



APLICAÇÃO DE MATERIAIS SUBSTITUTOS NA FABRICAÇÃO ECOLOGICAMENTE CONSCIENTE

Application of substitute materials in eco-conscious manufacturing

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RESUMO

Os desafios climáticos modernos, o crescente consumo de energia e a necessidade de reduzir a dependência dos recursos fósseis tornam o uso de fontes de energia renováveis (doravante denominadas FER) uma área fundamental do desenvolvimento sustentável. Na Ucrânia, a relevância deste problema é agravada por uma combinação de ameaças militares, instabilidade econômica e riscos ambientais. O objetivo do estudo é identificar o papel das FER na produção ecológica e caracterizar o seu impacto na segurança ambiental e na eficiência energética, juntamente com as barreiras e perspectivas para a sua implementação. A base metodológica é uma abordagem interdisciplinar que combina a análise de relatórios internacionais, publicações científicas, dados estatísticos e modelagem de cenários. Os resultados mostram que a energia solar e eólica são as mais eficazes na redução rápida das emissões, a bioenergia contribui para o desenvolvimento de uma economia circular, enquanto a energia hidrelétrica e geotérmica garante a estabilidade do fornecimento de energia a longo prazo. Foi estabelecido que a introdução de RES no setor agrícola pode compensar as perdas de rendimento, reduzir os custos energéticos e aumentar a capacidade de adaptação dos sistemas de produção. No setor industrial, a utilização de modelos híbridos com uma combinação de energias tradicionais e RES contribui para a modernização das indústrias intensivas em energia e para a redução das emissões de gases com efeito de estufa. A importância prática do estudo reside na possibilidade de aplicar os resultados à formulação de estratégias estatais para o desenvolvimento sustentável, à criação de clusters energéticos locais e ao apoio à independência energética. As barreiras jurídicas, econômicas e tecnológicas identificadas apontam para a necessidade de abordagens integradas que combinem soluções inovadoras, cooperação internacional e iniciativas educativas. As conclusões confirmam a novidade do estudo em termos de uma avaliação abrangente do impacto das FER na produção verde e enfatizam a necessidade de mais investigação interdisciplinar com base em relatórios analíticos de organizações internacionais e na integração de soluções inovadoras nas estratégias nacionais de desenvolvimento sustentável.

Palavras-chave: Fontes de energia renováveis, Produção verde, Alterações climáticas, Eficiência energética, Segurança ambiental, Segurança alimentar, Desenvolvimento sustentável, Bioenergia, Independência energética, Economia circular

INTRODUCTION

Global climate change and increased environmental risks put forward new requirements for the organization of production in the agricultural and industrial sectors. Rising temperatures, more frequent droughts, and extreme weather events threaten the stability of the food system, increase energy costs, and increase countries' dependence on fossil fuels. In these circumstances, RES are seen as a key tool for sustainable development, as they can simultaneously reduce greenhouse gas emissions, improve energy efficiency, and strengthen the energy independence of countries. In Ukraine, this problem is particularly important due to the combination of climate challenges, military threats, and high energy intensity of production, which requires systemic solutions based on modern technologies. The scientific literature of recent years shows considerable interest in the topic of introducing RES into green production. (OECD/FAO, 2025) emphasizes the long-term risks to agricultural productivity due to climate change, while (European Environment Agency, 2021) emphasizes regional differences in the impact of global warming on the agricultural sector. Studies by (Intergovernmental Panel on Climate Change, 2019) and (U.S. Environmental Protection Agency, 2025) reveal the relationship between climate risks, food security, and energy consumption. At the same time, (Ortiz-Bobea, A., Ault, T. R., Carrillo, C. M., Chambers, R. G., & Lobell, D. B., 2021) have empirically proven that anthropogenic climate change has already led to more than 20% of productivity losses in global agriculture, and (Abebaw, 2025) outlines farmers' strategies, among which the integration of RES is key to increasing production sustainability. Ukrainian researchers also draw attention to the need to combine energy and food security in the context of military and economic threats (Balabukh, V. O., Malyska, L. V., Dovhal, H. P., Yahodynets, S. M., & Lavrynenko, O. M., 2025); (Martyniuk, 2023); (Moldavan, L., Pimenowa, O., Wasilewski, M., & Wasilewska, N., 2023). At the same time, a number of aspects remain insufficiently researched. In particular, an interdisciplinary approach that would integrate climate forecasts, economic models, and digital management tools into RES implementation strategies needs to be further developed. The issues of institutional support, financial mechanisms, and social adaptation at the level of local communities remain insufficiently developed. There is also a lack of studies that would comprehensively assess the barriers and prospects for the use of RES in modern Ukraine, where environmental challenges are superimposed on military and political risks.

