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## **THE ROLE OF DIGITAL TECHNOLOGIES IN ACHIEVING CLIMATE NEUTRALITY IN THE INTERNATIONAL ECONOMY**

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## **РОЛЬ ЦИФРОВИХ ТЕХНОЛОГІЙ У ДОСЯГНЕННІ КЛІМАТИЧНОЇ НЕЙТРАЛЬНОСТІ В МІЖНАРОДНІЙ ЕКОНОМІЦІ**

*The aim of this article is to examine the role of digital technologies in facilitating the transition toward a climate-neutral international economy, as well as to identify key directions for their effective application in decarbonization processes. The study finds that digital technologies play a system-forming role in*

*achieving climate neutrality in the international economy. They function not only as tools for improving economic efficiency but also as key mechanisms for monitoring, analyzing, and managing multidimensional “enablers” that reflect and drive structural changes in the economy, politics, and technology. The analysis demonstrates that achieving climate neutrality is inherently multidimensional and is determined not only by emission reductions but also by such “enablers” as structural economic transformation, the development of renewable energy, increased investment in green technologies and innovation, the improvement of climate policies and regulatory mechanisms, coherence between objectives, policies, actions, and their effectiveness, as well as the deepening of international cooperation. It is further shown that the integration of digital solutions (artificial intelligence, big data, the Internet of Things, cloud computing and blockchain) into international economic processes enables the formation of transparent accounting systems, the optimization of multidimensional “enablers” within global value chains, and the enhancement of climate governance efficiency. This creates prerequisites for a shift from fragmented environmental measures toward a comprehensive digital–climate transformation of the global economy. The scientific value of the study lies in the development of an integrated approach to analyzing the interrelationship between digitalization, global economic processes, and decarbonization, as well as in advancing methodological foundations for assessing climate neutrality through a system of qualitative and quantitative indicators. Future research should focus on developing econometric and mathematical models for assessing the impact of digitalization on global CO<sub>2</sub> emission reductions.*

*Метою статті є дослідження ролі цифрових технологій у забезпеченні переходу до кліматично нейтральної міжнародної економіки, а також визначення ключових напрямів їх ефективного використання у процесах мінімізації викидів парникових газів. У результаті проведеного дослідження встановлено, що цифрові технології мають системоутворююче значення у процесах досягнення кліматичної нейтральності міжнародної економіки. Вони виступають не лише інструментом підвищення ефективності*

економічної діяльності, а й ключовим механізмом моніторингу, аналізу та управління багатовимірними «енаблерами», які визначатимуть та відбивають структурні зміни в економіці, політиці та технологіях. За змістом дослідження проілюстровано, що досягнення кліматичної нейтральності має багатовимірний характер і визначається не лише скороченням викидів, але й такими «енаблерами», як структурні трансформації економіки, розвиток відновлюваної енергетики, активізація інвестицій у «зелені» технології та інновації, удосконалення кліматичної політики та регуляторних механізмів, відповідність між цілями, політиками, діями та їх ефективністю, поглибленням міжнародної співпраці. Доведено, що інтеграція цифрових рішень (штучного інтелекту, великих даних, Інтернету речей, хмарних обчислень, блокчейну) у міжнародні економічні процеси забезпечує можливість формування прозорих систем обліку, оптимізації багатовимірних «енаблерів» у межах глобальних ланцюгів створення вартості та підвищення ефективності кліматичного регулювання. Це створює передумови для переходу від фрагментарних екологічних заходів до комплексної цифрово-кліматичної трансформації світової економіки. Наукова цінність дослідження полягає у формуванні інтегрованого підходу до аналізу взаємозв'язку між цифровізацією, глобальними економічними процесами та декарбонізацією та розвитку методологічних засад оцінювання кліматичної нейтральності через систему якісних і кількісних індикаторів. Подальші дослідження доцільно зосередити на розробці економіко-математичних моделей оцінювання впливу цифровізації на скорочення глобальних викидів CO<sub>2</sub>.

