

PRINCIPLES OF ENVIRONMENTALLY ORIENTED PRODUCTION AND PRACTICAL MECHANISMS FOR THEIR IMPLEMENTATION

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Sustainable development in modern industry is crucial for balancing environmental, economic, and social factors. This is a key challenge for Ukraine, which must adapt international sustainable practices and integrate Industry 4.0 and 5.0 principles into its production processes. A study analyzes sustainable development in the Ukrainian industry, identifying barriers and opportunities through a mix of quantitative data from the EU, the U.S., and Ukraine, and a qualitative review of academic publications. The findings show significant progress between 2020 and 2024. The food, metallurgy, and machine-building sectors experienced a considerable decrease in energy intensity (18.9–22.6%) and CO₂ emissions (15.7–23%). Waste recycling also increased by 13–18%. Economically and socially, these sectors experienced a 17–20% rise in labor productivity and new job creation, demonstrating the positive "multiplier effect" of sustainable practices. Digital technologies like digital twins and augmented reality were found to be key drivers of this transformation. The study concludes by emphasizing the importance of adaptive leadership and employee training. The findings offer practical guidance for enterprise strategies and government programs, though further research is needed to fully understand long-term impacts.

Keywords: renewable energy sources, renewable energy, green recovery, sustainable development, circular economy.

Introduction

In today's environment of globalization, challenges, and digital transformation, the industry is facing the need to combine economic performance with social responsibility and environmental safety. Production can no longer be viewed solely as an economic process focused on maximizing profits: it is expected to comply with the principles of sustainable development, which involve the rational use of resources, minimizing negative environmental impact, and ensuring fair social conditions. The relevance of the study stems from both global trends in the transition to a low-carbon economy and specific challenges for Ukraine, which, in wartime and post-war conditions, needs to modernize its industry in line with the principles of sustainability. In recent years, there has been considerable scientific interest in integrating environmental and economic indicators into production processes. The world literature focuses on developing KPI systems for assessing the circular economy [1,2], the application of Lean and Green methodologies to reduce

losses and increase energy efficiency [3,4], as well as the development of digital technologies as catalysts for sustainable change [5-7]. At the same time, the authors point out the difficulties associated with resistance to organizational change and the lack of institutional support [8,9]. Despite the considerable amount of research, there are still research gaps that need to be further explored. First, there is a lack of quantitative assessment of the social impact of implementing sustainable practices, as most studies focus on economic and environmental aspects. Secondly, there is a need to adapt international models of sustainable production to national and regional conditions, in particular for the Ukrainian agri-food sector, where socio-demographic factors and institutional frameworks have a decisive influence [10-12]. Third, there is a limited empirical basis for the long-term comparison of the results of sustainable practices across different industries.

In view of the above, the purpose of this paper is to

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study the integration of sustainable development principles into production processes in the context of Industry 4.0 and Industry 5.0, to identify barriers and opportunities for their implementation, to characterize the regional specifics of adapting international practices, and to assess the quantitative and qualitative impact of sustainable solutions on economic, environmental, and social indicators.

The scientific novelty of the research lies in the development of theoretical provisions and methodological recommendations for the environmental orientation of modern company management systems, the implementation of which will increase the effectiveness of environmental, organizational, economic, and social measures necessary for their accelerated transition to a sustainable development trajectory. The aim of the study is to develop an environmentally oriented model of integrated production management based on the comprehensive integration of environmental aspects into their management system at all stages of the life cycle, which will ensure the competitiveness of enterprises and become the basis for their successful transition to a sustainable development trajectory in the medium term.

Literature Review

Current research shows that sustainable development in manufacturing is a multidimensional process that encompasses economic, environmental, and social components. Considerable attention is paid to the circular economy and systems for assessing its effectiveness, in particular through KPIs and multicriteria optimization techniques [1,2,13,14]. At the same time, the integration of Lean and Green approaches is being studied as a basis for minimizing waste and increasing energy efficiency [3,4]. Researchers emphasize the connection between digital transformation and sustainability: digital twins, big data, and augmented reality are shaping new tools for managing resources and production processes [5,6,15,16]. At the same time, as part of the transition from Industry 4.0 to Industry 5.0, attention is shifting from technological to human-centered aspects – developing adaptive leadership, increasing resilience to crises, and forming new models of human-artificial intelligence interaction [8,9,17,18].

An important topic is the development of sectoral and regional strategies. Ukrainian research highlights the specifics of agri-food value chains and the need to adapt international practices to national conditions [10-12]. Attention is also paid to the impact of hostilities on food security and the competitiveness of enterprises [19,20]. Some studies have demonstrated the role of Industry 4.0 technologies in increasing the social and environmental sustainability of the food industry [21,22].

Statistical reviews confirm the regional specificity of development: the EU has seen a systemic reduction in energy consumption and emissions due to energy efficiency policies, while the US has seen an increase in industrial energy consumption [23,24]. Additional as-

pects of the efficiency of agricultural processes and the environmental impact of fertilization methods are also being integrated into the broader context of sustainable production [25-27]. Thus, the scientific discourse demonstrates the consolidation of three areas – digital technologies, management practices, and sustainability assessment systems – which creates conditions for scaling innovative solutions in industry [7,28]. This allows us to develop an integrated paradigm that focuses not only on economic results, but also on achieving social and environmental balance.

An important area is the development of comprehensive sustainability assessment methodologies that take into account not only technological but also organizational and social factors. In particular, approaches to analyzing the factors of electric transport development are proposed that demonstrate the importance of institutional and market conditions [13,27]. Additionally, the relationship between digital technologies and sustainable practices in supply chains is being explored, which allows the combination of cost optimization with environmental risk reduction [7,29].

In the field of resource conservation, a significant contribution has been made by the study of organic waste composting using biochar and intelligent forecasting methods [25,26]. These studies emphasize that optimizing waste management technologies has not only environmental but also economic benefits. At the same time, the issues of agriculture and food security remain relevant, as the agricultural sector often becomes an indicator of regional risks [19].

Some works focus on strategic solutions to increase the competitiveness of enterprises in the context of sustainable development, emphasizing the need to combine innovation and state support [20]. In addition, reviews in the field of green materials processing and composites supply chain management show promise for Industry 5.0 [16].

