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A ROAD MAP FOR THE TRANSITION TO A CARBON-FREE ECONOMY BASED ON THE ENERGY INNOVATIONS TRANSFER

ABSTRACT

This study aims to analyze existing scientific approaches to developing roadmaps in energy and innovation, identify key challenges hindering the transition to a carbon-neutral economy, and develop practical recommendations for Ukraine. Particular emphasis is placed on identifying and integrating legislative, economic, technological, and social aspects into energy innovation transfer to ensure an effective and sustainable transition. A literature review was conducted using key terms such as "roadmap", "energy", and "innovation", which allowed for the identification of the most relevant trends and approaches in this field.

The article outlines the main challenges Ukraine faces in transitioning to a carbon-neutral economic model based on the transfer of energy innovations. These challenges include legislative barriers, insufficient economic incentives, technological difficulties, and social factors that slow down the implementation of innovations.

Based on the identified problems and existing trends, a roadmap for Ukraine's transition to a carbon-neutral economy was developed, covering four key areas: legislative, economic, technological, and social. The sequence of steps and actions necessary to implement the transition scenario is detailed and presented visually.

The article offers specific practical recommendations for Ukraine regarding the implementation of the roadmap, including necessary legislative changes, economic incentives, investments in technology, and measures to increase social awareness and support. Thus, this article makes an essential contribution to the scientific and practical discourse on the transition to a carbon-neutral economy, particularly in the context of Ukraine, and can serve as a foundation for further research and policy development in this area.

Keywords: Carbon-neutral economy, energy innovations, roadmap, technology transfer, environmental policy, decarbonization

JEL Classification: Q55, Q58, Q42

INTRODUCTION

The transition to a carbon-neutral economy is one of the most pressing challenges of our time, requiring a comprehensive approach and swift action from governments, businesses, and society. Reducing greenhouse gas emissions is crucial for achieving global sustainable development goals. This issue is particularly relevant for Ukraine, which, on the one hand, has significant potential for developing "green energy," but on the other hand, faces barriers related to modernization, legislative constraints, and economic limitations. The urgency of this topic is heightened by the need to rebuild Ukraine's energy infrastructure amid the ongoing Ukraine-Russia conflict. The reconstruction period presents a valuable opportunity for Ukraine to develop a modern energy system that aligns with the principles of a carbon-neutral economy.

LITERATURE REVIEW

Research dedicated to formulating roadmaps for transitioning to a carbon-neutral economy represents a critical focus within the contemporary scientific literature. A pivotal component of this research involves the integration of innovative technologies within the energy sector, which are instrumental in mitigating greenhouse gas emissions and advancing sustainable development objectives.

Significant contributions to the exploration of the scientific and methodological foundations for developing roadmaps to a carbon-neutral economy have been made by scholars such as Richert, B. E. (2016), Pulselli, R. M., Broersma, S., Martin, C. L., Keeffe, G., Bastianoni, S., & van den Dobbelsteen, A. (2021), Chen, L., Msigwa, G., Yang, M., Osman, A. I., Fawzy, S., Rooney, D. W., & Yap, P. S. (2022), Maurya, P. K., Mondal, S., Kumar, V., & Singh, S. P. (2021), Carvalho, A., Riquito, M., & Ferreira, V. (2022), Caineng, Z. O. U., Xiong, B., Huaqing, X. U. E., Zheng, D., Zhixin, G. E., Ying, W. A. N. G., et. al. & Songtao, W. U. (2021). These researchers were identified through the Scopus database, by the thematic scope of their studies.

The development of reports on the formation of roadmaps was carried out by the following researchers: Pantelis Capros, Alessia De Vita, Nikos Tasios, Xenia Hanioti, Nikos Kouvaritakis, Panagiotis Fragkos, Dolf Gielen, Riccardo Gorini, Nicolas Wagner, Rodrigo Leme, Laura Gutierrez, and Gayatri Prakash.

The Ukrainian researchers who study and analyze the issue include: Pimonenko, T. V., Vakulenko, I. A., Matvieieva, Y. T., Minchenko, M. G., Yelnikova, Y. V., Golychenko, K. V., et. al. & Pushkar, A. Ya. (2022), Vasyliieva, T. A., Makarenko, I. O., Kurbatova, T. O., Letunovska, N. E., Samusevich, Y. V., & Myroshnychenko, O. Ju. (2021) Ivanyuta, S. P., & Yakushenko, L. M. (2022) and others.

Research dedicated to developing roadmaps for transitioning to a carbon-neutral economic model is becoming increasingly relevant, as the challenges of achieving a carbon-neutral economy through adherence to appropriate norms, principles, and standards remain unresolved. An integral component of the roadmap for transitioning to a carbon-neutral economic model is innovative technologies in the energy sector. Recent increases in publication activity on this topic are evident, as shown in Figure 1. The total number of publications on this subject over the entire period amounts to 400 documents.

