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THE IMPACT OF DIGITALIZATION ON THE IMPLEMENTATION OF CARBON-FREE ECONOMY PRINCIPLES IN UKRAINE[1]

ВПЛИВ ДИДЖІТАЛІЗАЦІЇ НА ВПРОВАДЖЕННЯ ПРИНЦИПІВ БЕЗВУГЛЕЦЕВОЇ ЕКОНОМІКИ В УКРАЇНІ

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This study explores the role of digitalization in implementing carbon-free economy principles in Ukraine, with a particular focus on how digital technologies contribute to enhancing energy efficiency and reducing CO2 emissions. Digitalization serves as a critical enabler of sustainable development by providing tools for optimizing energy consumption, improving resource management, and minimizing the environmental footprint of economic activities. Through correlation and regression analyses, the research investigates the relationship between investments in digital technologies, environmental protection measures, and CO2 emissions for the period from 2007 to 2020. The results reveal that while digitalization has the potential to improve energy efficiency, its current impact on reducing CO2 emissions remains limited. The findings indicate that increased investments in renewable energy sources and more comprehensive integration of digital technologies into the energy sector are essential to achieve significant reductions in emissions. Additionally, the study highlights the positive effect of innovation-driven activities on energy efficiency but points to the need for further development and deployment of environmentally friendly digital solutions. The research also underscores the importance of continued financial support for green technologies and emphasizes the necessity of improving greenhouse gas monitoring systems. Practical recommendations include increasing investment in renewable energy, expanding the use of smart technologies across industries, and promoting long-term innovation strategies aimed at achieving carbon neutrality. Overall, the research concludes that digital innovation plays a supporting role in achieving energy efficiency but requires stronger policy frameworks, investment, and coordination to realize its full potential in contributing to environmental sustainability.

Keywords: digitalization, carbon-free economy, energy efficiency, CO2 emissions, renewable energy sources, sustainable development.

У цьому дослідженні розглядається вплив цифровізації на впровадження принципів безвуглецевої економіки в Україні, зокрема, на підвищення енергоефективності та зменшення викидів CO2. Цифровізація є важливим фактором сталого розвитку, який сприяє оптимізації енергоспоживання та мінімізації екологічного впливу

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економічної діяльності. За допомогою кореляційного та регресійного аналізу було досліджено взаємозв'язок між інвестиціями в цифрові технології, екологічними заходами та викидами CO2 за період 2007–2020 років. Результати показують, що, хоча цифровізація має потенціал для підвищення енергоефективності, її вплив на зменшення викидів CO2 на даний час залишається обмеженим. Дослідження підкреслює важливість збільшення інвестицій у відновлювані джерела енергії та інтеграції цифрових технологій у енергетичний сектор для досягнення значних екологічних результатів. Практичні рекомендації включають активізацію інвестицій у зелені технології та посилення моніторингу викидів парникових газів.

Ключові слова: цифровізація, безвуглецева економіка, енергоефективність, викиди CO2, відновлювані джерела енергії, сталий розвиток.

Introduction. Digitalization integrates digital technologies into various sectors, transforming production, management, and service delivery. This process, which is accelerating globally, optimizes systems, improves efficiency, and facilitates data-driven decision-making.

While digitalization offers opportunities to enhance energy efficiency and reduce carbon emissions, it also presents challenges, such as high energy demands for certain technologies that could impact environmental sustainability.

In Ukraine, where energy efficiency and greenhouse gas emissions are critical issues, digitalization has the potential to play a key role in achieving a carbon-free economy. It can reduce energy consumption, improve resource management, and support sustainable development.

Studying the relationship between digitalization and energy efficiency is vital for identifying effective strategies to reduce carbon emissions and guide Ukraine's environmental efforts.

Literature review. The literature analysis indicates that digitalization, reduction of greenhouse gas emissions, and improvement of energy efficiency are current topics of research within the modern scientific community [20]. For instance, Smith and Brown (2021) explore the potential of information and communication technologies in reducing carbon emissions, emphasizing that digital technologies can significantly enhance energy efficiency through process optimization and data management [20]. They highlight the potential of digitalization to reduce the carbon footprint by improving technological processes [20, 22].

