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Economic efficiency of solar panel implementation in irrigated agriculture: Cost assessment, comparative cost analysis and economic justification

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Abstract. This study aimed to assess the economic efficiency of implementing photovoltaic (PV) systems in irrigated agriculture, taking into account the technical, financial and environmental aspects of their application. To achieve this objective, the energy efficiency levels of pumping stations, the cost of PV system installation, and mechanisms of government support were analysed. The findings showed that the introduction of solar energy in irrigation complexes reduced average electricity costs to USD 0.05-0.12 per kWh, compared to USD 0.20-0.35 for diesel generators and

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USD 0.10-0.30 for centralised electricity supply. It was determined that the average payback period of PV systems in irrigated farming is 5-8 years, which is significantly shorter than for diesel generators, which are not cost-effective due to high operating expenses. The research confirmed that the use of modern PV systems combined with intelligent pumps reduced energy consumption of irrigation units by 20-30%, increasing their autonomy and operational stability. Environmental impact analysis demonstrated that PV systems contributed to a 60-80% reduction in CO_2 emissions compared to conventional energy sources, which is a crucial factor in the transition to sustainable agricultural production. It was established that subsidy programmes, the Net Metering mechanism, and concessional loans helped reduce initial capital investment and encouraged farming enterprises to adopt solar power plants. Based on the findings, recommendations were developed for optimising financial incentive mechanisms for the implementation of PV systems in irrigated agriculture, improving the technological parameters of PV installations, and utilising digital platforms for energy management. In practice, the results can be used to justify public-private partnership projects for the construction of solar power stations at irrigation pumping facilities

Keywords: renewable energy sources; photovoltaic systems; circular economy; energy independence; energy consumption optimisation

Introduction

The relevance of this research stems from the need to enhance the energy independence of the agricultural sector amid energy market volatility and rising tariffs. The use of traditional energy sources entails high costs and dependence on external factors, necessitating the integration of renewable energy sources, particularly photovoltaic (PV) systems. Their application in irrigated agriculture enables reduced electricity costs, improved enterprise autonomy and lower CO_2 emissions (Havrysh *et al.,* 2020). At the same time, the effectiveness of such technologies depends on technical, economic and natural-climatic factors, necessitating a comprehensive analysis.

O. Holovnia & Y. Chemerys (2024) explored innovative technologies that are transforming agricultural production through information and communication technologies, the Internet of Things (IoT), artificial intelligence (AI), machine learning, automation and robotics. Their work highlighted the potential of Real Time Kinematic for precision navigation of agricultural machinery and the use of drones for crop condition monitoring. S.A. Kalysh (2024) investigated the ecological and economic aspects of energy conservation in crop production, identifying key energy consumption areas and methods of determining energy intensity and production costs, as well as possible measures to improve the efficiency of energy use. The study reviewed energy optimisation strategies for agricultural machinery fleets and ways to reduce fuel and energy resource consumption in greenhouse farming. However, these studies did not address the economic feasibility of alternative energy sources or the specifics of their implementation.

Studies by U. Andrusiv *et al.* (2020), I. Sierov (2024), examined the role of eco-innovations in ensuring the sustainable development of agribusiness, substantiating the need for environmentally orientated technologies and outlining key directions for innovation in this domain. They identified major obstacles to implementation and proposed solutions such as government support, research investment and improved awareness among agricultural producers. However, the studies did not offer a quantitative analysis of the effectiveness of these measures, the economic feasibility of implementing eco-innovations, or the influence of global environmental trends. Ye.M. Kryvokhyzha *et al.* (2024) explored resource management strategies in Ukraine's agricultural sector during the energy crisis, analysing the efficiency of energy-saving initiatives and the adoption of renewable energy sources. Bibliometric analysis of scientific publications revealed key trends and confirmed the strategic importance of energy resource diversification for food security. Nonetheless, the study lacked an assessment of the economic efficiency of the proposed measures, regional specifics of implementation, and regulatory aspects.

O. Petrenko (2023) examined the features of the green revolution in the agricultural sector, focusing on its impact on sustainable economic development and efficient resource use. The analysis confirmed that implementing environmentally friendly technologies reduces environmental impacts, optimises energy and water use, and increases yields. The study stressed the need for government support and collaboration between research institutions, industry, and rural communities to ensure the effective implementation of green innovations. However, it did not include a quantitative analysis of the economic benefits of the technologies discussed, nor did it consider the barriers to implementing green practices in small and medium-sized farms or compare the effectiveness of different international support models for the green revolution.

O.S. Froter & A.O. Revutska (2024) addressed the greening of agricultural production as part of innovative development but paid insufficient attention to the mechanisms of government support and funding – an essential aspect of implementation. Moreover, their study lacked a comparative analysis of international experience in the sustainable development of the agricultural sector. In V. Lazarenko's (2024) research, the post-war recovery of Ukraine's agricultural sector was examined in relation to achieving the Sustainable Development Goals. Focus was placed on soil resource management, water source conservation, biodiversity management and the development of renewable energy. However, the study did not offer a comprehensive assessment of economic compensation mechanisms or their integration into the international environmental finance system. D. Bytko & I. Krylova (2022) explored the impact of alternative energy sources on the operations of agricultural enterprises, with a particular focus on the potential utilisation of solar, wind and biomass energy. However, their study did not provide an in-depth analysis of the economic efficiency of these solutions, nor did it address the technical aspects of implementation or the potential regulatory barriers. Furthermore, the issue of state regulation and incentives for the development of renewable energy in Ukraine's agricultural sector remained largely unexplored.

A review of the relevant academic literature has shown that previous research has primarily focused on the general benefits of using alternative energy sources in agriculture, particularly in terms of reducing energy costs, enhancing energy independence, and delivering environmental benefits. However, there is still not enough detailed study on important areas, such as measuring how cost-effective renewable energy technologies are, how they are adopted in different regions, the laws and rules surrounding them, and the financial support available. The aim of this study was to assess the economic feasibility of implementing PV systems in irrigated agriculture, taking into account their impact on energy efficiency, the financial resilience of agricultural enterprises, and the environmental safety of agricultural production.