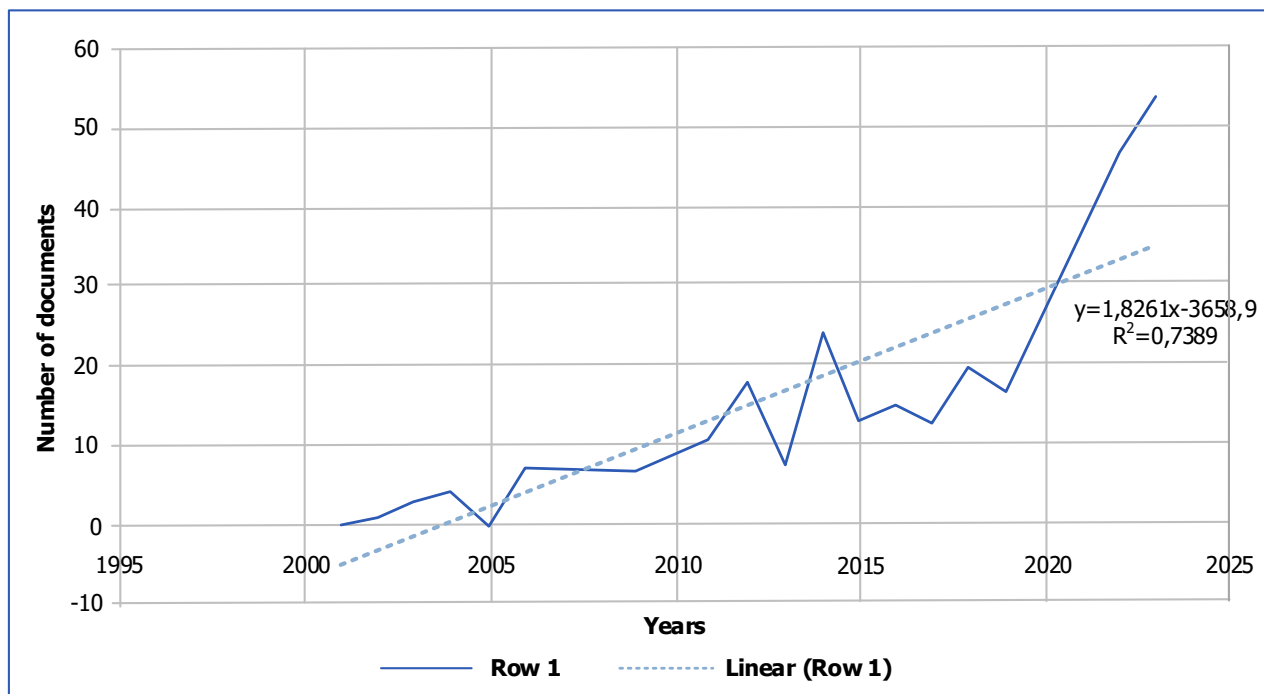
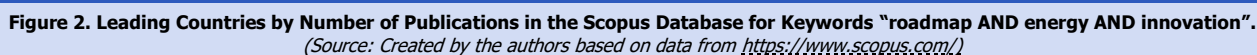


Figure 1. Dynamics of Publications in the Scopus Database for Search Terms "roadmap AND energy AND innovation" from 2000 to 2024.
(Source: Created by the authors based on data from <https://www.scopus.com/>)

The transition from coal-based energy to renewable energy sources, aimed at achieving carbon neutrality, is an unavoidable stage in transforming the energy system. This issue is most thoroughly investigated in the United States, China, and the United Kingdom, as shown in Figure 2. Ukraine ranks 37th in the number of publications on this topic among countries worldwide.



Data from the Scopus database have been used to cluster the conceptual network in developing roadmaps for transitioning to a carbon-neutral economic model based on the transfer of energy innovations. The visualization, created using VOSviewer software (version 1.6.16), depicts six research clusters, as shown in Figure 3. These clusters provide a more comprehensive understanding of the theoretical foundations for developing roadmaps for transitioning to a carbon-neutral economic model by transferring energy innovations.



The first (red) cluster has the most connections with other clusters and is centred around the term “roadmap”. This cluster explores issues related to energy efficiency, the use of Smart Grid technologies, technological innovations, and technology transfer. It also examines the formation of roadmaps in the context of energy resources, nanotechnologies, cost efficiency, and integrative approaches while considering human factors such as public health. Roadmaps are studied using the example of the U.S. economy.

Following the red cluster in terms of connection strength is the third (blue) cluster, formed around the fundamental concept of “innovation”. This cluster includes terms such as innovative technologies, information technologies, and technologies for developing roadmaps. These issues are examined concerning global warming.

The second (green) cluster contains terms related to decarbonization, carbon emission analysis and control, climate change, green innovations, and developing a low-carbon economy. It also studies economic and social effects and considers environmental management factors. The cluster has the highest number of connections around the concept of “sustainable development”, which is of particular scientific interest in China.

The fourth (yellow) cluster focuses on research on greenhouse gas emissions, energy policy, renewable resources, investment, international cooperation, and environmental regulation.

The fifth (purple) cluster includes research on renewable and clean energy sources, energy systems, energy gaps, and the prerequisites for utilizing sustainable energy.

In the sixth (blue) cluster, the most significant connections are around the terms “alternative energy” and “technological development”. The cluster also encompasses terms such as energy management, energy use, and open innovations.

The theoretical foundations for developing a roadmap for transitioning to a carbon-neutral economic model through the transfer of energy innovations were identified during the analysis of scientific papers in the Scopus database and reports on roadmap development.

AIMS AND OBJECTIVES

This article aims to develop a comprehensive roadmap for transitioning to a carbon-neutral economy based on the transfer of energy innovations, taking into account legislative, economic, technological, and social aspects. The article also seeks to identify critical issues and barriers hindering this process and offers practical recommendations for overcoming these challenges within Ukrainian realities.

