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TECHNICAL AND ECONOMIC ASPECTS OF PROVIDING PRODUCTION AND USE OF ALTERNATIVE ENERGY SOURCES IN AGRICULTURE USING THE EXAMPLE OF SOLAR MODULES

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The article examines the economic and technological aspects of the production and use of alternative energy sources in the agro-industrial complex using the example of solar energy. The relevance of the transition to alternative energy sources in the context of growing energy risks, rising prices for traditional energy sources, and the need to strengthen the energy independence of agricultural enterprises in Ukraine is substantiated. The prospects for using solar energy systems as one of the most accessible and effective areas of decentralized generation are proven. The current state of development of solar energy in the world and in Ukraine, trends in the growth of installed capacities are analyzed.

The features of photovoltaic conversion technologies and the dynamics of the introduction of solar power plants in households and enterprises are analyzed. The feasibility of using a hybrid energy supply scheme with the priority of consuming own generation and selling surpluses at a "green" tariff to increase the energy and financial sustainability of enterprises is proven. The energy supply potential of a conditional agricultural enterprise is calculated using various options for using solar energy systems. The estimated technical and economic parameters of three scenarios for the installation of solar power systems with a capacity of 12, 15 and 20 kW have been calculated, in particular the annual electricity generation, investment costs and economic efficiency indicators. It has been shown that the introduction of solar modules contributes to an increase in the level of energy autonomy, cost optimization and improvement of environmental performance of the enterprise.

The results obtained can be used to form directions for the development of alternative energy in the agricultural sector and to improve technological solutions for the energy supply of agricultural enterprises thanks to solar energy.

Key words: *alternative energy sources, solar energy, Agro-industrial complex, solar modules, solar panels, rooftop solar power plant.*

Fig. 6. Table. 4. Ref. 11.

1. Problem formulation

Ukraine has not ensured its own energy independence during the years of independence, having all the necessary resources for this. Therefore, the economic and technological challenges that have arisen now open up new opportunities for the introduction of innovative developments in the energy sector, which will ensure increased energy efficiency in all areas of the national economy. This is happening against the background of military aggression by the country, which has been a supplier of major energy resources for many years, so the elimination of external energy dependence should also become a political priority.

Therefore, it is relevant to study the prospects for the formation of energy independence of enterprises through the production and use of alternative energy sources in our country.

2. Analysis of recent research and publications

A number of scientists has devoted their works to the study of the contribution of alternative energy sources in general and solar to energy in particular, including H.M. Kaletnik [1; 2], O.A. Byalkovska [3], S.O. Kudrya [4], M. V. Mytko [5], etc.

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The use of solar energy for solar heat supply is well-developed in the world, thermal processes have been developed for almost all areas of solar heat technologies: heat supply (including hot water supply and heating), refrigeration, air conditioning, fresh water production, drying of materials and products. A wide range of necessary devices and equipment has been developed to implement these processes, and their serial production is carried out.

Depending on the conversion method, solar energy systems are divided into two main groups: active and passive [4]:

- active solar technologies, which are based on the use of technologies for converting solar radiation energy into electrical energy and for obtaining thermal energy in order to convert solar radiation into useful energy output. Solar energy is perceived, accumulated and transported in special devices in active energy systems;
- passive solar technologies, which are based on the selection and use of materials with effective thermal characteristics, favorable location of buildings relative to the position of the Sun, etc. The objects that are heated themselves serve as the receiver in passive systems.

The two main practical directions of using solar radiation energy can be distinguished in modern solar energy [2]:

1) conversion of solar energy into electrical energy, including:

- photoelectric conversion method (electromagnetic radiation of the optical range of the Sun is converted into direct current electricity);
- thermodynamic conversion method (concentrated solar energy is used to produce steam, which, rotating a turbogenerator, produces electricity);

2) conversion of solar energy into thermal energy, including:

- heating;
- hot water supply;
- technological processes.

Recently, solar energy has achieved significant development due to the creation and implementation of the latest equipment and technologies that ensure increased efficiency and reduced cost of electricity and thermal energy production. Effective methods of stimulating solar energy, primarily electric power, introduced in many countries of the world, play an important role.