Materials and Methods

The study covered the period from 2020 to 2024, enabling the inclusion of the most recent academic publications and trends in the fields of renewable energy and agricultural technologies. A comprehensive methodological approach was adopted to assess the economic efficiency of PV system implementation in irrigated agriculture. Economic analysis was applied to evaluate the viability of solar panel use in irrigation systems, including the calculation of energy supply costs, potential savings, and return on investment for PV systems. The assessment of economic feasibility was based on a comparison of costs incurred by agricultural enterprises when using conventional versus renewable energy sources, alongside an evaluation of potential long-term financial benefits. The cost of electricity generated by PV systems was analysed using data from the International Renewable Energy Agency (2024), which provides average electricity generation costs from renewable sources. Additionally, global energy market trends were taken into account, as presented in the International Energy Agency (2024) report, which includes forecasts on the development of renewables and their impact on the agricultural sector. Information from the World Bank (2024) on the deployment of sustainable energy solutions in the context of the Sustainable Development Goals was used to highlight the role of clean energy in enhancing the efficiency of agricultural systems. The analysis of regulatory requirements based on these data sources enabled an assessment of the level of state support and incentive mechanisms available to agricultural enterprises investing in solar energy. National and international programmes supporting subsidies, tax benefits and financial incentives for the adoption of renewable energy were also reviewed.

A comparative analysis was conducted to evaluate the efficiency of various energy sources used in irrigation agriculture. PV systems, centralised electricity supply, and diesel generators were compared to identify the most economically viable options for meeting the energy needs of agricultural enterprises. The analysis considered parameters such as initial capital investment, operational costs, payback period, and the degree of energy independence. Techno-economic modelling was used to design an energy supply scheme for irrigation systems powered by PV installations and to assess its efficiency under various scenarios. The analysis included parameters such as solar irradiation levels, panel capacity, the need for energy storage systems, and their influence on the stability of power supply to pumping stations. Optimal PV configurations were identified to ensure uninterrupted water supply, which is particularly important for the agricultural sector under changing climatic conditions.

To validate the forecast results, the model outcomes were compared against real-world data from implemented PV-based agricultural projects. This analysis included a comparison of electricity generation, cost savings, and payback periods with actual case studies of autonomous energy supply systems used by agricultural enterprises in different climatic zones. The use of an integrated approach allowed for a comprehensive assessment of the feasibility of PV systems in irrigation agriculture, considering economic, technical, and environmental factors. The findings contributed to the development of evidence-based conclusions on the prospects for solar energy development in agriculture and the formulation of recommendations to enhance the effectiveness of PV systems in irrigation complexes.

Results

Economic efficiency of solar panel implementation in irrigated agriculture

Irrigated agriculture is a vital component of modern farming, particularly in regions characterised by unstable water balance and periodic droughts. Irrigation systems help maintain optimal soil moisture levels, which contributes to improved crop yields, production stability, and risk mitigation in the face of climate change. The efficiency of irrigation infrastructure is largely dependent on a stable electricity supply, as most modern pumping stations rely on electrical energy. Power outages can disrupt irrigation schedules, negatively affecting crop growth and development. Irrigation systems are powered by pumping equipment that transports water from surface or underground sources to irrigated fields. The energy consumption of pumps depends on their type, capacity, lift height, and system output. Surface pumps drawing water from open sources typically consume between 0.5 and 5 kWh per cubic metre of water. Deep-well pumps, which extract water from boreholes, may require up to 10 kWh per cubic metre. Although drip irrigation systems consume less water overall, they require consistent system pressure, which also demands substantial energy input. To ensure effective operation, irrigation systems utilise various types of pumps, each differing in output, energy consumption, and operating pressure. The selection of a particular pump type depends on the water source, required system pressure, and overall water demand. Table 1 presents a comparative overview of the main types of pumping equipment used in irrigated agriculture.

Table 1. Comparative characteristics of pumping equipment

Pump type	Flow rate (m^3/h)	Operating pressure (bar)	Energy consumption (kWh/m^3)	Approximate cost of water pumping (USD/m^3)	Main application
Centrifugal surface pump	10-50	2-6	0.5-5	0.03-0.12	Open irrigation, water pumping from rivers and canals
Submersible pump	5-30	5-20	2-10	0.08-0.25	Pumping water from artesian wells
Screw pump	2-10	1-4	1-3	0.05-0.15	Use in high-pressure irrigation systems
Diaphragm pump	1-5	0.5-3	0.5-2	0.04-0.10	Mobile and autonomous irrigation systems
Low-pressure Pump for Drip System	0.1-1	0.2-1	0.1-0.5	0.01-0.05	Automated drip irrigation

Source: developed by the authors based on O. Glovatskii *et al.* (2023), J. Dyer & J. Shapiro (2023)

An analysis of pumping equipment characteristics reveals significant differences in energy consumption depending on the type of irrigation system. Centrifugal surface pumps, which are most commonly used in open irrigation systems, exhibit a wide range of performance capacities and energy consumption levels, which vary based on water lift height and required pressure. Deep-well pumps demonstrate the highest energy consumption, primarily due to the complexity of lifting water from substantial depths. In contrast, drip irrigation, despite its relatively low water output, is the most energy-efficient solution owing to the use of low-pressure pumps. The choice of optimal pumping equipment determines the overall level of energy expenditure in irrigated agriculture. The implementation of energy-efficient solutions, such as drip irrigation systems or low-pressure pumps, can significantly reduce electricity consumption. At the same time, for systems that require large volumes of water or operate with deep boreholes, the use of alternative energy sources – particularly photovoltaic (PV) systems – can be a key factor in economic optimisation. Thus, the evaluation of energy consumption by pumping equipment is a crucial component in assessing the economic feasibility of implementing solar panels in irrigated agriculture.

The high electricity costs associated with irrigated agriculture underscore the need to seek energy-efficient solutions. Traditionally, centralised power supply and diesel generators are used. While centralised electricity tends to have relatively stable tariff levels, its availability in remote areas is not always guaranteed. Diesel generators, although offering autonomy, entail high operational costs due to fuel prices and the need for regular technical maintenance. There is also the possibility of installing biogas power plants to supply electricity to irrigation systems, but this solution is only viable in the presence of large-scale livestock farms (Kalinichenko & Havrysh, 2019). The integration of PV systems into irrigated agriculture enables a substantial reduction in electricity costs and enhances the energy independence of agricultural enterprises. Solar energy is a renewable source that minimises dependence on unstable tariffs and fuel prices. The average cost of electricity generated by PV systems ranges between USD 0.05-0.12 per kWh, which is considerably lower than the cost of centralised electricity or diesel-generated power (International Renewable Energy Agency, 2024).