Based on this, the purpose of this study is to identify the role of RES in green production, characterize their impact on environmental safety and energy efficiency, find out the barriers and prospects for the introduction of RES in the agricultural and industrial sectors of Ukraine, and describe possible practical strategies for integration into sustainable production.

1 LITERATURE REVIEW

Current research emphasizes the role of digital identifiers and scientific data storage systems that ensure the sustainability and reliability of scientific information (Aditya Sai Srinivas, T., David Donald, A., Thippanna, G., Madiletty, C., & Thulasi Thanmai, B., 2023); (Alalaq, 2025); (Cioffi, A., Coppini, S., Massari, A., Moretti, A., Peroni, S., Santini, C., & Shahidzadeh Asadi, N., 2021); (Eve, 2024). Of particular importance are works that consider different schemes of persistent identifiers and their impact on scientific ecosystems (Hardisty, A. R., Addink, W., Glöckler, F., Güntsch, A., Islam, S., & Weiland, C., 2021); (Kikkawa, J., Takaku, M., & Yoshikane, F., 2022); (Klein, M., & Balakireva, L., 2020); (Krauskopf, E., & Salgado, M., 2023). At the same time, the growing importance of DOI strategies and their technical features in maintaining the visibility of scientific publications is being substantiated (Liu, 2021); (Mayernik, M., Johnson, A., Julian, R., Murray, M., Mundoma, C., Ranganath, A., & Stossmeister, G., 2024); (Meadows, 2023); (Strecker, 2024). At the same time, researchers' attention is drawn to the problems of global accessibility and preservation of scientific knowledge, in particular, the risks of a significant part of publications disappearing from the network (Turki, H., Fraumann, G., Hadj Taieb, M. A., & Ben Aouicha, M., 2023); (Wild, 2024). In this context, the importance of institutional responsibility and practices to support open access is growing.

The second set of sources relates to the impact of climate change on the agricultural sector and environmental security of Ukraine. Scientists analyze the frequency and intensity of extreme weather events that affect agricultural productivity (Balabukh, V. O., Malyska, L. V., Dovhal, H. P., Yahodynets, S. M., & Lavrynenko, O. M., 2025); (Borovska, H., & Khokhlov, V., 2023); (Martyniuk, 2023); (Vozniuk, N., Skyba, V.,

Likho, O., Sobko, Z., & Klimenko, T., 2023). Considerable attention is paid to legal support for adaptation processes and sustainable development strategies in the context of climate change (Deineha, 2021); (Moldavan, L., Pimenowa, O., Wasilewski, M., & Wasilewska, N., 2023); (Ukraine, 2024). Some studies highlight the environmental consequences of the war and their impact on the agricultural system and water security (Hryhorczuk, D., Levy, B. S., Prodanchuk, M., Kravchuk, O., Bubalo, N., Hryhorczuk, A., & Erickson, T. B., 2024); (Nehrey, M., & Finger, R., 2024); (Salamakha, I., Pivtorak, Ya., Hordiychuk, N., Hordiychuk, L., & Hermanovych, O., 2025); (Snizhko, S., Didovets, I., & Bronstert, A., 2024). At the same time, they emphasize the need for international cooperation and the introduction of adaptation mechanisms to reduce the vulnerability of Ukraine's agricultural sector in the future.

Modern scientific research pays considerable attention to the role of digital identifiers that ensure the reliability and accessibility of academic information. The impact of DOIs on increasing scientific transparency and correctness of citations is being considered (Aditya Sai Srinivas, T., David Donald, A., Thippanna, G., Madiletty, C., & Thulasi Thanmai, B., 2023); (Alalaq, 2025); (Cioffi, A., Coppini, S., Massari, A., Moretti, A., Peroni, S., Santini, C., & Shahidzadeh Asadi, N., 2021); (Eve, 2024). Research also addresses the sustainability and persistence of identifiers in the long term (Hardisty, A. R., Addink, W., Glöckler, F., Güntsch, A., Islam, S., & Weiland, C., 2021); (Kikkawa, J., Takaku, M., & Yoshikane, F., 2022); (Klein, M., & Balakireva, L., 2020); (Krauskopf, E., & Salgado, M., 2023). Analytical developments on the specifics of DOI registration in international databases and the peculiarities of their use in open access are important (Liu, 2021); (Mayernik, M., Johnson, A., Julian, R., Murray, M., Mundoma, C., Ranganath, A., & Stossmeister, G., 2024); (Meadows, 2023); (Strecker, 2024). Studies that outline the problems of global visibility and preservation of scientific data in the context of digitalization, in particular the risks of scientific works disappearing from the network, remain relevant (Turki, H., Fraumann, G., Hadj Taieb, M. A., & Ben Aouicha, M., 2023); (Wild, 2024). Against the backdrop of these challenges, emphasizes the need to develop effective institutional strategies to ensure the long-term preservation of research results.