METHODS

This study combines quantitative and qualitative analysis methods to develop a roadmap for transitioning to a carbon-neutral economy based on the transfer of energy innovations.

The Scopus database was utilized to analyze existing research and developments in roadmap formation. The search for academic articles was conducted using TITLE-ABS-KEY filters with keywords “roadmap”, “energy”, and “innovation”. This approach allowed the identification of key trends and leading researchers in the field. As a result, 400 scholarly documents relevant to the study's theme were analyzed.

A systems analysis method was employed to develop a general theoretical framework for the roadmap and identify critical issues. This method facilitated structuring the transition processes to a carbon-neutral economy, considering the complex interrelationships between legislative, economic, technological, and social aspects. Based on the data obtained, models of possible transition scenarios to a carbon-neutral economy for Ukraine were developed. The modelling accounted for the proposed solutions' economic feasibility, technological capability, and social acceptability.

Graphical visualization methods were used to represent the sequence of steps and actions in the roadmap, enabling easy identification of completed and proposed measures through colour coding. Visualization was carried out using Microsoft Visio software (version 2019).

RESULTS

The critical elements in developing a roadmap for transitioning to a carbon-neutral economic model based on the transfer of energy innovations include definition of decarbonization goals and timeline, assessment of the current state of the

energy system, development of innovative solutions and technologies, infrastructure modernization, funding and economic incentives, regulation and policy, awareness and public engagement, international cooperation, monitoring and progress evaluation, training and capacity building.

The theoretical framework for the roadmap for transitioning to a carbon-neutral economic model based on the transfer of energy innovations is illustrated in Figure 4.

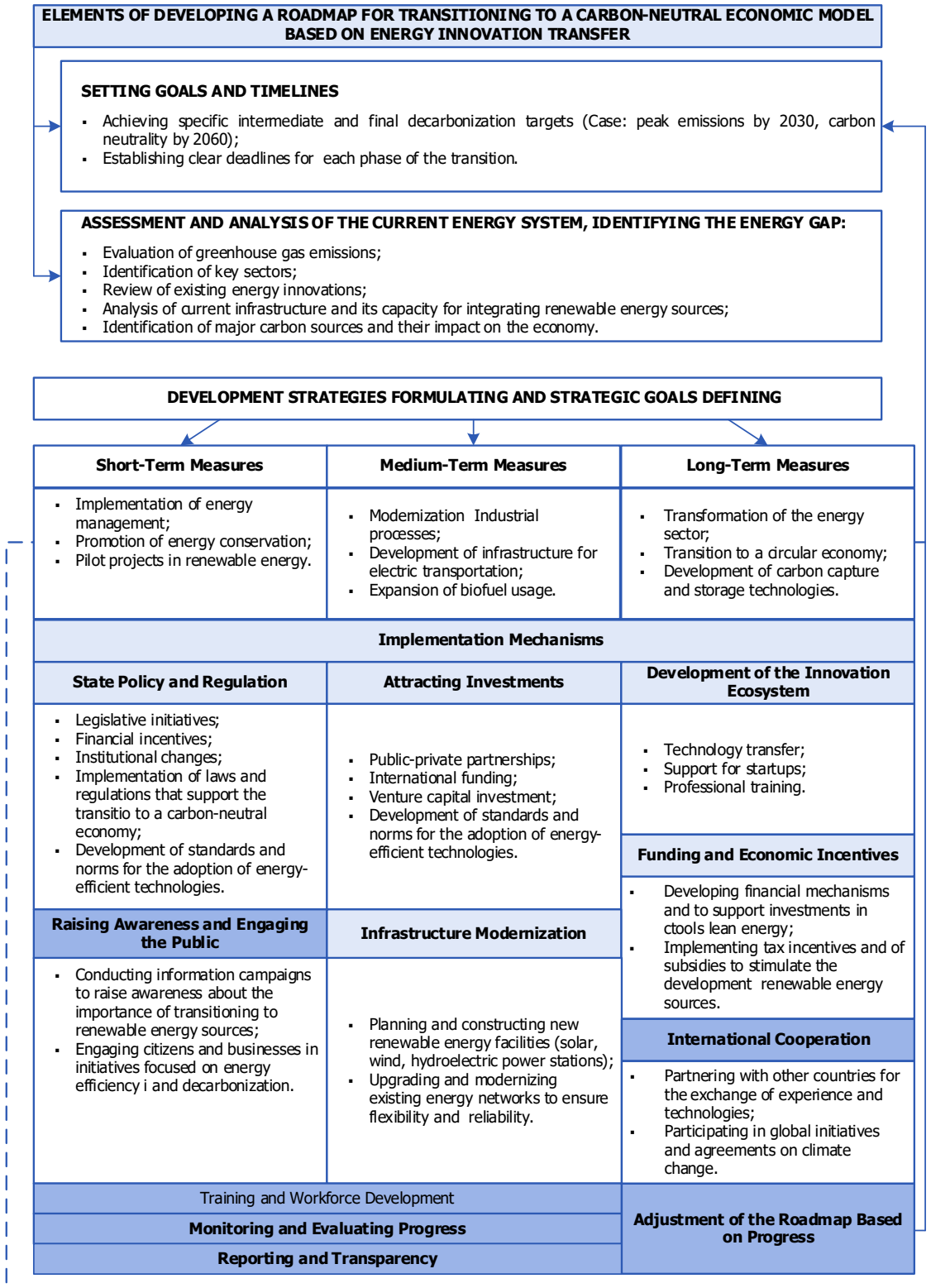


Figure 4. General Theoretical Framework of the Roadmap for Transitioning to a Carbon-Neutral Economy Based on Energy Innovation Transfer.

