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# Feasibility Study for Project of Agrophotovoltaic System Based on the Existing Solar Power Plant

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**Abstract**

The object of the research is an agrophotovoltaic system. An analysis of the operating conditions of one of the existing solar power plants was performed and limitations of electricity generation due to its excess in the power system or due to work mode restrictions both under the normal state of the power grid and under individual emergency or repair modes were identified. This leads to an underproduction of electricity and a decrease in the efficiency of using the installed capacity of the solar power plant (SPP). Therefore, it was proposed to introduce an agrophotovoltaic system, which allows for more efficient use of land resources, it also allows us to increase the yield of agricultural crops that can be planted on the territory of a solar power plant, to eliminate restrictions on the delivery of generated power to the power grid through its direct consumption at the site of the SPP. The feasibility study of the project of an agrophotovoltaic system based on the existing power plant shows that its payback period will not exceed 3 years, and the profit for the 5th year of exploitation of such a system will be up to € 279409.

**Keywords:** agrophotovoltaic system; solar power plant; work modes; power grid; feasibility study.

## 1. Introduction

For another decade in a row, the world is facing high demand for electricity, at the same time fossil fuel reserves are decreasing every year. Renewable energy sources are becoming increasingly important to meet these modern challenges. Photovoltaic systems deserve special attention, they have great potential and can be considered even more efficient than photosynthesis when it comes to using solar energy [1]. Many of these systems in the world are installed on land that can be used for agriculture. This causes the irrational use of land resources, land use conflicts between the production of electricity and the production of agricultural products. Large areas of land used for the construction of powerful ground-based photovoltaic installations have begun to scare people worried about the loss of land suitable for agriculture [2]. Considering this conflict, the development of agrophotovoltaic systems (APV), the concept of which was proposed in the 19th century by Getzberger and Zastrov, can be interpreted as a dual-purpose method: combining the production of electrical energy and agricultural products in the same area [3].

Some of the first experiments with APV technology and studies of its impact on crop production have shown that the use of land resources to combine the installation of solar panels and food crops can be more efficient than individual use [4], [5]. By increasing the density of installed solar panels, it is possible to achieve not only an increase in electricity production, but also an economic effect due to the reduction of epidermal radiation received by agricultural crops. This confirms the relevance of the combination of the production of agricultural products and electricity.

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Another problem is the operation of solar power plants as part of electric power systems, when the maximum generation of electricity often coincides with the minimum consumption in the power system. This leads to the creation of mode restrictions on the output of power by those power plants into the power system, which reduces their performance. This excess electricity generated can be used by increasing energy consumption in the area where the solar plant is located, for example to power irrigation systems. Although the world experience is not rich in research in the field of agrophotovoltaics, it is safe to say that the positive impact of APV on the electric power industry and agriculture is obvious [6]–[8]. It confirms the necessity and expediency of implementation and further research in this field.

**2. The purpose and objectives of the research**

The object of research is an agrophotovoltaic system. The purpose of the study is to establish the effectiveness of creating an agrophotovoltaic system based on one of the existing solar power plants in Ukraine. This will make it possible to increase the efficiency of the operation of renewable sources of electricity compatible with the rational use of land resources, which will positively affect the level of agriculture.

To achieve the goal, the following tasks should be solved:

- perform an analysis of the functioning of the operating SPP "Hlyniany – 2" as part of the electric power system of Ukraine;
- investigate the work modes of the section of the electrical network from the Hlyniany – 2 SPP and establish the feasibility of creating an agrophotovoltaic system on its basis;
- choose an agricultural crop to be grown on the territory of the existing SPP and perform a feasibility study of the effectiveness of creating such an agrophotovoltaic system.