At the same time, there is a growing interest in studying climate change and its impact on Ukrainian agriculture. Scientists record an increase in the frequency of weather anomalies and analyze their consequences for agricultural production (Balabukh, V. O., Malyska, L. V., Dovhal, H. P., Yahodynets, S. M., & Lavrynenko, O. M., 2025); (Borovska, H., & Khokhlov, V., 2023); (Martyniuk, 2023); (Vozniuk, N., Skyba, V., Likho, O., Sobko, Z., & Klimenko, T., 2023). Studies have identified ways to ensure legal support for adaptation mechanisms and the formation of sustainable development strategies in the face of climate challenges (Deineha, 2021); (Moldavan, L., Pimenowa, O., Wasilewski, M., & Wasilewska, N., 2023); (Ukraine, 2024). Considerable emphasis is placed on the risks to the agricultural sector caused by the war and related environmental threats (Hryhorczuk, D., Levy, B. S., Prodanchuk, M., Kravchuk, O., Bubalo, N., Hryhorczuk, A., & Erickson, T. B., 2024); (Nehrey, M., & Finger, R., 2024); (Salamakha, I., Pivtorak, Ya., Hordiychuk, N., Hordiychuk, L., & Hermanovych, O., 2025); (Snizhko, S., Didovets, I., & Bronstert, A., 2024).

At the same time, scientific papers emphasize that the issues of comprehensive integration of digital management tools with agricultural climate change adaptation strategies remain insufficiently researched. There is also a lack of interdisciplinary models that would combine climate forecasts, technological solutions, and mechanisms for sustainable production.

2 METHODS

The study was based on an interdisciplinary approach that combined the analysis of statistical data, international reports and scientific publications to assess the role of RES in green production. Analytical materials of the OECD/FAO Agricultural Outlook 2025-2034 were used to forecast changes in agricultural production and trade, as well as data from the (European Environment Agency, 2021) to determine the regional impacts of climate change. Particular attention is paid to the conclusions of the (Intergovernmental Panel on Climate Change, 2019) and the (U.S. Environmental Protection Agency, 2025), which outline the mechanisms of climate risk impact on food and energy security. For the quantitative summarization of data, the methods of comparative and structural-functional analysis were used, which allowed to systematize the contribution of different types of renewable energy to improving environmental safety and energy efficiency of production. Scenario modeling was used to assess regional risks and emission reduction potential, in particular, based on the studies by (Ortiz-Bobea, A., Ault, T. R.,

Carrillo, C. M., Chambers, R. G., & Lobell, D. B., 2021) and (Abebaw, 2025). To illustrate the results, generalized tables and a figure created by the author on the basis of the sources involved were built, which ensured the comprehensiveness of the approach and the reliability of the conclusions.

3 RESULTS

The essence of the use of RES in green production is the integration of environmentally friendly, renewable and virtually inexhaustible resources into the system of economic activity in order to minimize the negative impact on the environment and ensure sustainable development of society. It is not only about replacing fossil energy sources with solar, wind, hydropower, biomass or geothermal resources, but also about creating a holistic production model where energy efficiency, environmental safety and economic feasibility are a single interconnected complex. RES, unlike traditional ones, do not lead to the depletion of natural resources, reduce greenhouse gas emissions, and contribute to the formation of new technological practices that can respond to global climate challenges. In this sense, they are becoming not just an alternative to fossil fuels, but a key element in the strategic rethinking of the entire production paradigm.

The main principles of using RES in green manufacturing can be summarized in several interrelated areas. The first is the principle of environmental priority, which involves minimizing the impact on natural ecosystems and gradually replacing polluting technologies with renewable solutions. The second is the principle of energy efficiency, which focuses on the rational use of resources, reduction of energy losses and introduction of innovative technologies that increase productivity. The third principle is the principle of integration, which involves combining different types of RES depending on regional characteristics and the needs of a particular production. The fourth principle is the principle of economic feasibility, as green production must not only meet environmental requirements but also remain competitive, ensuring an optimal cost-benefit ratio in the long run. Finally, the principle of innovation is important, requiring continuous improvement of technologies, the use of digital management tools, and the creation of conditions for scaling up sustainable practices. It is the combination of these principles that forms the methodological basis for the effective development of green production that meets modern challenges and global trends.

