperature differences are much greater on sunny days than during the cloudy days. The temperature of PV modules is usually lower than the air temperature at night due to thermal radiation, while during the day it is on the contrary higher due to the absorption of solar radiation.

With increasing temperature, the efficiency of photovoltaic energy conversion decreases *(Poulek et al., 2018)*. For PV modules used, the manufacturer gives a decrease of 0.21% /°C. PV modules are glued directly to the roof waterproofing membrane, which prevents them from bottom cooling. During summer sunny days, therefore, their temperature reached more than 40°C, as shown in Fig. 4.

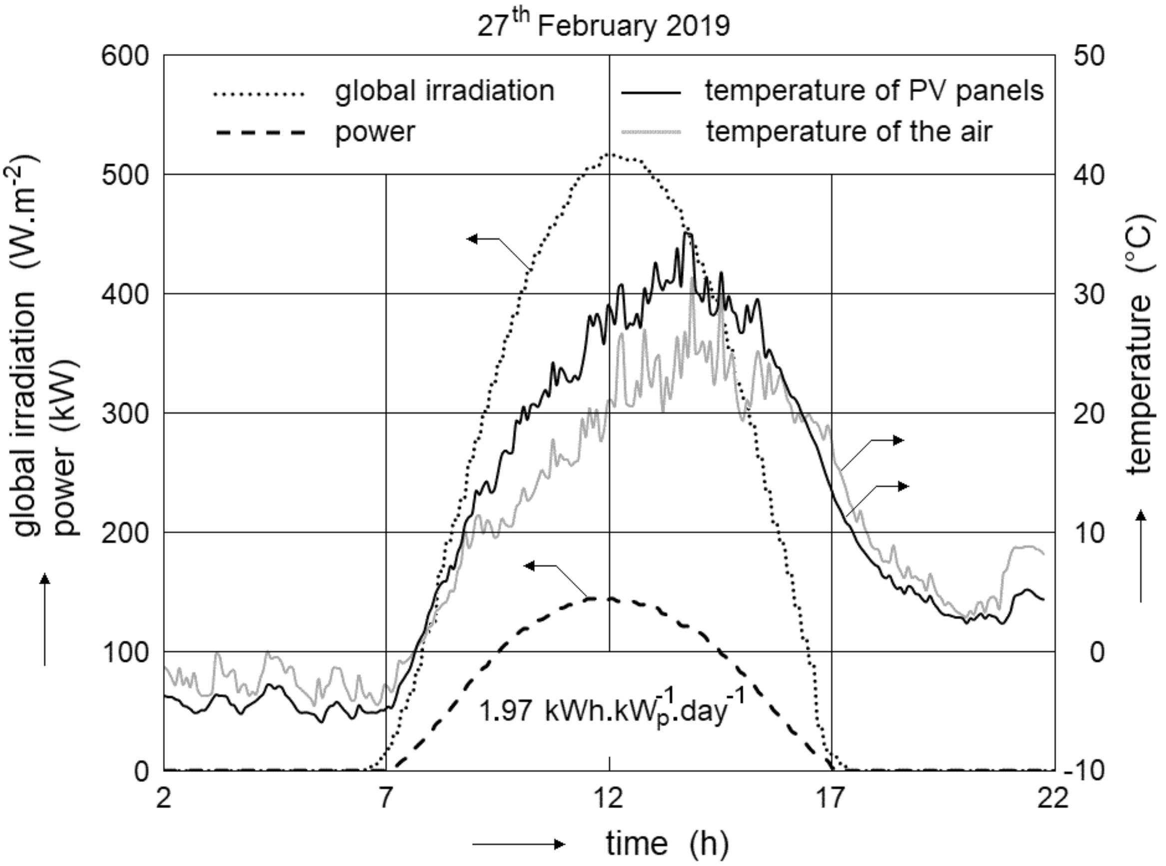

Fig. 5 Time dependence of instantaneous power, global radiation intensity, PV module temperatures and air temperatures for a sunny winter day

Previously, a similar smaller PV system was tested and the results were published in the work *(Libra et al., 2013)*. The distance between these two PV systems is approximately 5 km. In this case, similar flexible PV foils were used. The PV system was not exactly horizontal. A part of the PV system was oriented to the south with the slope approximately 3° and a part was oriented to the north with the same slope. The annual values of the produced electric energy were round 780 $kWh.kW_p^{-1}.year^{-1}$ on the north side and round 900 $kWh.kW_p^{-1}.year^{-1}$ on the south side. These values are a bit higher. There is the better self-cleaning because of the water flow and the laying dust do not reduce the transparency.

CONCLUSIONS

The PV system installed on the roof of the football stadium is considered a useful use of space. The design of a PV system based on flexible PV modules glued directly to the roof waterproofing membrane was the only option in terms of the design and static assessment of the roof and from the point of view of architectural integration into the city's urban planning concept. In the case of horizontally oriented PV modules, there is a higher summer-to-winter energy production ratio compared to south-sloping modules because the projection of the PV module surface into a plane perpendicular to the direction of the solar radiation is given by the cosine of the angle of incidence.

The PV system had worked without major problems during the past eight years, only in October and November 2014 had a storm failure. The values of the amount of electricity produced initially corresponded to expectations. During the aging of the PV system, there is a certain decrease, which is not dramatic yet. A larger drop in electricity production in 2018 may be in line with the natural fluctuation of meteorological conditions and does not necessarily mean degradation of the PV system parameters. This will show up next data monitoring. We intend to continue to collect the data and in particular to monitor further changes in the value of the electricity produced during the aging of the entire installation. The expected life of PV modules based on thin layers of amorphous silicon (a-Si) is about 12 years.

Our data can also be used for the construction of other PV systems and for the prediction of the amount of electricity produced in PV systems of similar design. We assume that roof PV systems will become increasingly important as additional energy sources, but the classic large power plants are not yet being replaced.

ACKNOWLEDGMENT
This study was supported by internal grant of the Faculty of Engineering n. 2019:31120/1312/3111.

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