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Development of a Green Smart Industry to Achieve the Principles of Sustainable Development and Environmental Protection

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ABSTRACT

A key factor shaping the competitiveness of national economies in global markets and their economic development goals is the growing concern about environmental challenges. This trend creates favorable conditions for advancing the principles of sustainable development, which are essential to economic policy aimed at implementing innovative solutions across regions worldwide. The article explores the potential of developing a green smart industry to achieve the principles of sustainable development and protect the natural environment. The article compares green and smart industries. It summarizes key characteristics of products manufactured by green and smart industries, production process organization, development drivers, strategic priorities, and the approaches used to achieve them. Based on this analysis, the authors outline the core principles of green smart industry and identify its distinguishing features as a sector of economic activity that integrates environmental sustainability, cyber-physical transformation of business processes, and production-logistics infrastructure. The article also presents the authors' vision for developing green smart industry, along with tools to foster a supportive environment for its growth and several practical recommendations.

Keywords: *Technological innovation, Green economy, Natural energy sources, Digitalization*

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INTRODUCTION

Environmental requirements across all stages of a product's life cycle have long served as significant competitive barriers in the market. Given the scale and persistence of economic digitalization, integrating national economies into the global Industry 4.0 trend has also become a top strategic priority.

This study is relevant because of several large-scale, persistent trends. First, the global economy is transforming in line with the concept of sustainable development, aimed at staying within the limits of the biosphere's biocapacity and assimilation potential. Second, the world is undergoing the Fourth Industrial Revolution, whose core enabling technology is digital communication (Akhmetshin *et al.*, 2025).

The current distribution of carbon-based, green, and smart industries in the modern global economy (69%, 8%, and 20%, respectively) (Blanchard *et al.*, 2023) indicates the dominance of the traditional industrial model (Gasanov, 2024) based on the "take-make-consume-dispose" pattern. This model relies heavily on ecologically dirty enterprises that exploit non-renewable natural energy sources (Aghion *et al.*, 2016; Degtyarev *et al.*, 2024).

Driven by growing competition for limited non-renewable natural resources, the United Nations Environment Programme (UNEP) developed initiatives under the Global Green New Deal. In parallel, the Organisation for Economic Co-operation and Development (OECD) officially adopted green growth as its core economic strategy through 2030 (Rodrik, 2014).

Smart, sustainable, and inclusive growth priorities have become central to the development strategies of many countries with advanced knowledge-based economies. Because of the so-called capture effect (Clough & Stammers, 2021), these countries exert

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decisive influence on global market dynamics by shifting demand, product ranges, and pricing for environmentally friendly smart products and services.

These trends create substantial competitive potential for the expansion and convergence of green and smart industrial domains. Smart industry increasingly aims to meet green standards, while green industry, influenced by the Fourth Industrial Revolution and the widespread adoption of digital innovations across all spheres of society (Nikiforova *et al.*, 2024), is gradually acquiring smart characteristics.

Thus, despite conceptual differences in the goals and tools of green and smart industry development strategies, their shared foundation (productive assets) and common driver (technological and technical innovation) make them complementary tools for addressing economic and environmental challenges through smart, sustainable, and inclusive development.

Literature review

An analysis of scientific publications (Qu *et al.*, 2019; Xie *et al.*, 2019; Skare & Riberio-Soriano, 2021) indicates that both green and smart industries are part of modern development strategies for knowledge-based societies, typical of technologically advanced countries with high investment and innovation potential and strong integration (Osadchy & Akhmetshin, 2015). Technological and technical innovation drives progress in both areas (greening (Korotenko & Togusakov, 2024) and cyber-physical transformation (Alcácer & Cruz-Machado, 2019)). These innovations involve changes to physical production assets and require substantial capital investment and highly qualified, specialized labor for R&D, establishing pilot platforms, and large-scale business process reengineering (Kane, 2019).

