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Strategic Prospects for the Management of Renewable Energy in Agriculture in the Context of European Integration

Abstract. Introduction*. The integration of renewable energy sources into agriculture represents a crucial strategic direction for ensuring sustainable rural development, particularly within the context of European integration. Given the growing environmental challenges, energy dependence and the need for economic revitalization, the transition to renewable energy in agriculture is becoming increasingly relevant. The study explores the potential of renewable energy technologies - including solar, wind, bioenergy, and biogas – to enhance energy efficiency, reduce greenhouse gas emissions, and stimulate economic activity in rural communities.*

Purpose*. The purpose of this research is to assess the strategic prospects and practical implications of implementing renewable energy in the agricultural sector of Ukraine, with an emphasis on aligning with European Union standards and sustainable development goals. The study aims to identify the key drivers, barriers, and policy instruments that facilitate the transition toward renewable energy in rural economies.*

Results*. The findings reveal that adopting renewable energy in agriculture contributes significantly to energy independence, environmental sustainability, and employment generation in rural areas. The use of solar panels, biogas plants, and biomass fuels has the potential to reduce reliance on fossil fuels and mitigate the impacts of energy crises. Comparative analysis shows that successful EU practices - such as those in Eastern Germany - offer valuable models for Ukraine. Additionally, the study highlights that international support mechanisms and EU integration processes create favorable conditions for advancing green energy transitions in the Ukrainian agricultural sector.*

Conclusions*. The development of renewable energy in agriculture is a vital component of Ukraine's sustainable development strategy and European integration trajectory. Institutional support, financial incentives, and legal harmonization with EU norms are essential to overcoming existing technical and economic barriers. The long-term benefits include reduced emissions, increased resilience in rural areas, and an improved quality of life for rural communities.*

Keywords*: renewable energy management; agriculture; European integration; sustainable development; energy efficiency.*

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Стратегічні перспективи управління відновлюваною енергетикою в сільському господарстві в контексті європейської інтеграції

Анотація. *Інтеграція відновлюваних джерел енергії в сільське господарство є стратегічно важливим напрямом забезпечення сталого розвитку сільських територій, особливо в умовах європейської інтеграції. З огляду на зростання екологічних викликів, енергетичну залежність та необхідність економічного відродження сільських регіонів, перехід аграрного сектору на відновлювані джерела енергії набуває дедалі більшої актуальності. У статті розкрито потенціал застосування технологій відновлюваної енергетики, зокрема сонячної, вітрової, біоенергетики та біогазу, для підвищення енергоефективності, зменшення викидів парникових газів і стимулювання соціально-економічного розвитку сільських громад. Досліджено стратегічні перспективи впровадження відновлюваної енергетики в аграрний сектор України в умовах євроінтеграційних процесів. Акцентовано увагу на важливості переходу до альтернативних джерел енергії як чинника сталого розвитку сільських територій, зміцнення енергетичної безпеки держави, поліпшення екологічної ситуації та зменшення залежності від викопного палива. Проаналізовано європейський досвід використання відновлюваних джерел енергії в аграрному виробництві, зокрема в Німеччині та Польщі. Обґрунтовано, що впровадження відновлюваних джерел енергії у сільському господарстві сприяє створенню нових робочих місць, активізації місцевої економіки та досягненню цілей сталого розвитку.*

Ключові слова: *відновлювані джерела енергії; сільське господарство; енергоефективність; сталий розвиток; європейська інтеграція; аграрний сектор.*

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Formulation of the problem. The current challenges affecting Ukraine's agricultural sector, including energy dependence, environmental degradation and socio-economic decline in rural areas, require a fundamental

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shift towards sustainable and resilient energy solutions. As a cornerstone of national food security and a significant contributor to the country's GDP, agriculture is inherently energy-intensive and increasingly vulnerable to external shocks in the energy supply, price volatility in fossil fuel markets and the escalating consequences of climate change.

In this context, the Ukrainian agricultural sector must respond to both immediate operational energy needs and the long-term imperative of aligning with broader global and European environmental strategies. European integration brings with it additional responsibilities and new opportunities. On the one hand, Ukraine must harmonize its environmental and energy legislation with EU directives, including those related to climate neutrality, carbon emission reductions, and the promotion of renewable energy. On the other hand, the EU's Green Deal and Common Agricultural Policy (CAP) provide a framework for financial, technological and institutional support that could accelerate the transition to a more environmentally friendly Ukrainian agriculture.