**3. Analysis of recent studies and publications**

At this stage, Europe is taking the first steps in installing and using APV systems. Some of the systems were created as test variants for research purposes, notably in France and Germany. Italy has the most powerful installations of that kind. Commercial projects called "Agrovoltaico" with a capacity of 1500 kW, located in the north of this country, use solar modules installed at a height of 4–5 m and equipped with solar trackers [9], [10]. Another example of the use of agrophotovoltaics is a field in Abruzzo. The power produced by the solar panels of this system is 800 kW [11]. One of the agrophotovoltaic systems was built in the south of France to study the impact on the distribution of solar energy [12]. The next test investigated the influence of the system on the growth and development of the plant, its yield and microclimatic conditions. The study concluded that increasing the efficiency of the studied agrophotovoltaic systems can be achieved with the help of trackers that monitor solar radiation [13], [14].

In Chile, near Santiago de Chile, another APV research system was built in collaboration with Fraunhofer Chile Research – Center for Solar Energy Technology, which studied the impact of implementing agrophotovoltaic energy in different climate zones [15].

Recently, the APV Biosphere 2 research center was established in Arizona, USA [16], [17]. At this facility, research focused on the impact of the cooling effect of solar panels on crop yields in arid regions.

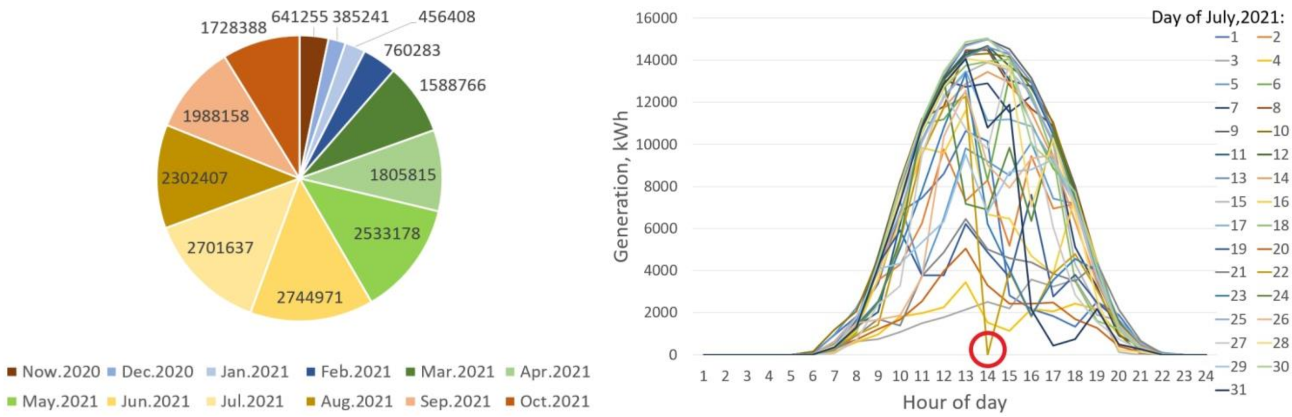
Following the experience of Europe and America, China is implementing large-scale agrophotovoltaics [18], [19]. The Chinese are building APVs with a capacity of up to 700 MW, equipped with additional functions such as irrigation and sun tracking [18], [19]. The most powerful APV with a capacity of 700 MW has also been commissioned in Ningix [18].

Today, world experience is not rich in the emergence of agrophotovoltaic systems. Their influence on the growth, development and yield of plants has been little studied. Countries with limited land resources have great prospects for the use of such technologies. APV research centers in China and Europe bring the first positive results regarding the potential of those systems [20]–[23].

**4. Presentation of the main material**

In the initial stage, we will analyze the operating conditions of one of the active solar power plants in the electricity system of Ukraine. The Hlyniany – 2 SPP, which is located in the western part of Ukraine near the city of Hlyniany, Lviv region, was chosen for the research. The power plant was commissioned in 2019 with an installed capacity of 18.26 MW. Solar modules of the TSM-PE06H type, 285–290 W, in the amount of 63240 units are installed at the SPP. 140 inverters of the SUN2000-105KTL-H1 type are used to convert direct current into alternating current, which supplies power to the power grid through 5 0.8/35 kV power transformers with a capacity of 3200 kVA each. The total area of the SPP is 36.85 hectares, of which 107712 $m^2$ is under solar panels, and 450 $m^2$ is allocated to transformer substations. The rest of the territory is occupied by office premises, roads, driveways and landscaping.