The concept of smart industry centers on creating highly knowledge-intensive (primarily innovative) end products with high added value through the full digitalization and automation of business processes (Kusiak, 2018). This approach involves using big data in modeling production processes (Gao *et al.*, 2020; Sergeeva *et al.*, 2024), high levels of innovation activity among economic actors (Wu *et al.*, 2018), remote management of core production assets via the Internet of Things (IoT) (Akhmetshin *et al.*, 2024), maximizing the role of intellectual capital in production, and minimizing reliance on low-skilled labor (Dmitrieva *et al.*, 2017; Syberfeldt *et al.*, 2017).

Industrial greening focuses on achieving sustainable development by minimizing the environmental burden of industrial activity while maintaining optimal economic growth rates (Abdullayev *et al.*, 2025). Implementing this strategy involves greening the entire life cycle of a product by reducing resource consumption or improving natural resource efficiency (Kuandykova *et al.*, 2024), lowering emissions (Bai & Sarkis, 2017), recycling waste through circular processes (D'Angelo *et al.*, 2023), and transforming the qualitative structure of exports. This latter aspect is particularly relevant for Russia, where the goal is to shift from low-value raw material exports to high-tech exports with greater added value (Safiullin, Elshin, & Mingazova, 2024).

Although the academic literature extensively covers the concepts of green and smart industry, research remains limited on the fundamental principles and practical recommendations for economic activities that combine both.

The article aims to identify the potential for developing a green smart industry to achieve the principles of sustainable development and ensure environmental protection.

MATERIALS AND METHODS

This article employs a comprehensive methodological approach that combines literature analysis with expert surveys to explore the theoretical and practical aspects of developing green smart industry as a means of achieving the principles of sustainable development (Sihidi *et al.*, 2025) and protecting the natural environment (Karshalova *et al.*, 2025).

Based on a review of the existing literature, this study examined the theoretical and practical aspects of green smart industry development. To guide this analysis, the following research questions were posed:

1) How do the concepts of smart industry and industrial greening interact in the context of long-term national economic development strategies? What are the core principles of a green smart industry?

2) What priority measures should be taken? What tools should be employed to foster the development of a green smart industry?

The collected material underwent qualitative analysis for presentation to a panel of experts. The selection criterion for participation in the expert pool was at least three publications on the research topic in peer-reviewed journals.

An online survey (Ivashkina *et al.*, 2024) was conducted among a sample of 45 experts. During the survey, the selected experts ranked the core principles and tools for developing a green smart industry by significance.

RESULTS AND DISCUSSION

The analysis identified the core principles of green smart industry **(Table 1)**.

Table 1. Principles of green smart industry.

No.	Principle	Ranking	Impact
1	Environmental integrity of the product life cycle	1	0.26
2	Absolute ecological commitment of economic agents and consumers	2	0.21
3	Digitalization of business processes	3	0.19
4	Cyber-physical transformation of business processes and core production assets	4	0.14
5	Fusion of high-tech physical products and digital services	5	0.11
6	Maximum customer orientation and product customization	6	0.09

Source: Original research and expert survey results; the concordance coefficient W = 0.63 (P < 0.01), indicating a strong level of agreement among expert opinions

In addition, the literature review identified tools for developing a green smart industry **(Table 2)**. Many countries worldwide have tested and implemented the proposed key instruments.

Table 2. Tools for developing a green smart industry.

No.	Tools	Ranking	Impact
1	**State support for environmental innovation through national technology programs and special investment funds**	1	0.28
2	Indicative development plans	2	0.22
3	Development roadmaps	3	0.20
4	Creation and support of innovation clusters	4	0.14
5	**Provision of targeted tax incentives**	5	0.10
6	Agreements between industry and the public sector	6	0.06

Source: Original research and expert survey results; the concordance coefficient W = 0.67 (P < 0.01), indicating a strong level of agreement among expert opinions

Referring to the research findings **(Table 1)**, the core principles of a green smart industry are as follows:

- Environmental cleanliness throughout the product life cycle: this entails ensuring ecological safety at every stage of a product's existence, minimizing resource intensity and waste generation, enabling recyclability or reuse as a secondary resource, and achieving a high level of final assimilation by ecosystems.
- Superhydrophobic clay–polymer composites have been explored to improve packaging durability, with potential to reduce agricultural plastic waste (Rozhkova *et al*., 2025);
- Absolute prioritization of ecological responsibility among economic agents and consumers: this principle implies the dominance of institutional norms of production and consumption (Abdullayev *et al.*, 2023) within society and business that do not harm the environment. Corporate social responsibility similarly links business conduct to environmental protection and responsible resource use (Bagratuni *et al*., 2023). In this context, altruistic environmental goals prevail over other individual interests;
- Digitalization of business processes: This refers to the conversion of information into a digital form or the digital transmission of data encoded in discrete signal impulses. Widely used in modern communication systems, digitalization represents a key pathway toward the development of an information society;
- Cyber-physical transformation of business processes and core production assets: This involves the integration of computing capabilities into physical processes. In such systems, sensors, equipment, and IT are interconnected along the entire value chain, extending beyond the boundaries of a single enterprise or business. These systems communicate using standard Internet protocols, enabling forecasting, self-adjustment, and adaptation to changing market conditions (Osadchy *et al.*, 2024). A mining simulation illustrates this integration through digital twins, IoT telemetry, and adaptive dispatch control (Uchkun *et al*., 2026). Contemporary examples of cyber-physical systems include big data, cloud computing, autonomous robotics, 3D modeling and simulation, 3D printing, the IoT, cybersecurity systems, and augmented reality. While these technologies are already widely applied across various areas of production and economic activity, their integration into a unified system has the potential to fundamentally transform existing relationships among producers, suppliers, and consumers;
- The fusion of high-tech physical products and digital services means that the final product represents a symbiotic combination of a tangible, high-tech, knowledge-intensive item with high added value, often requiring an internal and/or external energy source, and a set of broad functional capabilities, particularly in the IT sphere, delivered through or alongside that product. Typical physical components include smartphones, personal computers and laptops, television equipment, automobiles, next-generation household automation devices, and highly specialized industrial automation instruments. A defining feature of these products is that, without access to accompanying digital ICT services, they lose much of their value and utility for the end user;
- Maximum customer orientation (customization) implies that the consumer properties of a product are unique, tailored to the specific needs of individual clients. Such products are typically manufactured in small, specialized batches and are not intended for standardized mass consumption. Production, service, and maintenance are organized in real time, fully aligned with customer specifications, and involve direct interaction between the producer and the client.

Accordingly, the functions of green smart industry include:

- Creating a knowledge-intensive, environmentally friendly end product tailored to specific customer needs;
- Enabling remote management (Barmuta *et al.*, 2024) and real-time monitoring of high-tech, automated business processes;
- Creating development strategies and business plans based on analysis and forecasting (Jayaraman *et al.*, 2025) using big data, aligned with the priority of minimizing environmental impact by maximizing the role of intellectual capital;
- Applying the best available green advanced technologies and achieving a high level of innovation in production assets.

In line with the principles of green smart industry, its strategic development directions should be as follows:

- Transforming the degree of involvement of key production factors, namely, minimizing the use of natural capital by maximizing the contribution of intellectual capital to the production process;
- Strategic business planning aimed at minimizing environmental impact (Kuanyshbayeva *et al.*, 2025), particularly in terms of resource consumption, by maximizing the use of intellectual capital based on big data analytics;
- Creating a competitive, knowledge-intensive, eco-friendly product with high added value tailored to individual customer needs;
- Maximizing the fusion of high-tech physical products and digital services, creating hybrid offerings that combine material and informational components;
- Reengineering core production assets, involving modernization through the adoption of the best available clean technologies, the digitalization of business processes, and the cyber-physical transformation of both fixed assets and operational workflows;
- Remote management and real-time monitoring of high-tech automated business processes, enabling rapid response and adaptive control;
- Aggregation and interpretation of big data for the development of business plans and economic development strategies at both macro and micro levels;
- Acquisition of digital competencies by economic agents, ensuring their effective participation in green smart industrial ecosystems;
- Maximizing the greening of institutional rules governing production and consumption, fostering sustainability as a foundational principle in economic behavior.