The effectiveness of solar panel usage in irrigation systems depends on climatic conditions, the level of solar irradiance, the technical specifications of the pumping equipment, and the capacity to utilise energy storage solutions. In regions with an average annual solar radiation exceeding 4.5 kWh/m^2 per day, the use of PV systems can provide an uninterrupted power supply for pumping stations. The use of battery storage or hybrid solutions (solar energy combined with grid or generator power) contributes to stabilising energy supply and enhancing the reliability of irrigation systems. To ensure the efficient and autonomous operation of a solar-powered irrigation system, it is necessary to integrate a range of technological components that facilitate the accumulation, conversion, and distribution of electricity to power the pumping equipment. Figure 1 presents the operating principle of such a system, which includes PV modules, an inverter, an automated water supply system, and storage tanks.

The diagram illustrates how solar panels generate electricity, which is delivered via a power management system to an inverter for converting direct current (DC) into alternating current (AC). The energy is then directed to pumping equipment that lifts water from a borehole into a storage tank. The system also allows for the integration of alternative energy sources, such as a centralised power grid or a generator, ensuring stable operation in periods of insufficient solar activity. A dedicated pump automation subsystem is highlighted, enabling real-time control of water supply and optimising electricity consumption. A key feature of this system is the possibility of using wireless control devices for monitoring and regulating the irrigation process. This enhances the efficiency of water resource management by allowing water supply parameters to be adjusted based on the needs of specific crops. The presence of a storage tank makes it possible to regulate water supply independently of real-time solar generation, which is crucial for ensuring uninterrupted system operation. The overall concept of this solution contributes to increasing the energy efficiency of irrigation complexes while minimising operational costs through the use of renewable energy sources.

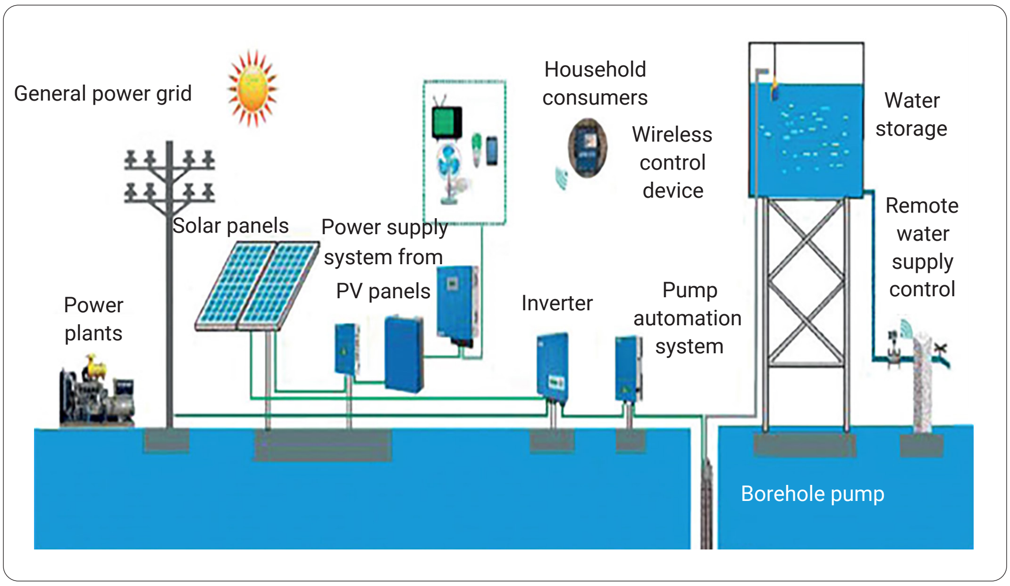

Figure 1. Power supply scheme of the irrigation system
Note: water from the well is supplied to the storage tank, from where it is distributed for irrigation. Integration with the power grid or a backup generator is provided for stable operation in case of insufficient solar generation. Automated pump control optimises water delivery, reducing energy and water consumption. The system can also supply household consumers and operate remotely
Source: S. Mikhnenko (2024)

The implementation of solar panels to power irrigation systems brings not only economic but also environmental benefits. Replacing diesel fuel reduces CO_2 emissions, contributing to the environmental sustainability of agro-industrial production. Moreover, using PV systems in combination with intelligent irrigation management algorithms allows for the optimisation of both water and energy consumption, thus increasing the operational efficiency of agricultural enterprises. The economic viability of using solar energy in irrigated agriculture is supported by calculations of electricity costs and operating expenses. However, to justify the selection of the most optimal energy supply option, a detailed comparative analysis of the costs associated with different energy sources is required.

Comparative cost analysis and payback assessment

Irrigation systems are among the most energy-intensive technologies in agriculture and require a reliable electricity source for the stable operation of pumping equipment. The choice of an energy supply system is determined by economic feasibility, technical specifications, and the availability of energy resources. The main options include connection to a centralised power grid, diesel generators, and photovoltaic (PV) systems. Comparing the costs associated with these sources makes it possible to determine the optimal energy strategy for irrigation complexes. Centralised electricity supply is one of the traditional energy sources for irrigation systems. Its advantages include relatively stable power delivery and the capacity to connect a large number of pumping stations without the need for local generators. However, the initial connection costs may be significant due to the need to install power lines and transformer substations and adapt the network infrastructure to accommodate high-power equipment. Electricity tariffs depend on regional policy and may fluctuate, introducing additional financial uncertainty. The selection of an energy source for irrigation systems is crucial for ensuring their economic efficiency. Initial capital expenditures, electricity costs, and operational expenses vary significantly depending on whether a centralised grid, diesel generators, or PV systems are used. Table 2 presents a comparative overview of the costs associated with these energy sources, enabling an assessment of their profitability and appropriateness for use in agriculture.

Table 2. Economic comparison of energy supply options for irrigation systems

Energy source	Initial costs (USD)	Electricity cost (USD/kWh)	Operating costs (USD/year)	Payback period (years)	Environmental impact
Centralised power supply	5,000-20,000 (grid connection)	0.10-0.30	Depends on tariffs	Not applicable	Depends on generation source
Diesel generators	10,000-20,000 (generator)	0.20-0.35	5,000-10,000 (fuel, maintenance)	Not cost-effective (high expenses)	High CO_2 emissions
PV Systems	24,000-36,000 (30 kW PV system)	0.05-0.12	300-500 (minimal maintenance)	5-8	Low CO_2 emissions

Source: developed by the authors based on International Energy Agency (2024), International Renewable Energy Agency (2024), World Bank (2024)

An analysis of the cost characteristics of energy supply reveals significant differences in expenditure structures depending on the selected source. Grid electricity requires an initial investment for connection, while subsequent costs depend on electricity tariffs, which may fluctuate in accordance with the state's economic policy. However, this option ensures a stable power supply, which constitutes its primary advantage. The use of diesel generators provides autonomy, yet the high cost of fuel and the need for regular technical maintenance make this option less economically attractive in the long term. Additionally, the high level of CO_2 emissions represents a considerable environmental drawback of diesel units.

