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CONSEQUENCES OF IMPLEMENTING RENEWABLE ENERGY SOURCES AND ENERGY STORAGE SYSTEMS IN INDUSTRIAL ENTERPRISES OF UKRAINE

The article analyses the consequences of integrating renewable energy sources (RES) and energy storage systems (ESS) into Ukraine's industry. Based on a meta-analysis of current research and official data, the results of using solar, wind and battery systems in enterprises are evaluated. It is shown that RES and ESS increase energy efficiency, reduce costs and improve the reliability of electricity supply. In particular, solar installations at enterprises reduce electricity costs by 20–40%. Storage systems (batteries, hydraulic accumulators, hydrogen) smooth out generation fluctuations and provide backup power during outages. The main barriers are related to high investment costs and imperfect regulation. Overall, the introduction of RES+ESS stabilises energy supply, reduces costs and increases the resilience of Ukrainian industry, although further political support and investment remain necessary.

Keywords: integration of renewable energy sources, renewable energy sources, energy storage systems, industry of Ukraine, sustainability of energy supply.

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НАСЛІДКИ ВПРОВАДЖЕННЯ ВДЕ ТА ESS НА ПРОМИСЛОВИХ ПІДПРИЄМСТВАХ УКРАЇНИ

У даній статті аналізуються наслідки інтеграції відновлюваних джерел енергії (ВДЕ) та систем зберігання енергії (ESS) у промисловому секторі України. Актуальність теми дослідження полягає в тому, що промисловий сектор України тривалий час залежав від централізованого енергопостачання, яке працювало на викопному паливі, що робило його вразливим до перебоїв у постачанні енергії та коливань цін. Це, в свою чергу, підкреслило необхідність енергетичної самодостатності. З метою виявлення особливостей впровадження ВДЕ та ESS в промисловості України висунуто гіпотезу, яка полягає у зростанні ролі цих елементів у розвитку енергетичного сектору в умовах сучасних елементів нестабільності у розвитку української енергетики. З огляду на це, метою даної статті є узагальнення фактичних даних про результати впровадження відновлюваних джерел енергії + ESS в українській промисловості. У дослідженні використовується метааналіз останніх емпіричних досліджень, офіційних звітів та відкритих даних для оцінки результатів використання сонячної, вітрової енергії та акумуляторів у промислових застосуваннях. Результати показують, що впровадження ВДЕ та ESS значно підвищує енергоефективність, знижує експлуатаційні витрати та енергоємність, а також підвищує стійкість електропостачання. Наприклад, підприємства, які використовують сонячні фотоелектричні установки на місці, щорічно знижують свої витрати на електроенергію на 20–40%. Водночас ESS (акумулятори, гідравлічні насоси, водень) вирівнюють коливання продуктивності та забезпечують резервне живлення під час відключень, гарантуючи безперерйність виробництва у разі відключення електроенергії. Проблеми включають високі капітальні витрати та прогалини в законодавстві. Загалом, практичне значення полягає в тому, що впровадження ВДЕ+ESS допомагає стабілізувати енергопостачання, зменшити витрати та підвищити стійкість української промисловості, хоча політика підтримки та інвестиції все ще мають вирішальне значення. Як елемент наукової новизни цього дослідження можна згадати структурування переваг впровадження відновлюваних джерел енергії / ESS на промислових підприємствах України, а також визначені ключові напрямки для майбутніх досліджень.

Ключові слова: інтеграції відновлюваних джерел енергії, відновлювальні джерела енергії, системи зберігання енергії, промисловість України, стійкість енергопостачання.

Problem statement. Ukraine's industrial sector has long been dependent on centralised energy systems powered by fossil fuels, making it vulnerable to energy supply disruptions and price volatility. Recent war-related attacks on the power grid and geopolitical risks have sharply highlighted the need for energy self-sufficiency. Analysts argue that decentralised small-scale generation (5-100 MW) is currently 'the only way to prevent a nationwide blackout' and ensure a stable electricity supply to businesses [1]. At the same

time, ambitious national targets (e.g., 50% renewable energy by 2035) are stimulating interest in cleaner energy solutions at the local level [2]. The integration of renewable energy sources (sun, wind, biomass) and local storage into industry opens up opportunities to reduce energy import dependency, reduce carbon dioxide emissions and increase competitiveness. However, the implementation of RES and ESS in industry is a complex task involving technical, economic and regulatory factors.