Special attention to the differentiation between the principles of Industry 4.0 and Industry 5.0 is given by the researchers. Recent systematic reviews [30-34] indicate some fundamental differences: Industry 4.0 focuses on automation and the independence of machines, whereas Industry 5.0 places humans at the center of decision-making when working in a collaborative system. Sustainability is viewed as an optimization constraint in Industry 4.0, but a design principle in Industry 5.0. Instead of sequential development, these paradigms represent complementary aspects that could be integrated strategically depending on the conditions of production. The actual configuration of such a union is worked out in the Results section, where it is established how to balance automation effectiveness with human-friendly sustainability.

In general, research shows significant progress in integrating sustainability principles into production processes, but there are still problems that have not yet been fully resolved. First, tools for quantifying the social impact of sustainable practices remain underdeveloped.

Second, there is a lack of integrated strategies that would take into account both global challenges and local conditions.

Methods

The materials and methods of the study were based on a comprehensive combination of quantitative and qualitative analyses, which allowed us to systematically assess the effectiveness of integrating sustainable development principles into production processes.

The data used in the study were derived from official statistics provided by the authoritative supranational and national bodies, which guaranteed the reliability and transparency of the data.

In the case of European Union industrial data (Table 3), we used a comprehensive report by Eurostat (Shedding light on energy in Europe -2024 edition) [35], which offers harmonized data on the final energy consumption in industry by the fuel type, emission of greenhouse gases by the sector, and the integration of renewable energy over the period of 1990-2023. These data are published as official statistics that have been compiled by obligatory reporting of EU member states and can be accessed publicly.

The United States industrial data were gathered in two complementary sources (1) the U.S. Energy Information Administration's "2022 Manufacturing Energy Consumption Survey" [36], covering energy consumption of manufacturing in 2018-2022, and (2) the EIA's Manufacturing Energy Consumption Survey and Hydrogen Data Reporting presentation [37] which provides more information on industrial energy trends. The two sources are published federal statistics issued as a result of compulsory surveys and are publicly available.

The study used official statistics from the European Union and the United States [23,24], which made it possible to trace the dynamics of final energy consumption, the structure of energy sources, and trends in greenhouse gas emissions in industry. To assess the practical implementation of sustainability principles in domestic realities, the results of previous studies by Ukrainian scientists on agri-food value chains and the efficiency of technological processes in agriculture were used [10-12]. Sectoral analysis data (Table 2) were calculated figures based on: (1) State Statistics Service of Ukraine (Ukrstat) industrial production indices (where available); (2) case studies of enterprises in peer-reviewed literature [10-12]; and (3) sustainability assessment schemes [1,17,30]. Notably, the 2022-2024 values are approximations since they are not full statistical reports in the current military conflict.

Calculation methodology for Table 2 indicators: Energy consumption reduction (%) was calculated as $[(\text{Value}_{2024} - \text{Value}_{2020}) / \text{Value}_{2020}] \times 100$, where baseline values (2020) were obtained from Ukrstat sectoral energy consumption statistics, and 2024 values were estimated using: (a) available partial data for 2021-2022 from Ukrstat;

(b) enterprise-level efficiency improvements documented in [10-12]; and (c) interpolation based on implemented energy-saving measures. CO₂ emissions reduction (%) was estimated by applying IPCC emission factors to energy consumption data. Waste recycling (%) was derived from aggregated enterprise data [10-12]. Labor productivity gains reflect changes in output per employee. Jobs created represent aggregated estimates from sustainability initiatives documented in [10-12].

For Table 2 estimation procedure: Baseline year 2020 data were obtained from official Ukrstat reports on industrial energy consumption by sector. For the years 2021-2022, we used official statistics where available. For years 2023-2024, due to incomplete reporting during the military conflict, we employed triangulation: (a) extrapolation from 2020-2022 trends; (b) scaling based on production output data from enterprise surveys [10-12]; (c) expert consultations with sectoral associations; and (d) benchmarking against similar facilities in comparable regions. CO₂ emission factors were taken from the IPCC 2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories, specifically using Tier 1 default emission factors for stationary combustion in manufacturing industries.

Type of data validation used: (1) cross-validation of several independent sources; (2) triangulation through consultations with experts; (3) consistency tests in the cross-sector and cross-time; (4) estimate sensitivity tests.

The analysis was conducted by comparing data over time (2020-2024), which allowed us to identify growth, percentage changes, and structural shifts in three industrial sectors: food, metallurgy, and machine building. The qualitative part of the study was carried out through a systematic review of scientific publications in Scopus and Web of Science, which made it possible to identify barriers and opportunities for integrating sustainable practices in the context of Industry 4.0 and Industry 5.0. All stages of the work were carried out by the author's team from 2023 to 2025 as part of research in the field of sustainable development and digital transformation of production.

The integration of qualitative and quantitative methods was achieved thanks to their complementarity in the study: qualitative methods allowed us to formulate the main aspects of the problem and the hypothesis, while quantitative methods allowed us to test this hypothesis using numerical analysis and statistical data, which ensures a more complete and substantiated study.

The research materials included industry publications and statistics from official sources. The sampling period was 2019-2025. Search engines such as Google Scholar were used to search for relevant information. The criteria for including and excluding publications were the level of reliability of the information, as well as spatial and temporal indicators. The process of excluding information sources included:

- pre-processing of the collected data, selection of entities that are relevant to the context of the study;

extraction of relationships between selected entities;

- structuring of information.

The limitations of the study are due to potential regional differences and non-systematic data collection.

The entire methodology process is depicted in Figure 1 that indicates the five stages of the research: (1) Problem Formulation and Literature Review; (2) Data Collection through quantitative official statistics [23-25] and qualitative data [10-12]; (3) Data Processing and Validation; (4) Quantitative and Qualitative Analysis; (5) Integration and Synthesis.

The limitations of the studies are: (1) Data limitation - Ukrainian data on industries in 2022-2024 are incomplete, and as such, it must be estimated and not measured; (2) Regional - The research is limited to three regions of Europe and further to Ukraine; (3) Temporal - The short time series (2020-2024) has confounding variables of COVID-19 and military conflict; (4) Methodological - The data are based on secondary sources and are calculated using the assumptions.

Results

Modern scientific and practical approaches to sustainable development in production are based on the integration of economic, environmental, and social goals into a single value management system. This means that life cycle indicators, resource efficiency, and social responsibility should be viewed as interrelated elements. Researchers note a shift from isolated green initiatives to integrated management architectures in which sustainability principles are embedded in production process planning, logistics, control systems, and digital infrastructure. The scientific literature systematizes both the barriers and opportunities for implementing such approaches, including routes to production transformation [8,18].