In the energy sector, Filatov and Boyko (2023) analyze the regulatory framework of the energy sector, noting the importance of digital transformations for achieving sustainable development [10]. Their research shows that the implementation of digital technologies in the energy sector can significantly reduce greenhouse gas emissions and improve overall energy efficiency, which is a crucial step toward sustainable development [10, 14].

Ivanova and Sokolov (2022) focus on the digitalization of Ukraine's economy and its impact on energy efficiency. They analyze how digital transformations can improve the country's energy indicators and contribute to the reduction of CO2 emissions [13]. This work underscores the importance of digitalization for the national economy, particularly in the context of enhancing energy efficiency and reducing greenhouse gas emissions [13].

The study by Gubarieva, Buka, and Bielikova (2023) focuses on assessing the level of digitalization of Ukraine's economy and comparing it with EU countries [11]. They emphasize the need for further development of digital infrastructure to improve energy and environmental indicators, and stress the importance of Ukraine's integration into European digital standards [11].

Lee and Kim (2022), in their work, investigate the global potential for emission reduction through digitalization, emphasizing the necessity of investing in environmentally friendly technologies. They point out that such investments not only contribute to reducing the carbon footprint but also stimulate economic growth, providing additional benefits for countries that actively implement digital solutions [15].

Despite the substantial number of studies exploring the impact of digitalization on energy efficiency and greenhouse gas reduction globally, these issues have not yet received sufficient attention in Ukraine [13, 14]. The absence of a comprehensive approach to analyzing the impact of digitalization on environmental indicators in Ukraine highlights the relevance of this research. This necessitates a more detailed examination of this issue, taking into account the specific national economic and environmental context [10, 14].

Thus, this research aims to fill the gap in existing studies concerning the impact of digitalization on environmental indicators and to develop recommendations for improving policies in this area.

Research objective. The aim of this research is to assess the impact of digitalization, invest-

ments in environmental technologies, and overall final energy consumption on CO2 emissions in Ukraine during the period from 2007 to 2020. The study aims to identify key factors that influence the reduction of greenhouse gas emissions and provide recommendations for improving environmental policies to ensure the country's sustainable development. Special attention is given to analyzing the relationship between the level of digitalization and environmental efficiency, as well as evaluating the long-term impact of investments in renewable energy sources and environmental technologies on the energy balance and environmental performance.

Methodology. Time Period: The analysis covers the period from 2007 to 2020, chosen due to the availability of reliable data and notable changes in Ukraine's digitalization and environmental policies. Future research updates are planned as new data become accessible [9, 13, 14].

Object of Study: The study focuses on Ukraine's economic indicators related to energy consumption, CO2 emissions, and the implementation of digital technologies.

Methods:

- **Correlation Analysis** was used to assess the relationships between digitalization, environmental technology investments, energy consumption, and CO2 emissions, revealing correlation dependencies.
- **Regression Analysis** established cause-and-effect relationships and quantified the impact of digitalization on environmental indicators [23, 10].

Key indicators include:

- **Total Final Energy Consumption (thousand tons)**: Reflects annual energy consumption, indicating economic activity and energy efficiency [24, 26].
- **Current Environmental Protection Expenditures (million UAH)**: Covers spending on pollution control and environmental protection [27].
- **Greenhouse Gas Emissions (thousand tons CO2)**: The key environmental indicator [25].
- **Level of Digitalization**: The adoption of digital technologies across sectors [31].
- **Investments in Environmental Technologies (million UAH)**: Spending on eco-friendly technologies [29].

Regression Model:

$$\gamma = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon \qquad (1)$$

Where

γ CO2 emissions volume.

X_1 Digitalization level.

X_2 Investments in environmental technologies.

X_3 Energy consumption.

β_0, Constant.

β_1, β_2, β_3 – Regression coefficients.

ε \epsilonϵ – Model error.