Despite Ukraine's agricultural sector having natural resources, technical potential and international partnerships, the current state of renewable energy integration remains fragmented and underdeveloped. Key obstacles include a lack of policy coherence, limited access to green financing for farmers, inadequate infrastructure and low awareness of modern energy technologies among rural populations. This situation contrasts sharply with that in EU countries, which have successfully implemented renewable energy systems in rural areas, often transforming farms into energy producers through the use of solar farms, wind turbines, biogas plants and biomass utilisation.

The central research problem is therefore the lack of a coherent, scalable and integrative strategy for embedding renewable energy into Ukraine's agricultural development model. There is an urgent need to examine how various renewable energy technologies can be systematically integrated into agricultural practices to enhance not only energy efficiency and environmental sustainability, but also the economic revitalisation of rural areas. This includes evaluating the institutional mechanisms, policy instruments, and investment models that could facilitate such a transition.

Addressing this issue is critical for achieving multiple national objectives, such as strengthening energy independence, meeting international environmental commitments, modernising agriculture, and ensuring the socio-economic uplift of rural communities. Therefore, developing a strategic approach to managing renewable energy in agriculture should be a priority for national policy and scientific research.

Analysis of recent research and publications. The development of renewable energy in agriculture is a topic that has attracted increasing scholarly attention in Ukraine and around the world, particularly given the urgent need for sustainable rural development and climate adaptation. Recent research highlights the multiple benefits of using renewable energy in agriculture, including environmental protection, increased energy efficiency, economic revitalisation and improved social outcomes for rural communities.

A prominent contribution to this field of study is that of I. Doronina [1], who examines the legal, technological and economic foundations for expanding the use of renewable energy in rural areas. She emphasises the necessity of a robust legal framework to support solar, wind and biomass energy initiatives in Ukraine and proposes specific regulatory tools to facilitate this transition.

H. Hryhoryeva focuses on state support mechanisms for renewable energy in agriculture, emphasising the economic feasibility and environmental benefits of biogas, biomass and solar energy projects. Her research provides valuable insights into how state policies can encourage adoption at farm level.

O. Chumachenko's research [3] focuses on the strategic role of renewable energy in maintaining the energy balance of Ukraine's agro-industrial complex. His research explores solutions for a stable and decentralised energy supply in the event of critical infrastructure damage, emphasising the importance of renewable energy for ensuring energy security.

International case studies have also informed Ukrainian academic discourse. E. Freier, I. Lishchynskyi and M. Lyzun [4] examine Eastern Germany's experience of promoting renewable energy in agriculture. Their findings reveal effective policy instruments, funding mechanisms and institutional practices that could be adapted to the Ukrainian context.

Taking a broader European perspective, I. Gernego and O. Liakhova [5] examine EU initiatives that support renewable energy in rural development. They suggest that integrating Ukraine into EU frameworks could accelerate the adoption of renewable technologies. Similarly, N. Bobrovska, A. Sukhorukova and A. Burkovska [6] examine the influence of European integration on business transformation processes, including those in agriculture and energy.

A. Poltorak, O. Khrystenko, A. Sukhorukova, T. Moroz and O. Sharin [7] introduce an innovative methodological perspective, proposing an integral approach to assessing the impact of innovation and household financial security on sustainable resource use, including energy. Their research highlights the intersection of financial policy, innovation, and sustainability.

A. Burkovska, O. Shebanina, T. Lunkina and others [8, 9] further develop the link between renewable energy and rural sustainability by examining how renewable energy strategies can enhance food security, environmental health and rural well-being. Their work emphasises the need to integrate technological, environmental, and socio-economic dimensions into national development strategies.

Finally, global studies by scholars such as T. Pimonenko et al. [10] and D. Gielen and K. Hansen [11, 12] provide insights at a macro level into the global energy transition, ethical considerations and the role of agriculture in achieving climate goals. These studies contextualise Ukraine's challenges within broader energy policy and sustainable development trends.

Overall, recent literature provides a strong conceptual and empirical basis for understanding the role of renewable energy in agriculture. However, there is still a need to synthesise these insights into a unified national strategy. The present study aims to address this issue by offering a strategic vision based on comparative analysis, policy alignment and rural development needs.

Formulation of research goals. The primary goal of this research is to substantiate the strategic directions and practical mechanisms for integrating renewable energy sources into the agricultural sector of Ukraine, with a particular focus on aligning these efforts with the requirements and opportunities of European integration.