Analysis of hourly electricity generation data for each day of the year shows that the months of June and July are the most productive ones (Fig.1,a). These periods are also characterized by the longest generation time during the day. During this analysis, specific hours of the day in the range of maximum daily generation were found, when the generation sharply decreased to zero. This phenomenon is caused by mode limitations of electricity generation by the solar power plant due to excess energy in the power system (Fig.1,b).




*a* *b*

Fig.1. *a*) Distribution of total electricity generation for each month during the year, [kWh]; *b*) Hourly generation every day in July.

In order to analyze the possible operating modes of the Hlyniany – 2 SPP as part of the electric power system of Ukraine, a digital network model of the electrical section of the Hlyniany – 2 SPP was created (Fig.2) and normal, emergency–repair, and promising modes of operation were investigated for the following cases: 1) a normal power grid scheme without SPP generation; 2) normal power grid scheme with SPP generation; 3) turning off the T–1 power transformer at the Krasne substation; 4) turning off the T–2 power transformer at the Krasne substation; 5) shutdown of the 35 kV overhead line "Krasne – Hlyniany SPP"; 6) shutdown of the 35 kV overhead line "Hlyniany SPP – Hlyniany"; 7) Repair mode of turning off the 35 kV overhead line "Hlyniany – OPS Kurovichi" (OPS – oil pumping station).

The study of the coordinates of the modes of the analyzed section of the electric network is performed with the help of the DAKAR Eleks digital software complex [24]. The modes of operation for normal and emergency repair schemes of the electric network with the maximum generating capacity of the "Hlyniany – 2" SPP of 16 MW during periods of maximum and minimum daily loads, as well as daily load reduction (when the SPP is operating at maximum capacity) for typical winter days were investigated and summer, including a day off for the year of SPP commissioning and for a 5–year perspective.

According to the results of studies of the modes of daily winter and summer load reduction, winter and summer maximum load on weekends, as well as for hourly winter and summer daytime load with a perspective of 5–year load growth, we see that the voltage levels on the substation buses and the currents of lines and transformers did not exceed the permissible values. However, for the emergency-repair mode of turning off the 35 kV overhead line "Krasne – Hlyniany SPP" the T–2 currents at the OPS Kurovichi substation exceeded the permissible values, therefore, mode restrictions are created regarding the output of SPP power up to at least 13 MW.

Thus, we draw conclusions about the presence of mode restrictions regarding the output of power by the existing SPP both under the normal state of the power grid and under separate emergency or repair schemes. This leads to an underproduction of electricity and a decrease in the efficiency of using the installed capacity of the SPP. To prevent numerical limitations of electricity generation, it is necessary to consider possible ways of increasing energy consumption for the power plant's own needs. One of the options for the implementation of such an approach may be the introduction of an agrovoltaic system, which will allow the use of the area under already installed solar panels for the cultivation of agricultural crops with the construction of an irrigation system for watering them. This will allow us: a) to use of land resources more efficiently, b) to increase the yield of agricultural crops that can be planted on the territory of the power plant, c) to eliminate restrictions on the delivery of generated power to the power grid through its direct consumption at the site of the SPP.