Results

2.1. Initial Data: Total Final Energy Consumption

The research assesses the impact of digitalization on Ukraine's carbon-free economy, focusing on the period from 2007 to 2020. Key indicators, including energy consumption and environmental expenditures, were analyzed.

From 2016 to 2020, environmental protection expenditures increased, particularly in waste management and air and climate protection, while total final energy consumption decreased [27, 28]. This suggests that higher environmental investments may reduce energy consumption, contributing to a carbon-free economy.

Correlation analysis shows a strong inverse relationship between environmental expenditures and energy consumption, with a correlation coefficient of -0.876 [27, 29]. Increased spending on waste management and air and climate protection coincides with reduced energy consumption [27, 28].

The results emphasize that active environmental policies and increased spending on protection measures significantly improve energy efficiency. Figure 2 illustrates this, showing how changes in environmental expenditures affect total energy consumption in Ukraine.

Correlation analysis shows a moderate negative relationship between capital investments and energy consumption, with a coefficient of -0.792, indicating that increased investments reduce energy use. Thus, capital investments are crucial for improving energy efficiency [28, 29].

Additionally, a strong positive relationship (0.855) was found between capital investments and the use of renewable energy sources, suggesting that higher investments contribute directly to a greater share of renewables in Ukraine's energy balance [24]. From 2016 to 2020, increasing capital investments correlated with improved environmental indicators and reduced energy consumption, demonstrating their positive impact on energy efficiency.

Figure 3 shows the growing role of renewable energy in Ukraine's energy balance, supported by a strong correlation between invest-

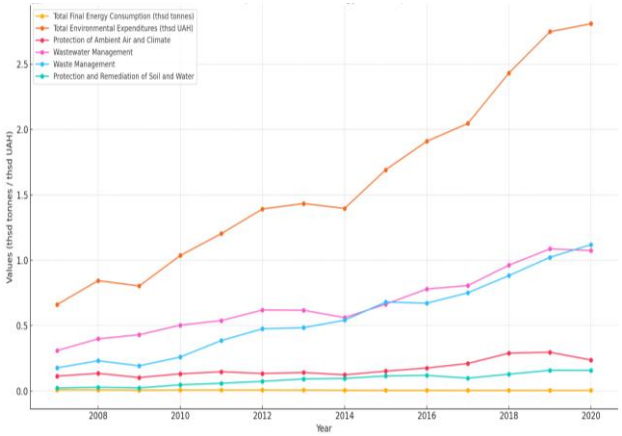

Figure 1. Total Final Energy Consumption (thousand tons) and Current Environmental Protection Expenditures by Sector (thousand UAH), (2007-2020)

Source: compiled by the author based on [26, 27]

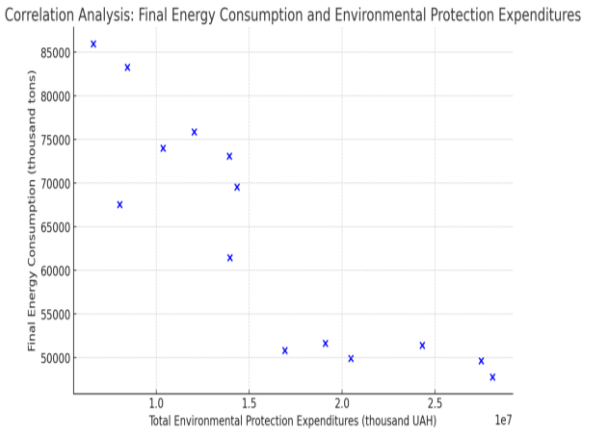

Figure 2. Final Energy Consumption and Environmental Protection Expenditures (2007-2020)

Source: compiled by the author based on [26, 27]