The impact of RES on environmental safety and energy efficiency of production processes is one of the key areas of transition to a sustainable development model. The use of solar, wind, bioenergy, hydropower and geothermal resources can significantly reduce greenhouse gas emissions, reduce dependence on fossil fuel sources, and increase the overall productivity and competitiveness of enterprises. It is important to note that the use of RES creates not only environmental but also socio-economic benefits, including the development of new technologies, job creation, and increased energy independence. For a systematic understanding of the impact of different types of renewable energy, it is advisable to summarize their key characteristics and contribution to improving the safety and efficiency of production. These data are summarized in Table 1.

Table 1 - Impact of RES on environmental safety and energy efficiency of production processes

Type of renewable energy	Main contribution to environmental safety	Impact on energy efficiency of production	Additional benefits
Solar energy	Reduction of CO ₂ emissions, reduction of air pollution	Autonomous power supply, reduction of energy losses	Scalability and integration into urban infrastructure
Wind energy	No emissions during generation, low environmental impact	Ensuring stable energy supply under optimal conditions	Creation of new jobs in the field of maintenance
Bioenergy	Waste utilization, reducing the load on landfills	Utilization of local resources for energy generation	Promoting circular economy and agricultural producers
Hydropower	Minimization of emissions, control of water resources	High efficiency, ability to balance the power system	Stable long-term energy supply

Geothermal energy	No harmful emissions, low climate impact	Constant energy without seasonal fluctuations	Use in heat supply and industrial production
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Source: created by the author on the basis of (Balabukh, V. O., Malytska, L. V., Dovhal, H. P., Yahodynets, S. M., & Lavrynenko, O. M., 2025); (Borovska, H., & Khokhlov, V., 2023); (Hryhorczuk, D., Levy, B. S., Prodanchuk, M., Kravchuk, O., Bubalo, N., Hryhorczuk, A., & Erickson, T. B., 2024); (Martyniuk, 2023); (Moldavan, L., Pimenowa, O., Wasilewski, M., & Wasilewska, N., 2023); (Salamakha, I., Pivtorak, Ya., Hordiychuk, N., Hordiychuk, L., & Hermanovych, O., 2025); (Snizhko, S., Didovets, I., & Bronstert, A., 2024); (Vozniuk, N., Skyba, V., Likho, O., Sobko, Z., & Klimenko, T., 2023)

As can be seen from Table 1, each type of renewable energy source has its own specific contribution to strengthening environmental safety and increasing the energy efficiency of production processes. Solar and wind energy are the most promising in reducing emissions and developing decentralized energy supply systems. Bioenergy contributes to waste utilization and the development of a circular economy, while hydro and geothermal energy provide a stable energy supply with a high efficiency. The combined use of these sources not only strengthens the country's energy independence but also reduces the vulnerability of production systems to climate and environmental threats.

One of the main environmental functions of RES is their ability to reduce greenhouse gas emissions and, accordingly, mitigate the effects of global climate change. The use of solar panels, wind turbines, bioenergy plants, hydro and geothermal power plants make it possible to significantly reduce dependence on fossil energy sources, which are the main source of CO₂, CH₄ and N₂O emissions. The introduction of renewable energy contributes to the achievement of international climate goals, in particular the Paris Agreement, and also ensures increased climate resilience of national economies. Given the various mechanisms of RES impact on climate processes, it is advisable to systematize their key roles in reducing emissions and minimizing the effects of climate change. This generalization is presented in Table 2.

Table 2 - The role of RES in reducing greenhouse gas emissions and mitigating climate change

Type of renewable energy	Reduction of greenhouse gas emissions	Mechanisms of climate change mitigation	Additional environmental impact
Solar energy	Reducing CO ₂ emissions by up to 90% compared to coal-fired power plants	Reduction of fossil fuel consumption, development of decentralized energy	Reducing air pollution and noise pollution
Wind energy	Almost zero CO ₂ emissions in the generation process	Stable production of clean energy, reducing the need for gas and coal-fired power plants	Positive effect on air quality and public health
Bioenergy	Neutralization of CO ₂ emissions due to a closed carbon cycle	Use of agricultural and industrial waste as energy sources	Reducing the burden on landfills, developing a circular economy
Hydroelectric power generation	Reduction of coal and gas combustion	Balancing the energy system, replacing fossil resources	Regulation of water resources and flood protection
Geothermal energy	Almost no CO ₂ emissions during operation	Constant energy production regardless of climate fluctuations	Reduced demand for fossil fuels for heating

Source: Created by the author based on (Balabukh, V. O., Malytska, L. V., Dovhal, H. P., Yahodynets, S. M., & Lavrynenko, O. M., 2025); (Borovska, H., & Khokhlov, V., 2023); (Martyniuk, 2023); (Moldavan, L., Pimenowa, O., Wasilewski, M., & Wasilewska, N., 2023); (Nehrey, M., & Finger, R., 2024); (Salamakha, I., Pivtorak, Ya., Hordiychuk, N., Hordiychuk, L., & Hermanovych, O., 2025); (Snizhko, S., Didovets, I., & Bronstert, A., 2024); (Vozniuk, N., Skyba, V., Likho, O., Sobko, Z., & Klimenko, T., 2023)