**Keywords:** *integration of digital solutions; artificial intelligence; big data; Internet of Things; blockchain; international economic processes; deepening of international cooperation.*

**Ключові слова:** *інтеграція цифрових рішень; штучний інтелекту; великі дані; Інтернет речей, блокчейн; міжнародні економічні процеси; поглиблення міжнародної співпраці;*

***Problem statement.*** Digital technologies have gradually become a key instrument for achieving climate neutrality in the international economy, as they offer extensive opportunities to improve resource efficiency, optimize production processes, and reduce greenhouse gas emissions. In particular, the implementation of Internet of Things (IoT) technologies and big data analytics in industry enables real-time monitoring of energy consumption and automatic load regulation, which significantly reduces energy costs and, consequently, CO<sub>2</sub> emissions. Namely, within the concept of “smart grids”, digital platforms ensure the balancing of supply and demand in the global electricity market, facilitate the integration of renewable energy sources, and minimize transmission losses, which represents an important step toward the decarbonization of the energy sector. Given these features, it is evident that in the context of contemporary global climate challenges and the strengthening of international environmental commitments, digital technologies act as a driver of international economic growth and a foundation for the transition to sustainable development models. The rapid advancement of AI, big data, the Internet of Things, and blockchain expands the possibilities for monitoring, forecasting, and managing environmental indicators across global value chains.

Overall, the relevance of the outlined research is driven by the need to achieve climate neutrality goals enshrined in international agreements, particularly under the Paris Climate Agreement, as well as by the intensification of neutrality and decarbonization policies and programs at the level of individual countries and regional associations. For instance, in autumn 2021, the European Union launched the EU Mission: Climate-Neutral and Smart Cities program, while in 2019, the European Commission introduced the European Green Deal strategy. Additionally, this goal is reinforced by the Race to Zero initiative launched under the auspices of the United Nations, which brings together states, cities, businesses, and financial institutions to accelerate the transition toward a net-zero economy by 2050.

***Actual scientific researches and issues analysis.*** Despite a significant body of research addressing digital transformation and environmental sustainability (notably Krasnova Y.A. [5], Borysiak O. [2], Shevchuk I., Arziantseva D., Zakharkevych N., Krushynska A., Samaricheva T. [10], Dushechkina N., Moroz

V., Yanitskys V. [1]), the comprehensive impact of digital technologies on achieving climate neutrality, specifically within the context of the international economy, remains insufficiently explored. It is noteworthy that this poses a range of methodological, analytical, and managerial challenges that significantly complicate both academic research and the practical implementation of relevant solutions.

Thus, studies on digitalization and environmental sustainability are often conducted separately, without integration into a unified system for analyzing international economic processes. This results in the absence of a coherent theoretical model of digital climate transformation. In addition, quantitative models that describe the relationship between digitalization, transnational resource flows, and greenhouse gas emission reductions remain underdeveloped, making it difficult to measure actual impact. In this context, there is a need to develop a systematic scientific and methodological approach that will overcome these limitations and ensure a holistic understanding of the digital climate transformation of the international economy.

**Research aim.** This study aims to examine the role of digital technologies in facilitating the transition toward a climate-neutral international economy and to identify key directions for their effective application in decarbonization processes. For this purpose, the following objectives are identified:

- identification of digital technologies that contribute to reducing the carbon footprint;
- identification of mechanisms for integrating digital technologies into international economic processes;
- assessment of the effectiveness of digital solutions in achieving climate neutrality in the international economy.