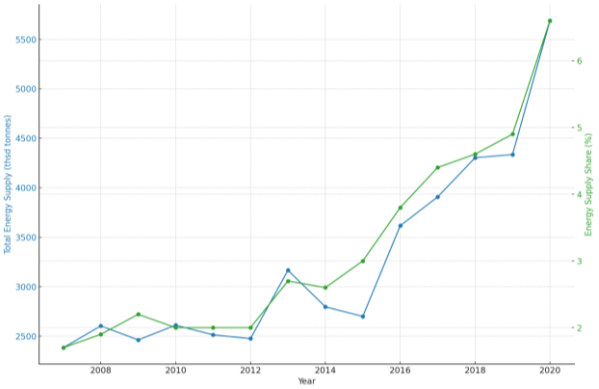

Figure 3. Total Energy Supply from Renewable Sources

Source: Energy consumption from renewable sources 2007–2020 [24]

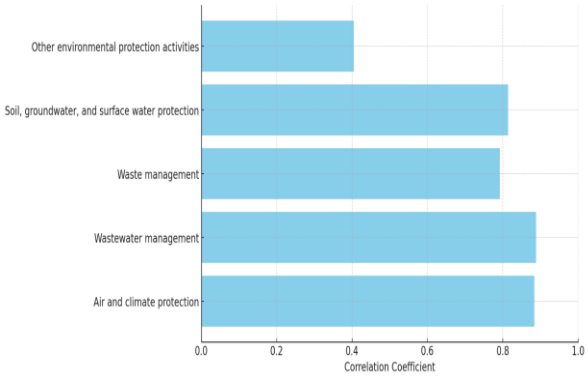

Figure 4. Analysis of the Relationship between Capital Investments and Current Environmental Protection Expenditures (2007–2020)

Source: compiled by the author based on [28, 27]

ments in environmental projects and the use of renewable energy sources [24, 28]. The graphs illustrate how increased investments in environmental measures reduce energy consumption and boost renewable energy use, highlighting their importance for achieving a carbon-free economy [10, 28].

The analysis underscores the critical role of capital investments in reducing energy consumption and increasing the share of renewable energy in Ukraine's overall energy balance. The negative correlation between capital investments and total energy consumption indicates that higher investments improve energy efficiency, while increasing investments in renewables correlates with a growing share of renewable energy in the energy balance.

Correlation analysis between capital investments and environmental activities in Ukraine (2007–2020) reveals the following:

- **Air and Climate Protection**: A very strong positive relationship (0.884) indicates its significant impact on the environmental budget.
- **Wastewater Treatment**: A strong positive correlation (0.888) emphasizes its priority within environmental expenditures.
- **Waste Management**: A moderate positive relationship (0.792) suggests its significance, though less pronounced compared to other categories.

- **Soil, Groundwater, and Surface Water Protection**: A strong positive relationship (0.814) confirms the importance of these measures.
- **Other Environmental Measures**: A weak positive correlation (0.405) indicates their lower significance in the expenditure structure.

Overall, the analysis demonstrates a close relationship between investments in environmental activities and their impact on Ukraine's energy balance. Further regression analysis is needed to assess the influence of each factor on the energy balance.

The results of the correlation analysis between total final energy consumption and various categories of environmental expenditures (Figure 5) provide valuable insights into energy efficiency in the context of environmental measures.

Capital investments in wastewater treatment showed the strongest negative correlation with energy consumption (-0.8885), indicating significant energy reductions, likely due to energy-efficient technologies. Similar results were observed for soil, groundwater, and surface water protection (-0.8140), demonstrating high efficiency in reducing energy consumption.

Waste management exhibited a moderate negative correlation (-0.7924), reflecting a positive, but less pronounced, effect. Air and climate protection measures also strongly contributed to energy reductions (-0.8840), highlighting their effectiveness.

In contrast, other environmental measures showed a weak positive correlation (0.4048), indicating less impact on energy efficiency or the need for further optimization.

These results suggest that capital investments in environmental technologies significantly reduce energy consumption, essential for sustainable development. However, other measures require further refinement to ensure their full impact on Ukraine's energy balance.

The analysis of correlations between the total supply of energy from renewable sources and various categories of environmental expenditures (2007–2020) highlights the importance of integrating renewable energy into environmental measures. A very strong positive relationship (0.9887) indicates a close link between environmental investments and the increased use of renewable energy.