In the roadmap mechanism, training and capacity building involve:

- Conducting training and educational programs to develop skills and competencies in renewable energy and energy efficiency.

The final element of the roadmap mechanism for transitioning to a carbon-neutral economic model based on the transfer of energy innovations includes monitoring and evaluating progress, which involves:

1. Implementation of Monitoring Systems: Develop a monitoring system to assess the effectiveness of measures and adjust strategies based on key indicators.
2. Regular Reporting: Providing transparent reports on achievements and challenges during the transition process, with adjustments to the roadmap as necessary.

Together, these elements form a comprehensive approach to creating a roadmap for transitioning to a carbon-neutral economic model by transferring energy innovations.

Reports on climate change (IPCC, 2019; 2023) highlight that climate deterioration is occurring faster than expected. These facts underscore the urgent need for countries worldwide to transition to a carbon-neutral economic model.

It is important to note that the formulation of a roadmap must be based on a country's unique energy policy, considering specific geographical contexts, social systems, and stages of development. For example, there are certain peculiarities in the approaches that some countries apply in their pursuit of renewable energy and hydrogen integration into their energy structures. Brazil, for instance, demonstrates significant potential in renewable energy, particularly in wind and solar power. Germany has a regulatory framework that supports innovation and technological development, reflecting its advanced social system and commitment to phasing out fossil fuels. Austria emphasizes its dedication to decarbonization, notably using biomethane to heat and cool residential buildings (da Silva, G. H. et. al., 2024).

Developing a roadmap for transitioning to a carbon-neutral economy in Ukraine based on the transfer of energy innovations will allow the country's enterprises to better coordinate their activities toward achieving a carbon-neutral economy. This roadmap is intended to implement a strategy for transferring energy innovations to develop operationally rational tasks. During the development of the methodology for this roadmap, it is necessary to balance reducing climate damage with maintaining the welfare of the most vulnerable segments of the population.

This topic is particularly relevant in light of the destruction of Ukraine's energy system due to the full-scale invasion by Russia. The roadmap development will provide a step-by-step plan for the restoration and modernization of Ukraine's energy system, considering the requirements for transitioning to a carbon-neutral economy.

Table 1 outlines the main problems related to the transition to a carbon-neutral economy based on the transfer of energy innovations in Ukraine.

Table 1. Analysis of the Challenges in Transitioning to a Carbon-Neutral Economy Based on the Transfer of Energy Innovations.

Current State	Problems
Past	1. Unpreparedness of the Legislative and Regulatory Framework
	2. Delayed Strategic Document Development
	3. Lack of Government Support
	4. Inadequate Funding
	5. Lack of Public Education Programs
Present	1. Increased government support announced by various countries, but lacking a mechanism to ensure transparency in the use of funds.
	2. Inconsistency of government actions with European standards for ensuring the transition to a carbon-neutral economy.
	3. Lack of legislative initiatives for implementing environmental standards in the transportation sector.
Future	1. Development of a Roadmap for Transitioning to a Carbon-Neutral Economy Based on Energy Innovation Transfer
	2. Modernization of Existing Infrastructure, Investments in New Infrastructure, Public-Private Partnerships
	3. Information Campaigns, Promotion of Environmental Awareness, Encouragement of Clean Technology Adoption
	4. International Agreements, Collaboration in Research and Development, Exchange of Technologies and Knowledge
	5. Consideration of Environmental Aspects in the Planning and Implementation of Energy Projects

Based on the transfer of energy innovations, a roadmap for Ukraine's transition to a carbon-neutral economy has been developed across four areas: legislative, economic, technological, and social. The sequence of steps and actions required

for implementing the transition scenario to a carbon-neutral economy is illustrated in Figure 5. Actions that have already been completed are depicted in a deep colour, while the actions proposed by the authors are shown in a transparent colour.