The toolkit for the development of a green smart industry **(Table 2)** aims at creating a supportive environment for the digitalization, innovation, and greening of the industrial sector; stimulating the domestic market for the production, application, and consumption of digital technologies (Borodina *et al.*, 2023); and increasing the output of eco-friendly high-tech products. Specifically:

a. State support for environmental innovation through national technology programs and special investment funds involves the direct initiation of positive qualitative shifts in the economy, attracting new participants to the process, developing the necessary infrastructure, and fostering links between economic agents. It also helps create sufficient market demand for green smart technologies. Rakhimov et al. (2024) identify the state budget as a potential source of financing for regional ecological entrepreneurship.

b. Indicative development plans serve as a non-directive, recommendation-based tool for influencing the trajectory of economic development, typically backed by clear quantitative targets. Examples of practical implementation include:
   - Long-term national development strategies and indicative planning of energy-saving temperature standards in the construction sector (Finland);
   - White papers on priority areas such as nanotechnology, biotechnology, electric vehicles, green technologies, medicine and healthcare, new materials, and information and communications (United Kingdom).

c. A development roadmap serves as a strategic plan outlining long-term actions to advance a sector or technology. It provides a visual, step-by-step scenario for the evolution of a specific object, direction, or project.

d. The creation and support of innovation-focused clusters involves fostering public-private partnerships in innovation-driven policy. These clusters help commercialize scientific research and form an active core of stakeholders. Through the capture effect, this core influences the development trajectory of dependent economic agents (Borodina *et al.*, 2023).

e. Targeted tax incentives can support eligible investments in green manufacturing (OECD, 2024). The proposed package may include the following measures (Protasova, 2024):
   - A 0.3% reduction in employer social insurance contributions as compensation for the carbon tax, along with an 80% reduction of the carbon tax for energy-intensive industries, conditional upon voluntary commitments to reduce expenditures over 10 years (United Kingdom);
   - Tax benefits (Abdullayev *et al.*, 2024) for private landfills and municipal waste recycling enterprises (Finland).

f. The conclusion of agreements between the industrial and public sectors as legally notarized contracts with clearly defined quantitative obligations for both parties promotes corporate social responsibility and increases public engagement in policymaking. Examples of such agreements include: energy-saving agreements in Finland; regulations on environmentally acceptable fuel consumption and CO_2 emissions in new vehicles in Sweden; voluntary climate and energy policy agreements in Denmark, Finland, the Netherlands, Sweden, and the United Kingdom (Ueldanov, 2024); voluntary carbon emission trading under private agreements with companies such as British Petroleum, Shell, Toyota, Scottish Power, etc.

To realize these principles of green smart industry development, we believe it is advisable to:

- Ensure (and legally guarantee) the incorporation and enforcement of environmental standards at the stage of drafting project documentation for new smart enterprises and new green smart enterprises (Dolgopolov *et al.*, 2024). This measure is intended to make environmental compliance a default and essential component in the development of smart industrial facilities;
- Develop a comprehensive set of long-term indicative plans (spanning at least 10 years) outlining the objectives, tasks, and mechanisms for fostering innovation and sustainability in the Russian industrial sector. These plans should define requirements for creating new green smart enterprises, as well as reengineering and modernizing existing industrial facilities to green, digitize (Safiullin, Elshin, & Kurbangalieva, 2024), and cyber-physically transform them. Implementation progress should be monitored;
- Legislate the introduction of effective incentives and disincentives (administrative-regulatory, fiscal, market-

based, informational, etc.) aimed at creating a favorable domestic environment for the sustainable development of green smart industry. This also includes promoting a shift in the qualitative structure of exports from raw materials to high-tech products;