Photovoltaic (PV) systems involve the highest initial investment; however, their low operational costs allow for relatively rapid payback. Due to the absence of fuel expenses and minimal maintenance requirements, PV systems represent a financially viable option in regions with sufficient solar irradiation. Furthermore, the use of renewable energy significantly reduces environmental impact, which is a crucial factor in the development of sustainable strategies for the agricultural sector.

Diesel generators are used in cases where grid electricity is either unavailable or economically unfeasible. They provide autonomy in operating pumping equipment, which is advantageous in remote agricultural regions. Nonetheless, the use of diesel generators entails significant operational costs, including fuel, regular maintenance, oil, and filter replacements. Moreover, diesel units pose environmental disadvantages due to high CO_2 emissions and noise pollution, rendering them less attractive in the long run.

The implementation of PV systems in irrigated agriculture enables a substantial reduction in operational expenses, as solar energy is a free and widely available resource. Initial investments in PV systems include the cost of solar panels, inverters, battery storage (if required), and power control automation systems.

The payback period for PV systems depends on the level of insolation, investment costs, and the availability of financial incentives. On average, it ranges from 5 to 8 years, which is a competitive indicator compared to traditional energy supply options. For diesel generators, the payback period may be shorter due to a lower initial investment, but high operational costs make them less economically viable in the long term. In the case of grid electricity, payback is determined by the applicable tariffs and the cost of connection to the distribution network.

To assess the economic feasibility of various energy supply sources in irrigated agriculture, it is necessary to compare their payback periods by accounting for initial investments and operating costs. Figure 2 presents a comparative chart containing statistical data on the key parameters of the payback period for grid electricity, diesel generators, and PV systems.

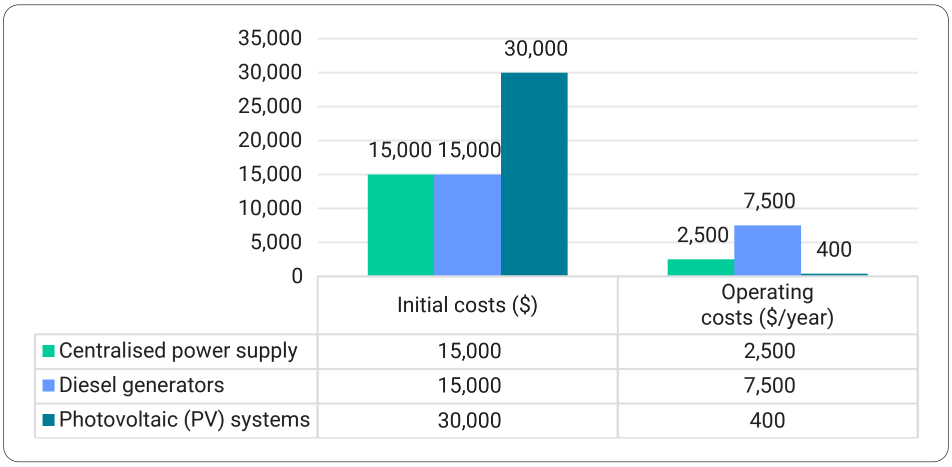

Figure 2. Assessment of the economic feasibility of using renewable energy sources
Source: developed by the authors based on International Energy Agency (2024), International Renewable Energy Agency (2024), World Bank (2024)

Analysis of Figure 2 highlights significant differences among the energy supply options. The centralised electricity supply requires substantial initial investment; however, its payback period is not typically calculated in the conventional sense, as ongoing costs are determined by electricity tariffs, which may fluctuate depending on political and economic factors. Diesel generators also fail to reach payback due to their high operating costs, which significantly exceed those of alternative systems. Dependence on fuel markets and the need for regular technical maintenance make this option economically unviable in the long term. PV systems, despite higher upfront costs, incur the lowest operational expenses, allowing for an average payback period of approximately 6.5 years. Key factors influencing the speed of payback include the level of solar irradiation in the region, the availability of government subsidies, and the efficiency of battery storage systems. In areas with high solar exposure, the payback period can be significantly reduced, making PV systems the most promising long-term solution for powering irrigation facilities.

The economic viability of PV systems also depends on the availability of financial support mechanisms, such as state subsidies, grant programmes, or cost-compensation schemes for PV installation. In several countries, renewable energy incentive programmes enable agricultural enterprises to receive financial assistance for the implementation of solar panels. Access to such mechanisms can reduce the payback period of PV systems and make them more accessible to a broader range of agricultural producers. A comparative cost analysis of different energy sources indicates the feasibility of adopting PV systems for irrigation complexes, particularly in regions with high solar irradiation. However, the implementation of such technologies requires not only economic justification but also consideration of regulatory factors that may influence their accessibility and operational effectiveness.

Financial and regulatory aspects of implementation

The financial and regulatory aspects of PV system deployment in agriculture are key determinants of their adoption scale. Government support, international grant programmes, and tax incentives stimulate the development of renewable energy by lowering the financial barrier to the adoption of PV technologies. However, the implementation of such projects may be complicated by regulatory requirements related to grid connection, equipment licensing, and component certification. Analysing financing mechanisms and regulatory frameworks enables the assessment of the effectiveness of solar energy incentive policies in different countries. To promote the deployment of PV systems in agriculture, various countries have introduced support programmes that include subsidies, grants, tax relief, and concessional loans. These mechanisms can significantly reduce the capital costs of installing solar power systems and accelerate their payback. Table 3 below outlines the main government support programmes in the EU, the USA, and China.