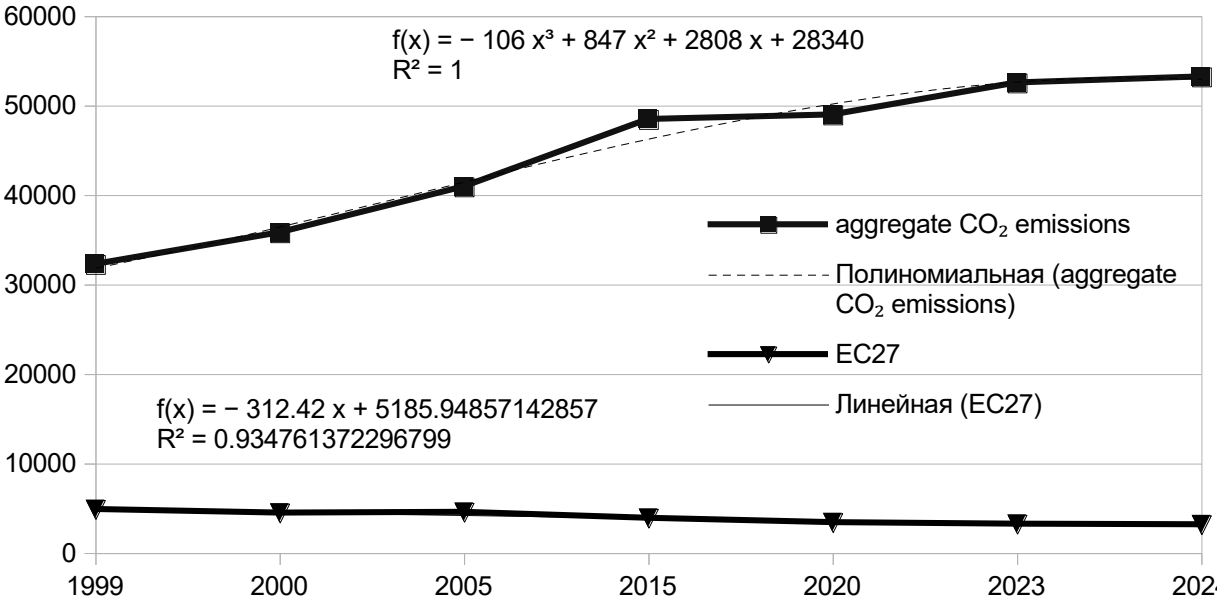
**Main findings of the research.** Contemporary definitions of climate neutrality are quite diverse. For instance, Krasnova Y.A. interprets this concept as a state in which human activity does not generate net greenhouse gas emissions, meaning that the volume of CO<sub>2</sub> and other greenhouse gases is equal to or lower than the capacity of natural ecosystems or technological solutions to absorb them [5]. Shevchuk I., Arziantseva D., Zakharkevych N., Krushynska A., and

Samaricheva T. view climate neutrality as a tool for environmental preservation and an important component of sustainable development strategy [10]. Borysiak O. defines it as implementing the provisions of the Paris Climate Agreement regarding the accounting and reduction of carbon dioxide emissions into the environment [2]. Indeed, although these approaches characterize different dimensions of climate neutrality, they form a multidimensional normative framework that allows for an expansion of the concept's content, in particular by including both the environmental dimension and the requirements related to transparency (including reporting, data verification, and financial accountability in relation to climate neutrality [5]) as well as inter-institutional responsibility. Therefore, within the framework of the present study, climate neutrality in the international economy will be considered as a specific state of functioning of the global economic system in which total greenhouse gas emissions generated through the processes of production, exchange, and consumption of goods and services at the global scale are reduced to a normative level (Nationally Determined Contributions (NDC) under the Paris Climate Agreement within the United Nations Framework Convention on Climate Change (UNFCCC))

In particular, the Paris Climate Agreement requires that each country's contribution to achieving the global objective (NDC) be determined individually, be "ambitious," and be designed "with a view to achieving the purpose of the Agreement." Furthermore, according to the Intergovernmental Panel on Climate Change (IPCC) report, in order to limit global warming to 1.5°C, global anthropogenic greenhouse gas emissions must be 45% lower in 2030 compared to 2010 levels [4]. At the practical level, this is expected to be achieved through a combination of emission reduction measures, improvements in energy efficiency, a transition to renewable energy sources, as well as the compensation of residual emissions through carbon sinks (including both nature-based and technological solutions), alongside reporting and monitoring mechanisms aimed at ensuring the development of the international economy within the required level of ambition.