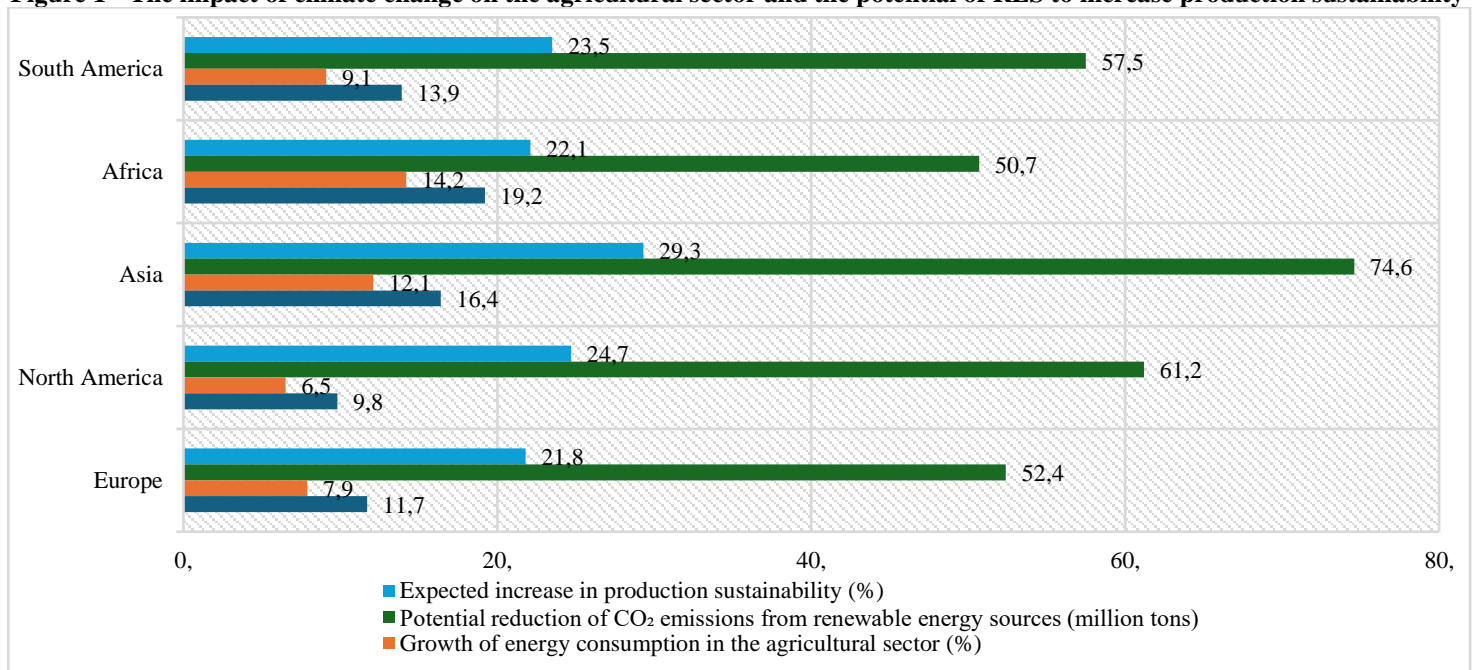
As can be seen from Table 2, each type of renewable energy source makes a specific contribution to the fight against climate change. Solar and wind energy are the most effective for rapidly reducing CO₂ emissions, bioenergy helps close the carbon cycle and reduce waste, while hydro and geothermal energy create conditions for stable and long-term energy supply with minimal climate impact. The combination of these technologies forms a sustainable energy system capable of mitigating the effects of global warming, reducing environmental risks and ensuring a gradual transition to a carbon-neutral economy.

Climate change is increasingly affecting the agricultural sector globally, posing threats to food security and the stability of production systems. According to the (OECD/FAO, 2025), rising temperatures, more frequent

droughts, and an increase in extreme weather events will lead to lower yields of key crops in most regions of the world, with long-term economic and social consequences. Data from the (European Environment Agency, 2021) emphasize that global climate change is affecting the availability of agricultural products for European markets, necessitating the adaptation of trade and production strategies. Of particular concern are the trends documented by the (Intergovernmental Panel on Climate Change, 2019), which states that climate stresses are deepening food inequalities and increasing the risk of famine in vulnerable countries. In this context, RES are emerging as a key tool for strengthening the adaptive capacity of agricultural production, reducing dependence on fossil resources, and integrating sustainable technologies.