Table 3. State financial support programmes for PV system implementation in agriculture

Country	Program	Main support mechanisms	Maximum cost compensation (%)	Additional incentives
EU	European Agricultural Fund for Rural Development	Grants and subsidies for PV system installation in agriculture	75	Preferential loans, technical support
USA	Rural Energy for America Program	Funding of up to 50% of costs for renewable energy installations	50	Tax incentives, reduced loan interest rates
China	Golden Sun Program	Subsidies, tax benefits, and financing for PV power plant construction	60	Duty-free import of PV components, government procurement of PV systems

Source: developed by the authors based on International Energy Agency (2024), International Renewable Energy Agency (2024), World Bank (2024)

An analysis of government support programs demonstrates an active policy promoting the adoption of solar energy in agriculture. In the EU, the highest level of cost compensation – up to 75% –makes the installation of PV systems highly accessible for farmers. In the USA, financial support is provided through the Rural Energy for America Program, which covers up to 50% of costs, while additional tax incentives and access to preferential loans further encourage the development of renewable energy. China's Golden Sun Program offers subsidies for the installation of PV stations, support for solar equipment manufacturers, and simplified import procedures for system components, contributing to the widespread deployment of solar power plants across the country.

The availability of public financial support significantly reduces the payback period of PV systems, enhances their economic attractiveness, and facilitates the broader use of renewable energy in agriculture. However, the effectiveness of such programmes depends on the ease of accessing funds, the level of bureaucratic barriers, and the degree of integration of PV systems into the country's overall energy policy. Financing mechanisms for PV projects include not only state grants but also concessional lending, investment funds, and private initiatives. Banking institutions in countries with well-developed renewable energy sectors offer special low-interest loan programmes for agricultural enterprises investing in solar generation. The green bond mechanism plays an important role by enabling the attraction of funds for environmentally sustainable projects, including the installation of solar power plants in agriculture. Despite the availability of substantial financial support, the deployment of PV systems may be hindered by regulatory barriers. The main challenge remains the complexity of connecting to centralised power grids, which requires obtaining permits and technical approvals. In some countries, the connection process for PV generation may take several months to a year, thereby delaying project implementation.

Innovative energy solutions for irrigation

The implementation of PV systems in irrigated agriculture represents a key strategy for optimising energy consumption and enhancing energy independence in the agro-industrial sector. The technical aspects of such systems include the selection of PV modules, integration with pumping equipment, automation of water supply processes, and the use of battery storage systems to retain surplus energy. The application of modern technologies increases the efficiency of irrigation systems and reduces operational costs associated with pumping equipment. The use of bifacial solar panels is a promising direction in the development of PV technologies, as these modules can generate electricity from both direct and reflected solar radiation. This capability enables an overall increase in electricity output by 10-20% compared to standard monocrystalline panels. Bifacial PV modules are particularly effective in environments with open ground and high albedo or when combined with white surfaces that enhance the reflection of sunlight. The choice between standard monocrystalline and bifacial solar panels is determined by their technical specifications, efficiency levels, and installation costs. Bifacial panels are capable of using reflected light, which boosts their productivity, while standard monocrystalline modules remain a more economical option for conventional solar power plants. Table 4 presents the key parameters of both panel types, allowing for a comparison of their effectiveness in the context of irrigated agriculture.

Table 4. Comparative characteristics of standard and bifacial monocrystalline solar panels

Characteristic	Standard monocrystalline panels	Bifacial monocrystalline panels
Efficiency (%)	18-22	20-24
Electricity generation (kWh/m²/year)	1,400-1,600	1,600-1,900
Temperature sensitivity (W/°C)	-0.3	-0.28
Additional generation from reflected light (%)	None	10-20
Average service life (years)	25-30	25-30
Installation cost (USD/kW)	800-1,000	900-1,200
Estimated cost of generated electricity (USD/kWh)	0.0167-0.0286	0.0158-0.03

Source: developed by the authors based on International Energy Agency (2024), International Renewable Energy Agency (2024), World Bank (2024)

Bifacial solar panels offer a higher electricity output due to their ability to capture both direct and reflected solar radiation. This feature enhances system efficiency, particularly in regions with high surface reflectivity – such as light-coloured soils or specially prepared reflective coatings. However, to achieve maximum performance, the panels must be precisely placed, which may require additional expenditures related to installation and tilt angle optimisation. Despite their higher electricity generation potential, bifacial panels entail increased initial installation costs, potentially affecting their payback period. On the other hand, their resistance to overheating and their more efficient utilisation of solar radiation make them attractive for use in autonomous energy systems, particularly in irrigation agriculture. The optimal choice between bifacial and conventional monocrystalline modules depends on specific operational conditions, available budget, and required energy supply levels. Estimates show that even though bifacial panels cost more to install at first, they can produce electricity at a lower cost (between USD 0.0158 and 0.030 per kWh) compared to traditional monocrystalline panels (USD 0.0167 to 0.0286 per kWh). This advantage is primarily due to their increased energy output and extended operational lifetime, which can significantly reduce long-term energy expenses for agricultural enterprises. Moreover, the need for additional investment in mounting and configuration can be offset by enhanced productivity and a shorter payback period in regions with favourable solar irradiation.

The increasing energy demand in irrigation agriculture, coupled with climate change, necessitates the adoption of energy-efficient and resource-conserving technologies. The integration of PV systems, implementation of bifacial solar panels, use of energy storage solutions, automation of water supply processes, and hybrid energy configurations contribute to reduced energy consumption, more efficient water use, and improved financial stability of agricultural enterprises. Table 5 presents comparative performance indicators of these technologies, including capital investment, energy savings, water cost reduction, and payback periods.

Table 5. Economic efficiency of innovative technologies in irrigation

Technology	Investment costs (USD/ha)	Energy savings (%)	Reduction in water supply costs (%)	Payback period (years)
Installation of PV systems	1,200-2,500	40-60	20-35	5-8
Use of bifacial solar panels	1,500-3,000	50-65	25-40	6-9
Integration of energy storage systems	1,800-3,500	55-70	30-45	7-10
Floating solar panels (Floating PV)	2,000-4,000	60-75	35-50	6-10
Automated irrigation with IoT and AI models	2,500-5,000	70-85	40-60	4-7
Hybrid system (solar + wind + biogas)	3,000-6,000	80-90	50-70	8-12

Source: developed by the authors based on International Energy Agency (2024), International Renewable Energy Agency (2024), World Bank (2024)

The analysis of the presented data indicated that the implementation of PV systems required relatively low capital investment while enabling a reduction in energy costs by 40-60% and a decrease in water supply expenses by 20-35%. Bifacial solar panels improved electricity generation efficiency, contributing to additional energy savings; however, their deployment required a higher initial investment and exhibited longer payback periods. The highest energy savings (up to 90%) were observed in hybrid energy systems, although they were also associated with the highest capital costs and payback periods exceeding 8 years. The adoption of automated irrigation systems using IoT and AI models resulted in the largest reductions in energy consumption (up to 85%) and water supply costs (up to 60%), yielding relatively short payback periods of 4–7 years. At the same time, energy storage technologies and floating PV systems demonstrated considerable potential for enhancing energy autonomy in agricultural enterprises. However, their efficiency strongly depended on regional climatic conditions and the availability of water resources.