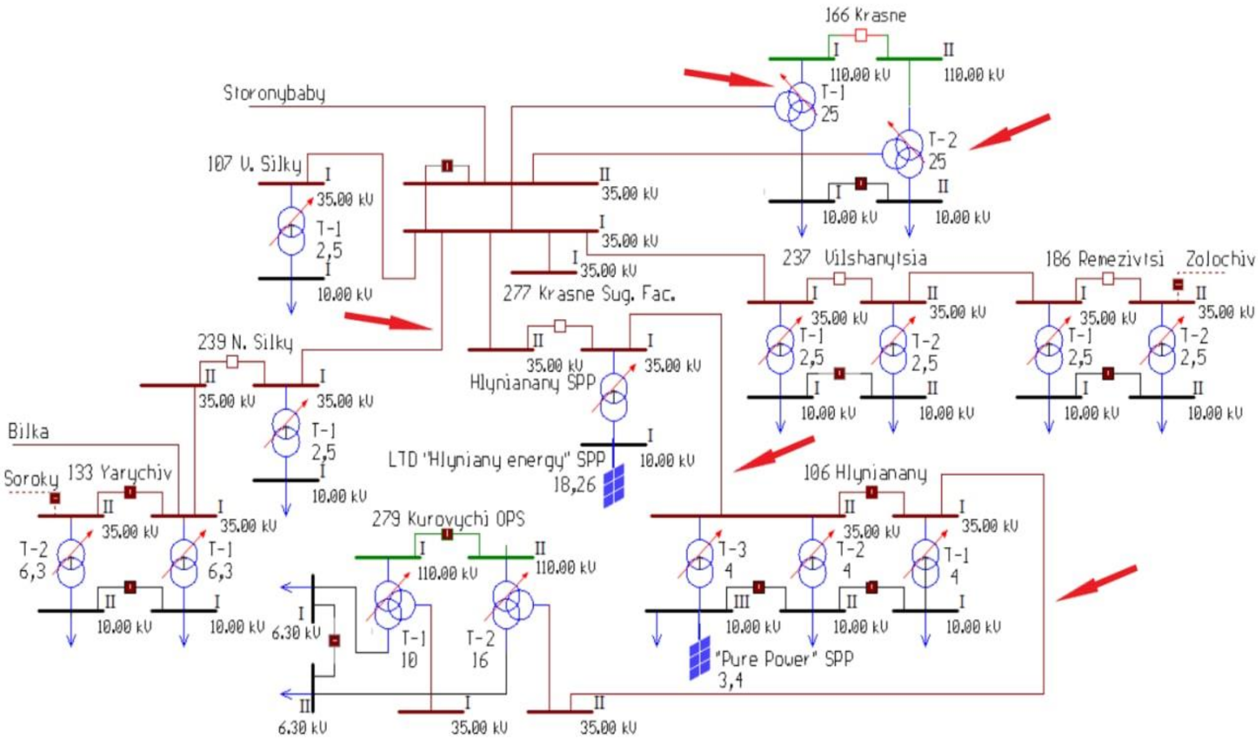



Fig.2. Digital model of the electrical section of the Hlyniany – 2 SPP in the DAKAR Eleks software complex.

The analysis of the electricity generation of the Hlyniany – 2 SPP during 2021 also shows that the largest share of electricity is produced in the summer, equal to 7749015 kWh, which is approximately 40% of all electricity generated. The second place in the total generation is occupied by spring, when 5927759 kWh were produced, which is approximately 30% of the annual generation. Autumn production of electricity amounted to 4357801 kWh, which is 22% of the annual total production. The lowest percentage of annual generation falls in winter, equal to about 8%, when only 1601932 kWh were produced. It can be seen that the maximum generation of electricity by the investigated SPP occurs in spring and summer. These very periods of the year are characterized by the highest energy consumption for growing agricultural crops in agrophotovoltaic systems.