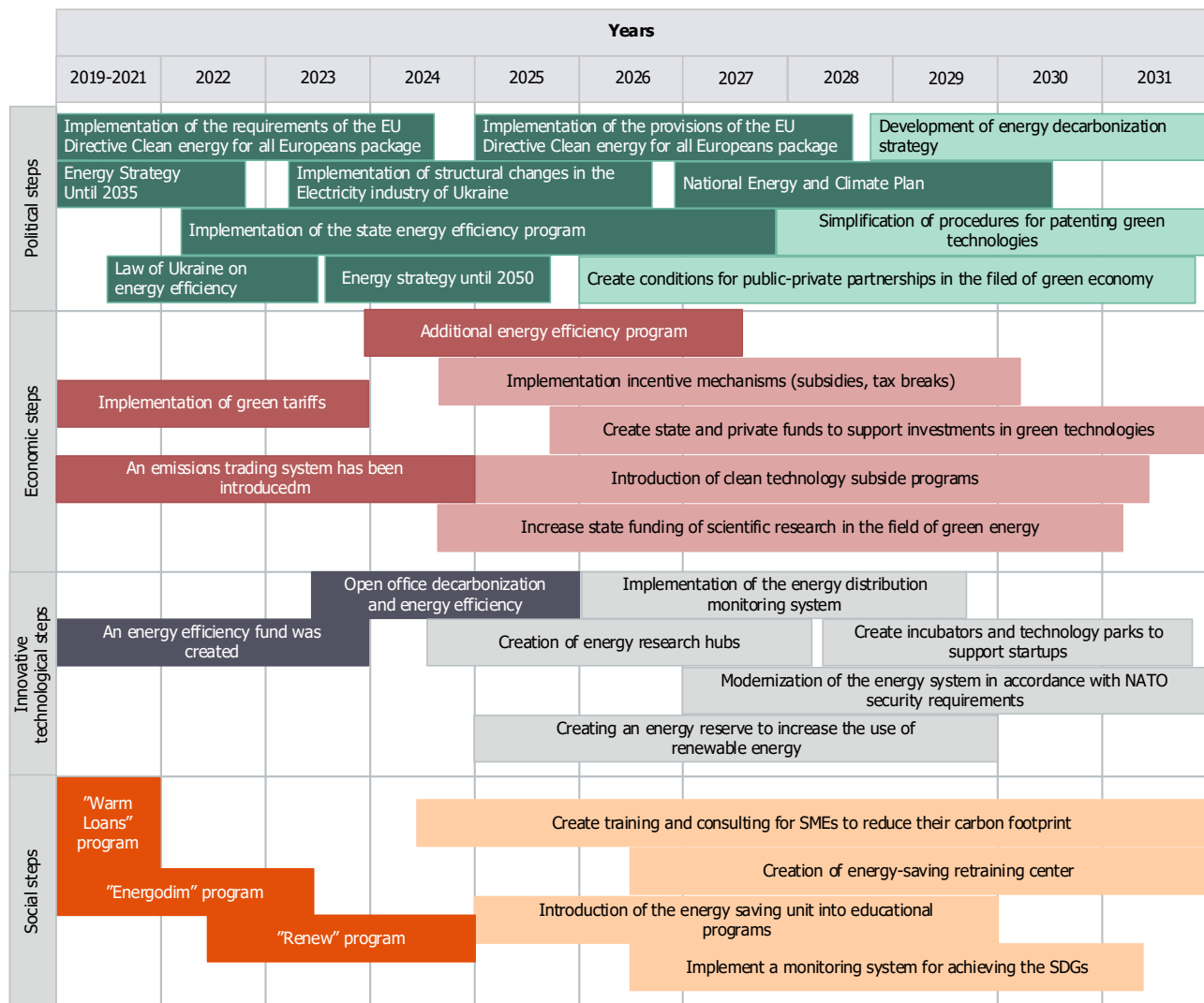


Figure 5. Roadmap for Ukraine's Transition to a Carbon-Neutral Economy Based on the Transfer of Energy Innovations. (Source: Created by the authors using Visual Paradigm (<https://online.visual-paradigm.com/app/diagrams/>))

Political Steps: Ukraine has implemented several EU directives related to transitioning to a carbon-neutral economy, including the Clean Energy for All Europeans (European Commission, 2016) and the Carbon Border Adjustment Mechanism (CBAM) (European Commission, 2021). Additionally, several institutional documents regarding energy policy have been updated, including the Law of Ukraine on Energy Efficiency, the Law of Ukraine on Alternative Energy Sources, and the National Energy and Climate Plan of Ukraine 2025-2030, which sets crucial goals for the 2025-2030 period such as improving energy efficiency, developing renewable energy sources, reducing CO₂ emissions, and adapting to climate change. The Energy Strategy of Ukraine until 2050 has also been developed, aiming for climate neutrality by reducing greenhouse gas emissions to zero. This involves shifting the energy system towards renewable sources, enhancing energy efficiency, and implementing carbon capture and storage technologies.

We propose developing a decarbonization strategy for the energy sector aimed at transitioning to a low-carbon energy system through the development and integration of renewable energy technologies, implementing energy efficiency measures across various economic sectors, modernizing energy infrastructure, and stimulating innovations in the energy sector, such as the development of new clean energy technologies, storage, and improvements in energy production processes.

One of the conditions for implementing energy technology transfers in the energy sector is creating conditions for public-private partnerships in green energy. Ukraine has already developed laws such as the Law on Public-Private Partnerships and the Law on Public Procurement, which create favourable conditions for the development of energy innovations. It is advisable to develop new energy standards that will encourage the private sector to participate in greenhouse gas reduction projects and the development of green infrastructure. Additionally, clear and transparent procedures for conducting tenders for green energy projects should be implemented to ensure fair competition and reduce corruption risks. To coordinate these partnerships, we propose creating specialized government agencies to coordinate and support the development of public-private partnerships in the green economy.

It is also advisable to introduce innovative financial instruments, such as green bonds, to attract investment in green economy projects and revolving credit facilities and establish a fund to support investments in renewable energy sources. This fund could include government funds, investments from international organizations, and private investors.

Transitioning to a carbon-neutral economy requires significant innovations in the energy sector. One key aspect of this transition is the creation of effective patenting procedures for green technologies, which will facilitate the transfer of energy innovations and stimulate the development of sustainable technologies. This requires introducing environmental efficiency and sustainable development requirements as part of the patenting process or establishing specific criteria for evaluating innovations in the green energy sector. Ensuring access to information about patenting green technologies and supporting innovators in this process will allow for creating online platforms for accessing information about green technologies and setting up systems for electronic applications and consultations.