Floating solar panels represent another effective solution, offering additional electricity generation while reducing water evaporation in irrigation reservoirs. Installing PV modules on water surfaces allows the use of natural cooling to improve performance, minimising overheating risks and panel degradation. Moreover, floating solar plants help optimise land use, as they do not occupy agricultural areas while ensuring a stable power supply to pumping systems. The automation of irrigation systems through IoT technologies enables the development of adaptive water management models based on real-time data on soil conditions, climate parameters, and crop needs. Moisture, temperature, and weather sensors transmit data to a cloud platform that automatically adjusts irrigation schedules according to current requirements. The use of AI algorithms for forecasting evapotranspiration and water consumption improves irrigation efficiency and minimises water losses. IoT- and AI-based automation of irrigation systems significantly enhances the management of water resources in agriculture. The integration of soil moisture sensors, temperature monitors, and cloud-based data analytics platforms ensures the optimisation of irrigation schedules tailored to crop needs. Figure 4 shows how an intelligent irrigation management system works by monitoring soil conditions, analysing data to predict needs, and automatically controlling the pumping equipment.

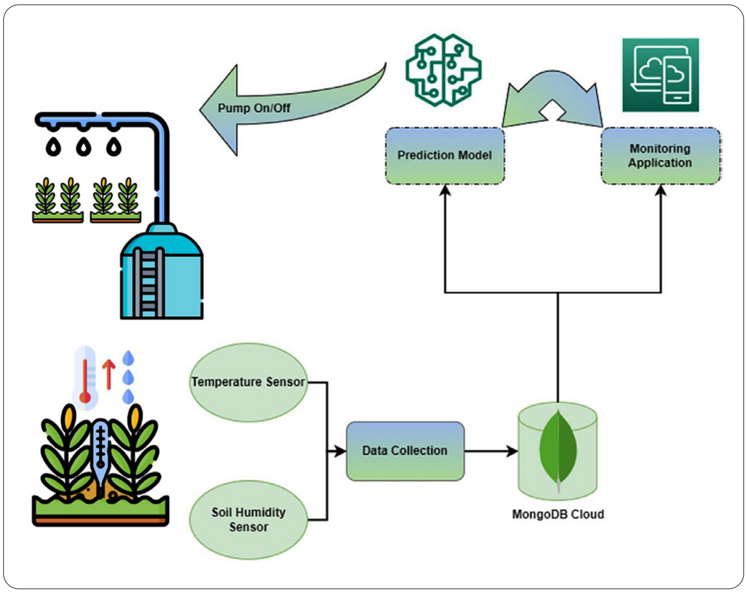

Figure 3. Intelligent system of automated irrigation management based on IoT and AI
Source: M.S. Hossain *et al.* (2023), Y. Tace *et al.* (2022)

Figure 4 illustrates the operating principle of an automated irrigation system that employs sensor technologies for data collection and further processing in a cloud environment. Soil temperature and moisture sensors record the current state of the agroecosystem and transmit the data to MongoDB Cloud for subsequent analysis. The use of cloud technologies enables the centralised storage of large volumes of agroclimatic data, which forms the basis for accurate forecasting and optimal water resource allocation. A predictive model analyses the collected data, assessing the plants' irrigation needs and generating recommendations for starting or stopping the pumping equipment. A control system connected to a Monitoring Application enables automatic water supply management, ensuring timely irrigation with minimal losses. The integration of IoT and AI technologies into irrigation systems enhances the efficiency of water use, reduces dependence on human intervention, and facilitates the adaptation of agricultural production to changing climate conditions.

Hybrid power supply systems that combine PV modules with other energy sources, such as wind turbines or biogas plants, enable the development of comprehensive energy solutions for the agricultural sector. The combination of PV systems with wind generation ensures electricity production during both sunny and windy periods, enhancing the stability of energy supply (Szafraniec *et al.*, 2021). The use of biogas installations allows for the additional generation of electricity from organic agricultural waste, contributing to the energy independence of farming enterprises. Energy storage systems are a critical component for improving the efficiency of solar energy use in irrigation systems. Modern lithium-ion and flow batteries make it possible to power pumping equipment during periods of insufficient solar activity. Energy consumption management based on forecasting algorithms enables the efficient distribution of energy resources and helps avoid system overloads.

The future development of solar energy in agriculture depends on technological innovations, regulatory conditions, and investment levels in PV systems. Using advanced automation, combining different energy systems, and applying smart resource management will help improve energy supply efficiency in irrigated agriculture. Further advancement of PV technologies will ensure the stable operation of the agro-industrial complex and reduce dependence on conventional energy sources.

Discussion

The introduction of PV systems in irrigated agriculture has contributed to increased energy independence of agricultural enterprises and reduced electricity costs. An analysis of behavioural factors influencing decisions on the adoption of solar technologies was conducted by A. Rahmani & A.B. Naeini (2023). The authors identified key motivational factors as economic benefit, reduced reliance on unstable energy sources, and the long-term efficiency of such solutions. Comparative analysis confirmed that in addition to technical and economic aspects, subjective factors such as farmers' awareness and access to financial support played a significant role. The relevance of integrating PV systems into irrigated agriculture was confirmed by their capacity to reduce electricity expenses and improve the energy efficiency of agricultural enterprises. A study by M. Trommsdorff *et al.* (2023) demonstrated the economic advantages of agrivoltaic systems that combine electricity generation with crop cultivation. Optimal placement of solar panels contributed to lower energy costs and efficient use of land resources. The comparative results confirmed that such systems can provide synergistic benefits by integrating renewable energy into agricultural processes without negatively affecting crop yields.