Currently, the use of crystalline silicon and thin-film technologies is dominates in the world market. Photovoltaic systems based on crystalline silicon are the oldest and most widespread in the world (about 85-90% of the photovoltaic market). In systems based on high-purity crystalline silicon, components are assembled into modules and electrically interconnected. Thin-film technology, on the other hand, uses a thin layer of semiconductor material deposited on substrates such as glass, polymer, or metal [5].

Solar power plants currently contribute about 4% of the electricity generated from alternative energy sources worldwide. The conversion of solar energy into electricity primarily takes place through photovoltaic (PV) cells. These power plants operate silently. Experience from the EU and North America demonstrates that solar energy can be harnessed on an industrial scale – even at night. In countries like Spain and the United States, facilities exist that generate electricity during nighttime using heat stored throughout the day. One major drawback of solar power plants is their large land requirement: producing just 1 MW of power typically requires at least 1.5 hectares of land. Another significant limitation is the inconsistency of energy output [5].

The majority of new renewable energy projects launched in the world in 2022 are almost 100 GW of solar power plants. The development of solar energy not only reduces the use of fossil fuels, but also contributes to the socio-economic development of countries, providing new jobs. Solar energy employs the largest number of people – 3.4 million, and a significant increase in capacity and, accordingly, the number of jobs is forecast in the future [6].

According to the International Energy Agency (IEA), the global solar renewable energy sector has seen significant growth in recent years. This growth is largely attributed to improvements in the levelized cost of electricity (LCOE), which represents the total cost of electricity generation over a project's entire lifecycle – including development, manufacturing, construction, operation, and decommissioning. Each year, experts at Lazard Ltd. evaluate various heat and electricity generation technologies using the LCOE metric. This approach enables an economically objective comparison of the cost of electricity production across different energy sources and technologies. Their latest findings confirm a continued decline in the cost of electricity generation from large-scale photovoltaic (PV) solar power plants [7].

Global solar power capacity grew particularly rapidly in 2022 – by 47%, in 2023 – by a record 85%, and in 2024 – by 33% (Fig. 1).

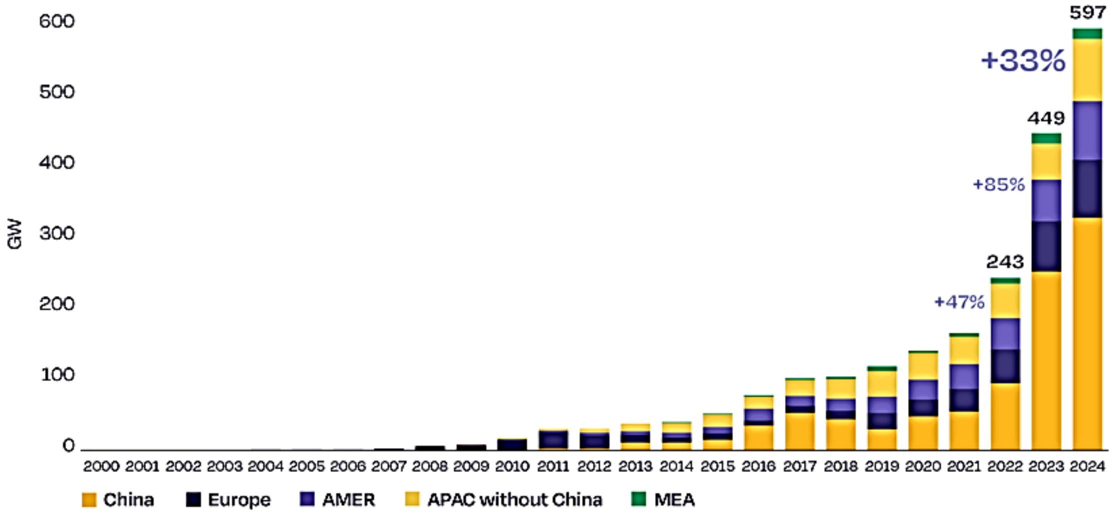


Fig. 1. Annual solar PV installed capacity, 2000-2024 [8]

In 2024, China dominated the global solar market with 55%, installing 329 GW that is more, then other top countries and rest of the world together (597GW) (Fig. 2).