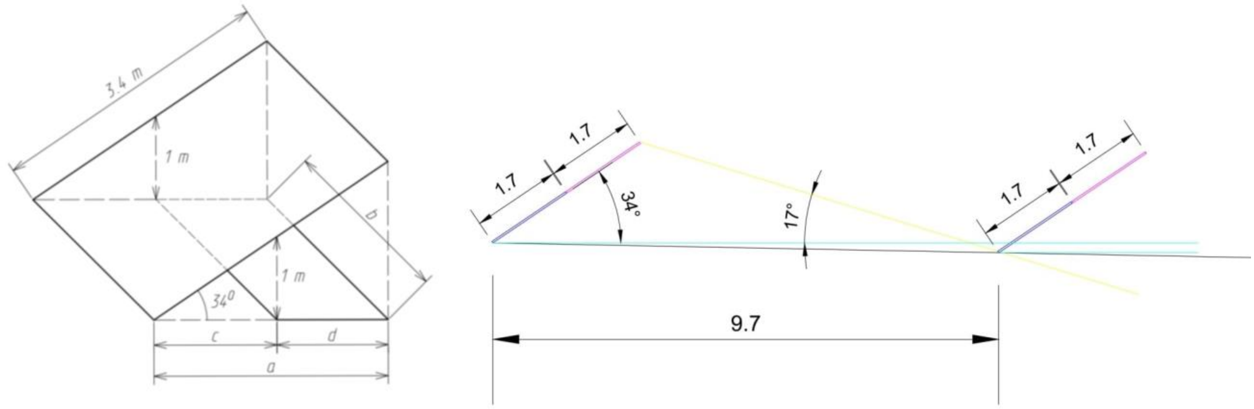
Let's make a feasibility study of the effectiveness of the suggested approach. Taking into account the weather conditions and the amount of precipitation according to [25], the Cumulius F1 hybrid asparagus was chosen for planting on the territory of SPP. Cumulus F1 is proposed to be planted on the area under the panels, but on the condition that the height from the ground to the solar panel will be at least 1 m for the convenience of growing and processing plants (Fig.3,a). Therefore, the effective area for plantation will be 51097 $m^2$ or 5.1097 hectares. To get a high–quality harvest, it is necessary to provide asparagus with a sufficient amount of moisture and fertilizers. The best way to solve this problem is drip irrigation. The water requirement of asparagus during the growing season is about 2000 $m^3$/ha of water [26]. The most special periods for the plant are the spring and summer seasons, as they are characterized by high temperatures and little precipitation, which often causes unfavorable conditions for growth, in drought. The largest number of electricity generation restrictions for our studied SPP "Hlyniany – 2" falls in the same period of the year. In view of this, in the spring it is necessary to carry out 3 irrigations at the rate of 250 $m^3$ /ha, and in the summer there should be 3 irrigations at the rate of 450 $m^3$/ha. It is proposed to use a 3GPE EVMSG10/3.0 type pumping station with three pumps to organize the irrigation of the asparagus plantation. The installed capacity of each pump is $P_{is}$ = 3 kW, and the productivity of water production with such a system $Q$ = 45 $m^3$ /ha.

Summarizing the calculations, it can be noted that the researched proposed agrophotovoltaic system will require 5 such pumping stations per hectare, that is, the total installed capacity of all irrigation system stations will be 45 kW. The annual electricity consumption for such an irrigation system will be 2115 kWh. However, it should be noted that there is a possibility of alternating operation of each of the pumping stations with their separate regulation. In addition, there will be additional electricity consumption for the operation of auxiliary devices, namely: inverters, computer systems, various sensors, sensors, etc. Therefore, taking into account the additional energy consumption, the total installed power of the irrigation system must be assumed to be equal to 50 kW.

The number of asparagus seedlings per 1 ha of the planting area can be calculated by the following formula [27]

$$N = \frac{100}{M} \cdot \frac{100}{A} = \frac{100}{9.7} \cdot \frac{100}{0.2} = 5155 \frac{pcs}{ha}, \quad (1)$$

where $N$ is the number of plants per 1 ha; $M$ = 9.7 m is the row spacing (Fig.3,b); $A$ = 0.2 m is the distance between seedlings in a row per linear meter.




