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Note

Agrivoltaics: dual usage of agricultural land for sustainable development**

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A b s t r a c t. In connection with renewable energy sources, the courtyards of the buildings provide space for the installation of agrivoltaics for sustainable development. This paper proposes the use of courtyards of low-rise buildings for agrivoltaics. This will increase the area for installing photovoltaic systems, which have so far only been installed on roofs or facades or on open fields. The advanced design of the photovoltaic systems will enable the dual use of the area both for the cultivation of crops and for the production of electricity at the same time. The increased amount of electricity produced in photovoltaic systems also contributes to reducing the carbon footprint. On the courtyard as well as on the open fields, it is possible to grow agricultural crops between rows of photovoltaic panels. The partial shading of seedlings during summer sunny days reduces their heat stress and slows down soil drying. Solar eclipses are rare, but their impact on electricity generation is significant. We evaluated the measured data and we assessed the electricity production and the influence of a solar eclipse on the electricity production in photovoltaic power plants in the Czech Republic. The daily loss in production depends on the size of the eclipse. A comparison of the annual electricity production in two selected PV power plants with the expected values according to PVGIS testifies to the quality of the construction and the PV panels used in both power plants.

K e y w o r d s: Agrivoltaics, carbon footprint, heat stress, photovoltaic system, solar eclipse

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1. INTRODUCTION

Electricity from photovoltaic (PV) systems has an important place in the energy mix today. For example, Feron *et al*. (2021) discussed the need to develop renewable energy sources in the context of mitigating global climate change and reducing the carbon footprint. The use of energy management practices can significantly reduce the energy requirements of many activities. The influence of the economic structure on the use of renewable and non-renewable energy sources was discussed, for example, in work (Can and Ahmed, 2023). They are constructed new and more energy-efficient equipment. Already in 1992, (Shahbazi, 1992) proposed a more significant use of energy from renewable sources in agriculture. Electricity from photovoltaic systems is proving to be an important alternative source of energy. It can substitute for conventional fossil energy supplies. The majority of PV power plants in the Czech Republic is installed on agricultural land and their design does not allow the land to be used for growing agricultural crops. That is why a new specialization of agrivoltaics has been created in recent years. The advanced

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design of photovoltaic systems will enable the dual usage of agricultural land both for the cultivation of crops and at the same time for the production of electricity (Feuerbacher *et al.*; 2021; Jo *et al.*, 2022). We consider such use of agricultural land to be very useful, as it also contributes to reducing of the carbon footprint (Kapica *et al.*, 2015). This is an attachment for sustainability. In addition, agrivoltaic systems contribute to maintaining water in the landscape, as they shade and thus reduce water evaporation during warm and sunny days (Omer *et al.*, 2022). On the farmland, it is possible to grow agricultural crops between rows of photovoltaic panels. Partial shading of seedlings during summer sunny days reduces their heat stress. The courtyards of the low-rise buildings provide space as well for the installation of agrivoltaics for sustainable development. This offers an alternative to installations on roofs and facades of buildings. Figure 1 shows an example of the agrivoltaic system on the courtyard. It can be directly connected to the network. Many similar agrivoltaic systems were constructed.

For small agrivoltaic systems in the courtyyards of low-rise buildings, the maintenance of the agricultural land under the photovoltaic system can take place with hand tools. For medium and large agrivoltaic systems, the construction of the PV panel stands allows passage autonomous agricultural equipment (Fig. 2). Therefore, the design of the construction of the agrivoltaic system must correspond to the planned maintenance method of the agricultural land.

The paper (Velasco, 2021) deals with the time prolong of daylight in greenhouses in Nordic countries using LED-based light sources powered by accumulated electric energy from agrivoltaics. Thus, it is possible to extend the growing season for some crops. The work (Bechini *et al*., 2000) deals with the distribution of natural global solar radiation.

The electricity production in PV systems is affected by many factors (Havrlík *et al*., 2022) and detailed production planning is thus limited. Some factors we can expect on, some we cannot. For example, we cannot influence the weather, but we can expect on average values over a longer period (Rezk *et al*., 2015). In the Central Europe, annual production is over 1 000 kWh kW_p^{-1} $year^{-1}$. The energy storage is of great importance here. We have dealt with this issue before, see for example (Poulek *et al*., 2020). We have constructed a compact unit - a PV panel with an integrated electric energy accumulator. Large PV power plants can contribute significantly to energy storage in large pumped storage power plants. The position of the Sun in the sky can be expected depending on time (Božiková *et al.*, 2021).