The industrial sector in Ukraine is characterised by high energy intensity of production and significant dependence on centralised generation based on fossil fuels. This makes enterprises vulnerable to energy price shocks, disruptions in the operation of transmission networks and targeted attacks on energy infrastructure. The events of 2022–2024 showed that the shutdown of large power plants and network nodes instantly translates into a halt in production, while dispersed RES facilities (solar, wind, and bioenergy plants) often remain operational and maintain local energy supply. At the same time, heavy industry, which accounts for the lion's share of energy consumption, is facing decarbonisation requirements and tighter environmental restrictions, which necessitate a transition to renewable energy sources and modern storage systems. Despite the obvious potential, the integration of RES and ESS in industrial enterprises is complicated by high initial investments, an underdeveloped equipment market, regulatory barriers and a lack of expertise in energy management. Therefore, the scientific problem is the lack of a comprehensive assessment of the technical, economic and systemic implications of the introduction of decentralised RES/ESS for Ukrainian industry, the extent to which they reduce the risk of power outages, lower energy intensity and costs, and the factors that limit the scaling of such solutions.

Analysis of recent research and publications. Studies conducted in Ukraine and around the world confirm the significant advantages of using renewable energy sources on site for manufacturers. For example, Perevozova et al. proved that switching an industrial enterprise to solar energy ‘guarantees a reduction in its energy intensity,’ emphasising a significant increase in efficiency [3]. Their work showed that industrial solar capacity in Ukraine increased (5.5 times in 2019 compared to 2018) thanks to ‘green tariffs’. Similarly, industry reports indicate that the installation of industrial-scale photovoltaic systems can reduce electricity costs by 20–40% per year. These savings are achieved by replacing electricity supply systems during periods of peak prices. Importantly, ESS (batteries, hydro pumps, hydrogen) contribute to this by storing excess generation and smoothing out energy supply. VoxUkraine emphasises that modern battery systems are ‘no longer a technology of the future’ but are already reducing dependence on energy supplies at peak prices, increasing reliability and even generating income (by regulating price differences) [4].

The integration of renewable energy sources also contributes to energy security. According to a NREL study, combining solar photovoltaic installations with backup generators (e.g., diesel) can double the operating time in crisis conditions [5]. Such microgrid schemes allow key industrial facilities (e.g., food or defence enterprises) to continue operating during outages. In addition, decentralised RES are in line with Ukraine's sustainable development strategy [6]; experts are calling for the restructuring of the energy system using a multitude of distributed sources rather than a few large power plants. Modelling explores more detailed storage roles: According to the Child et al. project, existing hydroelectric power plants initially meet most storage needs, but as renewable energy sources exceed ~60% of supply, batteries (for daily balancing) and energy conversion to gas (seasonal hydrogen storage) become

dominant [7]. By 2050, assuming 100% renewable energy use, batteries and gas storage will be needed to fill the gaps.

However, barriers remain. The UNIDO assessment notes that the high capital costs of renewable energy systems often lead to ‘excessively long payback periods’ for industrial projects [8]. The immaturity of the equipment market and the complexity of regulation can deter companies. Nevertheless, there has been a sharp decline in costs in recent years – the cost of batteries has fallen by a factor of 8–10 between 2019 and 2025, making ESS increasingly viable.

Formulating the purposes of the article. The purpose of this article is to summarise the actual data on the results of the implementation of RES + ESS in Ukrainian industry, answering the question: what are the technical, economic and operational consequences of the implementation of renewable energy sources and storage systems at industrial facilities? We conduct a meta-analysis of peer-reviewed literature, official project reports and industry data. Methods include qualitative content analysis of case studies and quantitative assessment of claimed performance indicators (energy intensity, cost savings, reliability indicators). No primary fieldwork is conducted; instead, the study synthesises existing data to draw generalised conclusions.