*a* *b*

Fig.3. *a*) Projection of the solar module on the plane of the earth ($a$ = 2.819 m, $c$ = 1.481 m; $b$ = 2.416 m is the length of the seedling planting area, $d$ = 1.338 m is the width of the seedling planting area);
*b*) Geometrical parameters of the mutual placement of panels at the Hlyniany – 2 SPP.

Thus, for planting an asparagus on an area of 5.1097 ha, the total number of seedlings will be $N_t$ = 26341 pcs. To calculate the average yield, we use the data of F. Belane [28] for asparagus, according to which the average number of plants $n_p$ during the harvest will be 3; 16.6; 24.5; 26.4 and 27.5 pieces for each of the first five years of plant growing. The average weight of the plant $m_p$ for the first five years will be 18.1; 22.8; 25.5; 25.6 and 25.9 g, respectively. To calculate the yield of asparagus under normal conditions, it is necessary to multiply the total number of plants by the average number of plants and by the average weight of the plant, then for the first year of harvesting:

$$Y = N_t \cdot n_p \cdot m_p = 26341 \cdot 3 \cdot 18.1 = 1430316.3 \text{ g} = 1.43 \text{ t}, \quad (2)$$

where $Y$ is the yield of asparagus; $N_t$ is total number of plants, pcs.; $n_p$ is the average number of plants, pcs.; $m_p$ is the average weight of the plan, g.

The results of calculations for the harvest of the following years are shown in Table 1. To increase the yield of the studied agrophotovoltaic system, it is suggested to apply fertigation. Fertigation yields are much higher, and the cost per unit of production is lower. Fertigation increases the asparagus yield by 10–30% [29].

In order to carry out a feasibility study of the project of the studied agrophotovoltaic system, the Ukrainian agricultural market was studied and the average prices of the main materials, devices and works necessary for the creation of this system were determined. The calculated costs of the main material and technical costs are shown in Table 2, it also shows the results of the calculations of the profit and payback of the project on the condition that the yield of asparagus will increase by 20% thanks to the installation of the irrigation system. During the calculations, it is also taken into account that the purchase and installation of a protective film is expected, so the final product will be white asparagus, the average price of which in Ukraine is 4.95 € per kilogram, and there will be no need for further processing of the plantations.

Table 1. Results of calculating the yield increased by fertigation for the following years.

| Harvest year | Harvest under normal conditions | Harvest in the presence of fertigation | | |
|---|---|---|---|---|
| | Y [t] | $Y_{+10\%}$ [t] | $Y_{+20\%}$ [t] | $Y_{+30\%}$ [t] |
| 1 | 1.430 | 1.573 | 1.716 | 1.859 |
| 2 | 9.970 | 10.966 | 11.963 | 12.960 |
| 3 | 16.457 | 18.102 | 19.748 | 21.394 |
| 4 | 17.802 | 19.583 | 21.363 | 23.143 |
| 5 | 18.761 | 20.638 | 22.514 | 24.390 |

Table 2. Economic indicators of the agrophotovoltaic system project under the condition that the yield of asparagus will increase by 20% due to the installation of the irrigation system.

| Price, € | Year | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 |
| Seedlings | 60848 | 0 | 0 | 0 | 0 | 0 |
| Soil preparation | 1650 | 0 | 0 | 0 | 0 | 0 |
| Ridge formation and cultivation | 1650 | 0 | 0 | 0 | 0 | 0 |
| Planting seedlings | 1980 | 0 | 0 | 0 | 0 | 0 |
| Irrigation system | 13200 | 0 | 0 | 0 | 0 | 0 |
| Electric energy for irrigation | 225.926 | 225.926 | 225.926 | 225.926 | 225.926 | 225.926 |
| Fertilizers and pesticides | 3300 | 1980 | 1980 | 1980 | 1980 | 1980 |
| Protective film and its installation | 12210 | 0 | 0 | 12210 | 0 | 0 |
| Manual harvesting | 0 | 2970 | 2970 | 3300 | 3300 | 3630 |
| Total expenses | 95063.636 | 5175.926 | 5175.926 | 17715.926 | 5505.926 | 5835.926 |
| Product output (kg) | 0 | 1716 | 11963 | 19748 | 21363 | 22514 |
| Income | 0 | 8494.2 | 59216.85 | 97752.6 | 105746.85 | 111444.3 |
| Profit | -95063.64 | 3318.274 | 54040.924 | 80036.674 | 100240.924 | 105608.37 |
| Payback | -95063.64 | -91745.363 | -37704.439 | 42332.234 | 100240.924 | 105608.37 |