A very specific phenomenon is the solar eclipse, it also can be expected in advance. It occurs very rarely, but the decrease in electricity production in PV plants is significant, especially in areas with a total eclipse (Reda, 2015). We have dealt with this issue before (Libra *et al*., 2016). At that time, we presented the evaluation of the data from the partial solar eclipse (68% of the surface of the solar disk on March 20, 2015) and our own conclusions regarding the

Fig. 1. An example of the agrivoltaic system on the courtyard.

Fig. 2. The agrivoltaic system allows passage of the autonomous agricultural equipment (an example).

impact on the production of electricity in PV power plants. Thanks to the unique Solarmon (2.0) monitoring system, we have detailed data from the operation of approximately 85 large PV power plants in the Czech Republic and abroad. This monitoring system (Beránek *et al*., 2018) was developed in cooperation with Solarmonitoring, Ltd. and Faculty of Engineering. We compared the data with the internationally used application Photovoltaic Geographical Information System (PVGIS, 2023) and found a good agreement between theory and experiment.

On buildings, PV panels were installed on roofs and facades. In connection with renewable energy sources, the farmland mainly provide biomass energy (Enes *et al.*, 2019; Egnell *et al*., 2011). The objectives of this study is to propose agrivoltaic systems as an alternative and at the same time to propose directions for further study in this field. In the next work, we want to focus on the measurement of soil moisture and compare the drying of an unshaded area and an area partially shaded by an agrivoltaic system. We will collaborate with biologists to compare the development of plants under the agrivoltaic system and growing freely.

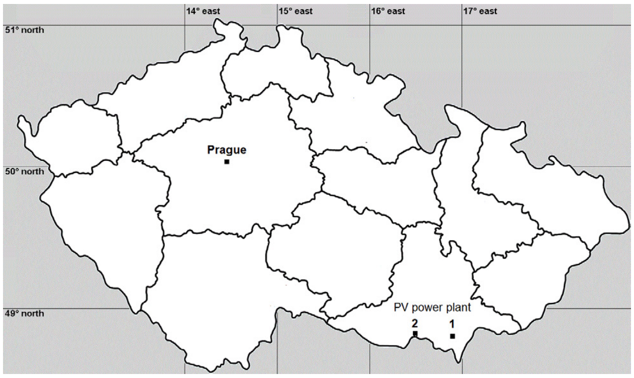

Fig. 3. Location of selected PV power plants on the map of the Czech Republic.

2. MATERIALS AND METHODS

In this article, we present the evaluation of data from two selected PV power plants in the Czech Republic during long-term operation and during the partial solar eclipse on October 25, 2022. The results from the other monitored PV power plants were similar. The Solarmon (2.0) monitoring system is used to data monitoring. The detailed location of selected PV power plants on the map of the Czech Republic can be seen in Fig. 3. We used the collected data to evaluate the electricity production and to evaluate the influence of the solar eclipse on the production of electricity in PV power plants. PV power plant 1 has coordinates 48.8°N, 16.9°E and a nominal output of 4 026 kW_p, PV power plant 2 has coordinates 48.8°N, 16.5°E and a nominal output of 2393 kW_p. Both PV power plants use PV panels (of first tier) based on crystalline silicon placed on fixed stands with an inclination of 35° with an orientation almost to the south (5° to the west). In this configuration, the highest annual electricity yield is achieved in the Central Europe in the standard PV systems with fixed stands. Both PV power plants started the operation in 2015.

On October 25, 2022, there was a partial eclipse of the Sun, which accounted for approx. 30% of the covered surface of the solar disk (approx. 42% of the diameter of the solar disk). The area of the Czech Republic is relatively small, so the differences in different places of the republic were also small.

3. RESULTS

Figure 4 shows electricity production in selected PV power plants during the last two years. During previous years, the values were similar. Table 1 shows expected values of produced electricity according to the Photovoltaic Geographical Information System (PVGIS, 2023) in the given location. From the comparison of the values, we can see that both selected PV power plants provide more than 10% more energy compared to the expected values. This fact testifies to the quality of both, the PV panels used and the construction of PV power plants.

Table 1. Expected values of produced electricity according to the Photovoltaic Geographical Information System (PVGIS)

Month	Energy harvest ($kWh\ kWp^{-1}\ month^{-1}$)
1	41.9
2	61.8
3	100.9
4	132.6
5	132.0
6	135.0
7	139.2
8	132.0
9	112.0
10	81.0
11	47.9
12	38.4
Σ	1 154.7