In the sphere of the international economy, climate neutrality implies coordinated actions by states, transnational corporations, and international organizations aimed at decarbonizing global value chains. In our view, this refers

to a practical process of reducing (and ideally eliminating) greenhouse gas emissions across all stages of the product life cycle, where production is distributed across different countries: from raw material extraction to manufacturing, logistics, consumption, and disposal. However, at present, there is no mechanism to compel a country to set a target within its Nationally Determined Contribution or to ensure accountability if such a target is not achieved [6]. Hence, we contend that the phenomenon of decarbonization of global value chains has not yet been fully achieved. This is most evident in the dynamics of total global greenhouse gas emissions, which show a steady increase from 32,249.9 Mt CO<sub>2</sub> in 1990 to 53,206.4 Mt CO<sub>2</sub> in 2024, or by 64.98% (see Fig. 1).



Indicator	Actual values of the indicator over the study period						
	1990	2000	2005	2015	2020	2023	2024
Aggregate CO <sub>2</sub> emissions	32249,9	35794	40919,6	48451,4	48962.1	52540.8	53206.4
EC27	4864.28	4468.66	4552.22	3885.94	3395.60	3222.52	3164.66

**Fig. 1. Dynamics of aggregate CO<sub>2</sub> emissions worldwide for 1990–2024, Mt CO<sub>2</sub>**  
 Source: compiled based on [8]

Per capita CO<sub>2</sub> emissions at the global level have also increased from 6.05 t CO<sub>2</sub>/person in 1990 to 6.56 t CO<sub>2</sub>/person in 2024 [8]. At the same time, a number of countries have achieved a substantial reduction in this indicator. In particular, Australia reduced its level from 27.03 to 22.26 t CO<sub>2</sub>/person, Austria from 10.38 to 8.01 t CO<sub>2</sub>/person, Belgium from 14.05 to 9.15 t CO<sub>2</sub>/person, Canada from 21.32

to 19.76 t CO<sub>2</sub>/person, Denmark from 13.43 to 6.5 t CO<sub>2</sub>/person, Finland from 14.62 to 8.61 t CO<sub>2</sub>/person, France and Monaco from 9.32 to 5.68 t CO<sub>2</sub>/person, Sweden from 8.78 to 5.07 t CO<sub>2</sub>/person, and the United Kingdom from 10.19 to 4.25 t CO<sub>2</sub>/person [8]. It should be noted that China, the United States, India, several EU-27 countries, Russia, and Indonesia were among the world's largest sources of CO<sub>2</sub> emissions in 2024. Considering that global value chains are inherently transnational in nature, the process of reducing carbon emissions must be transparent and rely on coordinated actions involving a large number of countries, companies, and regulators [6; 4].

On this basis, reports by the Ecologic Institute and the European Climate Neutrality Observatory emphasize that the process of achieving climate neutrality requires a system of multidimensional “enablers” (from English *enabler* — an entity that enables or facilitates), which reflect and drive structural changes in the economy, politics, and technology. Based on an analysis of recent studies on climate neutrality, the following enablers can be identified [3; 9]:

- reduction of greenhouse gas emissions or movement toward the so-called “net-zero” balance;
- structural transformation of the international economy, encompassing energy, industry, transport, and agriculture;
- large-scale deployment of renewable energy sources and clean technologies, including electrification and hydrogen-based solutions;
- the presence of effective climate policies and regulatory mechanisms, including carbon pricing systems and international coordination;
- increased investment in green technologies and innovation, ensuring long-term reductions in carbon footprints;
- integration of financial, managerial, and behavioral factors (changes in consumption patterns and social responsibility);
- international cooperation and policy alignment supporting the decarbonization of global value chains;

- coherence between objectives, policies, actions, and their effectiveness, which is considered a key framework for assessing progress.

Climate neutrality in the international economy should be considered through the prism of the multidimensionality of its “enablers,” the features of which include not only emission reductions but also a profound transformation of economic systems, institutions, and international interaction.

In essence, this implies that measuring climate neutrality requires the quantitative assessment of:

- the current state of key emission-related indicators and their dynamics over time, in accordance with the set of indicators presented in Table 2.