Economic Steps: Ukraine is already advancing in developing economic incentives to support energy innovations. One such incentive is green tariffs, which are a crucial tool for supporting renewable energy sources and promoting the development of green energy. The introduction of green tariffs in Ukraine has been established by legislation to encourage the production of electricity from renewable sources: the Law of Ukraine "On Electric Power Industry" and the Law of Ukraine "On Alternative Energy Sources." The National Commission for State Regulation of Energy and Public Utilities (NERC) regulates green tariffs in Ukraine at the legislative level. The introduction of green tariffs has had a significant positive impact on the development of the renewable energy market in Ukraine, leading to an increase in the production of "green" electricity, an influx of foreign and domestic investments into the renewable energy sector, and infrastructure development.

Another step toward transitioning to a carbon-neutral economy has been implementing a greenhouse gas emissions trading system, regulated by the Law of Ukraine No. 377-IX "On Principles of Monitoring, Reporting, and Verification of Greenhouse Gas Emissions." The emissions trading system is an economic tool for reducing greenhouse gas emissions by establishing a market mechanism where businesses can buy and sell emission rights.

During a meeting on June 21, 2024, the Government announced the approval of an additional energy efficiency program, which aims to implement projects to reduce energy costs and introduce alternative energy sources. The program includes lowering interest rates on loans for energy efficiency projects. This is intended to facilitate access to financing for businesses and organizations implementing energy-saving projects. The program will fund projects for installing new alternative energy sources, such as solar panels, wind turbines, and biogas installations.

The next step could be implementing incentive mechanisms (tax benefits, subsidies) for energy-saving projects. For example, on July 5, 2024, the Cabinet of Ministers of Ukraine adopted a resolution that expands the opportunities of the state program "Affordable Loans 5-7-9%". Now, homeowners' associations (HOAs) and housing construction cooperatives (HCCs) can use loans to purchase and install electricity generation systems from alternative sources, energy storage systems, and auxiliary equipment. Another program initiated by the Entrepreneurship Development Fund (EDF), "Add Energy to Your Business," will help small and medium-sized enterprises reduce energy consumption and CO₂ emissions and continue business development even amid the war. Entrepreneurs can receive concessional loans to implement energy-saving technologies, such as installing new heating systems, lighting, insulation, and alternative energy sources (Entrepreneurship Development Fund, 2024).

In the context of climate change and the need to transition to sustainable development, it is crucial to establish effective mechanisms for financing green technologies. Both public and private funds can play a vital role in stimulating investments in green technologies in Ukraine. The government collaborates with international organizations and EU countries to create such programs. For example, making the green innovation fund Innovate Ukraine with British funding, establishing the International Action Platform for Green Recovery of Ukraine, and Germany's ongoing support for Ukraine's environmental sector are noteworthy initiatives. Thus, creating a state fund for financing investments in green technologies will help reduce greenhouse gas emissions, improve energy efficiency, and promote the development of renewable energy sources.

Implementing clean technology subsidy programs is essential for transitioning to a carbon-neutral economy. These programs help lower the costs of adopting environmentally friendly technologies and encourage investment in sustainable development. In the initial stage, developing and passing legislation regulating the conditions and mechanisms for subsidies on clean technologies is necessary. Following this, criteria should be established for evaluating subsidy applications and their outcomes, monitoring project implementation, and controlling expenditure effectiveness. Additionally, a financing mechanism for these programs should be developed.

Another tool that will contribute to achieving carbon neutrality and sustainable development is increasing government funding for scientific research in the green economy sector. The authors propose developing a national strategy that outlines critical priorities for scientific research in the green economy, including developing new technologies and solutions for ecological sustainability. The next step will be establishing the "National Strategy for Scientific Research in the Green Economy until 2030" and organizing consultations with research institutions, universities, and other stakeholders to identify priority research areas. These measures will foster the development of green energy's innovation and technology sector.

Technological and Innovative Steps: The transition to a carbon-neutral economy is a strategic goal for Ukraine, requiring the implementation of innovative technologies and new approaches across various economic sectors. Despite some progress in ecological sustainability and carbon neutrality, the Ukrainian government faces critical challenges and limitations that hinder achieving ambitious goals. For instance, on September 22, 2017, the Ukrainian Parliament established the Energy Efficiency Fund under the Law of Ukraine "On Energy Efficiency" (No. 2117-VIII). This fund was created to support projects to increase energy efficiency and reduce greenhouse gas emissions in Ukraine. Its primary objective is to provide grants and loans for projects that enhance energy efficiency. In 2023, the Ukrainian Cabinet of Ministers established the Decarbonization Office under Resolution No. 1275 to coordinate efforts among government bodies, enterprises, and public organizations to achieve national decarbonization strategy goals, support innovation, and engage in educational activities.

The authors propose creating Energy Research Hubs modeled after Swiss examples. Energy Research Hubs are integrated platforms for research, development, and implementation of innovative energy technologies. They provide an environment for collaboration among research institutions, businesses, government agencies, and public organizations. Establishing such hubs in Ukraine could be crucial to the national green energy strategy.

