Agronomy Research **14**(4), 1386–1394, 2016

Low degradation of a-Si solar panels of the building integrated PV power plant in Prague historical area

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Abstract. The unique photovoltaic power plant installed in Prague on the roof of the new buildings of National Theatre in Prague has been investigated. As the new buildings are very close to the old historical building of National Theatre designed in late 19th century, the PV power plant has to be totally invisible from the streets of Prague to not disturb historical panorama of the city. Flexible a-Si photovoltaic foils in the nearly horizontal position have been used because the placing is in the urban conservation area in the historical city centre. The operation started in the autumn 2009. The photovoltaic power plant is described in this paper and results of its operation are presented. The energy production data indicate that the degradation of the nearly horizontally installed a-Si panels is below 5% within 5 years period.

Key words: Photovoltaics, thin film a-Si panels; degradation; soiling.

INTRODUCTION

Recently investigation of the energy efficient building is more and more important especially because of the increasing availability of the renewable energy sources. Different types of PV panels and PV arrays were described for instance in next reports: photovoltaic (Poulek & Libra, 2000; Libra et al., 2011), photothermal (Cerón et al., 2015; Matuška et al., 2015), hybrid (Crisostomo et al., 2015). A review about the photovoltaic self-consumption in buildings and household power consumption was written for example in (Luthander et al., 2015; Munkhammar et al., 2015), data about building energy consumption and renewable energy consumption were presented in (Depoorter et al., 2015; Mathew et al., 2015). Measurement of energy production from BIPV system including a-Si PV panels is presented in (Davis et al., 2003) and (Dougherty el al., 2005).

The photovoltaic (PV) power plant in Prague on the National Theatre roof was designed and installed during the years 2008 and 2009. There was a photovoltaic's boom in the Czech Republic due to subsidiary policy and a number of larger or smaller solar PV power plants have been built. This boom culminated in the year 2010 and then a strict change of legislation has been adopted. Approximately 2000 MW_p (in total) of PV power plants and PV systems were installed in the Czech Republic before 1st January 2011 and this value remains same up to the present time.

A reconstruction of the Service Building roof and New Scene Building roof was realized from 2008 to 2009 and the unique PV power plant was designed and installed on the roofs. This power plant exhibits certain specific features and it is thus interesting from several points of view. With respect to its location in Prague historical area and national heritage protection it was impossible to use a classical construction with southward inclined PV panels based on crystalline silicon. It was very imperative to decide for a construction that would fully rest on the roof with its entire surface and would not interfere with the roof's contour in this precious locality. The flexible photovoltaic foils based on thin semiconductor layers have been therefore used to conform to the modern outlook of the buildings in a maximum measure.

Our many years of experience in the field of photovoltaics was already summarized in the book (Poulek & Libra, 2010). In this paper, we will describe a PV power plant of a completely different construction mentioned above and discuss our results of five-years monitoring of its operation.

The similar PV power plants were installed like building integrated (BIPV) or field installation. They were constructed like on-grid or off-grid. The reference (Dursun & Zden, 2014) shows for example the off-grid PV power plant used for irrigation. The construction of flexible PV foils on other bases is dealt with in detail elsewhere (Larsen-Olsen et al., 2012). The other various types of electrical interconnection for photovoltaic arrays are discussed in the reference (La Manna et al., 2014). The partially shaded PV system was tested and discussed in the reference (Kofinas et al., 2015). Another building integrated PV (BIPV) systems are investigated also in (Mandalaki et al., 2014; Shan et al., 2014).

Figure 1. PV power plant on the National Theatre roofs (New Scene Building left, Service Building right).