**Table 2. Quantitative indicators of the transformation of the international economy toward climate neutrality**

Enabler	Quantitative indicators
Reduction of greenhouse gas emissions	CO <sub>2</sub> emissions volume (t/year); emission reduction rate (%); achievement of net-zero balance; emissions intensity per unit of GDP
Progress toward net-zero balance*	Difference between CO <sub>2</sub> emissions and removals (t CO <sub>2</sub> ); share of compensated emissions (%); volume of greenhouse gas removals by natural and technological systems; emission–removal balance index

Note:

An indicator reflecting the difference between greenhouse gas emissions and their removal (or compensation) relative to achieving a net-zero level.

Source: compiled based on [1-2; 5]

- changes in qualitative indicators attributed to the “enablers” of climate neutrality, in accordance with the list presented in Table 3.
- For the general formalization of the process of achieving climate neutrality in the international economy, it is advisable to represent it in the form of an integrated mathematical model (or a progress assessment algorithm) based on a system of defined “enablers,” which can be expressed as follows:

$$CN = \sum w_i I_i, \quad (1);$$

- where:

CN — the integral level of achieving climate neutrality in the global economy;

- $I_i$  — normalized indicators (ranging from 0 to 1);
- $w_i$  — weighting coefficients reflecting the significance of the indicators ( $\sum w_i = 1$ ).

**Table 3. Qualitative indicators of the transformation of the international economy toward climate neutrality**

Enabler	Qualitative indicators of change
Structural transformation of the economy	Decarbonization of carbon-intensive sectors; transition to low-carbon industries; electrification of production; industrial digitalization; formation of “green” global value chains
Renewable energy and clean technologies	Dominance of renewable energy in the energy mix; development of hydrogen technologies; implementation of smart grids; substitution of fossil fuels; development of energy storage systems
Climate policy and regulation	Functioning of carbon pricing systems; harmonization of emission standards; mandatory environmental reporting; implementation of international agreements; integration of climate policy into economic regulation
Green investment and innovation	Growth of ESG financing; development of the green bond market; investment in low-carbon technologies; support for R&D in decarbonization; commercialization of environmental innovations
Financial, managerial, and behavioral factors	Formation of sustainable consumption patterns; integration of ESG into corporate governance; increased environmental awareness; development of corporate responsibility; transition to a low-carbon economic culture
International cooperation and policy coordination	Global climate alliances; alignment of national strategies; transfer of green technologies; coordination of emission standards; participation in net-zero initiatives
Coherence of goals, policies, and actions	Alignment between strategies and actual actions; monitoring and verification systems; transparency in performance evaluation; reduction of gaps between targets and outcomes; integration of climate policy KPIs

Source: compiled based on [2-3; 10; 8]

Based on the above provisions, the system of “enablers” can be represented as follows [3; 9]:

$$\begin{aligned}
 I_1 &= f(E) \text{ (emission reductions and the achievement of net-zero )} \\
 I_2 &= f(S) \text{ (structural transformation of the economy )} \\
 I_3 &= f(R) \text{ (share of renewable energy sources and clean technologies)} \\
 I_4 &= f(P) \text{ (effectiveness of climate policy )}, \\
 I_5 &= f(Inv) \text{ (green investments)}
 \end{aligned}
 \tag{2}$$

$I_6 = f(B)$  (behavioral and managerial factors)

$I_7 = f(Coop)$  (international cooperation)

$I_8 = f(Align)$  (coherence between goals, policies, and actions)

At the same time, scholars most frequently define the condition for achieving climate neutrality in the international economy as a state in which:

$$CN \geq CN, \quad (3);$$

where: CN is the threshold value (e.g., 0.9–1), corresponding to a climate-neutral state.

If the process of achieving climate neutrality in the international economy is expressed as a dynamic model (a time-based algorithm), it can be represented as follows:

$$CN(t) = CN(t-1) + \sum w_i \Delta I_i(t), \quad (4);$$

where:  $\Delta I_i(t)$  — change of the corresponding indicator over time.

It should be noted that this algorithm requires the use of big data and, other digital technologies and therefore must be implemented and continuously adjusted through the integration of digital technologies into international economic processes. This integration makes it possible to clearly formalize the system of “enablers” and their dynamic interaction, as it is based on the following components (Table 4): digitalization of international supply chains; platformization of the international economy; implementation of digital monitoring and analytics systems; and digital regulation and standardization.