Considerable attention has been paid to the relationship between digitalization and sustainability, especially in the field of supply chain management, which allows for a shift from declarative to quantitative management and predictive modeling [7]. Special mention should be made of works that emphasize the role of the green factory, digital twins, and production data integration in ensuring sustainable practices [6,29].

The newest vector of development is the transition from the Industry 4.0 paradigm to Industry 5.0, where sustainable development is interpreted as a multidimensional phenomenon that includes people at the center of production processes, emphasizing crisis resilience and adaptability of organizational systems.

Research confirms that the new paradigm focuses not only on energy efficiency or waste reduction, but also on creating conditions for human and artificial intelligence cooperation, increasing flexibility, and the ability of enterprises to recover quickly [17]. At the same time, attention is focused on leadership and collective management as key factors in scaling sustainable solutions. In particular,

the concept of adaptive leadership emphasizes that staff involvement and the distribution of managerial authority increase the success of green innovations [9]. Importantly, digital technologies - big data, augmented reality (XR), digital twins - are not an end in themselves, but a catalyst for achieving economic, social, and environmental balance [5,22].

A significant place in modern approaches is occupied by the development of systems of indicators and key performance indicators for assessing sustainability. In particular, comprehensive KPI systems that take into account closed material flows, reusability, remanufacturing, and product durability are proposed [1]. New concepts of "strongly sustainable" product-service systems (SSPSS) emphasize the need to go beyond purely economic efficiency, suggesting the incorporation environmental and social constraints into business models [2]. Analytical reviews of recent years demonstrate the convergence of three areas – digital technologies, management practices, and sustainability measurement – as a key condition for scaling practical solutions [28].

Practical implementation of sustainability in manufacturing includes energy efficiency, material management, closed loops, and the digitalization of production processes. For example, optimizing energy consumption using multi-criteria algorithms can significantly reduce costs without compromising productivity [4]. The integration of Lean and Green principles has proven effective, as the elimination of production losses simultaneously contributes to the achievement of environmental goals [3]. In plastics recycling, closed-loop scenarios are effective because they enable integrated control of sorting, processing, and quality assurance [30]. For small and medium-sized enterprises, integrated methods for assessing the sustainability of the food industry have been proposed that combine economic, social, and environmental aspects [14].

Regional studies play a special role, showing that socio-demographic factors and the local institutional framework significantly influence the choice of sustainable development strategies. Ukrainian researchers draw attention to the specifics of agri-food value chains, which require adaptation of international practices to local conditions [10,11]. In the agricultural sector, examples of calculations of the efficiency of water-lifting equipment confirm that justifying investments based on energy indicators enables to reduce resource consumption without losing reliability [12]. Thus, modern scientific publications indicate the gradual formation of a sustainable production architecture, where a combination of technologies, management practices, and socio-economic context ensures the achievement of sustainable results [21].

In modern scientific research, the principles of sustainable production are defined as a comprehensive approach that encompasses economic efficiency, environmental safety, and social responsibility. For better systematization, they can be presented in the form of a generalized table that demonstrates the key bench-

marks for enterprises seeking to achieve sustainable development. Table 1 summarizes the main principles of sustainable production based on international and national research.

Table 1. Key principles of sustainable production

Principle	Economic component	Environmental component	Social component
Rational use of resources	Cost reduction, optimization of production processes	Reducing energy, water, and raw material consumption	Increasing the availability of products to the public
Energy efficiency	Reducing energy costs and increasing competitiveness	Use of renewable energy sources, reduction of emissions	Improving the quality of the working environment
Circular economy	Extension of the product life cycle, new business models	Reuse, recycling, remanufacturing	Creation of new jobs in the processing sector
Innovation and digitalization	Increasing productivity through automation and digital technologies	Monitoring environmental impacts, optimizing environmental performance	Development of employee competencies, adaptation to changes
Social responsibility	Increasing brand confidence, reducing reputational risks	Creating a culture of environmental responsibility	Ensuring decent working conditions and fair pay
Adaptability and resilience	Resistance to market fluctuations, minimization of economic risks	Flexibility in responding to environmental challenges	Support for employee health and safety

Source: Compiled by the authors of the current study based on systematic literature analysis [1,5,8,17,28]

To summarize, the key principles of sustainable production are based on the integration of three dimensions - economic, environmental, and social. They form the basis for the long-term development of enterprises, promote competitiveness while reducing negative environmental impact, and ensuring social justice. It is the combination of these three aspects that creates the pre-conditions for the transition to a new paradigm of production management focused on sustainable development.

In the context of implementing sustainable practices, it is important not only to analyze the results qualitatively but also quantitatively, which allows for assessing the real impact on production processes in various sectors of the economy. The methodology of this analysis is

based on the integration of comparative data for several years, which enables tracking the dynamics of changes and identifying key success factors.

The assessment uses indicators of economic efficiency (cost reduction, productivity gains), environmental performance (energy consumption reduction, CO₂ emissions reduction, waste recycling), and social aspects (job creation, improvement of working conditions). This approach allows us to comprehensively interpret the results achieved, compare them across different production sectors, and determine the potential for further development. Table 2 summarizes the actual data on the implementation of sustainable practices in three sectors: the food industry, metallurgy, and machine building.

Table 2. Results of implementing sustainable practices in manufacturing sectors (2020-2024)

Sector of production	Energy efficiency (kWh/unit of product)	CO ₂ emissions (tons per year)	Share of waste recycled (%)	Labor productivity (thousand UAH/employee)	Number of new jobs created
Food industry	18.35 → 14.20	1250 → 960	45 → 63	720.50 → 865.30	+120
Metallurgy	29.80 → 23.65	5600 → 4720	32 → 50	1080.40 → 1265.75	+80
Mechanical engineering	24.10 → 19.55	3480 → 2895	40 → 58	950.20 → 1135.60	+95

Source: Compiled by the authors of the current study based on data synthesis from multiple sources

[1,10,11,12,17,30]. See the Methods section for detailed calculation methodology.