PV systems have shown potential for ensuring stable water supply, which is a critical factor in irrigated agriculture. The study by S.W. Sharshir *et al.* (2023) explored the use of solar energy for drying agricultural produce, which helped reduce energy costs. However, it did not address the use of PV systems in irrigation complexes. Comparative findings highlight the need for further research on the integration of such technologies into water supply systems. Lower operational costs and the optimisation of water use are key benefits of implementing PV technologies in agriculture. The work of F. Raza *et al.* (2022) demonstrated the socio-economic impact of solar irrigation systems, which contributed to water supply stability and energy savings. The transition of agricultural enterprises to PV systems reduced dependence on centralised power supply, aligning with conclusions on the increased economic efficiency of such technologies. The effectiveness of solar pumps with single-axis tracking systems for irrigation was confirmed by the study of P. Abhilash *et al.* (2021). These technologies improved water delivery performance by optimising panel orientation relative to solar radiation. Data analysis indicated that combining such technologies with intelligent energy management systems enhanced the efficiency of irrigation systems.

A study by I.M. Bezhenar (2023) on the financial aspects of solar energy development in Ukrainian farms confirmed the importance of expanding state support programmes in this field. The author found that the availability of financial incentives could foster wider adoption of PV systems in agriculture. Comparative analysis showed that investment accessibility and subsidies are key factors for the effective expansion of renewable energy technologies in irrigated farming. The architectural features of PV systems and their impact on agroecosystems were examined in a study by M.A. Zainol Abidin *et al.* (2021). The authors concluded that the optimal spatial arrangement of solar panels could enhance crop yields by creating a favourable microclimate. Comparative results confirmed that integrating PV systems into irrigation complexes not only reduces energy costs but can also have a positive effect on agricultural productivity.

The application of PV systems in irrigated agriculture increased the energy efficiency of agricultural enterprises and reduced operational costs. In a study by A. Lingayat *et al.* (2021), the use of solar energy across various industrial sectors, including agriculture, was analysed. The authors found that solar power plants have considerable potential to meet the energy needs of agricultural enterprises, helping to reduce their reliance on fossil fuels and centralised power grids. The comparison showed that using solar energy in irrigation systems fits well with the worldwide move towards renewable energy and helps farms become more self-sufficient in their energy use. The economic feasibility of applying PV technologies in agriculture has largely depended on the availability of financial incentives (Ismanzhanov *et al.,* 2012). The study by I. Sotnyk *et al.* (2022) highlighted the development of solar energy in households in Ukraine and Latvia, emphasising the importance of state support. The authors found that subsidies, preferential loans, and Net Metering mechanisms contributed to the active deployment of solar power plants. A comparison of the findings confirmed that financial mechanisms played a key role in the development of PV systems in agriculture, reflecting general trends in the promotion of renewable energy.

The integration of PV systems into irrigation complexes enabled simultaneous optimisation of energy consumption and rationalisation of water use. The study by D. Soto-Gómez *et al.* (2024) demonstrated that agrivoltaic systems facilitated the combined production of electricity and agricultural crops without significant yield losses. Optimal placement of solar panels promoted efficient land use and supported microclimatic conditions. A comparison of the results confirmed the need to improve management methods of PV installations in irrigated farming, which could offer additional economic and environmental benefits. The stability of power supply to pumping equipment is a critical factor for the effective operation of irrigation systems. The work by S. Gorjian *et al.* (2021a) explored the integration of PV, photovoltaic-thermal, and solar thermal collectors in greenhouse complexes. It was found that these technologies contributed to a significant reduction in CO_2 emissions and energy consumption optimisation. A comparative analysis highlighted the importance of energy storage systems in irrigation setups to ensure the reliable operation of pumping equipment and mitigate the impact of variable PV generation.

Financial support has been an important factor in expanding the use of PV systems in agriculture. The study by A.K. Thakur *et al.* (2022) found that government subsidies, concessional loans, and other financial incentives significantly accelerated the adoption of solar technologies in Indian farming enterprises. A comparison of the results confirmed that expanding financing mechanisms in irrigated agriculture could enhance its energy efficiency and resilience. The use of PV technologies in agriculture contributed to increased productivity through automated production processes. The study by M.A. Muñoz-García & L. Hernández-Callejo (2021) showed that autonomous energy systems improved resource management and reduced CO_2 emissions by decreasing dependence on fossil fuels. A comparative analysis confirmed that PV-powered autonomous pumping stations had significant potential for optimising irrigation processes by ensuring stable water supply and reducing energy costs.

PV systems contributed to improved water use efficiency in agriculture. The study by G.H. Tariq *et al.* (2021) revealed that the implementation of solar energy in irrigation systems enhanced water delivery control, reduced moisture losses, and increased the overall productivity of the agricultural sector. A comparison of the findings emphasised the need to modernise the energy infrastructure of irrigation systems to ensure optimal energy consumption and sustainable water resource management. Climatic and topographical conditions had a significant impact on the performance of PV systems in agriculture (Semenenko *et al.,* 2024). The study by A. Ashraf & K. Jamil (2022) found that solar irradiance levels, temperature fluctuations, and local terrain characteristics substantially affected PV module productivity and their capacity to provide a stable energy supply. The comparison of results showed that it is important to adjust pumping stations to fit local conditions, which includes choosing the best PV system setups, using battery storage, and combining different energy sources to make the irrigation energy supply more reliable.

The use of PV-powered pumping stations in irrigated agriculture allowed for a reduction in operating costs and ensured a stable energy supply independent of fossil fuels. In the study by S. Hilarydoss (2023), a comparative analysis of the economic efficiency of PV and diesel pumps was conducted, demonstrating the financial advantages of solar generation. The author found that despite higher initial capital costs, PV systems had lower operating expenses and a longer service life, resulting in faster investment payback. A comparison of findings confirmed the economic viability of solar generation for irrigation systems, in line with broader trends toward sustainable energy solutions in the agricultural sector. The adoption of alternative energy sources enhanced the resilience of food production and energy supply stability in agriculture (Yerniyazova *et al.*, 2024). The study by Y. Majeed *et al.* (2023) found that integrating solar power with other renewable energy sources ensured stable operation of irrigation systems while reducing reliance on unstable centralised power grids. A comparative analysis confirmed the need for integrated energy resource management in agriculture, including the use of PV systems, energy storage, and hybrid solutions to guarantee uninterrupted energy supply.