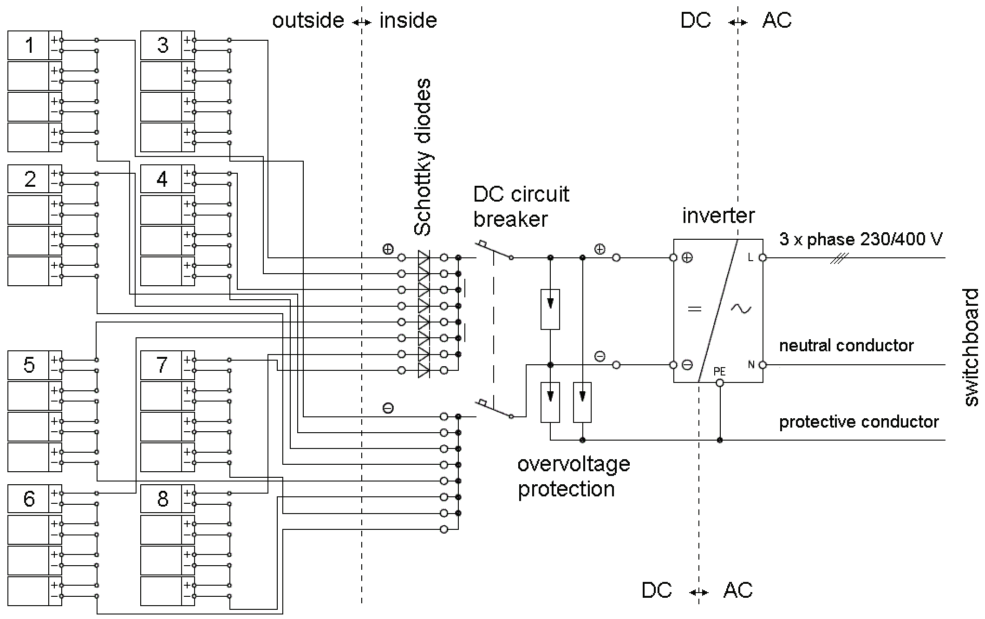

Figure 2. Wiring diagram of the PV power plant on the National Theatre New Scene Building roof.

MATERIALS AND METHODS

The PV power plant on the New Scene Building roof of Prague National Theatre (see Fig. 1 left) was designed so that it comprises two identical parts on the southern and northern halves of the roof. The only difference is given by the fact that the southern part was inclined by about 3° southward and the northern part by about 3° northward. Flexible PV foils of the nominal output power 0.406 kW_p have been used. PV cells based on thin semiconductor layers are encapsulated in the plastic material, they are mutually interconnected and they are directly integrated into the common roof PVC foils. Waterproof connectors are located on their back side. In both parts of this PV power plant, four PV foils were connected in series, eight of these series were connected in parallel and via a three-phase invertor Fronius IG 150 Plus, the generated electric power was supplied to the main power network. Fig. 2 shows the wiring diagram. On the National Theatre New Scene's roof are altogether 64 foils with an overall rated output of 26 kW_p (in two independent branches per 13 kW_p). A certain difference in the generated electric power can be expected, because one branch is slightly inclined southward and the other northward.

PV power plant on the National Theatre Service Building roof (see Fig. 3) was designed in the form of four independent branches. Flexible PV foils on an identical basis have been used, however with a somewhat lower nominal output power 0.203 kW_p. In two of these branches always six PV foils have been connected in series, these four series have been connected in parallel and via a single-phase invertor Fronius IG 40 the generated electric power was supplied into main network. In the other two branches, six PV foils were connected in series, five of these series were connected in parallel and via a single-phase invertor Fronius IG 60 the generated electric power was supplied into main network. Altogether 108 foils with the overall nominal output power 22 kW_p (in four separate branches of 2 x 4.9 kW_p and 2 x 6.1 kW_p) have been installed on the National Theatre Service Building roof. It is evident from Fig. 3 that part of this PV power plant is inclined about 3° eastward a part of the PV power plant is inclined about 3° westward to allow draining of water and self-cleaning of dust.

Figure 3. PV power plant on the National Theatre roofs (Service Building).

RESULTS AND DISCUSSION

The results of five-years monitoring of the electric power production by the PV power plant described above are presented in the following diagrams. Fig. 4 shows results from the PV system on the National Theatre New Scene Building roof, Fig. 5 shows results from the PV system installed on the National Theatre Service Building roof. To make the results comparable the values are recalculated to 1 kW_p of installed peak output power. It is evident that the year-round values correspond with the values expectable in Prague (50° north latitude) and that in winter months the amount of produced electric power is affected by the snow deposits on the roofs. Provided that snow would be regularly removed the amount of produced electric energy would be somewhat higher, but this could not be proved. This is evident from the zero amount of produced electric energy in January 2010 and from the minimum amount in December 2010. In the years 2011 and 2014 there was nearly no snowfall in Prague.

We can also see from these diagrams (Fig. 4) that on the New Scene Building there is always the amount of produced electric energy higher in parts inclined southward in comparison with parts inclined northward. On the Service Building roof, inclined eastward and westward, the values are not comparable and they are displayed like one value (Fig. 5).