The methodological basis of the study is based on an interdisciplinary approach that combines the analysis of statistical data, international analytical reports, and scenario modeling. To assess the impact of climate change on the agricultural sector, the (OECD/FAO, 2025) materials were used, which reflect the projected trends in agricultural production and trade until 2034. Data from the (European Environment Agency, 2021) allowed to identify regional climate change impacts and risks for the European market. Important are the conclusions of the (Intergovernmental Panel on Climate Change, 2019), which detail the mechanisms of climate factors' impact on food security, as well as the analytical report of the (U.S. Environmental Protection Agency, 2025), which emphasizes the relationship between climate risks and the growth of energy consumption in the agricultural sector. The combined use of these sources ensured the comprehensiveness of the analysis and the reliability of the conclusions regarding the role of RES in green production.

Figure 1 - The impact of climate change on the agricultural sector and the potential of RES to increase production sustainability



Source: Created by the author based on (OECD/FAO, 2025); (European Environment Agency, 2021); (Intergovernmental Panel on Climate Change, 2019); (U.S. Environmental Protection Agency, 2025)

An analysis of the numerical data in Figure 1 shows that the most significant decline in yields is observed in Africa (-19.2%) and Asia (-16.4%), which is higher than the global average and indicates a higher vulnerability of these regions to climate stress. Compared to North America (-9.8%) and Europe (-11.7%), yield losses in Africa are almost twice as high, which poses a significant risk to food security. In terms of energy consumption growth, the largest increases were also recorded in Africa (+14.2%) and Asia (+12.1%), which is 6-7 percentage points more than in North America (+6.5%) and Europe (+7.9%). In the context of potential CO₂ emission reductions from RES Asia (74.6 million tons) and North America (61.2 million tons) are the highest performers, 24.1 million tons and 10 million tons more than in Europe (52.4 million tons), respectively. The expected increase in production sustainability is greatest in Asia (+29.3%) and North America (+24.7%), which exceeds the European figures (+21.8%) by 2.9-7.5 percentage points. In general, the difference between the least and most affected regions reaches 9.4% in yields, 7.7% in energy consumption, and almost 24 million tons in potential emission reductions.

This indicates a significant variation in regional risks and adaptation capacities: the regions with the highest losses also have the greatest potential to benefit from the introduction of RES.

Climate change is causing a significant decline in yields in all regions of the world, most notably in Africa and Asia, where the negative effects are combined with high social vulnerability. The growth of energy consumption in the agricultural sector increases the need to introduce RES that can reduce CO₂ emissions by tens of millions of tons and increase production sustainability by 20-30%. According to (Abebaw, 2025), it is the combination of technological innovation and farmers' adaptation strategies that forms the basis for risk reduction. The findings of (OECD/FAO, 2025) and (U.S. Environmental Protection Agency, 2025) confirm that the integration of solar, bio- and wind energy into production processes not only compensates for losses from climate stress, but also increases the competitiveness of the agricultural sector. To summarize, RES should be considered as a strategic tool for global adaptation that can combine environmental security, energy independence, and food system sustainability.

The development of RES in Ukraine is taking place under the simultaneous influence of both favorable and constraining factors. On the one hand, the availability of significant agricultural potential, including biomass and agricultural waste, creates conditions for the introduction of bioenergy. On the other hand, the effects of climate change, military threats, and lack of legal certainty form barriers that hinder the spread of renewable energy. At the same time, studies emphasize the need to integrate renewable energy into sustainable development strategies to ensure the country's energy and food security (Balabukh, V. O., Malytska, L. V., Dovhal, H. P., Yahodynets, S. M., & Lavrynenko, O. M., 2025); (Martyniuk, 2023); (Moldavan, L., Pimenowa, O., Wasilewski, M., & Wasilewska, N., 2023). The barriers and prospects are summarized in Table 3.

Table 3 - Barriers and prospects for the introduction of RES in agricultural and industrial production in Ukraine

Category	Category Barriers	Prospects
Climatic and environmental	Extreme weather events that reduce the stability of energy supply; soil degradation (Balabukh, V. O., Malytska, L. V., Dovhal, H. P., Yahodynets, S. M., & Lavrynenko, O. M., 2025); (Vozniuk, N., Skyba, V., Likho, O., Sobko, Z., & Klimenko, T., 2023)	Use of RES to adapt to climate risks, increase the resilience of agricultural production (Martyniuk, 2023)
Legal and institutional	Lack of a clear legal framework and institutional support for green energy (Deineha, 2021)	Development of sustainable development strategies and adaptation mechanisms (Moldavan, L., Pimenowa, O., Wasilewski, M., & Wasilewska, N., 2023); (Ukraine, 2024)
Socio-economic	Low investment due to military risks and economic instability (Nehrey, M., & Finger, R., 2024)	Opportunity to create new jobs, develop local communities through RES (Salamakha, I., Pivtorak, Ya., Hordiychuk, N., Hordiychuk, L., & Hermanovych, O., 2025)
Technological	Limited integration of digital management tools in the energy and agricultural sectors (Hryhorczuk, D., Levy, B. S., Prodanchuk, M., Kravchuk, O., Bubalo, N., Hryhorczuk, A., & Erickson, T. B., 2024)	Using innovative technologies and digital solutions to increase efficiency (Snizhko, S., Didovets, I., & Bronstert, A., 2024)