To achieve this overarching aim, the study sets the following specific objectives:

- to analyze the current state and dynamics of renewable energy use in agriculture in Ukraine and globally, with emphasis on the potential of solar, wind, biogas, and biomass technologies;

- to identify the key environmental, economic, legal and technological factors that influence the adoption of renewable energy in rural regions;

- to examine successful European Union practices and policy frameworks for promoting renewable energy in the agricultural sector, considering their applicability in Ukraine;

- to assess the role of renewable energy in enhancing rural development, food security and energy independence, particularly in the context of climate change;

- to develop strategic recommendations for improving national energy policy, institutional support, and investment mechanisms aimed at stimulating the green energy transition in agriculture.

By achieving these goals, the research will contribute to the development of a scientifically grounded vision for Ukraine's agricultural transformation that is aligned with EU environmental and energy strategies.

Presentation of the main research material. Primary energy is the energy inherent in natural resources such as crude oil, coal and wind before they are transformed. For instance, crude oil can be refined into secondary fuels such as gasoline or diesel, while wind can be used to generate electricity, which is a secondary source of energy itself. Therefore, a country's total primary energy supply indicates its primary energy sources. Meanwhile, final energy consumption refers to the energy used directly by consumers, including both primary fuels, such as natural gas, and secondary sources, such as electricity and gasoline [13].

A closer look should be taken at global primary energy consumption statistics by leading countries (see Fig. 1).

China is the world's largest consumer of primary energy, using around 159.39 exajoules in 2022. This is significantly more than the United States, which ranks second. Most primary energy sources are still derived from fossil fuels, such as oil and coal [13].

Notably, China's primary energy balance has shifted from a reliance on coal to an increased use of natural gas and renewable sources. Since 2009, the share of renewable energy in China's total energy consumption has increased by approximately 16% [13].

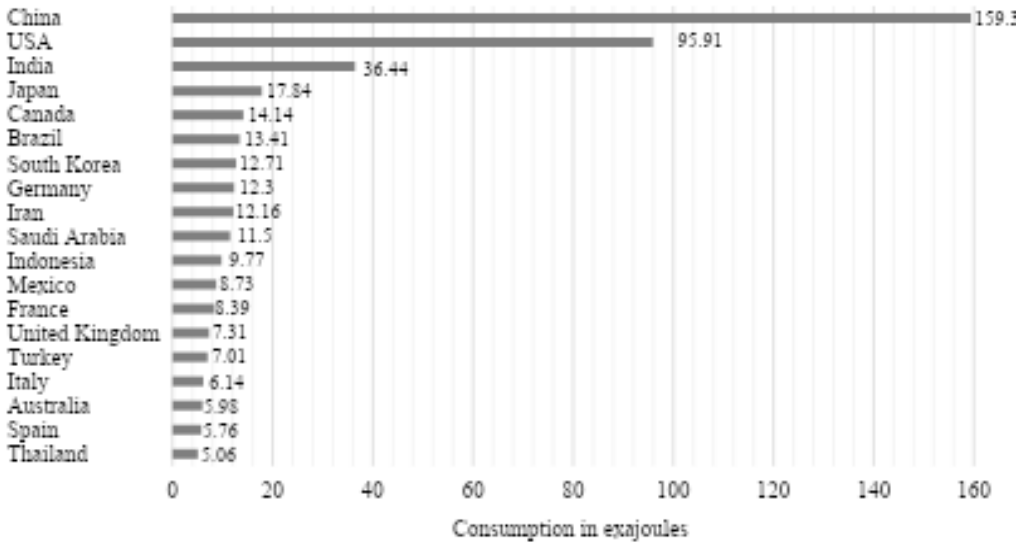

Figure 1 – **Primary Energy Consumption in 2022 by Selected Countries (in Exajoules)**

Source: built by the authors on the basis [13].

Overall, global primary energy consumption has increased over the past decade, with the highest growth expected in developing economies such as the BRIC countries [14].

The distribution of the global primary energy supply by source is a critical contemporary issue that requires close attention. The primary goal of energy management is to ensure the sustainable, efficient and environmentally safe production and use of energy.

Several key sources dominate the global energy mix, including coal, oil, natural gas, nuclear power and renewable energy.

Fig. 2 shows the global distribution of primary energy supply by source.