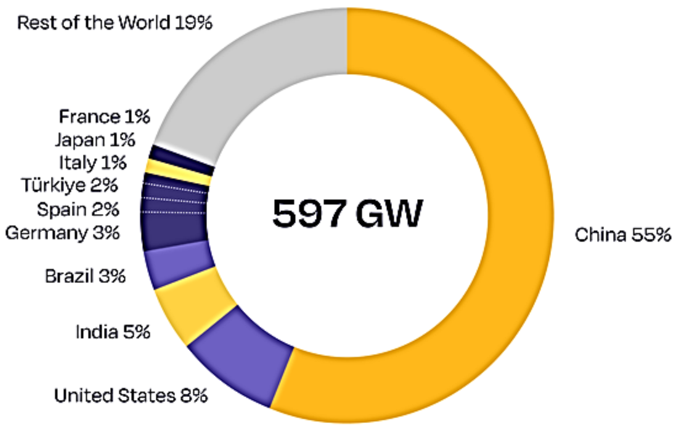


Fig. 2. Top 10 countries solar capacity share, 2024 [8]

Given the prospects for the development of solar energy, the issues of improving the technical and economic energy supply of the production and use of solar energy systems, in particular in the agricultural sector, require further research.

3. The purpose of the article

The aim of the study is to is to determine the prospects for ensuring the use of alternative energy sources in the agricultural sector on the example of solar energy, taking into account modern technological solutions in this field.

4. Results and discussion

One of the strategic ways to solve the problematic issues in Ukraine's energy supply can be the use of alternative energy sources – solar energy, wind energy, small rivers and streams, geothermal energy, biomass energy and environmental energy [3].

The orientation towards the development of alternative energy involves the following basic provisions: a modern energy system based on non-traditional and renewable energy sources should most fully take into account the peculiarities of the energy source itself and the characteristics of its consumer, which makes it possible to reduce the losses of such energy and reduce its cost; it is necessary to calculate the efficiency of the non-traditional energy system. On this basis, it is necessary to use such energy more fully and reduce its losses, since an economically perfect system will be more profitable, despite the large specific capital investments, due to lower fuel consumption and a longer equipment life; to increase the efficiency of the energy system, it is also necessary to improve its management methods; it is necessary to conduct not only a simple comparison of individual technologies based on renewable energy sources, but also to study their relationship within a specific energy system. Moreover, this must be done for power systems located in different geographical zones, which differ in their structure, volumes and rates of energy supply. All this makes it possible to develop comprehensive models for optimizing local power systems.

Alternative energy sources can make up a significant share of the energy balance in certain regions and districts of Ukraine [1]. It is well known that equipment such as wind turbines, wind power plants, and solar panels allows for substantial financial savings while also providing complete energy independence – an increasingly relevant issue today due to the constant rise in prices for gas, fuel oil, diesel fuel, oil, and electricity.

The advantages of solar radiation as an energy resource, compared to fossil fuels, lie in its practically inexhaustible nature, the ability to harness solar radiation across most areas of the Earth's surface as a local energy source, and the potential for direct conversion of solar radiation into thermal and electrical energy.

Solar energy systems are installations that convert solar radiation into other forms of energy. The most common method of generating electricity is through the photovoltaic method of direct conversion of solar energy using photovoltaic converters (PVCs), which are variously referred to in different sources as photovoltaic panels (PVPs), solar cells, or photoelements.

Photovoltaic conversion of solar energy is currently one of the key directions in solar energy utilization. This is due to several advantages: electricity can be produced virtually anywhere, the conversion process is environmentally friendly, photovoltaic systems have a long operational lifespan, require minimal maintenance, and their efficiency is not dependent on installed capacity.

Modern solar cells offer the following advantages:

- they have no moving parts that can wear out;
- they have an unlimited service life;
- they require minimal maintenance (or none at all);
- they do not pollute the environment;
- unlike other types of electric generators, they can be used across a wide range of capacities– from just one watt to several thousand megawatts.