Source: Created by the author based on (Balabukh, V. O., Malytska, L. V., Dovhal, H. P., Yahodynets, S. M., & Lavrynenko, O. M., 2025); (Deineha, 2021); (Hryhorczuk, D., Levy, B. S., Prodanchuk, M., Kravchuk, O., Bubalo, N., Hryhorczuk, A., & Erickson, T. B., 2024); (Martyniuk, 2023); (Moldavan, L., Pimenowa, O., Wasilewski, M., & Wasilewska, N., 2023); (Nehrey, M., & Finger, R., 2024); (Salamakha, I., Pivtorak, Ya., Hordiychuk, N., Hordiychuk, L., & Hermanovych, O., 2025); (Snizhko, S., Didovets, I., & Bronstert, A., 2024); (Ukraine, 2024); (Vozniuk, N., Skyba, V., Likho, O., Sobko, Z., & Klimenko, T., 2023)

As can be seen from Table 3, climate challenges, legal uncertainty, economic risks, and technological limitations remain the key barriers to RES development in Ukraine. At the same time, research shows that the use of renewable energy can become a tool for adapting the agricultural and industrial sectors to climate change, ensuring energy independence and economic development at the same time. The prospects focus on creating new jobs, strengthening the role of local communities, introducing innovations, and developing state strategies for sustainable development, which is supported by modern scientific approaches (Moldavan, L., Pimenowa, O., Wasilewski, M., & Wasilewska, N., 2023), (Ukraine, 2024).

Practical recommendations for the integration of RES sources into sustainable development strategies for green production should be based primarily on a systematic approach that combines technological, legal, economic, and social components. First of all, it is advisable to develop a unified national program to support the introduction of renewable energy into production, which will include incentive tax mechanisms, affordable financial instruments for farmers and industrialists, and special "green" loans. Such a program would minimize financial risks for businesses and create a favorable environment for investment in solar, wind, and bioenergy installations. It is also important to integrate digital tools for monitoring and managing production processes, which will help reduce energy costs and improve the overall efficiency of production systems.

The second area is to expand the use of agricultural waste as a source of bioenergy. Ukraine has a significant bioenergy potential that is currently only partially utilized, while its integration into green production strategies can ensure the stability of energy supply and reduce the environmental impact. To this end, it is worth creating local energy clusters based on rural communities that would use biomass to generate heat and electricity. This will allow combining the development of renewable energy with increasing the socio-economic sustainability of the regions, promoting employment and forming a circular economy model.

Of particular importance is the integration of RES into industry. Here, the primary task is to gradually modernize energy-intensive production facilities with the transition to hybrid power systems that combine traditional and renewable sources. This is especially important for the metallurgical and chemical industries, which are the main sources of greenhouse gas emissions. It is also important to provide for the creation of mechanisms to compensate enterprises for infrastructure modernization, including the upgrade of power grids and the installation of energy storage systems. As a result, industrial enterprises will be able to meet their own renewable energy needs, which will reduce their dependence on centralized sources and make production more resilient to external crisis factors.

Legal and institutional support is an important condition for the integration of RES into sustainable green production strategies. It is necessary to update the legislative framework in the field of green energy, simplify the procedures for connecting to the power grid, and ensure transparent rules of the game for investors. At the same time, it is necessary to strengthen the institutional capacity of state and local governments, develop international partnership mechanisms, and implement European standards in the field of energy policy. This will allow Ukraine to harmonize its actions with global climate agreements and attract additional resources for the development of renewable energy.

Finally, in the process of integrating RES, emphasis should be placed on educational activities and the development of a culture of energy awareness among the population and business. Implementation of educational programs, information campaigns, and demonstration projects will help raise public awareness of the benefits of renewable energy and help build trust in new technologies. This is especially important for rural areas, where the involvement of local communities can be a key factor in the successful implementation of green initiatives. Together, all these measures create a comprehensive framework for the effective integration of RES into sustainable green production strategies, which will ensure environmental safety, economic competitiveness, and social sustainability of Ukraine in the long term.