Figure 2 – **Global Distribution of Primary Energy Supply by Source**

Source: built by the authors on the basis [14].

Thus, oil remains the largest source of primary energy supplied worldwide. In 2019, it accounted for 30.9% of all energy produced globally; in 1973, this figure was close to 50%. The most significant increases observed over the analysed period were in the shares of natural gas and nuclear energy [14].

Coal consumption is associated with high levels of air pollution, greenhouse gas emissions and adverse health effects. Nevertheless, many countries still rely on coal to meet their energy needs due to its availability and low cost.

Despite its advantages, such as low greenhouse gas emissions and high output, nuclear energy presents challenges, including the risk of accidents and the issue of radioactive waste disposal.

Consequently, renewable energy sources, such as solar, wind and hydro power, are becoming increasingly important in the global energy landscape. These sources have significant potential to reduce greenhouse gas emissions and decrease dependence on imported fuels. However, large-scale deployment is constrained by technical, economic and political factors.

Fig. 3 shows the countries leading the world in renewable energy consumption.

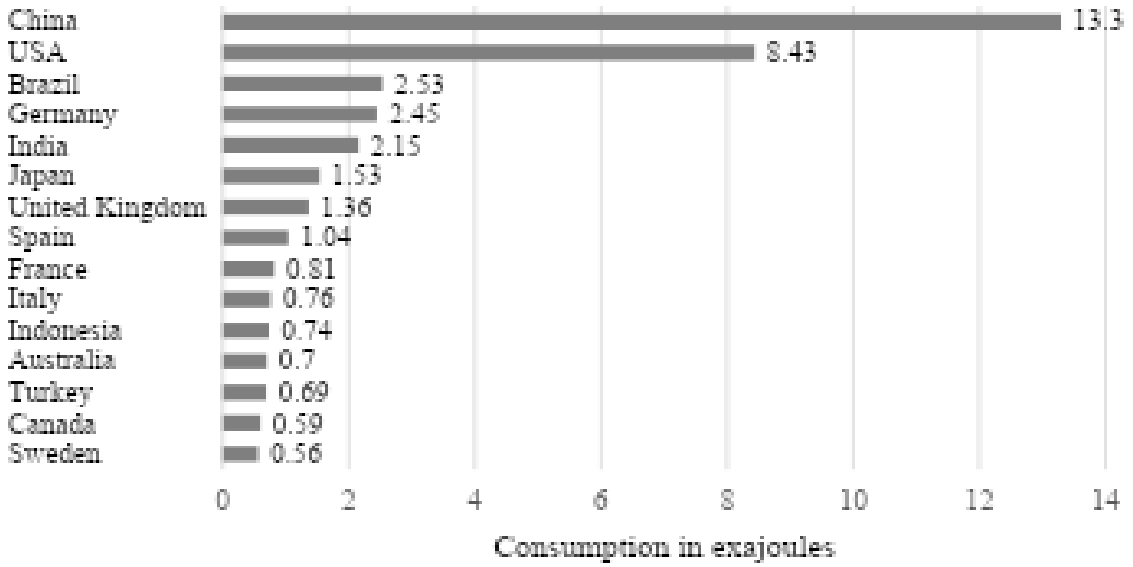

Figure 3 – **Leading Countries in Renewable Energy Consumption Worldwide, 2022**

Source: built by the authors on the basis [15].

Thus, in 2022, renewable energy consumption in China reached 13.3 exajoules, more than in any other country in the world. Renewable sources such as geothermal, wind, solar, biomass, and waste energy were included in this measurement, while cross-border electricity trade was excluded [15].

China is undoubtedly the leading consumer of hydropower, using three times more than other major countries such as Canada and Brazil. Several of the world's largest hydroelectric power stations by generating capacity are located in China, many of which have been constructed over the past two decades [15].

The United States ranked second after China in renewable energy consumption globally. Both countries were also the top consumers of primary energy overall. The U.S. aims to achieve energy independence by reducing the import of foreign energy sources. As renewable energy continues to gain momentum in a fossil fuel-dominated industry, U.S. renewable energy production in recent years has slightly exceeded domestic consumption [15].

The use of renewable energy across economic sectors has become an increasingly important topic in the context of global efforts to reduce greenhouse gas emissions and transition to sustainable energy development. Over the past few decades, there has been significant growth in the use of renewables in various sectors of the economy, including industry, agriculture, construction, transportation, and others. The development of renewable energy use carries important implications for the economic, environmental, and social development of regions around the world.