It should be noted that the integration of digital technologies into climate and economic governance is already taking place globally; however, it is uneven across countries and regions and remains at the stage of active development rather than full maturity. The most advanced progress is observed in the EU, the United States, Japan, South Korea, and partially China.

**Table 4. Mechanism of integration of digital technologies into international economic processes**

Component of the mechanism	Specifics of formalization of the system of “enablers” and their dynamic interaction	Role in achieving climate neutrality
Digitalization of international supply chains	Involves the use of Internet of Things (IoT), blockchain, and big data technologies to track resource flows, optimize logistics, and reduce transaction costs.	Ensures transparency of product origin, control of carbon footprints, and increased resilience of global production systems.
Platformization of the international economy	Based on the development of digital platforms that integrate producers, consumers, and suppliers into unified ecosystems.	Facilitates rapid data exchange, scaling of business models, and integration of small and medium-sized enterprises into global markets.
Implementation of digital monitoring and analytics systems	Ensures real-time collection and processing of large datasets related to greenhouse gas emissions, CO <sub>2</sub> emissions per capita, etc.	Enables assessment of economic process efficiency, emission levels, and compliance with international climate standards.
Digital regulation and standardization	Involves the formation of international norms and rules governing the use of digital technologies in trade, finance, and environmental governance.	Ensures interoperability of digital systems across countries and promotes harmonization of economic policies.

Source: compiled based on [2; 4-5; 9]

In particular, in the EU-27, digital technologies are being actively integrated into climate regulation mechanisms through emission monitoring systems, ESG reporting frameworks, and the development of “green” digital platforms. In the United States, a key role is played by private technology companies and innovation ecosystems, which develop solutions based on artificial intelligence, big data, and satellite monitoring for emission assessment and optimization of energy consumption within global supply chains. Japan focuses on the application of digital technologies in industry and energy, particularly through the development of “smart” manufacturing systems, hydrogen economy solutions, and high-precision real-time monitoring of energy flows. In South Korea, digitalization is closely linked to state-led “smart economy” programs, which include IoT solutions, automated energy management systems, and digital platforms for climate monitoring. China also demonstrates large-scale implementation of digital technologies in environmental governance systems, including satellite monitoring,

big data analytics, cloud computing and digital emission management platforms, although the level of ecological transformation remains uneven due to the significant share of coal-based energy generation.

Although still fragmented, these experiences demonstrate that the integration of digital technologies into international economic processes can ensure the alignment of technological, economic, environmental, and institutional factors within global value chains and facilitate the incorporation of digital solutions into international production, logistics, and management processes.

***Conclusions.*** The study finds that digital technologies play a system-forming role in achieving climate neutrality in the international economy. They function not only as tools for improving economic efficiency but also as key mechanisms for monitoring, analyzing, and managing multidimensional “enablers” that reflect and drive structural changes in the economy, politics, and technology.

The analysis demonstrates that achieving climate neutrality is inherently multidimensional and is determined not only by emission reductions but also by such “enablers” as structural transformation of the economy, development of renewable energy, increased investment in green technologies and innovation, improvement of climate policy and regulatory frameworks, coherence between objectives, policies, actions, and their effectiveness, as well as deepening international cooperation.

It is further shown that integrating digital solutions (artificial intelligence, big data, the Internet of Things, cloud computing, and blockchain) into international economic processes enables the development of transparent accounting systems, the optimization of multidimensional “enablers” within global value chains, and the enhancement of the efficiency of climate governance. This creates prerequisites for a transition from fragmented environmental measures to a comprehensive digital climate transformation of the global economy.

The scientific value of the study lies in the development of an integrated approach to analyzing the interrelationship between digitalization, global economic processes, and decarbonization, as well as in advancing methodological

foundations for assessing climate neutrality through a system of qualitative and quantitative indicators.

Further research should address on developing econometric and mathematical models for assessing the impact of digitalization on global CO<sub>2</sub> emission reductions.

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