Similar calculations were performed for other options for changing the yield, as well as for the cultivation of ordinary asparagus. Analysis of the obtained results shows that due to the significantly higher price of white asparagus and the increase in yield due to the installation of irrigation, such systems are more efficient, and the payback period will be approximately 3 years.

The profit during the first 5 years of operation of the APV system will be € 248181.532 assuming a 20% yield increase. If, thanks to irrigation, the yield increases by 10 or 30%, the payback period will remain the same, but the profit for the 5th year of operation of the system will be € 215624 and € 279409 respectively.

## 5. Conclusion

1) According to the results of the analysis of the operating conditions of the Hlyniany – 2 SPP, typical hours of the day in the range of the maximum daily generation were found when the generation sharply decreased to zero – this phenomenon is caused by the regime restrictions on the generation of electricity by the solar power plant due to the excess in the power system.

2) Studies of the operation modes of the section of the electrical network from the Hlyniany – 2 SPP have established the presence of mode restrictions regarding the output of power by this power plant to the power system both under the normal state of the power grid and under separate emergency or repair schemes. This leads to an underproduction of electricity and a decrease in the efficiency of using the installed capacity of the SPP. In order to prevent numerical limitations of electricity generation, the introduction of an agrovoltaic system is proposed.

3) The feasibility study of the project of the agrophotovoltaic system based on the existing power plant shows that its payback period will not exceed 3 years. The implementation of such an approach will also allow us: a) to use of land resources more efficiently; b) to increase the yield of agricultural crops that can be planted on the territory of a photovoltaic power plant; c) to eliminate restrictions on the release of generated power into the power grid through its direct consumption at the site of the SPP.

4) Taking into account all the previously mentioned advantages of implementing agrophotovoltaic systems, there are certain obstacles to the practical implementation of such projects, the main of which are the peculiarities of national legislation that limit the use of agricultural land for energy purposes. Therefore, it is necessary to carry out further thorough studies of the effectiveness of the application of agrophotovoltaic systems with the justification of the need to introduce changes to this legislation.

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# Техніко-економічний аналіз проєкту агрофотовольтаїчної системи на базі існуючої сонячної електростанції

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**Анотація**

Об'єктом дослідження є агрофотовольтаїчна система. Виконано аналіз умов функціонування однієї з діючих фотовольтаїчних електростанцій та виявлено обмеження генерації електроенергії через її надлишок в енергосистемі, або через режимні обмеження, як за нормального стану електромережі, так і за окремих аварійних чи ремонтних ситуацій. Це призводить до недовиробництва електроенергії та зниження ефективності використання встановленої потужності сонячної електростанції (СЕС). Тому було запропоновано впровадження агровольтаїчної системи, що дозволяє більш ефективно використовувати земельні ресурси, підвищити врожайність сільськогосподарських культур, які можна висадити на території фотовольтаїчної електростанції, усунути обмеження з видачі генерованої потужності в електромережу шляхом її безпосереднього споживання на майданчику СЕС. За результатами техніко-економічного аналізу проєкту агрофотовольтаїчної системи на базі існуючої електростанції показано, що термін його окупності не перевищуватиме 3 років, а прибуток на 5 рік експлуатації такої системи становитиме до 279409 €.

**Ключові слова:** агрофотовольтаїчна система; сонячна електростанція; режими роботи; електрична мережа; техніко-економічний аналіз.