Given the ongoing threat of energy resource destruction from Russia, the authors suggest developing a decentralized energy supply and storage system, which includes creating energy reserves to increase the use of renewable energy. In the face of variable and unpredictable characteristics of renewable energy sources, such as solar and wind power, backup systems help ensure continuous energy supply and support grid stability. These systems may include various energy storage technologies, such as batteries, pumped hydro storage, biomass, and other technologies.

Implementing a smart energy distribution monitoring system is crucial to ensuring efficient management of electrical grids, reducing energy losses, and integrating renewable energy sources into the energy system. Smart monitoring systems utilize modern technologies to collect real-time data and analyze and manage energy resources. Sensors are installed at various points within the electrical grid to gather data on voltage, current, frequency, energy consumption, and other critical parameters. These sensors measure electricity consumption in real-time and transmit the data to a central system (Dhaou, I. B., 2023).

Upgrading energy systems to NATO security requirements is critical for ensuring the reliability, resilience, and security of energy infrastructures in Ukraine. This process involves adapting national energy systems to international standards and NATO requirements to guarantee their efficiency and protection against potential threats. It encompasses physical security, cybersecurity, and operational resilience. The primary goal is to protect energy facilities from potential threats and enhance their ability to recover from crises. Physical security includes safeguarding energy facilities from physical threats, such as sabotage, terrorist attacks, and vandalism. This includes constructing barriers and installing perimeter access control systems to protect critical infrastructure, securing airspace from drones and missiles, installing surveillance cameras to monitor the area around energy facilities and detect potential threats, and deploying physical security personnel for constant patrolling and access control to critical sites (Gitelman, L., Magaril, E., & Kozhevnikov, M., 2023).

Cybersecurity measures focus on protecting the information systems that manage energy facilities from cyber threats and attacks. This involves implementing firewalls, intrusion detection systems, and antivirus solutions, regularly updating systems to eliminate vulnerabilities and ensure up-to-date protection, and establishing cybersecurity centres to monitor and respond to cyber threats (Govea, J., Gaibor-Naranjo, W., & Villegas-Ch, W., 2024).

Operational resilience involves developing plans to ensure the continuity of energy systems during crises and emergencies.

To support enterprises in the field of advanced energy technologies, we propose the establishment of incubators and technology parks to assist startups. These entities will provide startups with infrastructure, consulting services, and access to funding, which are critical for their growth and success. The primary goal of these formations is to offer financial support during the early stages of development, create a network of connections between potential investors and startup stakeholders, and provide mentorship from high-level experts in the energy sector.

Incubators and technology parks will serve as platforms for exchanging knowledge and technology between researchers and stakeholders from commercial or governmental spheres. They will foster innovation and sustainable development and help Ukraine integrate into the global effort to combat climate change.

Social Steps: As of 2024, Ukraine has already implemented several programs to enhance energy efficiency and support sustainable development. For instance, the "Warm Loans" program allows citizens to obtain loans to implement energy-saving measures with partial interest rate compensation. This program enables citizens to modernize their homes, reducing energy costs and improving living comfort. It also helps to alleviate energy poverty by allowing low-income households to adopt energy-efficient solutions.

The "Energy Home" program, funded by Ukraine's Energy Efficiency Fund, supports the energy modernization of multi-apartment buildings. This program helps to reduce energy consumption and enhance social stability in urban areas.

Another initiative, the "Rebuild Home" program, was launched in November 2022 to modernize damaged housing in regions affected by military actions. This program addresses housing issues, contributes to environmentally sustainable development, and reduces social tension.

The proposal emphasizes the need to raise public awareness regarding energy efficiency and consumption to advance these efforts further. For example, it suggests creating educational and consulting programs for small and medium-sized enterprises (SMEs) to reduce their carbon footprint. These programs would help SMEs adapt to new environmental standards, reduce costs, and contribute significantly to climate change mitigation through the following steps:

Incorporating energy conservation education into curricula: This includes teaching about the importance of the green economy and environmental standards in school programs, university courses, public seminars, and workshops. These programs would foster an awareness among the younger generation of the importance of energy conservation and encourage responsible behaviour toward sustainable development.

Establishing retraining centres for energy conservation specialists would create a professional cluster capable of more effectively implementing ecological initiatives and projects at all levels of governance. This approach would enhance the capacity of both public and private sectors for sustainable resource management.

Implementing a monitoring system for achieving sustainable development goals (SDGs): To track progress, it is proposed that a monitoring system be introduced to measure the achievement of SDGs. This monitoring aims to ensure effective control and evaluation of progress in implementing actions aimed at sustainable development. This system would allow the government, businesses, NGOs, and other stakeholders to monitor task completion, assess impacts, and adjust strategies to improve the effectiveness of actions. Ukrainian legislation has already implemented the main principles of sustainable development. For instance, in 2015, the "Ukraine – 2020" Sustainable Development Strategy was adopted, aiming to implement reforms for economic growth, social justice, and environmental sustainability. In 2019, the President's decree outlined Ukraine's Sustainable Development Goals for up to 2030 [34]. However, the draft law "On the Sustainable Development Strategy of Ukraine until 2030" has not yet been adopted. Thus, Ukraine needs to develop a comprehensive national strategy that defines the fundamental principles, goals, and approaches for monitoring progress in achieving the SDGs.