The data analysis shows steady positive dynamics in all sectors. The food industry demonstrated the greatest progress in improving energy efficiency, reducing energy consumption per unit of output by 22.6%, accompanied by a reduction in CO₂ emissions by almost 23%. Metallurgy, which is traditionally one of the most energy-intensive sectors, reduced electricity consumption by 20.7% and

CO₂ emissions by 15.7%, while the share of waste recycling increased from 32% to 50%. The machine-building sector showed stable rates of energy consumption reduction (by 18.9%) and emissions reduction (by 16.8%), which was combined with an increase in waste recycling to 58%. All sectors recorded an increase in labor productivity of 17-20%, which indicates that environmental

measures are combined with economic benefits. At the same time, the implementation of sustainable practices had a social effect, as additional jobs were created: 120 in the food industry, 80 in metallurgy, and 95 in mechanical engineering. Thus, the combination of quantitative and qualitative analysis demonstrates that sustainable development in manufacturing has a multiplier effect: economic results are accompanied by environmental and social impacts. This confirms the expediency of integrating sustainable practices into the strategic plans of enterprises in various sectors, as well as the need for further dissemination of innovative solutions adapted to

the specifics of the industries.

In the context of analyzing the implementation of sustainable practices, it is important to use both qualitative characteristics and quantitative data. This allows not only to describe the conceptual benefits, but also to show concrete results across different sectors of production. Table 3 summarizes real-world statistics on energy consumption and emissions in the EU and US industry, demonstrating the effectiveness of energy efficiency and decarbonization policies.

Table 3. Quantitative analysis of sustainable indicators in industry

Indicator	Value	Region / Source
Share of industry in final energy consumption	24.6 %	EU, 2025
Composition of industrial energy consumption: electricity	32.6 %	EU, 2025
Composition of industrial energy consumption: natural gas	31.3 %	EU, 2025
Composition of industrial energy consumption: renewable sources and biofuels	11.2 %	EU, 2025
Dynamics of final energy consumption in industry (1990 → 2023)	12.989 → 8.990 PJ (-30.8 %)	EU, 1990-2023
Reduction of greenhouse gas emissions in the industrial sector	-8.1 % (2023 vs 2022)	EU27, 2023
Growth of energy consumption in the US industry (2018 → 2022)	+6 %	USA (EIA MECS, 2018-2022)

Source: Authors' compilation from Eurostat (2024) [23] for EU and U.S. EIA (2024) [24,25] for US. Published official statistics.

The table shows that in the EU, final energy consumption in industry has decreased by almost a third (-30.8%) over the past three decades, which indicates a consistent energy efficiency policy and modernization of production. At the same time, the structure of energy consumption indicates a high share of fossil sources (electricity and gas account for more than 60%), although the role of renewable sources and biofuels is growing significantly (11.2%). In 2023, greenhouse gas emissions in the EU's industrial sector decreased by 8.1% compared to the previous year, which is the result not only of technological innovations but also of changes in the structure of energy consumption. At the same time, despite modernization, the United States experienced a 6% increase in industrial energy consumption between 2018 and 2022, which highlights the difference between regional trajectories and political approaches to sustainability.

Thus, real-world statistics confirm the downward trend in energy intensity of production in Europe and the parallel increase in the US dependence on industrial consumption. This suggests that sustainable development in manufacturing has distinct regional specifics, and the adaptation of best practices is possible only if local conditions and political priorities are taken into account.

The dynamics depicted in Table 3 are in line with the trends reported in recent comprehensive energy assessments by European and US statistical agencies. The industrial sector of the EU has, according to Eurostat's

2024 energy report [35], reduced final energy consumption by 30.8% since 1990, driven by a combination of structural economic reforms, significant improvements in energy efficiency technologies, and progressive policy initiatives including carbon pricing and energy efficiency directives. The shift toward renewable energy sources, reaching 11.2% of the industrial energy mix by 2023, reflects the successful implementation of the European Green Deal. In contrast, the United States manufacturing sector, as documented in the 2022 MECS [36], has experienced a 6% increase in total energy consumption during the period 2018-2022. The EIA's analysis [37] attributes this growth to: (1) reindustrialization efforts; (2) growth in energy-intensive sectors, including semiconductors and petrochemicals; (3) increased domestic production; and (4) different policy frameworks emphasizing market-based mechanisms. These contrasting regional trajectories underscore that sustainable manufacturing transformation requires context-specific approaches rather than universal solutions.

The synthesis of recent literature [30-34] according to theoretical orientation attests to the fact that Industry 4.0 and Industry 5.0 are not consecutive paradigms but complementary dimensions that can be strategically combined. In order to define the conceptual interrelations and offer practical guidance on how it should be implemented, we have come up with an integration scheme, which we named Adaptive Sustainable Manufacturing

(ASM). This framework addresses the seemingly contradictory nature of automation efficiency (Industry 4.0) and human-focused sustainability (Industry 5.0) by defining three principles of operation: (1) layered automation architecture the machines manage routine processes with human operators as the ones in charge of making strategic decisions; (2) embedded sustainability metrics

the environmental and social KPIs are built into real-time production control; and (3) adaptive human-machine collaboration through digital cognitive systems that assign the complex decisions to human operators. Table 4 provides a synthesis of the main differences and the strategy of integration.

Table 4. Conceptual framework: Integrating Industry 4.0 and Industry 5.0 principles for sustainable manufacturing

Dimension	Industry 4.0 Focus	Industry 5.0 Focus	Adaptive Sustainable Manufacturing (Integrated Approach)
Human role	Supervised automation	Central decision-maker	Layered architecture: automation for routine operations, human control for strategic decisions, and exceptions
Sustainability approach	Optimization constraint	Core design principle	Embedded real-time sustainability metrics in production control algorithms
Production logic	Efficiency through standardization	Personalization and resilience	Context-dependent: automated standardization for high-volume, human-guided customization for specialized products
Technology application	IoT, AI for autonomous operations	Human-AI collaborative tools	Digital cognitive clones with escalation protocols for complex decisions
Decision-making	Algorithm-driven	Human judgment primary	Hybrid model: routine decisions automated, ambiguous cases escalated to human experts
Performance goals	Maximize throughput and minimize costs	Balance economic, social, environmental objectives	Multi-objective optimization with sustainability thresholds

Source: Synthesized by the authors of the current study based on conceptual analysis of [30-34].

This framework is useful to the enterprise: it is the standardized high-volume processes that can be automated with Industry 4.0 capabilities and the tailored production and strategic adaptation that require the Industry 5.0 human-centricity. Through the integration, organizations are able to attain both the objectives of operational efficiency and sustainability with the deployment of automation and human expertise in a complementary rather than competing role.