The aim of the article is to summarise and systematise factual data on the consequences of implementing renewable energy sources and energy storage systems at industrial enterprises in Ukraine in the context of the transition to decentralised energy systems. To achieve this goal, it is planned to:

- characterise the main configurations for integrating RES (solar, wind, bioenergy installations) and ESS (battery, pumped storage, hydrogen solutions) into the activities of industrial enterprises;
- summarise the results of existing case studies and research on the impact of RES/ESS on the energy intensity of production, operating costs, reliability and continuity of electricity supply;
- identify key groups of effects from the implementation of RES+ESS (technical, economic, environmental and systemic) for the industrial sector of Ukraine;
- identify the main barriers, risks and prerequisites for scaling decentralised solutions based on RES/ESS in industrial enterprises, which allows for the formation of practical recommendations for business and public policy.

Presentation of the main research material. Decentralised energy systems are based on local energy production from renewable energy sources (RES) and local energy storage systems (ESS). The main examples of integrating renewable energy sources into the activities of industrial enterprises are the installation of solar photovoltaic systems (e.g., on roofs or on the ground on the factory premises), own wind turbines (if land and wind resources allow), as well as biomass or biogas systems that use organic waste from industrial production [9].

Figure 1 shows the share of solar photovoltaic energy, wind energy and biomass in the use of renewable energy sources in industry (by region).

Solar energy is one of the most accessible sources of renewable energy for industry, as many companies use the roofs of their buildings or adjacent land to install solar panels. Wind energy can be profitable for large companies that have sufficient land (or have entered into contracts to

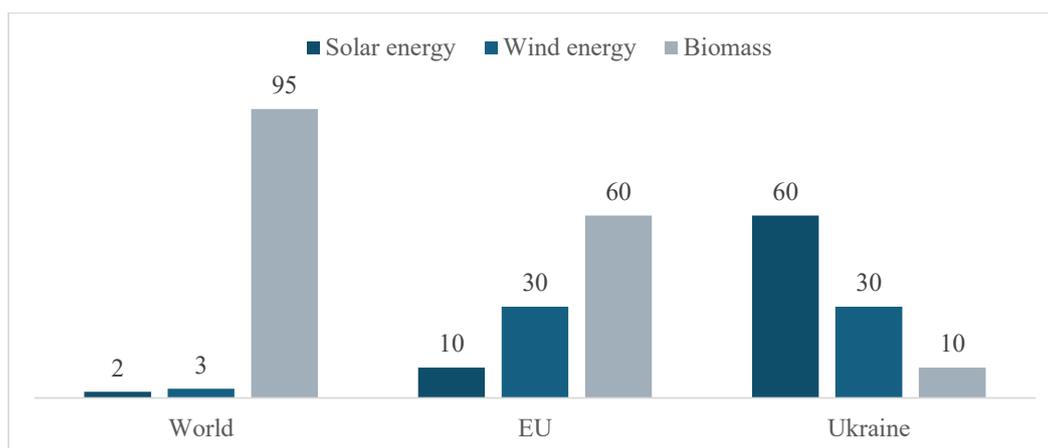


Figure 1. Share of solar photovoltaic energy, wind energy and biomass in the use of renewable energy sources in industry (by region: world, EU countries, Ukraine), 2024, %

Source: [10–12]

purchase wind energy from third-party producers), although it is more dependent on location. Bioenergy is particularly attractive for industries that produce biomass by-products (wood, agricultural waste, biogas from wastewater), as it provides a reliable source of energy and heat while solving the problem of waste disposal.

According to the International Renewable Energy Agency, only about 20% of the energy consumed in the manufacturing sector is electricity (used, in particular, in aluminium smelting, for drives, lighting and cooling). At the same time, more than 75% of energy in industry is consumed by heavy industry (metallurgy, chemical, cement, pulp and paper industries), although its share in total production is less than 5% [13]. This indicates high demand from energy-intensive sectors and, therefore, high economic potential for the integration of renewable energy sources, although they may face challenges due to constant energy needs. Nevertheless, renewable energy sources are one of the most effective ways to reduce dependence on fossil fuels and negative environmental impacts, and manufacturers around the world are implementing unique solutions to achieve energy efficiency through RES.