As part of an applied research project funded by the state budget, "The latest concept of the development of the agro-industrial complex of Ukraine based on the principles of the "green" economy", researchers at Vinnytsia National Agrarian University have developed a mobile unit that optimizes the performance of solar panels by adjusting the tilt angle and frame position using movable components. A scheme of the mobile solar unit is shown in Figure 1.

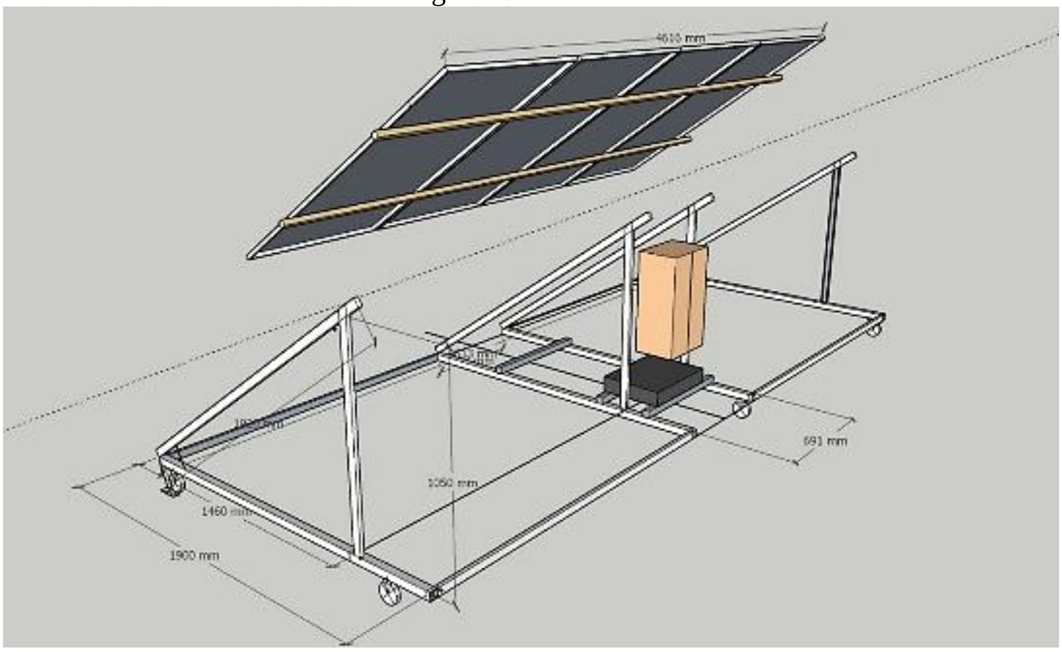


Fig. 1. Scheme of the VNAU mobile installation with solar panels

Close integration between science and industry is essential in Ukraine to ensure that advanced scientific ideas are translated into practical applications, particularly in the implementation of solar systems with optimized operational parameters.

According to the register of the National Commission for State Regulation of Energy and Utilities (NEURC), as of April 24, 2024, there are 1,369 solar power plants in Ukraine. Their geographic distribution is shown in Figure 4.