Developing theoretical foundations is essential for creating a clear and consistent strategy for transitioning to a carbon-neutral model, ensuring a comprehensive approach to addressing environmental and economic challenges. The scientific and methodological principles of transferring innovative energy efficiency and renewable energy technologies have been applied in developing Ukraine's Roadmap for transitioning to a carbon-neutral economy. This approach is crucial in achieving the nation's environmental goals and ensuring sustainable economic development.

The main elements of the Roadmap can provide a comprehensive approach to achieving carbon neutrality in Ukraine and simplify mechanisms for attracting investment, thereby enhancing the competitiveness of the Ukrainian economy in the global market. A vital component of the successful implementation of the Roadmap is support from the state, business, and society. The specific measures and recommendations outlined in this study lay the foundation for creating a sustainable and effective strategy for transitioning to a carbon-neutral economy, which will not only meet climate goals but also

promote Ukraine's economic development in the long term. However, to achieve tangible results, continually adapting strategies in response to changing conditions and challenges is crucial.

DISCUSSION

At present, Ukraine has developed a large number of programmatic documents for the transition to a carbon-neutral economy based on energy innovation transfer. Some of these documents focus solely on technical aspects, while others address only legislative issues. This article summarizes four main elements of the roadmap development: legislative, economic, technical, and social. Some of these documents were developed before the full-scale invasion and did not consider the complete reconstruction of the energy system based on the principles of decentralization.

Other documents support the results of our research. For instance, studies by national and international experts have repeatedly emphasized the need for legislative regulation of energy efficiency, stimulation of green energy development, and the creation of public-private partnerships in this field.

However, during our research, we identified specific challenges for Ukraine: the restoration of destroyed energy infrastructure, the ongoing war, which hinders restoration work in occupied territories, and funding limitations, among others. Therefore, the issues of modernizing the energy system and implementing energy innovations during the reconstruction of the energy system have become more relevant than in previous years.

CONCLUSIONS

This article examines the comprehensive challenge of transitioning Ukraine to a carbon-neutral economy amidst ongoing challenges and constraints imposed by internal and external factors. The main aspects discussed include legislative, economic, technical, and social components of developing a Roadmap. It has been identified that an effective transition to carbon neutrality requires a holistic approach that involves harmonizing legislation, incentivizing investment in the green sector of the economy, implementing cutting-edge technologies, and actively engaging society in sustainable development processes.

The research findings confirm that, despite numerous policy documents developed by national and international experts, Ukraine faces specific challenges related to the restoration of destroyed energy infrastructure, military actions that hinder reconstruction in occupied territories, and limited financial resources. This underscores the urgent need for modernization of the energy system and the implementation of innovative solutions to achieve sustainable development goals.

Therefore, the strategy for transitioning to a carbon-neutral economy in Ukraine requires constant adaptation to changing conditions and challenges. Developing a clear, consistent, and comprehensive national strategy, which involves active collaboration between the government, business, and society, is crucial for ensuring sustainable economic growth and achieving environmental goals in the long term.

ADDITIONAL INFORMATION

AUTHOR CONTRIBUTIONS

All authors have contributed equally.

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CONFLICT OF INTEREST

The Authors declare that there is no conflict of interest.

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ДОРОЖНЯ КАРТА ПЕРЕХОДУ ДО БЕЗВУГЛЕЦЕВОЇ ЕКОНОМІКИ НА ОСНОВІ ТРАНСФЕРУ ЕНЕРГЕТИЧНИХ ІННОВАЦІЙ

Метою дослідження є аналіз існуючих наукових підходів до розробки дорожніх карт у царині енергетики та інновацій, виявлення основних викликів, що перешкоджають переходові до вуглецево нейтральної економіки та розробка практичних рекомендацій для України. Особлива увага приділена визначенню та систематизації законодавчих, економічних, технологічних і соціальних аспектів у процесі передачі енергетичних інновацій, щоб забезпечити ефективний сталий розвиток. У роботі проведено огляд літературних джерел у наукометричних базах за ключовими термінами: «дорожня карта», «енергетика» й «інновації», що дозволило виявити найактуальніші тенденції та підходи в цій царині.

У статті описані основні виклики, з якими стикається Україна під час переходу до вуглецево нейтральної економічної моделі економіки на основі передачі енергетичних інновацій. До цих викликів відносяться законодавчі бар'єри, недостатні економічні стимули, технологічні труднощі та соціальні фактори, що вповільнюють упровадження інновацій. На основі виявлених проблем та існуючих розробок автори модернізували дорожню карту переходу України до вуглецево нейтральної економіки, яка охоплює чотири ключові сфери: законодавчу, економічну, технологічну та соціальну. Деталізовано та візуально представлено послідовність кроків і дій, необхідних для реалізації сценарію переходу.

Стаття пропонує конкретні практичні рекомендації для України щодо реалізації дорожньої карти, включаючи необхідні законодавчі зміни, економічні стимули, інвестиції в технології та заходи для підвищення соціальної обізнаності й підтримки. Таким чином, стаття робить суттєвий внесок у науковий і практичний дискурс щодо переходу до вуглецево нейтральної економіки, зокрема в контексті України, і може слугувати основою для подальших досліджень і розробки політики в цій царині.

Ключові слова: вуглецево нейтральна економіка, енергетичні інновації, дорожня карта, трансфер технологій, екологічна політика, декарбонізація

JEL Класифікація: Q55, Q58, Q42