Let us examine the dynamics of the share of renewable energy across global economic sectors in Fig. 4.

Figure 4 – **Share of Renewable Energy in Final Energy Consumption Worldwide by Economic Sector**

Source: built by the authors on the basis [16].

Thus, the share of renewable energy in the industrial sector's final energy consumption reached 16.8% in 2020, up from 12.3% in 2010.

Of the considered sectors, industrial production had the highest proportion of renewable energy in total energy consumption in 2020, followed by construction and agriculture [16].

As a producer of food and raw materials for industry, agriculture has high electricity demand for various operations, including irrigation, lighting, processing and preserving products, and for automation and modern agricultural machinery. However, compared to other sectors of the economy, the agricultural sector's share in total final electricity consumption remains relatively low (see Fig. 5).

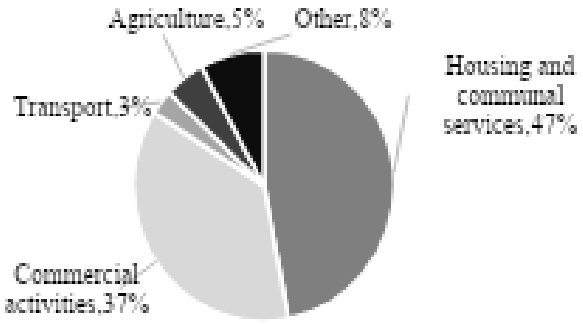

Figure 5 – **Distribution of final electricity consumption in the world in 2018 by economic sectors**

Source: built by the authors on the basis [17].

Thus, the industrial sector accounts for the largest proportion of global final electricity consumption.

As of 2018, industry was responsible for around 42% of total electricity consumption. By comparison, households accounted for just over a quarter of global electricity consumption. Agriculture accounts for only 3% of the global distribution of final electricity consumption. Ensuring a reliable and affordable electricity supply is essential to supporting agriculture, its development and its contribution to global food security. Using electricity in agriculture enhances productivity, efficiency and sustainability. As technology advances and the need to reduce environmental impact grows, electricity is becoming an increasingly important resource for agricultural operations.

One of the main areas of electricity use in agriculture is irrigation. In regions with dry climates, irrigation systems require substantial amounts of energy to power the pumps that supply water to fields. This is particularly important for ensuring stable production during droughts or periods of low rainfall.

Energy consumption in agriculture and forestry affects the economy, ecology and sustainable development of regions. In Central and Eastern Europe, this issue has gained particular relevance due to the need to increase energy efficiency and reduce dependence on traditional fossil fuels [18].

In 2022, oil and petroleum products were the main energy sources used in agriculture and forestry in Central and Eastern European countries. Poland was the largest consumer, using 38 terawatt-hours of energy. By contrast, Slovenia consumed just 860 gigawatt-hours (see Fig. 6).

Biogas plants, which use agricultural waste, are becoming increasingly popular in EU countries. Additionally, farmers are installing solar panels to reduce electricity costs. Modern methods of converting wood waste into biofuels are being implemented in EU forestry to help reduce dependence on fossil fuels. Furthermore, the EU government is encouraging farmers to adopt energy-saving technologies [18].

