MODELLING ELECTRICITY PRODUCTION FROM 49.9 KWP FIXED VERTICAL AGRI-VOLTAIC POWER PLANT AS FUNCTION OF SPOT SALES IN THE CZECH REPUBLIC

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Abstract. Agrivoltaics is a relatively young technology combining power generation and crop production. There are 2 basic types of agrivoltaic technologies, namely vertical and horizontal technologies. Vertical technology consists of rows of bifacial photovoltaic panels, which are usually vertically positioned with one side facing east and the other facing west. Horizontal technology consists of structures on which PV panels are placed horizontally at different inclinations and can be placed on all cardinal directions except north. This paper presents the results of modelling power generation throughout the year in fixed vertical agrivoltaic technology. The modelling is focused on the conditions of the lowlands of the Czech Republic, more precisely on the Rakovník region. The modelling was carried out in PVGIS software. The modelling of electricity production was carried out for a plot of land located in the municipality of Zavidov. For the modelling, a fixed vertical structure was selected, which is fitted with bifacial panels with an albedo effect of 20%. In case of negative prices, it is considered that the plant would be disconnected from the grid. The reliability of this modelling will be verified in the following years with a real power plant with the parameters given in the modelling. The power plant is already under construction for the purpose of exploratory verification of operation. The modelling results show that the highest electricity production is in July with 123.6 kW per 1 kWp of installed capacity, while the lowest electricity production is in December with 18.4 kW per 1 kWp of installed capacity. The power generation curve is more favourable compared to horizontal designs because there is not only one peak in the power curve that peaks at noon, but there are two peaks, one in the morning and one in the afternoon. This feature is advantageous in that spot prices are higher the further away they are from 12 noon.

Keywords: agrivoltaics, vertical agrivoltaic system, renewable energy, economy.

Introduction

Agrivoltaic systems are among the newest systems in the decentralized energy sector. Agrivoltaics conceptually means the simultaneous cultivation of crops and electricity generation on a single plot of land. Although the primary idea is not entirely new, the development of this technology has only occurred in the last few years, where different types of designs are being tested together in synergy with the cultivation of different field crops and even fruit production [1]. Unlike conventional photovoltaic power plants, the primary purpose is the cultivation of crops, energy production is only a complementary activity. The design in the optimal case does not pose a threat of radically reducing the yield potential of the land, in some cases it can even increase it (suitable shading for sensitive plants – especially fruit and vegetable production). The agrivoltaic system must always minimally interfere with the cultivated area and must not degrade the soil (not even, for example, by erosion of falling droplets from the panels). The foundations for the structure are designed without concrete footings to avoid soil degradation and to allow the field to be restored to its original condition at the end of the structure's lifetime. Agrivoltaics are currently being intensively tested in a number of countries both in Europe and in other parts of the world [2].

However, agrivoltaics are not suitable for all crops and all locations. Profitability will also depend on local energy use and other factors. One measure of meaningfulness is the indicator of agricultural land use efficiency [3]. This value shows the ratio of profits from the production of combined land use and separate land use. For agrivoltaics to be meaningful, the resulting ratio must exceed 100%. The results at the experimental plot of the University of Hohenheim in 2017 showed an overall land use efficiency of 160% when growing wheat in combination with photovoltaics [4].

The weakness of agrivoltaics appears to be the high acquisition costs of elevated structures, especially for horizontal structures over field crops, where existing structures cannot be used as in permanent crops. The economic aspects of agrivoltaics are currently not sufficiently mapped. Future research should analyze and quantify the costs and benefits of agrivoltaic systems and the overall environmental impact. Among the renewable energy sources, photovoltaics has a significant potential in the Czech Republic. According to a study carried out by EGÚ Brno, the total technical potential of PV installed on residential and non-residential buildings is 23.8 GWp [5]. An estimate of the potential of agrivoltaics for the Czech Republic has not been made, but in this case, we can compare with neighboring Germany, because the intensity of solar radiation is similar there. The Fraunhofer Institute states in its manual that only about 4% of arable land in agrivoltaic mode is needed to cover the current total electricity consumption in Germany (about 500 GWp of installed capacity). According to their preliminary estimates, the technical potential of agrivoltaics in Germany is around 1700 GWp [6]. In the Czech Republic, the aforementioned 4% corresponds to the area sown with rapeseed for energy purposes. In terms of energy and food yields, agrivoltaics seems to be much more efficient than just growing energy crops.