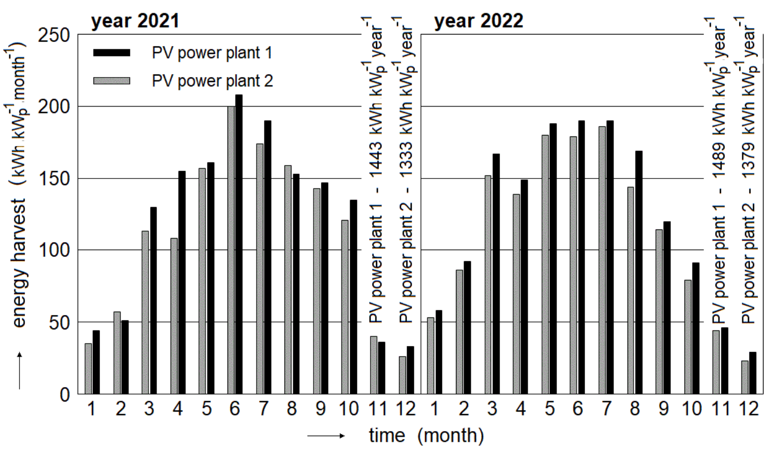

Fig. 4. Electricity production in selected PV power plants during the last two years.

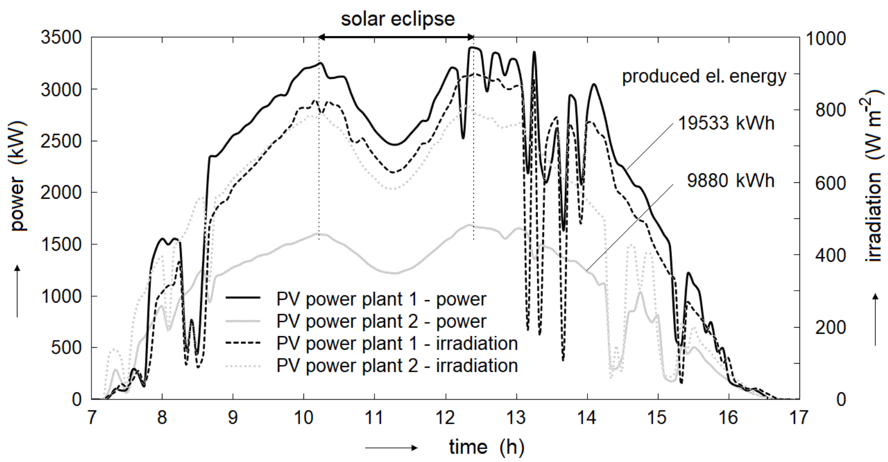

Fig. 5. Dependence of instantaneous power and radiation intensity per area of PV panels on time during the day on October 25, 2022.

Figure 5 shows the dependence of the instantaneous power and radiation intensity per area of the PV panels on time during the day of October 25, 2022. The graphs show data from both mentioned PV power plants. The drop in instantaneous power due to a solar eclipse is clearly visible here due to the clear sky at the time of the eclipse. Short-term drops in power in the morning and afternoon correspond to cloud cover, which fortunately dissipated in the time of the eclipse. In Fig. 6, for a better comparison, the values of the instantaneous power are calculated per 1 kW_p of the nominal power of PV power plants, and there are also approximate interpolated dotted curves to eliminate the effect of the eclipse. The partial solar eclipse began at 10:13 a.m., peaked at 11:17 a.m. and ended at 12:23 p.m. CET. At the different places in South Moravian region, these times may differ by only a few minutes. The given eclipse time is also marked on the figures.

4. DISCUSSION

It can be seen, that at the maximum of the eclipse the instantaneous value of the power corresponds to approximately two thirds of the interpolated value eliminating the influence of the eclipse. The drop in power by one-third approximately corresponds to the coverage ratio of the solar disk. The area under the graph corresponds to the produced electrical energy W because:

$$\int_{t1}^{t2} P \, \mathrm{d}t = W,$$

where: P is instantaneous power and t is time of power plant operation.

From the interpolated curve, we used a planimeter to measure the area corresponding to the loss in electricity production due to the solar eclipse and converted it to the drop in electricity production. The results are clearly presented in Table 2.