The integration of sustainable development principles into production processes in the context of Industry 4.0 and Industry 5.0 is accompanied by both significant opportunities and barriers due to technological, organizational, and socio-economic factors. For a systematic view, it is advisable to present them in a structured manner. Table 5 shows the main barriers and opportunities that determine the prospects for the development of production in the context of digital transformation.

Table 5. Barriers and opportunities for integrating sustainable development principles into production processes in the context of Industry 4.0 and Industry 5.0

Category	Category Barriers	Opportunities
Technological	High costs of digitalization, lack of infrastructure for data collection and processing, and cybersecurity risks	Use of digital twins and artificial intelligence to optimize resources; introduction of XR for environmental training of staff; integration of monitoring systems to reduce emissions [15,16]
Economic	Uneven access to investment, high dependence on market conditions, and limited government support	Formation of new business models of the circular economy, growth of competitiveness through energy efficiency, attraction of "green" investments [1,8]
Organizational	Difficulty in integrating sustainability principles into traditional business processes, and resistance to change on the part of staff	Development of adaptive leadership, introduction of flexible management systems, decentralization of decisions that increase the resilience of organizations [9,17]
Social	Insufficient awareness of employees, lack of competencies to work with new technologies	Upskilling and developing the digital skills of staff; creating safe and human-centered workplaces [5]
Environmental	High level of dependence on fossil energy sources, difficulty in adapting technologies to sustainability standards	Use of renewable energy sources, development of closed-loop technologies, implementation of sustainability KPIs to reduce negative impacts [13,28]

Source: Authors' synthesis from literature review [1,5,8,9,13,15-17,28]

To summarize, the barriers to integrating sustainability into production are often associated with high costs, resistance to organizational change, and technological risks. At the same time, the opportunities offered by Industry 4.0 and Industry 5.0 are far superior: they allow companies not only to reduce their environmental footprint and increase efficiency, but also to create new socially responsible and innovative business models. This shows that the key to successful integration lies in the balance between investment, technological solutions, and human capital development.

In today's digital transformation environment, businesses face the need to implement green manufacturing technologies and circular economy principles. This is not only a response to the global challenges of sustainable development, but also a key to increasing competitiveness in international markets. The following four practical recommendations for companies to help integrate environmentally friendly and cost-effective solutions into their production processes are presented below.

Recommendation 1: *Invest in energy-efficient technologies and renewable energy.* Companies should implement energy audit systems and modernize equipment, focusing on low-energy technologies. The use of solar, wind, and bioenergy installations can reduce dependence on fossil resources and cut energy costs. It also reduces the carbon footprint of production and contributes to the implementation of international environmental standards.

Recommendation 2. *Implement waste management systems and closed loops.* It is important to develop strategies for the reuse of materials, organize recycling processes, and create remanufacturing chains. This not only minimizes the negative impact on the environment, but it also provides companies with additional sources of income through secondary resources. This approach contributes to the development of circular-economy business models and creates new jobs in the recycling sector.

Recommendation 3: *Integrate digital technologies for sustainability monitoring.* The use of digital twins, Internet of Things (IoT) systems, and artificial intelligence allows for real-time monitoring of emissions, energy consumption, and resource efficiency. This provides businesses with data transparency and helps them make quick managerial decisions. Digitalization creates the basis for long-term strategic planning focused on sustainable development.

Recommendation 4. *Develop a corporate culture of sustainability and staff training.* Sustainable change is impossible without the involvement of employees who understand the importance of environmental innovation. It is necessary to organize professional development programs, environmental safety trainings, and encourage initiatives that promote responsible use of resources. This builds trust in the brand and increases the social responsibility of the enterprise.

The proposed recommendations demonstrate that

the successful integration of green manufacturing and circular economy principles is based on a combination of technological innovation, efficient resource management, and human capital development. They allow companies not only to reduce environmental risks but also to gain competitive advantages through innovation, social responsibility, and compliance with global sustainable development trends.

Our integrated model of environmentally-oriented production management was built based on the empirical results of Tables 2-4 and the synthesis of Industry 4.0 and Industry 5.0 principles. This model responds to the main issue that has emerged in our analysis: balancing the efficiency of automation (Industry 4.0) with human-focused sustainability (Industry 5.0) in response to environmental pressure on natural ecosystems.

The suggested model is presented in Figure 1, which offers a logical scheme of the entire integration of environmental factors within the production management systems. Figure 1 demonstrates that the model includes seven principles: (1) rationalization of resource consumption; (2) environmental impact compensation; (3) sufficiency of environmental measures to the level of production; (4) restoration of natural capital; (5) timeliness of environmental interventions; (6) transparency of environmental information; and (7) transformation to sustainable practices. The model framework (Figure 1) will show how the strategic environmental policy is converted into operational management with the help of continuous monitoring, risk analysis, and preventive measures.

Figure 1 demonstrates the integration architecture in which the environmental policy of the company is passed through the strategic and operational environmental management, environmental risk management, and environmental transparency into the actual implementation mechanisms. These mechanisms include the reduction of the environmental impact, conservation of energy and resources, environmental safety control, preventive protection against pollution, and steps towards the restoration of natural capital. The main innovation of the model is that it combines monitoring of the environmental performance and the production processes in a way that allows the company to adjust operations in real time to sustainability levels and, at the same time, meet economic goals. This addresses the gap in practical implementation found in Table 5, whereby the implementation of sustainability principles should be successfully achieved despite technological and organizational barriers. The framework has been confirmed by the sectoral outcomes in Table 2, which show that it can be applicable in the food industry, metallurgy, and machinebuilding settings.