In terms of design, there are basically two types of agrivoltaic systems– horizontal and vertical. Horizontal photovoltaic panels are placed on a raised structure above the soil surface so that both labour and farm machinery can move underneath. The clear height of the structure is usually 3.5 to 5 metres. It depends on the height of the equipment used and the crops grown. In the case of hops, for example, the height of the structure can be over 8 metres. The area of the photovoltaic panels is south-facing, or single-axis 'tracking' photovoltaic systems are used, which follow the movement of the sun to maximize the energy yield during the day. The structure takes up approximately 2% of the site area. Panels with different ratios of PV cells to glass or semi-permeable panels are also being tested [7].

The second option is vertical structures. In this case, the panels are placed vertically towards the ground surface in a supporting structure. The weakness is the difficulty of farming the area directly under the panels to a distance of about 0.5 m buffer strip on each side, due to the need to minimize the possibility of damage to the panels during the passage of agricultural equipment. The distance between panel lines may vary. Here, the question of the footprint of the equipment used and its multiples logically arises. The line of a vertical PV system can also be used as a fence - this solution can also be used around orchards or vineyards, for example [8].

The aim of this study was to model the electricity production from a 49.9 kWp fixed vertical agrivoltaic power plant in relation to spot sales in the conditions of the Czech Republic. This study will be followed by a field experiment. The agrivoltaic power plant is installed on the test plot with the exact parameters that were used for the calculation.

Materials and methods

A model was created in PVGIS (Photovoltaic Geographical Information Systém, available at the internet address: https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en) for the project's experimental site to produce electricity. For bifacial panels, an albedo effect (reflectance from the surrounding area) of 20% was assumed. The data obtained is from 2005 to 2020, from which an average was created. The power generation data are at intervals of one hour per day. For the calculation, it was assumed that the panels are oriented with one side facing east and the other side facing west and are in a vertical position. All calculations were performed for a unit of 1 kWp of installed capacity.

The first step was to generate the total electricity production in each month from both orientations of the PV panels. This was followed by analyzing the power generation data by hour of each day in the months when power generation is highest and lowest. Spot prices were used to model the return on electricity sales. The spot market purchase price values were obtained from OTE, a company that deals in energy commodities. The modelling of the revenue from the sale of electricity was carried out for the period from December 2023 to November 2024. This period was chosen as the modelling will be followed by data collection from the experimental plant from December 2024 onwards. For each day and each hour in each month, the electricity revenue was calculated, from which the average price per kW of energy produced was also calculated. This was followed by the calculation of the electricity yield in each month. All these calculations to date have been made per unit of 1 kWp of installed capacity. The final return is calculated for an agrivoltaic plant with 49.9 kWp of installed capacity. The data were processed with MS Excel (Microsoft Corp., USA).

As part of the experimental validation, an agrivoltaic power plant was installed at the Zavidov site (50.0599292N, 13.6215481E), which has been operational since December 2024 and data collection is ongoing, the plant has the same parameters as those used for the modelling. The vertical structures are equipped with bifacial PV panels with an albedo effect of 20%. The area of these panels is oriented with one side facing east and the other facing west. Thanks to the lines of the agrivoltaic system, the fields are divided into smaller units, thus representing some eco-services of the frontier without compromising the economics of the operator. These lines could have a similar positive effect as the borders, protection against water and wind erosion and promotion of biodiversity. The experiment used a simulation of a vertical agrivoltaic system with the land divided by 6 m biobelts on the edges of which a simulation of a vertical agrivoltaic system was planted. This study was funded by the Czech Technological Agency, Project No. SS05010243.

Results and discussion

The graph below shows the electricity generation by month from both panel orientations, including the total yield in each month. The graph shows that the lowest agri-voltaic generation is in December with a value of 18.446 kW per 1 kWp of installed capacity, while the highest agri-voltaic generation is in July with a value of 123.598 kW per 1 kWp of installed capacity. In total, according to the model of a vertical agri-voltaic power plant equipped with bifacial panels, under the conditions of the lowlands of the 50th parallel, a yield of up to 883.446 kW of electricity per 1 kWp of installed capacity can be achieved. For comparison, a conventional photovoltaic power plant that is located to the south with a panel inclination of 35° produces 1065.14 kW of electricity per year from 1 kWp of installed capacity, if an east-west installation with a panel inclination of 25° were chosen, the production would be very close to an agrivoltaic power plant, the east side would produce 892.24 kW from 1 kWp of installed capacity, the west side 869.64 kW. The comparison was made in terms of electricity production per 1 kWp of installed capacity, as the installed capacity per hectare can vary from one implementation to another.