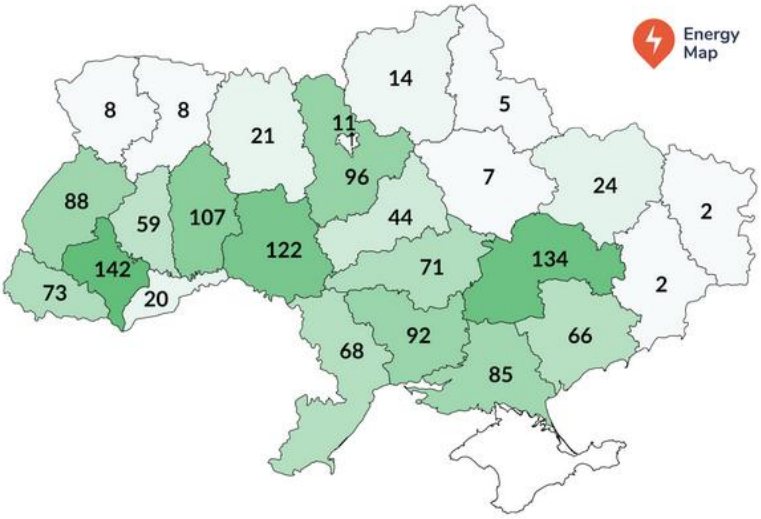
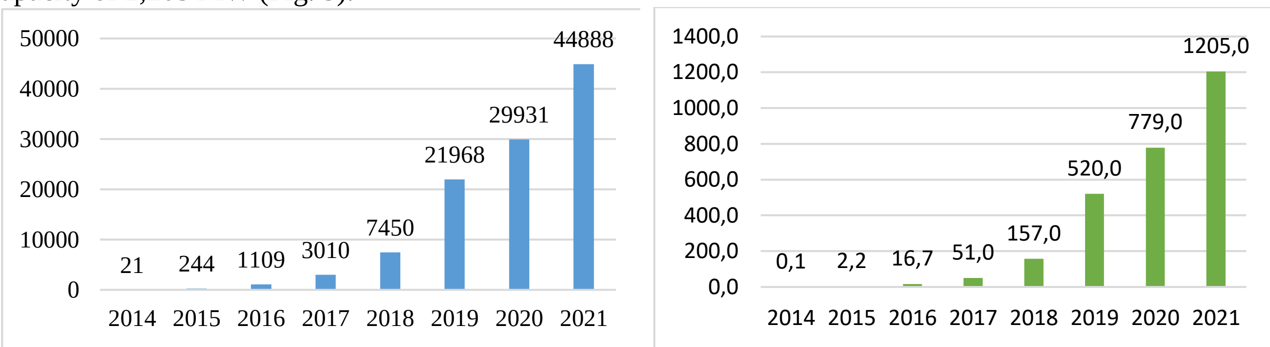


Fig. 4. Number of solar power plants as of April 24, 2024 by regions of Ukraine [9]

In 2024, the total installed capacity of solar power plants in Ukraine exceeds 7 GW. The share of solar generation in the total energy balance is about 6%. The number of prosumers has exceeded 45,000. There is a trend towards an increase in the number of small and medium-sized solar power plants, especially in the household segment.

The segment of home solar power plants (HSPPs) has been actively growing in recent years in Ukraine. As of the end of 2021, almost 45 thousand households in Ukraine have installed solar power plants with a total capacity of 1,205 MW (Fig. 5).



a ***b***

Fig. 5. Solar power plants in private households in Ukraine [10]:
a – installation dynamics, units; b – total capacity, MW

The leading regions in the adoption of residential solar power stations are Dnipropetrovsk, Ternopil, Kyiv (excluding the city of Kyiv), Ivano-Frankivsk, and Zakarpattia.

Households that have installed residential solar power systems (RSPS) fully meet their electricity needs and are among the most energy-efficient. This is because the surplus of generated clean energy is sold under the "green" tariff, which was €0.1626/kWh in 2020 and decreased to €0.1464/kWh in 2024 (a 10% reduction). Additionally, income from the sale of surplus electricity is subject to a 19.5% tax.

On September 30, 2025, the National Commission for State Regulation of Energy and Utilities issued Resolution No. 1568, which set electricity tariffs for power generated by solar energy systems with capacities of up to 30 kW installed in private households. The tariff rates depend on the year the solar power stations were commissioned (see Table 1).

Table. 1

The amount of the "green" tariff for electricity generated from solar energy by generating installations of private households, the installed capacity of which does not exceed 30 kW, depending on the year of commissioning in Ukraine [11]

Period of commissioning	"Green" tariff, kopecks/kWh (excluding VAT)
from April 1, 2013 to December 31, 2014	1737.48
from January 1, 2015 to June 30, 2015	1562.69
from July 1, 2015 to December 31, 2015	970.49
from January 1, 2016 to December 31, 2016	920.92
from January 1, 2017 to December 31, 2019	876.57
from January 1, 2020 to December 31, 2023	787.87
from January 1, 2024 to December 31, 2024	709.60
from January 1, 2025 to December 31, 2025	639,.6

Ukrainian families have invested approximately €450 million in these power plants. However, since there are over 6.5 million households in Ukraine, only 0.3% of them have installed home solar power plants.

When choosing solar photovoltaic technologies, it is necessary to find a compromise between initial costs, module efficiency and electricity tariffs.