Strong positive correlations in wastewater treatment (0.8559) and waste management (0.8798) demonstrate the role of renewable energy in these areas. A moderate positive relationship (0.7550) with soil, groundwater, and surface water protection reflects the dependence of these measures on renewable energy sources.

Additionally, a strong negative relationship with total energy consumption (-0.9071) suggests that a growing share of renewable energy leads to decreased overall energy consumption, indicating improved efficiency in energy use.

2.2. The Impact of Digitalization on Environmental Indicators

The correlation analysis identified significant relationships between digitalization expenditures (e.g., software and equipment spending) and environmental indicators, such as CO2 emissions and total final energy consumption. These correlations suggest a possible impact of digitalization, though they do not prove causality, only the presence of relationships between variables [10, 13, 14].

To further understand this impact, regression analysis was conducted, allowing for the identification of causal relationships and the assess-

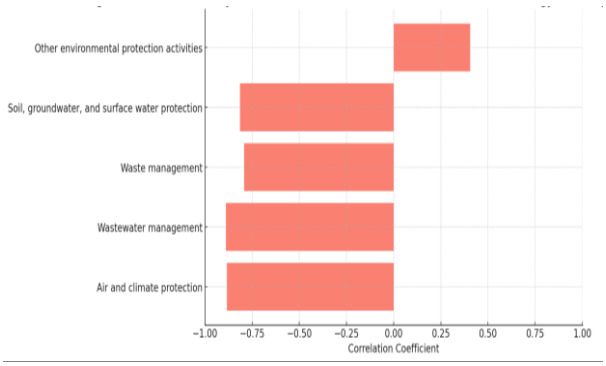

Figure 5. Correlation Analysis – Environmental Protection Investments vs. Final Energy Consumption (2007–2020)

Source: compiled by the author based on [28, 26]

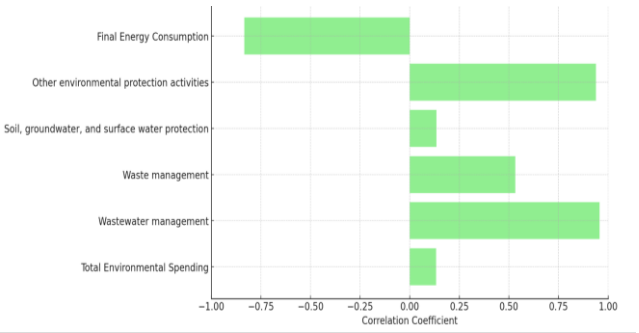

Figure 6. Correlation Analysis: Final Energy Consumption

Source: compiled by the author based on [26, 28]

ment of how effectively digital technologies contribute to reducing CO2 emissions and energy consumption. This analysis complements correlation by considering additional factors, providing a clearer understanding of the impact of digitalization on environmental sustainability [23]. This is critical for developing sustainable development policies and directing investments in renewable energy [6, 15].

To assess the impact of digitalization on environmental indicators, a correlation analysis was conducted between digitalization indicators, such as expenditures on software and equipment, the share of innovation-active enterprises, and environmental indicators, such as CO2 emissions and total final energy consumption. The source data for this analysis cover the period from 2007 to 2020 [24, 25, 26].

Missing data for 2019 and 2020 were estimated using the extrapolation method, allowing for the prediction of values based on available trends from previous years. For instance, the share of innovation-active enterprises was extrapolated at 16.6% in 2019 and 16.8% in 2020, considering an annual growth of 0.2%. Similarly, software and equipment expenditures were estimated at 10,683.8 million UAH in 2019 and 13,076.3 million UAH in 2020, based on an annual increase of 2,392.5 million UAH [30, 31].

Table 1 presents key indicators for CO2 emissions, energy consumption, and innovation expenditures from 2007 to 2020. Missing data for 2019 and 2020 were estimated using extrapolation, predicting trends based on earlier years [30, 31].

- **CO2 Emissions** showed a moderate positive correlation with software and equipment expenditures (0.445), suggesting that digital investments have not yet contributed to a reduction in emissions. This could be due to inefficient use of the technologies or suboptimal allocation of expenditures [25, 31].
- **Innovation activity** had a negative correlation with total energy consumption (-0.621), indicating that innovation contributes to improved energy efficiency [24, 31].