- Develop and approve standardized calculation methodologies and electronic statistical reporting forms hosted on a dedicated online platform to continuously monitor the dynamics of the green, smart, and green smart industrial sectors in Russia;
- Initiate a state-funded mandate for the creation of specialized task forces, involving targeted research agencies (in areas such as targeting, reengineering, and environmental modernization) and IT specialists. These groups would audit industrial sectors, focusing on budget-forming industries, to assess current competitiveness and forecast their potential to serve as growth points or active cores capable of generating qualitative improvements in the economy. The key evaluation criteria for such assessments should include: investment attractiveness; competitive advantages (current and potential); current and potentially achievable economically viable levels of techno-technological development; current and potentially achievable levels of environmental performance; estimated likelihood and cost of greening and modernizing the sectors or specific enterprises under review;
- Conduct a nationwide inventory of value chains and analyze the product life cycles within selected promising, budget-forming industries. This should include a classification and prioritization hierarchy for their reform, with a focus on greening, digitalization, and cyber-physical transformation. The reform process should adhere to the principle of maximizing positive impact while minimizing the costs of technological reengineering of business processes;
- Develop a roadmap, standard procedures, and step-by-step guidelines for transitioning selected promising industrial enterprises to environmental quality standards. This should include their gradual modernization following smart industry principles, as well as an effective monitoring and evaluation mechanism to assess the progress and effectiveness of implemented measures and make situational adjustments as needed;
- Design a strategic roadmap for the development of Russia's green and smart industrial sectors based on a long-term indicative plan. This roadmap should outline a step-by-step integration trajectory, merging these sectors into a single unified industry, with quantitative benchmarks (both final and interim) and clearly defined timelines;
- Organize competitive tenders for individual projects focused on the modernization and/or reengineering of industrial facilities, with the aim of greening production, building digital infrastructure, and implementing digitalization and cyber-physical transformation of business processes. Projects demonstrating the greatest economic efficiency should be awarded fiscal and credit incentives;
- Align existing legislation in economic, industrial, and environmental sectors (Mukhlynina, 2024) with the revised strategic priorities of industrial policy, particularly the shift toward the principles of a green smart industry. Portnova (2024) identifies legal regulation, state supervision, and public–private partnerships as key dimensions of environmental digitalization.

In our opinion, the implementation of these recommendations will enable the following:

- Reducing the overall burden on ecosystems by decreasing the extraction of natural resources and the emission of pollutants (Saparov *et al.*, 2024);
- Preventing the outflow of raw materials from the domestic market by reducing exports of low-value-added products;
- Increasing exports of high-tech, high-value-added products;
- Boosting economic activity in the domestic market, including higher employment rates and fuller utilization of production capacity, which aligns with the principles of inclusive economic growth.

The ideal model of green smart industry is a network of interconnected high-tech production facilities that operate through continuous, optimized technological schemes with conditionally closed (recycling-based) material, energy (Faizulina *et al.*, 2024), and information flows. This model implies:

First, reducing emissions of pollutants into the environment to environmentally safe levels, including wastewater discharges, atmospheric emissions, and solid waste generation, thus achieving zero-waste production (Kuandykova *et al.*, 2024);

Second, ensuring the mandatory recycling of products at the end of their life cycle (due to either physical or moral wear and tear), through post-consumer waste disposal and sorting on an industrial scale (Syberfeldt *et al.*, 2017);

Third, digitizing and cyber-physically transforming business processes, core production assets, and logistics infrastructure; establishing continuous (24/7) connectivity of entrepreneurs, researchers and developers, suppliers, distributors, consumers, and other stakeholders through ICT tools (mobile Internet, IoT, and cloud technologies) within a global digital platform for coordinating economic agents across the value chain (Gao *et al.*, 2020).

The final product of a green smart industry must meet the following key requirements:

- Environmental integrity across all stages of the product life cycle, which is a core priority for any green industry (Abdullayev *et al.*, 2025);
- Symbiotic integration of physical goods with ICT services;
- Maximum customer orientation, ensuring products are tailored to specific user needs;
- High knowledge intensity and technological sophistication;
- A high share of added value, which is typical of smart industries (Wu *et al.*, 2018).

CONCLUSION

A green smart industry can be defined as eco-friendly, consumer-oriented production based on cyber-physical systems. It is characterized by the absolute prioritization of ecological responsibility among economic agents and

consumers, the digitalization of business processes, the cyber-physical transformation of business operations and production-logistics infrastructure, the fusion of high-tech physical products with digital services, and the maximum customization of products to meet individual customer needs.

A promising direction for future research involves developing quantitative criteria to assess the current and projected levels of green smart industry development. These would include integral indicators reflecting the availability and intensity of digital technology adoption, levels of innovation activity, and the effectiveness of environmental practices.

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