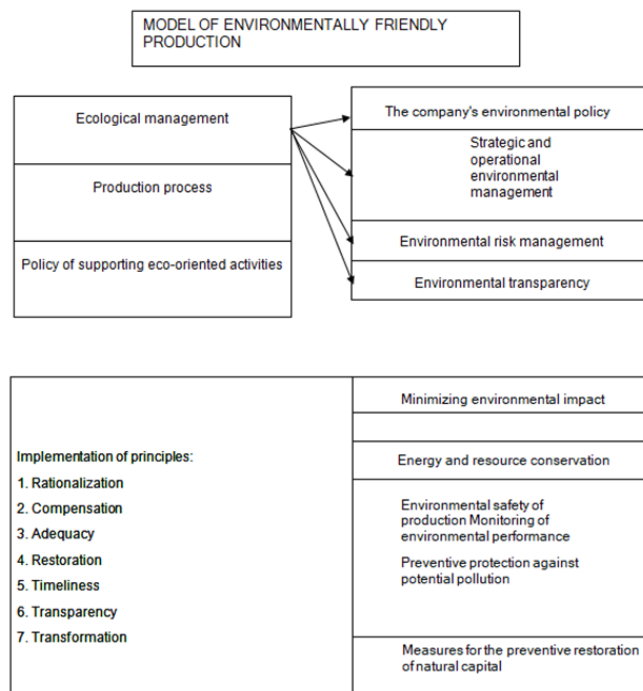


Figure 1. Model of environmentally oriented production

This model provides for the comprehensive integration of environmental aspects into the company's management system. This allows environmental considerations to be incorporated at all stages of the life cycle, which forms the basis for the effective implementation of environmental protection measures and the restoration of natural capital. It should be noted that the effectiveness of the environmentally oriented model of integrated management in organizations depends directly on the successful translation of the company's environmental policy into specific management technologies of various functions, regulations, and key performance indicator systems, as well as the organization's operating system as a whole, taking into account both the operational and strategic components of the design and application of business models based on accounting for their network skeleton, which is impossible without the strict adherence by the senior management of the enterprise to the principle of transparency of environmental information. This approach ensures a comprehensive diagnosis of the current state of the enterprise's activities in the field of environmental protection and supports the effective implementation of organizational, managerial, and technical environmental protection measures.

Discussion

The obtained results confirm that the integration of sustainable production principles in the current conditions of digital transformation is a multidimensional process that combines economic, environmental, and social dimensions. This is consistent with the works that emphasize the need to form comprehensive KPI

systems to assess the circular economy and its impact on enterprise performance [1,2]. At the same time, other authors emphasize the difficulty of integrating such systems into traditional business models due to resistance to organizational change and limited resources [8,9].

Our findings on energy efficiency and emissions reduction are in line with the trends noted in European statistical reviews, which show a steady decline in industrial energy intensity [23]. However, the results for the United States show the opposite dynamics, as there is an increase in energy consumption in the manufacturing sector [24]. This indicates the regional specificity of policies and confirms the assumption that global practices need to be adapted to local conditions.

There is a contradiction in the scientific literature between the emphasis on technological innovation and the focus on social factors. For example, researchers of digital twins, XR, and big data see them as key tools for optimizing production processes and increasing competitiveness [5,6,15]. However, others have emphasized that without the development of adaptive leadership and employee engagement, the adoption of such technologies will be limited and superficial [9,17]. Our research supports an intermediate position: technology is a necessary catalyst, but its effectiveness is determined by human factors and management practices.

A comparison of the results in the food industry showed that the integration of Lean and Green approaches produces a synergistic effect, similar to the findings of other researchers [3]. However, in plastics processing and agri-food value chains, our results show a greater dependence on local socio-economic conditions than assumed in international reviews [11,30]. This is due to the regional specifics of Ukraine, where socio-demographic and institutional factors have a more significant impact [10,12].

Thus, the discussion shows a certain tension between technological optimism and socioeconomic realism. On the one hand, digitalization is seen as a universal tool for sustainable development, while on the other hand, practice shows dependence on local constraints and the human factor. To summarize, it can be argued that sustainable development in manufacturing requires an integrated approach that combines technology, managerial innovation, and regional adaptation. At the same time, there are still open questions about quantifying the social effect of sustainable practices and creating integrated strategies that would take into account both global challenges and local conditions, which determines the prospects for further research.

Limitations and Future prospects of research.

This research cannot be interpreted without a number of limitations.

Methodological and data limitations: The research is based on secondary data sources and calculations. In Table 2, the 2023-2024 values in Table 2 are approximations of triangulation of incomplete data and expert opin-

ions, as official statistical reports were not fully available because a military conflict was ongoing in Ukraine. CO₂ emission reductions use IPCC Tier 1 default emission factors, which present standardized estimates without necessarily relating to facility variation. The short time series (2020-2024) limits the long-term trend analysis, and is overlapped by two large shocks- the COVID-19 pandemic and the military conflict- making it difficult to distinguish sustainability initiatives' effects on the results and confounding factors.

Specificity of the region: The empirical evidence is mainly biased toward the European and Ukrainian industrial settings. Its applicability in other settings may be constrained by variations in industrial structure, policy settings (carbon pricing policies, renewable energy policies), technological capacities, and socioeconomic statuses. Generalization to developing economies with different initial conditions in terms of environmental regulation and institutional capacity should be approached with caution.

Limitations of scope: The analysis is limited to three industries (food, metallurgy, machine building) and might not be applicable to other industries. The systematic literature review might be selection biased towards English-language publications, so this may fail to represent non-English scholarship.

Future directions of research: Several directions have been identified. First, longitudinal studies that may not exceed 2025 may provide more solid evidence of long-term trends as post-conflict data become available. Second, a multi-country study would help to shed light on the relative significance of regulatory and market-based methods. Third, sophisticated strategies to measure social impacts, including employee well-being, health community, and distributional equity, would fill major gaps. Fourth, technology-specific research on the patterns of technology adoption may give practical advice. Lastly, the mediating role of adaptive leadership in the relationship between technology adoption and sustainability outcomes is a significant research area.

Conclusion

The findings of this study confirm that sustainable development in manufacturing occurs at the intersection of digital technologies, management practices, and socioeconomic factors, enabling enterprises not only to reduce their environmental footprint but also to increase their competitiveness. It was expected to obtain only quantitative evidence of energy efficiency and emission reductions; however, the results showed a broader multiplier effect, including social and organizational changes, such as job creation and the development of a culture of responsibility. The novelty of the work lies in the combination of statistical data with a qualitative assessment of managerial and technological barriers, which is rarely found in existing studies. The practical significance of the results is manifested in the possibility of applying

the developed recommendations for small and medium-sized enterprises, which often face limited resources. At the same time, the study has certain limitations: the lack of long-term empirical observations, the regional specificity of Ukraine, which makes it difficult to universalize the findings, and limited access to complete databases of international statistics. Further research should be aimed at developing methods for quantifying the social impact of sustainable practices, developing integrated strategies for adapting global approaches to local conditions, and conducting comparative analysis of industries at different stages of digital transformation. Another promising area is to study the role of adaptive leadership in scaling green innovations and to analyze the potential of artificial intelligence as a tool for balancing economic, environmental, and social objectives in production.