PV systems contributed to reducing the environmental impact of the agricultural sector by cutting CO_2 emissions and lowering fossil fuel use (Dovgal *et al.,* 2024). In the study by C.M. Kumar *et al.* (2023), it was shown that the implementation of solar energy in Indian agriculture significantly reduced greenhouse gas emissions and supported the transition to environmentally sustainable energy solutions. A comparison of findings confirmed that the use of PV systems was aligned with general trends in sustainable agricultural technology development, providing both economic and environmental benefits. The use of solar technologies in agriculture enabled reductions in operational costs and increased the energy autonomy of the agricultural sector (Ismanzhanov & Tashiev, 2016). In the study by S. Gorjian *et al.* (2021b), the economic aspects of solar technology implementation in agriculture were analysed, confirming their ability to reduce energy supply costs through the use of renewable energy sources. The authors found that transitioning to PV systems allowed agricultural enterprises to avoid significant expenses for fuel and centralised electricity while also mitigating financial risks associated with tariff instability. A comparison of findings confirmed the economic effectiveness of solar technologies in agriculture, which could become a key factor in their further adoption in irrigation systems.

Diversification of energy sources contributed to increasing the energy independence of agricultural enterprises and ensured the resilience of energy supply. The study by S. Mathur *et al.* (2022) established that a combination of biofuels, solar, and wind energy allowed for the optimisation of energy consumption, a reduction in dependence on conventional energy resources, and the enhancement of operational stability in agricultural enterprises. A comparison of results confirmed the prospects of implementing PV technologies in agriculture, particularly when combined with other renewable energy sources to create integrated energy solutions. The application of PV systems in irrigated agriculture proved to be economically viable, contributing to reduced electricity costs, improved energy efficiency of agricultural enterprises, and lower CO_2 emissions. The analysis showed that integrating PV technologies into irrigation systems ensured stable water supply, reduced reliance on unstable centralised networks, and could be effectively combined with other renewable energy sources. A comparison of the results obtained with previous scientific studies confirmed the importance of financial incentives, optimal panel placement, and advancements in energy storage technologies for improving the efficiency of PV systems in agriculture.

Conclusions

The study assessed the economic feasibility of using PV systems in irrigated agriculture, considering financial, technical, and environmental aspects of their implementation. The analysis of energy supply costs revealed that the use of PV stations enabled a reduction in operational expenses for agricultural enterprises through the utilisation of renewable energy. It was found that transitioning to solar power stations enhanced the energy autonomy of agricultural production and reduced dependence on fluctuating tariffs for conventional energy resources. Furthermore, it was demonstrated that the availability of Net Metering mechanisms and government funding programmes facilitated the wider adoption of PV systems in agriculture. The technical analysis indicated that integrating PV systems into irrigation complexes contributed to the improved efficiency of pumping stations. The use of modern inverter technologies, energy storage systems, and automated power regulation algorithms enabled the optimisation of energy consumption and ensured the stable operation of pumping equipment. It was established that the performance of PV systems largely depended on the level of solar insolation, the design features of the panels, and the capabilities of energy consumption automation. In addition, it was confirmed that combining solar panels with energy-efficient pumps contributed to a reduction in overall electricity consumption and increased the productivity of irrigation systems.

The environmental analysis showed that the use of PV systems in irrigated agriculture significantly reduced CO_2 emissions by decreasing the consumption of traditional energy resources. The introduction of solar technologies helped lower environmental pollution levels, improve the ecological sustainability of agricultural production, and rationalise water resource use. It was confirmed that agrivoltaic systems had the potential to increase crop yields by protecting plants from overheating and conserving soil moisture. Based on the results obtained, recommendations were formulated regarding the expansion of PV system use in irrigated agriculture. One of the key factors in scaling up solar energy is the development of financial support mechanisms, including government subsidy programmes and preferential crediting. It was found that the implementation of energy storage technologies, optimisation of electricity consumption management algorithms, and the development of digital monitoring platforms would enhance the efficiency of solar energy use in the agricultural sector.

Further research in the field of PV system integration into irrigation complexes may focus on the development of models for forecasting electricity generation and consumption under various climatic conditions. The issue of assessing the long-term stability and reliability of PV panels in regions with high insolation levels and seasonal water consumption fluctuations remains relevant. A promising research direction is the integration of solar generation into comprehensive water resource management systems, which would enable the optimisation of both energy and natural resource use in agriculture.

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Conflict of Interest

None.

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Економічна ефективність впровадження сонячних панелей в зрошувальному землеробстві: оцінка витрат, порівняльний аналіз витрат та економічне обґрунтування

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Анотація. Метою цього дослідження було оцінити економічну ефективність впровадження фотоелектричних (ФЕ) систем у зрошуваному землеробстві з урахуванням технічних, фінансових та екологічних аспектів їх застосування. Для досягнення цієї мети було проаналізовано рівні енергоефективності насосних станцій, вартість встановлення ФЕ систем та механізми державної підтримки. Результати дослідження показують, що впровадження сонячної енергії в зрошувальних комплексах знизило середні витрати на електроенергію до 0,05-0,12 доларів США за кВт · год порівняно з 0,20-0,35 доларів США для дизельних генераторів та 0,10-0,30 доларів США для централізованого електропостачання. Було визначено, що середній термін окупності ФЕ систем у зрошуваному землеробстві становить 5-8 років, що значно менше, ніж для дизельних генераторів, які не є економічно ефективними через високі експлуатаційні витрати. Дослідження підтвердило, що використання сучасних ФЕ систем у поєднанні з інтелектуальними насосами зменшило споживання енергії зрошувальними установками на 20-30 %, підвищивши їхню автономність та стабільність роботи. Аналіз впливу на навколишнє середовище показав, що фотоелектричні системи сприяють скороченню викидів CO_2 на 60-80 % порівняно з традиційними джерелами енергії, що є вирішальним фактором переходу до сталого сільськогосподарського виробництва. Було встановлено, що програми субсидування, механізм нетто-лічильника та пільгові кредити сприяють зменшенню початкових капіталовкладень та стимулюють сільськогосподарські підприємства до впровадження сонячних електростанцій. На основі отриманих результатів розроблено рекомендації щодо оптимізації механізмів фінансового стимулювання впровадження фотоелектричних систем у зрошуваному землеробстві, покращення технологічних параметрів фотоелектричних установок та використання цифрових платформ для управління енергією. На практиці результати можуть бути використані для обґрунтування проектів державно-приватного партнерства з будівництва сонячних електростанцій на зрошувальних насосних спорудах

Ключові слова: відновлювані джерела енергії; фотоелектричні системи; циркулярна економіка; енергетична незалежність; оптимізація енергоспоживання