These findings suggest that, while digitalization (especially software and equipment expenditures) has not yet led to significant reductions in CO2 emissions, innovation activities have had a more positive effect on energy efficiency. However, further measures, including the introduction of new technologies and broader implementation of digital solutions, are necessary for more pronounced environmental benefits.

Further research should consider additional factors such as changes in environmental policy, legislation, and economic conditions to provide a deeper understanding of digitalization's environmental impact. The support of innovation-active enterprises, which have already shown potential in improving energy efficiency, is also vital for further progress in this area.

The analysis also revealed significant correlations between capital investments in environmental technologies and total final energy consumption. Increasing investments in environmental projects not only reduce energy consumption but also contribute to a higher share of renewable energy in the country's energy balance, highlighting the need for continued investments in renewable energy and environmental technologies to support sustainable development and the transition to a carbon-free economy [25, 31].

2.3. Regression Analysis of the Impact of Innovation Activity on Energy Consumption and CO2 Emissions in Ukraine

This section presents regression analysis results on the impact of innovation and digital-

Table 1

Key Indicators for CO2 Emissions, Energy Consumption, and Innovation in Ukraine (2007–2020)

Year	CO2 Emissions (thousand tons):	Total Final Energy Consumption (thousand tons):	Innovation Expenditures (million UAH)	Share of Innovation-Active Enterprises (%):	Expenditures on Software and Equipment (million UAH):
2015	215892	50831	13813.7	17.3	11141.3
2016	233220	51649	23229.5	18.9	19829
2017	224376	49911	9117.5	16.2	5898.8
2018	233620.9	51408	12180.1	16.4	8291.3
2019	224352.2	49665	14220.9	16.6	10,683.8
2020	207671.8	47773	14406.7	16.8	13,076.3

Sources: CO2 Emissions [25], Total Final Energy Consumption [26], Innovation Expenditures [29], Share of Innovation-Active Enterprises (%) [30], Expenditures on Software and Equipment [31]

ization on energy consumption and CO2 emissions in Ukraine. The data for the analysis cover the period from 2007 to 2020 and include key indicators such as CO2 emissions, total energy consumption, innovation expenditures, and capital investments in environmental protection.

Figure 7 and Table 2 provide key indicators for the regression analysis, with sources compiled from [25, 26, 29, 30, 31].

The regression results confirm that energy consumption is a key driver of CO2 emissions. Each 1,000-ton increase in energy consumption results in an additional 4.1334 thousand tons of CO2 emissions, which is statistically significant ($p < 0.01$). This highlights the importance of controlling energy consumption to reduce greenhouse gas emissions.

Table 3 presents the regression analysis results. Energy consumption has a strong, statistically significant impact on CO2 emissions, while innovation and environmental protection expenditures show less influence.

Although spending on digital technologies (software, equipment) is crucial for the modern economy, its current impact on CO2 emissions is limited. This may reflect insufficient integration of digital solutions into areas affecting environmental indicators or a time lag before their effects manifest. Meanwhile, innovation activity shows a positive effect on energy efficiency, though its influence on CO2 reductions is still modest.

Energy consumption remains the key factor influencing CO2 emissions, and reducing it should be a primary focus of environmental policy. Current investments in digital technologies need to target solutions that directly reduce greenhouse gas emissions.

Conclusions. The study identified key trends in the impact of digitalization, innovation activity, and environmental expenditures on energy consumption and CO2 emissions in Ukraine from 2007 to 2020.