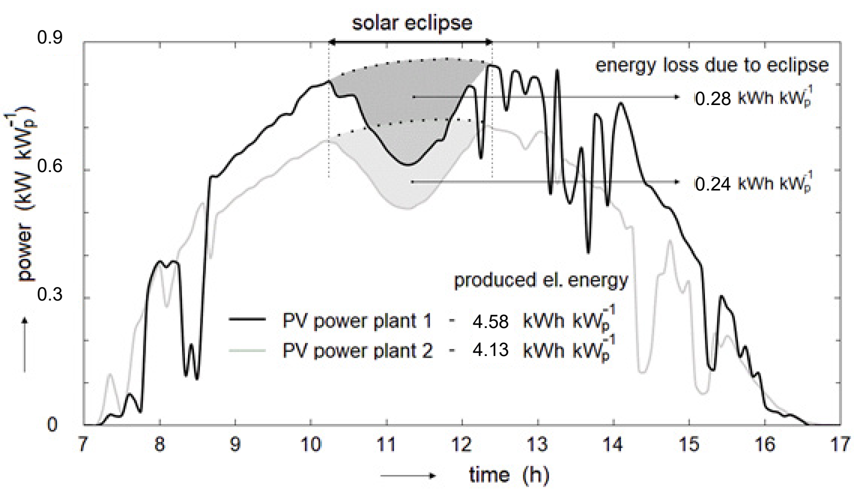

Fig. 6. Dependence of the instantaneous power calculated per 1 kW_p of the nominal power of the PV plant and the interpolated eclipse-eliminating curve during the day on October 25, 2022.

Table 2. Values of the produced electricity and the loss in production due to the eclipse calculated per 1 kW_p of the nominal output power of the PV power plant

PV power plant	Daily energy	Daily loss due to eclipse	Total	Loss due to eclipse (%)
	(kWh kW_p^{-1})			
1	4.58	0.28	4.86	5.84
2	4.13	0.24	4.37	5.52

The partial eclipse of the Sun on October 25, 2022 was relatively small, therefore the loss in the production of photovoltaic power plants is also small (Table 2). With a larger eclipse, the loss in production would be larger, as can be estimated from the data presented in the article (Libra *et al.*, 2016), when the maximum eclipse was 68% of the covered surface of the solar disk. The loss in energy harvest also depends on the time of day of the solar eclipse. The biggest loss is when the eclipse takes place around noon. In the morning and early evening, the instantaneous power is lower, so the mentioned energy loss would be also lower. In the case of a larger number of PV power plants in one location, it could also cause a problem in the distribution network because the balance between supplied and consumed instantaneous power in the distribution network may be disturbed. Small off-grid networks in particular may be most at risk. In the courtyards of low-rise buildings as well as on the open fields, a structure with a high stand and with the orientation of the PV panels horizontally or with a slight inclination to the south is advantageous. This minimizes the effect of shielding the walls of the building). On farms, it is possible to install PV panels in a vertical position and to make the gaps between the rows wide enough for technical vehicles to pass through. Such a construction of an agrivoltaic system will provide less electricity, but a higher use of the farmland. In addition, the vertical position of the PV panels minimizes the sedimentation of dust or snow. We have seen such agrivoltaic farms in Germany, for example. We discussed in details economic consequences of relations between lifetime of PV system and price of electricity in the previous article (Libra *et al.*, 2023).

5. CONCLUSIONS

We consider the dual use of agricultural land for the cultivation of crops or grow tree seedlings and at the same time for the production of electricity using agrivoltaics to be a very effective solution. Courtyards of low-rise buildings can also be used for this. The contribution of agrivoltaics to reducing the carbon footprint or energy accumulation into hydrogen production and storage is also significant. This is a contribution to sustainability. Agrivoltaic systems in the courtyards of low-rise buildings can augment photovoltaic systems installed on roofs or on open fields. In addition, partial shading of the plants during sunny days reduces the thermal shock of the plants and slows down the drying of the soil.

The production of electricity in the monitored power plants exceeds the expected values. Solar eclipses rarely occur, but they have a significant impact on the production of electricity in PV systems. We have evaluated data from PV power plants monitored by our Solarmon (2.0) monitoring system. We assessed the effect of a solar eclipse on the loss in daily electricity production. The presented results from two selected PV power plants show a good agreement between theory and experiment, data from other PV power plants are similar. The eclipse on October 25, 2022 covered only about 30% of the surface of the solar disk and resulted in a loss of 5.52÷5.84% in daily electricity production. With a larger eclipse, the loss would be larger not only as a result of the above mentioned equation. Usually, during a major eclipse, there is a rapid drop in temperature, vapour condensation in the atmosphere and the formation of clouds. This subsequently leads to a further loss in electricity production.

A solar eclipse is a phenomenon known in advance and it can be expected in advance. However, the production of electricity in PV power plants is also influenced by other factors that cannot be expected in advance. But over a longer period of time, we can expect average values, which are also calculated by the internationally used PVGIS application. A comparison of the production of electricity in two selected PV power plants with the expected values according to PVGIS testifies to the quality of the construction and the PV panels used in both power plants. Energy accumulation is important here, due to the unevenness of electricity production during the day and throughout the year.

Only photovoltaic systems of limited capacity can be installed in the courtyards of buildings. But we believe that this is also important from the point of view of saving energy taken from the grid or for cases of a backup source in case of emergency or emergency situations.

Conflicts of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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