In countries with significant solar energy resources and high electricity tariffs, electricity generated by photovoltaic systems has already become comparable to retail prices for the population.

With the help of solar energy, it is possible to partially provide electricity to residents of the private sector (in parallel with the operation of the electricity grid). For this, photovoltaic elements are used, which are located on the roof of the house. For low-power stations, the roofs of houses can serve as a place for installation, provided that their carrying capacity is increased (Fig. 6).

Fig. 6 Rooftop solar power plant

Photovoltaic cells are widely used for autonomous lighting as well. Demand for them continues to grow each year due to technological advancements and decreasing equipment costs.

To reduce energy dependence, agricultural enterprises have the option of installing solar modules on rooftops. For the purpose of estimating potential energy savings, a hypothetical medium-sized agricultural enterprise engaged in crop production was used as a case study. Various options for installing a solar energy system were developed. These involve mounting solar modules directly on the roofs of warehouses or production facilities. The system components are listed in Table 2.

Table 2

Purpose of equipment components in a solar energy system

Component	Purpose
Solar Panels	Perform the primary function of generating electricity during daylight hours
Batteries	Provide autonomous operation at night and during cloudy periods
Charge Controller	Ensures efficient battery charging management
Inverter	Operates in hybrid or standalone mode and allows simultaneous power supply to multiple devices

Solar panels are installed either on building rooftops or in open areas, where they convert sunlight into electric current. This electricity is then used to power equipment or stored for later use. Batteries accumulate excess energy generated during daylight hours. The internal power supply system follows the principle of renewable energy priority: solar-generated electricity is used first; any surplus is stored in batteries. If there is still excess energy after that, it can be fed into the general electricity grid and sold under the “green” tariff.

A modern controller will be used to manage the entire system. It regulates the batteries' charge and discharge cycles, and protects them from deep discharge and overheating. An inverter will convert the direct current (DC) produced by the solar panels into alternating current (AC), which is suitable for use by equipment or for export to the grid.

Additionally, a monitoring system will be installed to provide real-time oversight of system performance, including energy generation, consumption, battery charge levels, and emergency notifications.

The enterprise may choose from several solar energy system configurations under different implementation scenarios (Table 3).

Table. 3

Estimated costs according to scenarios for ensuring energy independence of a small agricultural enterprise thanks to solar energy systems

Scenario	Panel Capacity	Estimated Generation/year*	Equipment (panels + inverter + batteries)	Estimated Total Cost, UAH**
Scenario A (12 kW)	~22–24 panels × 550 W ≈ 12 kW	12,000 kWh	22 panels + 5 kW inverter + batteries (e.g., 4–6 blocks of 48 V)	350,000
Scenario B (15 kW)	~27 panels × 550 W ≈ 15 kW	15,000 kWh	27 panels + 5 kW or 2×5 kW inverter + larger battery bank	550,000
Scenario C (20 kW)	~36 panels × 550 W ≈ 20 kW	20,000 kWh	36 panels + inverter(s) ~2×5 kW or 10 kW + high-capacity battery bank	700,000-750,000

*Estimated based on ~1000kWh/kW of installed capacity/year.
**Estimate without installation, cables, fasteners, network connection and “green” tariff registration.

The economic efficiency indicators for implementing the solar energy supply project at a small agricultural enterprise are presented in Table 4.

Table. 4

Economic efficiency of implementing a solar energy system for a small agricultural enterprise

Indicator	Value
Equipment cost, UAH	450 000
Installation and assembly costs, UAH	98 000
Total investment costs, UAH	548 000
Estimated annual electricity generation, kWh	12 000
Annual revenue from electricity sales, UAH	74 400
Estimated payback period, years	7.4

The economic effect of implementing a solar power system for a small agricultural enterprise is achieved due to several key factors. First of all, it is the ability to cover the farm’s own needs for electricity, which allows to significantly reduce the cost of paying for energy supply from traditional sources. Refusal to purchase electricity at commercial tariffs reduces the enterprise’s dependence on the unstable energy market and reduces costs in conditions of rising prices.