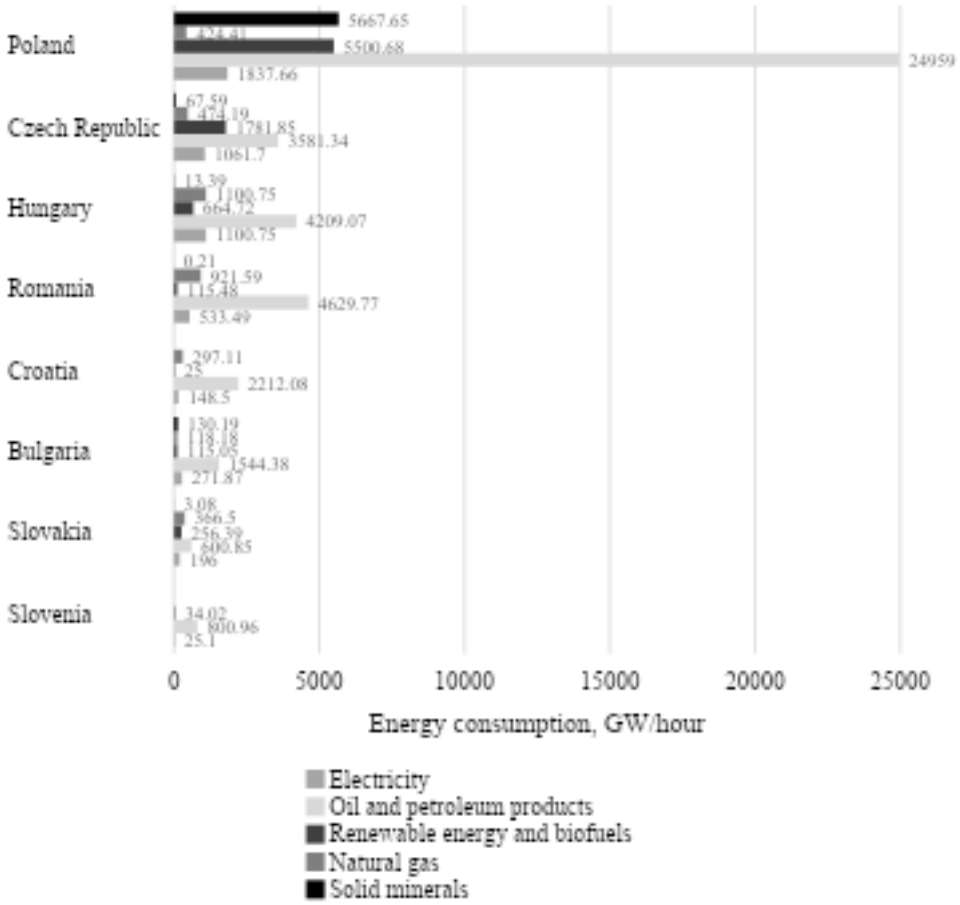

Figure 6 – **Energy consumption in agriculture and forestry in selected Central and Eastern European countries in 2022 by type of resource**

Source: built by the authors on the basis [18].

Thus, as of 2022, the main energy resources used in agriculture in EU countries were fossil fuels, particularly diesel and natural gas. However, there has recently been growing interest in renewable energy sources. Agricultural enterprises are increasingly using biomass, solar panels and wind turbines to reduce their dependence on fossil fuels and decrease their carbon emissions.

Electricity plays a critical role in the development of modern agriculture in the EU and worldwide by supporting mechanisation, automation, and the efficient irrigation, storage, and processing of agricultural products, as well as climate control in greenhouses. Integrating renewable energy sources further strengthens the resilience of the agricultural sector. Using electricity makes agriculture more productive, environmentally safe and economically beneficial, which is key to ensuring food security and sustainable development.

Renewable energy, particularly solar, wind and biomass energy, can significantly reduce energy costs for agricultural enterprises, enabling farmers to save money and invest in the further development of their farms. Furthermore, support programmes for sustainable agriculture funded by the EU provide a financial foundation for farmers to implement renewable energy sources. European integration promotes the exchange of knowledge and best practices among member countries, fostering the development of cutting-edge renewable energy technologies in agriculture, particularly in countries that previously did not utilize such practices.

Conclusions. In 2022, fossil fuels, particularly diesel and natural gas, were the main energy sources used in agriculture across the European Union. However, there has been a noticeable shift towards renewable energy sources in recent years. Agricultural enterprises are increasingly using biomass, solar panels and wind turbines to reduce their dependence on fossil fuels and lower their carbon emissions.

Electricity plays a crucial role in the modern development of agriculture, both within the EU and on a global scale. It enables mechanization, automation, and the efficient irrigation, storage, and processing of agricultural products, as well as climate control in greenhouses. Integrating renewable energy sources further strengthens the resilience of the agricultural sector, making farming more productive, environmentally friendly and economically advantageous. This is essential

for ensuring food security and promoting sustainable development.

Solar, wind and biomass energy can significantly reduce energy costs for agricultural businesses, enabling farmers to save money and invest in further development. Furthermore, European funding programs supporting sustainable agriculture provide a financial basis for farmers to adopt renewable energy. European integration facilitates the exchange of knowledge and best practices among member countries, fostering the development of innovative renewable energy technologies and practices in agriculture, particularly in countries that had not previously implemented them.

The shift towards renewable energy reduces reliance on fossil fuels and contributes to achieving sustainability goals in the agricultural sector, offering economic and environmental benefits.

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