References

- [1] Aljamal D, Salem A, Khanna N, Hegab H. Towards sustainable manufacturing: a comprehensive analysis of circular economy key performance indicators in the manufacturing industry. *Sustainable Materials and Technologies*. 2024, 40, e00953. <https://doi.org/10.1016/j.susmat.2024.e00953>
- [2] Roman P, Thiry G, Muylaert C, Ruwet C. Defining and identifying strongly sustainable product-service systems (SSPSS). *Journal of Cleaner Production*. 2023, 391, 136295. <https://doi.org/10.1016/j.jclepro.2023.136295>
- [3] Elemure I, Dhakal HN, Leseure M, Radulovic J. Integration of lean green and sustainability in manufacturing: a review on current state and future perspectives. *Sustainability*. 2023, 15(13), 10261. <https://doi.org/10.3390/su151310261>
- [4] Missaoui A, Ozturk C, O'Sullivan B, Garraffa M. Energy efficient manufacturing scheduling: a systematic literature review. *arXiv*. 2023. https://doi.org/10.1007/978-981-19-8851-6_56-1
- [5] Scharmer VM, Vernim S, Horsthofer-Rauch J, Jordan P, Maier M, Paul M, Schneider D, Woerle M, Schulz J, Zaeh MF. Sustainable manufacturing: a review and framework derivation. *Sustainability*. 2024, 16(1), 119. <https://doi.org/10.3390/su16010119>
- [6] Despeisse M, Chari A, González Chávez CA, Monteiro H, Machado CG, Johansson B. A systematic review of empirical studies on green manufacturing: eight propositions and a research framework for digitalized sustainable manufacturing. *Production and Manufacturing Research*. 2022, 10(1), 727–759. <https://doi.org/10.1080/21693277.2022.2134584>
- [7] Schilling L, Seuring S. Linking the digital and sustainable transformation with supply chain practices. *International Journal of Production Research*. 2023, 62(3), 949–973. <https://doi.org/10.1080/00207543.2023.2201905>
- [8] Dennison MS, Kumar MB, Jebabalan SK. Realization of circular economy principles in manufacturing: obstacles, advancements, and routes to achieve a sustainable industry transformation. *Discover Sustainability*. 2024, 5, 438. <https://doi.org/10.1007/s43621-024-00585-3>
- [9] Rasheed R, Rashid A, Ngah AH, Hashmi R. Engaging for a sustainable manufacturing: the power of adaptive leadership in Industry 5.0. *Production and Manufacturing*