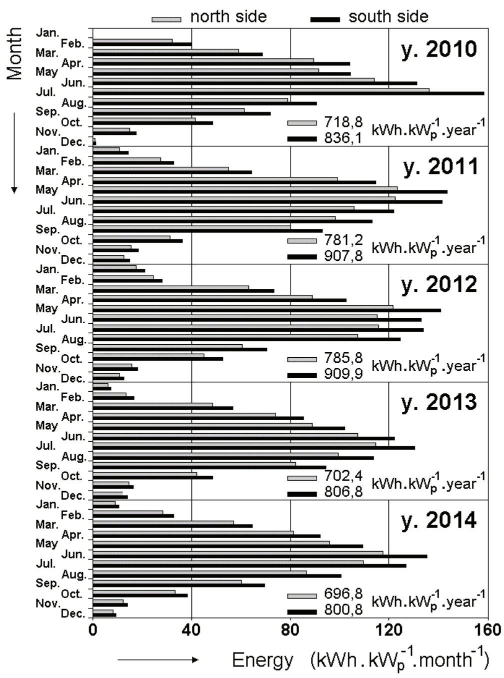

Figure 4. Electric energy produced in the PV power plant on the National Theatre New Scene Building roof during the years 2010–2014.

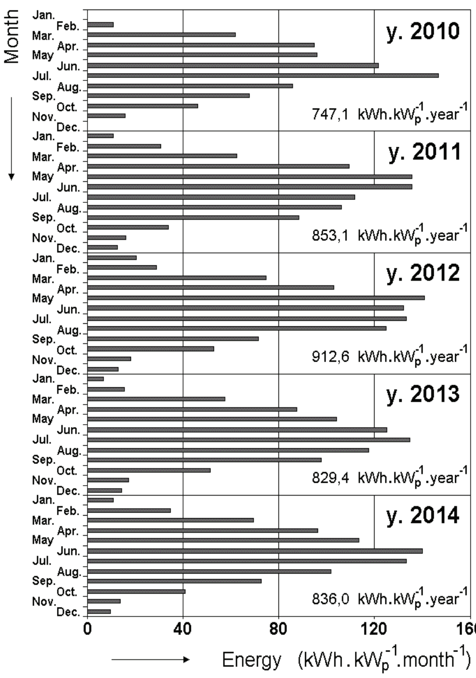

Figure 5. Electric energy produced in the PV power plant on the National Theatre Service Building roof during the years 2010–2014.

The PV panel area projection into the plane perpendicular to the Sun radiation is given by the incidence angle cosine ($S' = S_0 \cos\alpha$, where S_0 is the PV panel area and α is the incidence angle). The inclination of PV systems orientated northward and southward is approximately $\varphi = \pm 3°$. The incidence angle is 67° and 73°, respectively south/north part, at a low Sun elevation of 20° at the noon and the difference in the PV panels area projection into the plane perpendicular to the Solar radiation direction amounts to about 33%. The incidence angle is 27°and 33°, respectively south/north part, at a high Sun elevation of 60° at noon and the difference of the PV panels area projection into the plane perpendicular to the Solar radiation direction amounts to about 6%. Comparison of the results from the months in 2011 with a low Sun elevation, when the results were not distorted by snow deposits, reveals that the difference between the amounts of the produced electric energy was about 20%, in January it was even 31%. This difference is lower than the value of 33% evaluated above as along to the direct Sun radiation a small part of electric energy is also produced by the diffuse components, regardless of the incidence direction. In cloudy weather the difference between the produced electric energy is negligible. On the other hand, in spring and summer months with high Sun elevation the difference between the amounts of produced electric energy is about 15%. This difference is higher than the value of 6 % evaluated above as the Sun is at high elevations only for few hours round noon and for majority of the day it is at lower elevations and it does not radiate precisely from south. However, the difference is lower than in the winter months.

Finally Fig. 6 shows low degradation of the PV power plant energy production ~3% and ~4% respectively within 5 years period. It is less than expected as the plastic laminated a-Si degradation should be about 5% and the additional loss because of soiling (Cano, 2011) should be at least 2–3%.

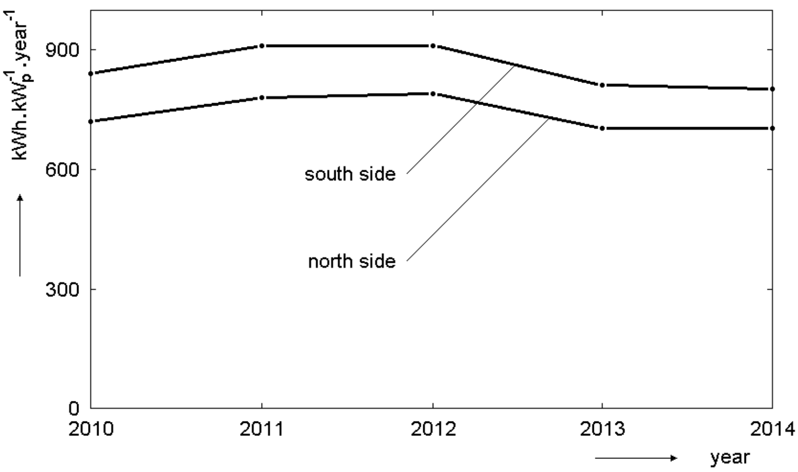

Figure 6. The annual energy production during the years 2010÷2014.