The review shows numerous positive effects of implementing RES/ESS. Energy intensity at manufacturing enterprises is steadily decreasing with the introduction of renewable energy sources. According to Perevozova et al., solarisation of a plant ‘guarantees’ lower energy intensity [3]. The cost savings are also evident: many industrial consumers immediately reduce their monthly bills by a fifth or more after installing solar panels. These savings accumulate over time; VoxUkraine notes an annual reduction in electricity costs of 20–40% for companies that use solar panels on site [4]. In practice, companies that once sold surplus photovoltaic energy cheaply (under the old ‘green tariff’ rules) can now store it and use it during peak consumption hours or sell it at higher market prices, thanks to ESS.

It also increases independence from the power grid and reliability. Energy storage reduces interruptions in operation: batteries are charged during sunny/windy periods and discharged at night, during periods of peak electricity prices or during outages. A VoxUkraine analysis explicitly states that modern batteries ‘reduce businesses’ dependence

on peak tariffs’ and increase production reliability [4]. For businesses operating 24/7 (e.g., chemical plants), ESS can provide immediate power during grid outages, preventing costly downtime. Unofficial data obtained during the war in Ukraine shows that companies with local storage facilities are better able to cope with night-time attacks and constant power cuts.

From a systems perspective, increasing the volume of distributed RES+ESS also reduces overall system costs and emissions. Child et al. concluded that scenarios with high levels of renewable energy use reduce the levelised cost of energy (LCOE) for Ukraine’s power system. It is noteworthy that by 2030–2040, batteries will become predominant when the share of renewable energy sources exceeds 60–90%, indicating a clear trajectory: as companies increase their production of photovoltaic/wind energy, they will simultaneously invest in energy storage. Recent large-scale projects illustrate this trend. For example, DTEK’s project to build 200 MW of battery storage has been highly praised for improving Ukraine’s energy security and sustainable infrastructure [14]. Such projects demonstrate that private-public capital is flowing into industrial storage facilities.

Challenges are holding back these achievements. High initial costs can slow down implementation. A UNIDO assessment showed that many SMEs still face very long payback periods for investments in renewable energy sources [8]. In Ukraine, unstable policies (e.g., changes in feed-in tariffs) sometimes lead to uncertainty. Moreover, the integration of RES/ESS requires new management methods and grid connection procedures. For example, obtaining a permit to install photovoltaic installations with a capacity of more than 1 MW can be a difficult task, and companies need to develop energy management systems to manage variable production. A professional approach (energy audit, digital monitoring) is necessary to fully realise the benefits (see Table 1).

Increasing the share of RES in the energy mix is crucial for reducing greenhouse gas emissions and combating climate change. Many countries see decentralised renewable energy sources as a way to achieve the goals of the Paris Agreement and carbon neutrality.

Decentralisation increases resilience and energy security. The presence of numerous distributed generators

Table 1

Benefits of implementing RES/ESS in industrial enterprises in Ukraine

Area of influence	Description	Specific effects
Energy efficiency	Reduction in energy intensity of production	The introduction of solar and wind power plants leads to a systematic reduction in energy consumption per unit of output.
Economic benefits	Reduction in electricity costs	After installing solar panels, many industrial enterprises reduce their monthly bills by 20% or more. It allows you to store energy and use it during peak demand hours, as well as sell it at a higher market price.
Energy independence and reliability	Reduction in dependence on the centralised power grid	ESS batteries provide backup power during outages and stabilise power supply during grid interruptions. 24/7 continuity of operation, preventing costly production stoppages. Companies with local energy storage systems are better equipped to cope with night-time attacks and power outages during wartime.
Systemic and environmental effects	Reduction in total system costs and emissions	The growth in the share of distributed RES and ESS reduces the levelised cost of energy (LCOE) and carbon footprint.
Investment dynamics and infrastructure	Influx of private and public capital	Growth in the number of industrial projects with ESS, development of sustainable infrastructure

and storage facilities creates a more modular network that is less prone to catastrophic failures. A striking example of this is the missile strikes on Ukraine's power grid in 2022–2023, during which many large centralised power plants were knocked out, but small, scattered RES (e.g. rooftop solar panels) proved more difficult to disable and helped maintain part of the local power supply [16]. Typically, a network of local microgrids and renewable decentralised energy sources (hereinafter referred to as RDES) can continue to provide critical loads during large-scale power outages caused by natural disasters or other disruptions.