The power generation is not symmetrical for the east and west sides. The explanation is the model data from 2005 to 2020, which shows that in the morning hours, electricity production was higher on the east side than on the west side due to more favourable weather for electricity generation. The biggest disadvantage is the seasonality of power generation, a large amount of power is produced in summer, but on the contrary, only a fraction is produced in the winter months.

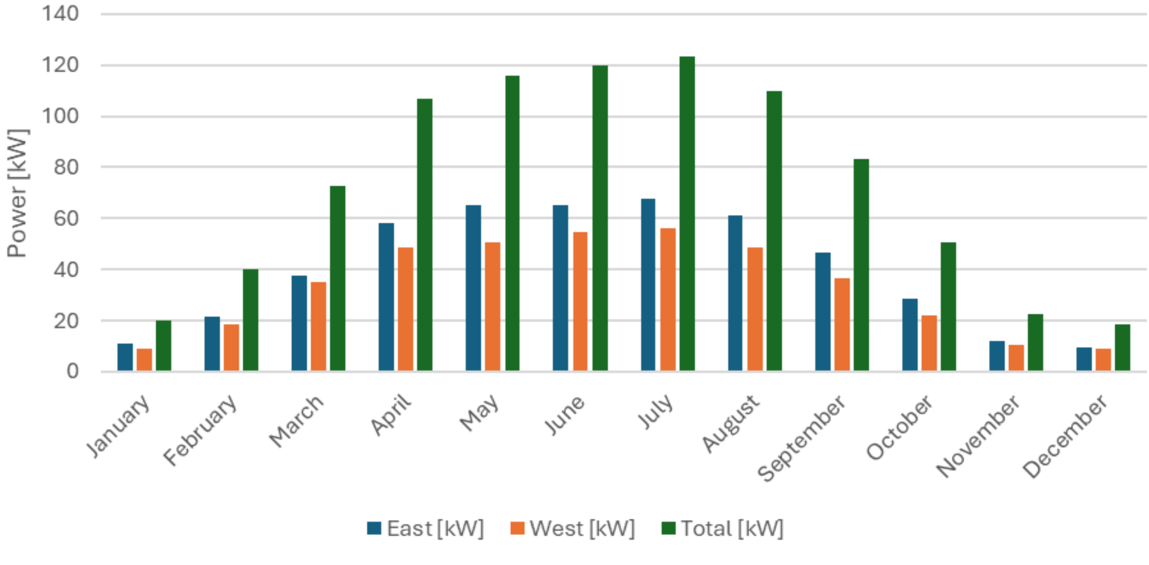

Fig. 1. **Electricity generated by month**

The agrivoltaic power plant, which is made up of vertical bifacial panels, has the undeniable advantage of spreading power generation over the day. Compared to conventional horizontal structures, there are two peaks of electricity production, one in the morning and one in the afternoon. This factor can have a positive effect on the immediate purchase price of electricity and then the overall payback of the technology. The highest performance of a vertical agrivoltaic plant can be achieved when one side of the panels is oriented directly east and the other side directly west. The left peak in the graph below is formed by the illumination on the panels from the east side and the right peak is formed by the illumination on the panels from the west side. The highest power generation was in the morning hours of July, where it was around 400 W per 1 kWp of installed capacity, while the lowest power generation was in December, where the hourly peaks were only around 100 W per 1 kWp of installed capacity.