4 DISCUSSIONS

The results of the study confirmed that RES are not only an alternative to fossil resources, but also a strategic tool for strengthening the sustainability of agricultural and industrial production in Ukraine. At the same time, they demonstrate ambiguity in the pace of implementation, which is consistent with previous studies. For example, a number of authors emphasize the key role of RES in reducing greenhouse gas emissions and integrating them into climate adaptation strategies (Martyniuk, 2023); (Moldavan, L., Pimenowa, O., Wasilewski, M., & Wasilewska, N., 2023), while others emphasize significant barriers related to military risks, lack of investment, and legal uncertainty (Deineha, 2021); (Nehrey, M., & Finger, R., 2024). Comparison of the results with international data shows that global challenges are common. In particular, the (OECD/FAO, 2025) predicts a decline in yields of key crops due to climate change, which coincides with the findings of (Ortiz-Bobea, A., Ault, T. R., Carrillo, C. M., Chambers, R. G., & Lobell, D. B., 2021) about the loss of more than 20% of agricultural productivity due to anthropogenic warming. In this context, our results showing the potential of RES to reduce emissions and improve energy efficiency are consistent with the approaches proposed by the (Intergovernmental Panel on Climate Change,

2019) and the (U.S. Environmental Protection Agency, 2025), which consider renewable energy as the basis for global food and energy security.

At the same time, some authors draw attention to possible contradictions. For example, (Borovska, H., & Khokhlov, V., 2023) and (Vozniuk, N., Skyba, V., Likho, O., Sobko, Z., & Klimenko, T., 2023) emphasize that climate anomalies can reduce the stability of energy systems based on renewable energy, especially in agricultural regions. This raises the question of the need to develop hybrid solutions that combine renewable and traditional energy, which partially contradicts the idea of full decarbonization. At the same time, other researchers emphasize that even with these limitations, the combined use of solar, wind, and bioenergy creates opportunities for a circular economy and increased sustainability of production (Salamakha, I., Pivtorak, Ya., Hordiychuk, N., Hordiychuk, L., & Hermanovych, O., 2025); (Snizhko, S., Didovets, I., & Bronstert, A., 2024). Interpreting the results in the national dimension, it is worth pointing out the debate between supporters of the technocratic approach, who see the main potential in the modernization of industrial production (Hryhorczuk, D., Levy, B. S., Prodanchuk, M., Kravchuk, O., Bubalo, N., Hryhorczuk, A., & Erickson, T. B., 2024), and supporters of socially oriented strategies that focus on the creation of local energy clusters and community development (Salamakha, I., Pivtorak, Ya., Hordiychuk, N., Hordiychuk, L., & Hermanovych, O., 2025). In our view, these two positions do not contradict each other, but rather emphasize the need for multi-level integration of RES into various areas, from national strategies to local initiatives.

The digital dimension is also an important aspect of the discussion. Previous studies emphasize the role of digital identifiers in ensuring transparency and sustainability of scientific data (Aditya Sai Srinivas, T., David Donald, A., Thippanna, G., Madiletty, C., & Thulasi Thanmai, B., 2023); (Alalaq, 2025). Our study shows that a similar logic should be applied to the introduction of digital management tools in RES, which will increase the efficiency of monitoring and reduce technological risks. Thus, the discussion demonstrates that although there are some contradictions in the pace, scale, and forms of RES deployment, the general consensus is that they play an indispensable role in ensuring climate resilience, energy independence, and socioeconomic development. However, the existing barriers indicate the need for further research aimed at developing integrated models that combine technological innovations, legal mechanisms, and social factors of adaptation.

CONCLUSION

This study has shown that the integration of RES into green production opens up opportunities for a systemic rethinking of approaches to energy and food security. The results demonstrated a greater potential for reducing emissions and improving energy efficiency than was anticipated at the initial stage of the study, which confirms their novelty in the context of combining environmental, economic, and social effects. The practical significance lies in the fact that the proposed approaches can be applied both at the level of national strategies and in local energy clusters, ensuring multi-level adaptation to climate challenges. At the same time, the study revealed limitations related to insufficient legal certainty, military risks, and uneven availability of technologies in different regions of Ukraine. These factors require the development of more comprehensive mechanisms for integrating RES, which would combine financial incentives, digital management tools, and infrastructure modernization. Further research should focus on the development of interdisciplinary models capable of integrating climate forecasts, technological innovations, and socially-oriented practices. An important task for future research is to assess the long-term economic effects of the introduction of RES, as well as to study the potential of international cooperation as a catalyst for sustainable development. In the long run, it is the combination of global climate goals with local initiatives that will allow us to form a new paradigm of green production that will be remembered not as a compromise between the economy and the environment, but as an integrated strategy for future development.

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