Decentralised RES provide local communities and businesses with more opportunities. They allow industrial and commercial consumers to control their energy costs and even generate income from the sale of surplus electricity, and they also promote community involvement in energy (e.g. through cooperatives) [17].

From an economic perspective, investment in RES drives innovation and job creation – the renewable energy sector employs millions of people worldwide and continues to grow. Countries that are actively implementing renewable energy sources also seek to reap industrial benefits by developing production supply chains for solar panels, wind turbines, batteries, etc., leading to the creation of new industries and export potential.

It is also worth noting that the cost of equipment continues to decline (the cost of batteries has fallen by more than 80% in recent years), and LiFePO₄ (lithium-iron-phosphate battery) technology has proven itself. Both Ukrainian and international studies emphasise that combining local generation with storage is not only possible but also economically attractive. The figures given as examples (20–40% cost savings, multiple capacity growth) convincingly demonstrate the broad potential [12] (see Table 2).

Table 2

Main risks and quantitative indicators of RES+ESS integration at industrial enterprises in Ukraine

Risk category	Description	Quantitative indicators	Expected impact
1	2	3	4
High capital expenditure	High initial costs for installing RES and ESS; long payback periods hinder implementation	Typical industrial capital costs remain high; UNIDO estimates indicate a long payback period; battery costs have fallen by a factor of 8–10 (2019–2025), but remain significant	Slowdown in implementation, especially for small and medium-sized enterprises; financial barriers
Regulatory and political uncertainty	Gaps in legislation, unstable support schemes, complex permitting procedures for systems larger than 1 MW	–	Delays in project implementation, decline in investor confidence
Variability of renewable energy production	Fluctuations in solar and wind energy complicate energy planning; ESS are needed to balance fluctuations	Daily fluctuations in photovoltaic energy are significant (not quantified); meta-analysis shows high variability, requiring smoothing with ESS	Mismatch between production and consumption; operational instability
ESS capacity limitations	ESS stabilise supply but are prone to efficiency losses, degradation and insufficient capacity	ESS provides backup power during outages; hydrogen fuel systems and pumped storage systems help	Decline in long-term reliability; need to increase storage capacity
Grid instability and outages during wartime	Attacks on energy infrastructure cause supply disruptions; centralised power plants fail faster than decentralised RES	Military attacks (2022–2024) significantly disrupt the power grid; decentralised RES maintain partial functionality	Production downtime; increased need for on-site backup
Restrictions and operational limitations	Grid operators may restrict RES exports or operation during instability	–	Loss of generated energy; reduced economic impact

Continue Table 2

1	2	3	4
Market price volatility	Savings depend on electricity tariffs; ESS arbitrage effect varies depending on market conditions	Savings from on-site photovoltaic systems: 20–40% annually; ESS reduces the impact of peak tariffs	Economic benefits lower than expected in the event of volatility
Availability of supply chains and equipment	Underdeveloped domestic market; dependence on imported photovoltaic, wind components, batteries	Only qualitative data: “immaturity of the equipment market”	Delayed implementation, increased costs
Lack of technical knowledge	Insufficient energy management expertise limits the effectiveness of RES/ESS	Qualitative data: ‘lack of expertise in energy management’	Insufficient system performance; inefficient operation

Conclusions. Overall, the introduction of renewable energy sources and storage systems at industrial enterprises in Ukraine offers clear advantages: reduced energy consumption and costs, improved operational reliability and energy security. The transition also contributes to the achievement of environmental goals by reducing greenhouse gas emissions. To take full advantage of these benefits, Ukrainian industry and policymakers must prioritise support mechanisms: financial incentives, grid

access reforms, and technical assistance for ESS integration and smart energy management.

Future research should continue to collect empirical data from industrial pilot projects, quantify long-term economic impacts, and develop best practices for operating under Ukraine's unique energy regime. In a broader perspective, our analysis shows that the integration of RES+ESS is not just a theoretical ideal, but also a practical path to a more sustainable and efficient industrial sector in Ukraine.

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