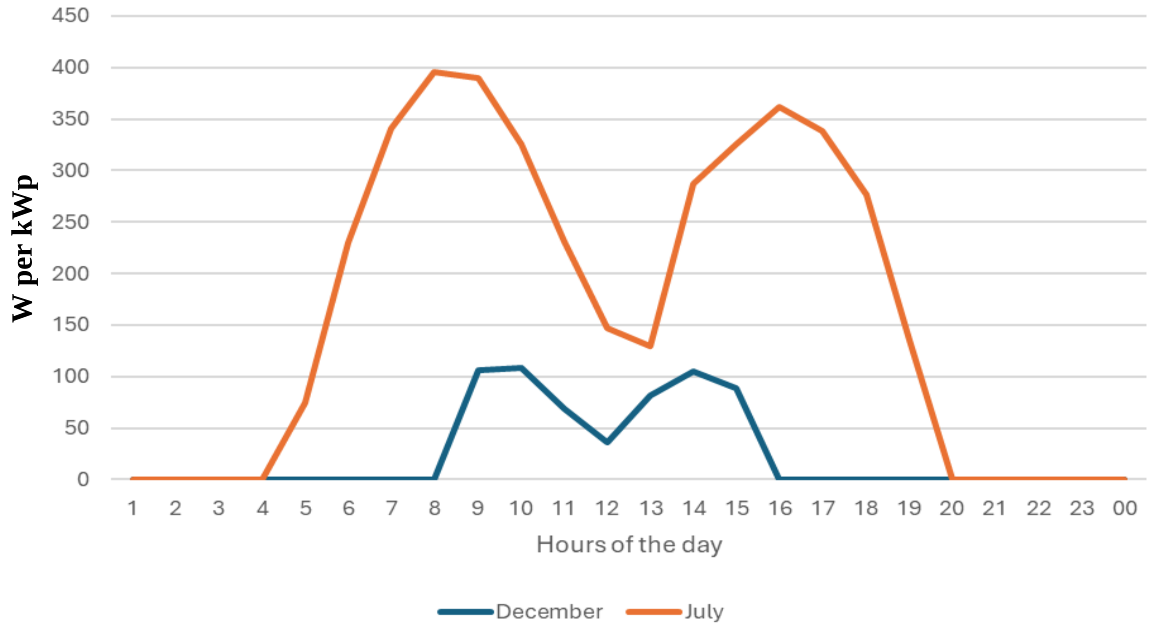

Fig. 2. **Electricity production during a day in December and July**

Comparing the graph above and on the next page, it is already evident why vertical bifacial plants are so popular in terms of the distribution of power generation and the spot market feed-in tariff. The power purchase price values were taken from OTE (energy trading company that maintains a database of electricity prices on the Czech market, available at the internet address: https://www.ote-cr.cz/cs).

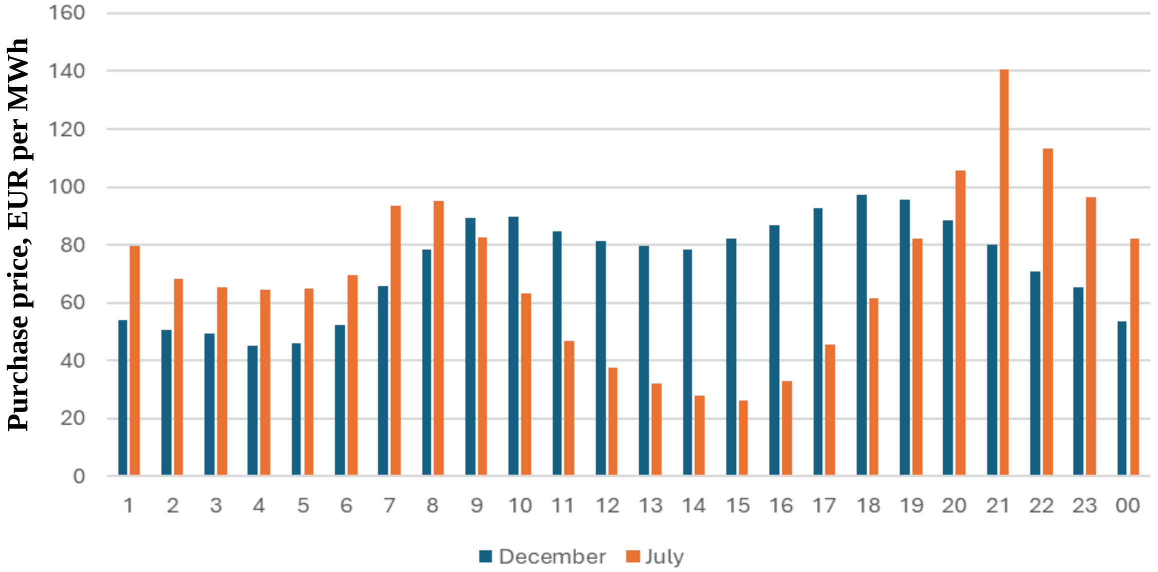

Fig. 3. **Average electricity purchase prices during a day in July and December**