In addition, thanks to the generation of excess electricity that is not consumed for its own needs, the enterprise has the opportunity to sell it to the network at a “green” tariff. This provides an additional source of income, which significantly increases the profitability of investments in installing a solar system. In the complex, this contributes to increasing the energy independence of a small agricultural enterprise, improving the financial stability of the enterprise, and also creates the prerequisites for the further development of production infrastructure.

It is also important to note the positive environmental effect – reducing carbon emissions, abandoning fossil fuels and preserving the environment.

Calculations indicate high economic efficiency of the project: with total investment costs of UAH 548,000, the expected annual income from the sale of excess electricity at the "green" tariff is about UAH 74,400. This allows for a return on investment in an average of 7.4 years, which is an acceptable period for the agricultural sector, taking into account the long-term reduction in energy costs.

5. Conclusion

1. Energy independence of agricultural enterprises is a critically important condition for ensuring the food security of the state, especially in the face of external challenges and threats in Ukraine. Solar energy systems have high potential to meet the energy needs of the agricultural sector, reducing its dependence on traditional energy sources.

2. Photovoltaic systems based on solar modules demonstrate high economic efficiency due to reduced energy costs, long service life and low maintenance costs. Agricultural enterprises can use excess electricity as an additional source of income through sales at a "green" tariff.

3. A proposal has been developed for a conditional small agricultural enterprise to reduce energy dependence by implementing a system of autonomous and backup energy supply based on solar modules located on the roof of the enterprise. The results showed the effectiveness of the project and its investment attractiveness due to a short payback period (about 5-6 years) and stable income from energy generation. The integrated use of solar panels, batteries, inverters and controllers ensures efficient energy supply to the enterprise regardless of the time of day and season.

4. Further development of solar energy use in the agricultural sector requires active participation of the state in the formation of a favorable legal and financial environment, as well as improvement of technological solutions for energy generation.

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ТЕХНІКО-ЕКОНОМІЧНІ АСПЕКТИ ЗАБЕЗПЕЧЕННЯ ВИРОБНИЦТВА І ВИКОРИСТАННЯ АЛЬТЕРНАТИВНИХ ДЖЕРЕЛ ЕНЕРГІЇ В АПК НА ПРИКЛАДІ СОНЯЧНИХ МОДУЛІВ

У статті досліджено економічні та технологічні аспекти виробництва й використання альтернативних джерел енергії в агропромисловому комплексі на прикладі сонячної енергетики. Обґрунтовано актуальність переходу до альтернативних джерел енергії в умовах зростання енергетичних ризиків, подорожчання традиційних енергоносіїв та необхідності зміцнення енергонезалежності аграрних підприємств в Україні. Доведено перспективність використання сонячних енергетичних систем як одного з найбільш доступних і ефективних напрямів децентралізованої генерації. Проаналізовано сучасний стан розвитку сонячної енергетики у світі та в Україні, тенденції зростання встановлених потужностей. Визначено особливості технологій фотоелектричного перетворення й динаміку впровадження сонячних електростанцій у домогосподарствах та підприємствах.

Доведено доцільність використання гібридної схеми енергозабезпечення із пріоритетом споживання власної генерації та продажем надлишків за «зеленим» тарифом для підвищення енергетичної та фінансової стійкості підприємств. Обраховано потенціал енергозабезпечення умовного аграрного підприємства за різними варіантами застосування сонячних енергосистем. Обраховано орієнтовні техніко-економічні параметри трьох сценаріїв встановлення сонячних енергосистем потужністю 12, 15 і 20 кВт, зокрема річну генерацію електроенергії, обсяги інвестиційних витрат та показники економічної ефективності. Показано, що впровадження сонячних модулів сприяє підвищенню рівня енергетичної автономії, оптимізації витрат і покращенню екологічних показників діяльності підприємства.

Отримані результати можуть бути використані для формування напрямів розвитку альтернативної енергетики в АПК та вдосконалення технологічних рішень енергозабезпечення аграрних підприємств завдяки сонячній енергетиці.

***Ключові слова**: альтернативні джерела енергії, сонячна енергетика, АПК, сонячні модулі, сонячні панелі, дахова сонячна електростанція.*

Рис. 6. Табл. 4. Літ. 11.

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