- Research. 2025, 13(1). <https://doi.org/10.1080/21693277.2025.2371129>
- [10] Dziamulych M, Petrukha S, Yakubiv V, Zhuk O, Maiboroda O, Tesliuk S, Kolosok A. Analysis of the socio-demographic state of rural areas in the system of their sustainable development: a case study of Ukraine. *Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development*. 2021, 21(4), 223–234.
- [11] Ryzhakova G, Petrukha S, Petrukha N, Krupelnyska O, Hudenko O. Agro-food value added chains: methodology, technique and architecture. *Financial and Credit Activity: Problems of Theory and Practice*. 2022, 4(45), 385–395. <https://doi.org/10.55643/fcaptop.4.45.2022.3848>
- [12] Batsurovska I, Dotsenko N. Estimation of efficiency of use of water-lifting equipment in technological processes of agricultural production. *IOP Conference Series: Earth and Environmental Science*. 2022, 1049(1), 012047. <https://doi.org/10.1088/1755-1315/1049/1/012047>
- [13] Digalwar AK, Saraswat SK, Rastogi A, Thomas RG. A comprehensive framework for analysis and evaluation of factors responsible for sustainable growth of electric vehicles in India. *Journal of Cleaner Production*. 2022, 378, 134601. <https://doi.org/10.1016/j.jclepro.2022.134601>
- [14] Santoso I, Wafi'uddin I, Lu'ayya NM, Choirun A, Purnomo M, Sulianto AA. An integrated performance assessment method for SMEs fruit processing sustainability in Indonesia. *Cogent Engineering*. 2024, 11(1). <https://doi.org/10.1080/23311916.2024.2392034>
- [15] Cao H, Söderlund H, Despeisse M, Johansson B. Exploring the current applications and potential of extended reality for environmental sustainability in manufacturing. *arXiv*. 2023. <https://doi.org/10.48550/arXiv.2312.17595>
- [16] Hasan MR, Khan MA, Wuest T. Towards Industry 5.0: a systematic literature review on sustainable and green composite materials supply chains. *arXiv*. 2024. <https://doi.org/10.48550/arXiv.2402.06100>
- [17] Dacre N, Yan J, Frei R, Al-Mhdawi MKS, Dong H. Advancing sustainable manufacturing: a systematic exploration of Industry 5.0 supply chains for sustainability, human-centricity, and resilience. *Production Planning and Control*. 2024, 36(11), 1499–1528. <https://doi.org/10.1080/09537287.2024.2334976>
- [18] Karuppiyah K, Sankaranarayanan B, Lo H-W. A systematic literature review on the evolution of sustainable manufacturing practices: key findings and implications. *Cleaner Engineering and Technology*. 2024, 22, 100798. <https://doi.org/10.1016/j.clet.2024.100798>
- [19] Pushak Y, Zaichenko V, Kornicheva H, Petrukha S, Kharabovskiy Y. Features of the impact of military actions on food security. *International Journal of Computer Science and Network Security*. 2022, 22(6), 33–38.
- [20] Vahonova O, Tryfonova O, Bondar O, Petrukha N, Kyrychenko O, Akimov O. Economic justification for strategic decisions to improve the competitiveness of the enterprise. AD ALTA: *Journal of Interdisciplinary Research*. 2022, 12(1)-XXVII, 198–202. <https://www.magnanimitas.cz/ADALTA/120127/papers/29.pdf>
- [21] Stefanini R, Vignali G. The influence of Industry 4.0 enabling technologies on social, economic and environmental sustainability of the food sector. *International Journal of Production Research*. 2023, 62(10), 3800–3817. <https://doi.org/10.1080/00207543.2023.2245041>
- [22] Machado CG, Winroth MP, Ribeiro da Silva EHD. Sustainable manufacturing in Industry 4.0: an emerging research agenda. *International Journal of Production Research*. 2019, 58(5), 1462–1484. <https://doi.org/10.1080/00207543.2019.1652777>
- [23] Eurostat. Final energy consumption in industry: detailed statistics. Statistics Explained, European Commission. 2025. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_industry_-_detailed_statistics.
- [24] Wang C, Sun H, Zhang J, Zhang X, Lu L, Shi L, Zhou S. Effects of different fertilization methods on ammonia volatilization from rice paddies. *Journal of Cleaner Production*. 2021, 295, 126299. <https://doi.org/10.1016/j.jclepro.2021.126299>
- [25] Abdi R, Shahgholi G, Shorabiani VR, Rezvanivand Fanaei A, Szymanek M. Prediction compost criteria of organic wastes with biochar additive in in-vessel composting machine using ANFIS and ANN methods. *Energy Reports*. 2023, 9, 1684–1695. <https://doi.org/10.1016/j.egy.2023.01.108>
- [26] Lei J. Green supply chain management optimization based on chemical industrial clusters. *arXiv*. 2024. <https://doi.org/10.48550/arXiv.2406.00478>
- [27] Setyadi A, Soekotjo S, Lestari SD, Pawirosumarto S, Damaris A. Trends and opportunities in sustainable manufacturing: a systematic review of key dimensions from 2019 to 2024. *Sustainability*. 2025, 17(2), 789. <https://doi.org/10.3390/su17020789>
- [28] Tiuncika L, Bormane S. Sustainable management of manufacturing processes: a literature review. *Processes*. 2024, 12(6), 1222. <https://doi.org/10.3390/pr12061222>
- [29] Maldonado-Romo J, Ahmad R, Ponce P, Mendez JI, Mata O, Rojas M, Molina A. Advancing sustainable manufacturing: a case study on plastic recycling. *Production and Manufacturing Research*. 2024, 12(1). <https://doi.org/10.1080/21693277.2024.2355030>
- [30] Xu X, Lu Y, Vogel-Heuser B, Wang L. Industry 4.0 and Industry 5.0—Inception, conception and perception. *Journal of manufacturing systems*. 2021, 61, 530–535. <https://doi.org/10.1016/j.jmsy.2021.10.006>
- [31] Ghobakhloo M, Iranmanesh M, Tseng ML, Grybauskas A, Stefanini A, Amran A. Behind the definition of Industry 5.0: a systematic review of technologies, principles, components, and values. *Journal of Industrial and Production Engineering*. 2023, 40(6), 432–447. <https://doi.org/10.1080/21681015.2023.2216701>
- [32] Golovianko M, Terziyan V, Branytskyi V, Malyk D. Industry 4.0 vs. Industry 5.0: Co-existence, transition, or a hybrid. *Procedia Computer Science*. 2023, 217, 102–113. <https://doi.org/10.1016/j.procs.2022.12.206>
- [33] Singh T, Singh D, Singh CD, Singh K. Industry 5.0. Factories of the Future: Technological Advancements in the Manufacturing Industry. 2023, 21–45. <https://doi.org/10.1002/9781119865216.ch2>
- [34] Zizic MC, Mladineo M, Gjeldum N, Celent L. From industry 4.0 towards industry 5.0: A review and analysis of paradigm shift for the people, organization and technology. *Energies*. 2022, 15(14), 5221. <https://doi.org/10.3390/en15145221>
- [35] Eurostat (2024). Shedding light on energy in Europe – 2024 edition. Publications Office of the European Union. <https://ec.europa.eu/eurostat/web/interactive-publications/energy-2024>
- [36] U.S. Energy Information Administration (2024). 2022 Manufacturing Energy Consumption Survey: Highlights from Data Releases 1 & 2. U.S. Department of Energy.

<https://www.eia.gov/consumption/manufacturing>

- [37] Aloulou, F. (2024). EIA Manufacturing Energy Consumption Survey and Hydrogen Data Reporting. Presentation at the 2024 Annual Merit Review and Peer Evaluation Meeting, U.S. Department of Energy Hydrogen Program. Arlington, VA. Available at: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review24/eia000_aloulou_2024_o.pdf?sfvrsn=5c9ed504_3

Izvod

PRINCIPI EKOLOŠKI ORIJENTISANE PROIZVODNJE I PRAKTIČNI MEHANIZMI NJIHOVE IMPLEMENTACIJE

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Održivi razvoj u savremenoj industriji od ključnog je značaja za uspostavljanje ravnoteže između ekoloških, ekonomskih i društvenih faktora. To predstavlja jedan od ključnih izazova za Ukrajinu, koja mora prilagoditi međunarodne prakse održivog razvoja i integrisati principe Industrije 4.0 i 5.0 u svoje proizvodne procese. Studija analizira održivi razvoj u ukrajinskoj industriji, identifikujući prepreke i mogućnosti primenom kombinacije kvantitativnih podataka iz EU, SAD i Ukrajine, kao i kvalitativne analize naučne literature. Rezultati istraživanja ukazuju na značajan napredak ostvaren u periodu 2020-2024. godine. Sektori prehrambene industrije, metalurgije i mašinogradnje zabeležili su značajno smanjenje energetske intenzivnosti (18,9-22,6%) i emisija CO₂ (15,7-23%). Istovremeno, reciklaža otpada povećana je za 13-18%. Sa ekonomskog i društvenog aspekta, u navedenim sektorima zabeležen je porast produktivnosti rada od 17-20%, kao i otvaranje novih radnih mesta, što potvrđuje pozitivan „multiplikativni efekat“ održivih praksi. Utvrđeno je da digitalne tehnologije, poput digitalnih blizanaca i proširene realnosti, predstavljaju ključne pokretače ove transformacije. Studija zaključuje da su adaptivno liderstvo i kontinuirana obuka zaposlenih od presudnog značaja za uspešnu implementaciju održivih industrijskih strategija. Dobijeni rezultati pružaju praktične smernice za razvoj strategija preduzeća i kreiranje državnih programa, iako su dodatna istraživanja neophodna radi potpunijeg razumevanja dugoročnih efekata održivog razvoja.

Ključne reči: obnovljivi izvori energije, obnovljiva energija, zeleni oporavak, održivi razvoj, cirkularna ekonomija

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