Spot sales were chosen to model the revenue from the sale of electricity from the agrivoltaic plant. The period from December 2023 to November 2024 was chosen for modelling the revenue from sale of electricity, the purchase price during this period ranged from – 80 EUR to 200 EUR. The purchase price is highly variable because it is the variable amount of electricity produced from renewable sources that leads to a surplus of electricity at times when demand is not at its highest. Due to this factor, it can be observed that on some days the price of electricity on the spot market went into negative territory. Overall, the electricity purchase price in the summer months is lower than in the winter months, where demand is usually higher due to the heating season. The lowest average purchase price was in July 2024 when it reached 0.054 $EUR \cdot kW^{-1}$, while the highest average purchase price was in January when it reached 0.089 $EUR \cdot kW^{-1}$. In case of negative spot market prices, the plant was planned to be disconnected from the grid in order not to prolong the payback period. It can be seen from the table that the highest amount of electricity sold may not mean the highest electricity yield, this is due to the variability of spot market prices.

Table 1

Table of average spot prices by month

Month	Electricity production, kW per 1 kWp	Income from electricity, EUR per 1 kWp	Average price, EUR per kW
December 2023	18.446	1.514	0.082
January 2024	20.037	1.774	0.089
February 2024	39.842	2.774	0.070
March 2024	72.694	4.087	0.056
April 2024	106.638	6.069	0.057
May 2024	115.931	6.894	0.059
June 2024	119.975	7.102	0.059
July 2024	123.598	6.604	0.053
August 2024	109.683	8.189	0.075
September 2024	83.379	5.400	0.065
October 2024	50.644	3.952	0.078
November 2024	22.599	2.157	0.064
Total	883.466	56.516	–

Unfortunately, the return on agrivoltaic plants that would only sell electricity to the grid at spot prices is reaching high numbers that are already beyond payback. In this model case, the payback period of an agrivoltaic plant would be 25.4 years, which is beyond its lifetime, as it is calculated to have a lifetime of around 20 years. The input conditions for the lifetime calculation were: agrivoltaic power plant 49.9 kWp, price 72 000 EUR, annual revenue from electricity sales for 1 kWp of installed capacity would be 56.516 EUR. However, if the electricity generated by the agrivoltaic power plant were at least partly used on the farm, the return would be reduced to a realistic level that would no longer be a wasted investment. For small farms, agrivoltaic plants could be a way to save operating costs, especially for small farms with livestock production, vegetable or fruit farming, where the cost of keeping produce in cold storage is high. Agrivoltaic power stations would be built close to the farm settlements and would therefore eliminate distribution problems, as the power stations would be connected directly to the farm buildings where the electricity would be consumed. The disadvantages lie in the relatively high upfront investment. Another factor reducing the agrivoltaic power plant's return could be the rapid rise in energy prices on the spot market. In order to compare the payback of an agrivoltaic plant, an attempt was found to install an agrivoltaic plant in the USA, where the annual return is at least 80.64 EUR/1 kWp of installed capacity. If the conditions were similar in our environment, then the return on the plant would be lower [9].

Conclusions

Agrivoltaic systems are one of the interesting and promising technologies of a simultaneously changing agriculture. A vertical agrivoltaic power plant that is oriented east and west will achieve a similar value of electricity produced as a conventional photovoltaic power plant with the same orientation. The advantage of an agrivoltaic plant is the partial conservation of agricultural production. According to the model for a vertical agrivoltaic plant with bifacial panels, up to 883.44 kW of electricity can be produced from 1 kWp of installed capacity.

In the conditions of the Czech Republic there is certainly a suitable segment for the potential use of this technology. Another essential part is the current search for solutions to maximize the use of the energy obtained directly for agriculture itself. Thus, the importance of agrivoltaics will undoubtedly increase along with the introduction of new technologies such as field robots, autonomous machines and, in general, technology with alternative propulsion. This will paradoxically return agriculture as an autonomous energy industry. The risk of installation is then the negative impact on agricultural activity, which can be effectively eliminated by using the latest farming methods, including robotics and autonomous technologies. Future optimization of the legislative framework is then a very challenging task with many partly conflicting arguments. Local energy consumption optimally for sub-plot management and other tasks is also a future challenge.

Author contributions

The entire author team contributed equally to this research in all its aspects. All authors have read and agreed to the published version of the manuscript.

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