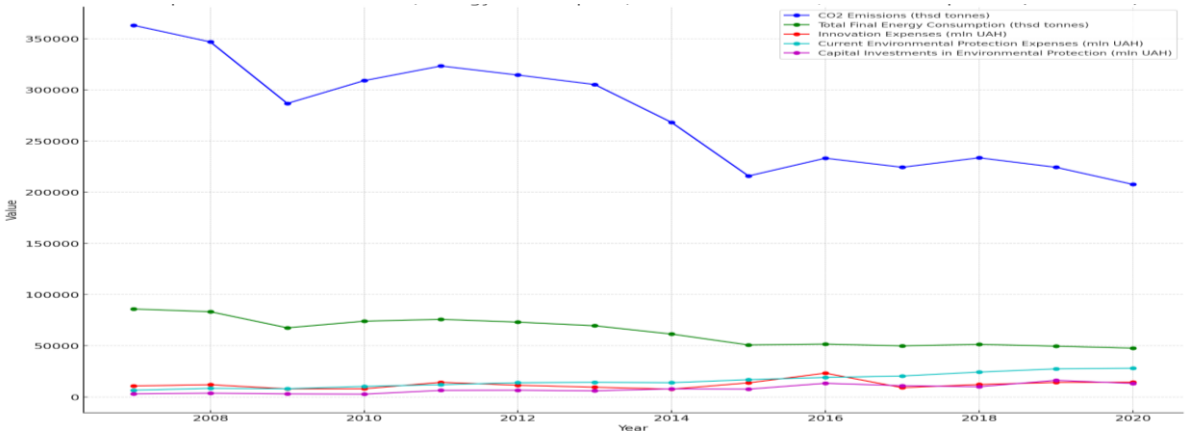

Figure 7. Key Indicators for Regression Analysis (2007–2020)

Source: compiled by the author based on [25, 26, 29, 30, 31]

Table 2

Key Indicators Used in the Regression Analysis (2007–2020)

Year	CO2 Emissions (thousand tons)	Total Final Energy Consumption (thousand tons)	Innovation Expenditures (million UAH	Current Environmental Protection Expenditures (million UAH)	Capital Investments in Environmental Protection (million UAH)
2015	215892	50831	13813.7	16915.535	7675.597
2016	233220	51649	23229.5	19098.225	13390.477
2017	224376	49911	9117.5	20466.423	11025.535
2018	233620.9	51408	12180.1	24317.991	10074.279
2019	224352.2	49665	14220.9	27480.19	16255.672
2020	207671.8	47773	14406.7	28092.552	13239.65

Source: compiled by the author based on [25, 26, 29, 27, 28]

Table 3

Results of Regression Analysis

Variable	Coefficient	Standard Error	t-Value	P-Value	95% Confidence Interval
Constant (const)	7739.9653	2.05E+04	0.377	0.715	[-3.87e+04, 5.42e+04]
Energy Consumption	4.1334	0.225	18.399	0	[3.625, 4.642]
Innovation_Expenditure	-0.3617	0.487	-0.742	0.477	[-1.464, 0.741]
Environmental Protection Expenditure	-0.2991	0.656	-0.456	0.659	[-1.783, 1.185]
Capital_Investment_ Environmental	1.6948	1.126	1.506	0.166	[-0.852, 4.241]

Source: compiled by the author based on [25, 26, 29, 27, 28]

Firstly, increasing environmental protection expenditures and capital investments showed a strong inverse relationship with energy consumption, confirming the effectiveness of these measures in improving energy efficiency. Regression analysis also confirmed that energy consumption is a significant driver of CO2 emissions.

Secondly, the impact of innovation and environmental expenditures on CO2 emissions was mixed. Although negative coefficients suggested potential reductions, they were not statistically significant, indicating the need for long-term investments and innovation improvements to achieve more substantial results.

Thirdly, the study revealed a positive link between environmental investments and the increased share of renewable energy in Ukraine's energy balance, underscoring the importance of continued investment in this sector to reduce reliance on fossil fuels.

Finally, digitalization, particularly spending on software and equipment, has not yet had a significant impact on reducing CO2 emissions. Innovation activity has shown some positive effects on energy efficiency, but these have been insufficient to achieve significant reductions. Further implementation of digital technologies and support for innovation-active enterprises are needed for greater environmental impact.

In conclusion, energy consumption remains a key factor influencing CO2 emissions, and long-term implementation of innovative measures and digital technologies is essential for achieving significant reductions. The transition to a cleaner, more energy-efficient economy requires further research, investment, and coordinated policy efforts.

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