Tests with the same flexible PV foil were executed already in 2009 at the Czech University of Life Sciences Prague. Fig. 7 shows the PV foil with the nominal output peak power 0.406 kW_p. Fig. 8 presents examples of measurements of the instantaneous output power in dependence on the time during the selected days in 2009. The amount of the produced electric energy is given by the area under the graph because the amount of the electric energy produced in the time period Δt is given by the equation $W = \int_{\Delta t} P \mathrm{d}t$, where P is the instantaneous output power and t is the time. There are examples of the sunny days and cloudy days as well and the total produced electric energy amount is written. The average produced electric energy amount corresponds with our expectation and with the PV power plant mentioned above during the corresponding period (the years are different).

CONCLUSIONS

We consider the reconstruction of the National Theatre roofs with the incorporated PV power plant a suitable solution as the theatre management behaves ecologically (‘green’ solution). Regardless of the fact that the PV power plant described above can cover only a small part of the power consumption of the theatre, the roofs are purposefully used. The PV power plant construction on the basis of flexible PV foils was the only acceptable alternative with respect to the Prague historical centre conservation requirements. The power plant is not visible and the view on the Neo-Renaissence building of the National Theatre is not distracted as well as the view on the New Scene Building and Service Building.

Figure 7. The PV foil with the nominal output peak power 0.406 kW_p at the Czech University of Life Sciences Prague.

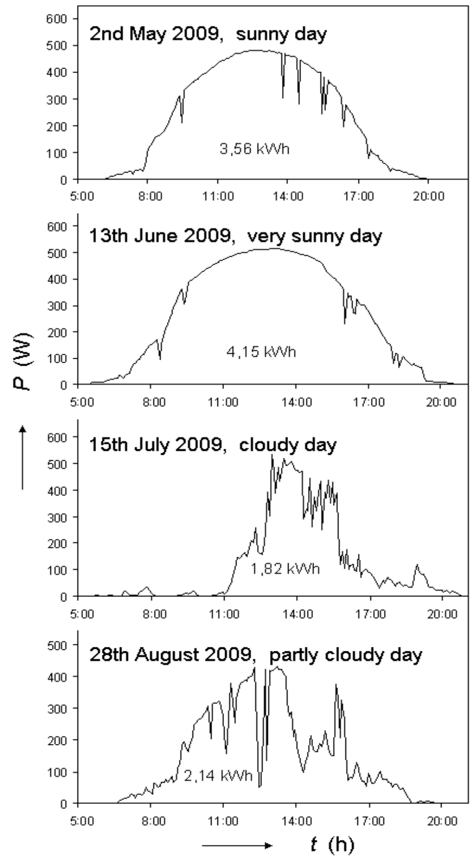

Figure 8. Examples of the instantaneous output power of the PV foil in dependence on the time during the selected days in 2009.

The energy production within the 5 years period is better than expected. The energy production degradation is ranging from 3÷4%. It is low value for a-Si thin film panels laminated in polymer foils. The typical degradation value is about 5% (Radue & Dyk, 2010). Additionally, the panels are installed with very low tilt angle 3 degrees only. The polluted air in the center of big city is contributing to substantial soiling of the panels. So the soiling loss alone can contribute to 2–3% of the degradation. These results indicate that a-Si PV panels laminated in plastic film can have low degradation of the energy production even if it is installed horizontally in polluted urban environment.

Although the difference between the tilled angle of the both sides of the PV system is 6° only, the annual energy production difference is cca 15%.

We intend to continue in the collection of data and it will be certainly interesting to observe how the measured values will change in connection with the whole construction ageing. Another 440 kW_p BIPV power plant with the same a-Si PV panels in Prague is installed on the roof of the stadium of the SK Slavia football club (Fig. 9). The data have been collected too. Annual energy of this PV system production in the years 2011–2015 was in the range 789÷654 kWh kW_p^{-1} $year^{-1}$. The lifetime of the PV panels was simulated in (Hasan & Arif, 2014). The comparison with our collected data will be interesting. These data will be of interest also for designers of other roof PV systems.

Figure 9. PV power plant on the roof of the SK Slavia football club, Prague.

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