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ECONOMIC FOUNDATIONS OF DECARBONIZATION: INTERNALIZATION OF ENVIRONMENTAL EXTERNALITIES AND IDENTIFICATION OF COLLABORATIVE DECARBONIZATION HUBS

Summary. *Introduction. This study considers concept of developing a hybrid economic–machine learning framework to analyze decarbonization as a multidimensional structural trans-formation process integrating environmental externalities, macro-financial dynamics, geopolitical risks and cross-country heterogeneity. The proposed approach is grounded in environmental economics theory extending it through da-ta-driven clustering techniques to identify structurally similar decarbonization pathways and collaborative transition hubs to internalize environmental externalities.*

Purpose. The purpose of the study is to consider the integration of green economy relevant theoretical and methodological directions into a single conceptual model for the analysis of decarbonization. Therefore, the author proposes to combine the theory of environmental externalities, principles of macroeconomic efficiency, concepts of sustainable financing and ESG investing, analysis of geopolitical and climate risks, modern methods and mechanisms of clustering and machine learning for common management of decarbonization as the basis of the proposed concept of the approach.

Materials and methods. The methodological framework consists of proposed four interconnected analytical steps. Firstly, the study establishes an economic foundation based on Pigouvian externality theory, where decarbonization is interpreted as a market correction mechanism addressing the divergence between marginal private and social costs. Second step proposes the construction of a structured cross-country dataset, incorporating key indicators related to emissions intensity, renewable energy integration, ESG performance, financial system development, institutional quality and geopolitical risk exposure. Third, a latent decarbonization potential function was proposed to be specified to capture multidimensional national capabilities for low-carbon transition. Fourth, unsupervised machine learning methods, including self-organizing maps (SOM) was proposed to be applied to classify countries into homogeneous decarbonization system.

Results. The empirical logic of the framework suggests that decarbonization is not a linear emissions-reduction process but a systemic transformation shaped by interactions between financial structures, institutional capacity, technological development and geopolitical constraints. The clustering results will provide a taxonomy of countries characterized by distinct transition profiles, including high-efficiency decarbonization economies, transition economies, and fossil-dependent economies. These clusters will be served as analytical foundations for identifying collaborative decarbonization hubs that enhance policy coordination, climate fi-nance efficiency and technology diffusion of countries. The study contributes to the *literature by integrating economic externality theory with machine learning–based classification of national decarbonization pathways, offering a unified analytical framework for evidence-based climate governance and sustainable economic transformation.*

Discussion. Further research should be aimed at quantitative testing of the proposed model, the application of dynamic forecasting and artificial intelligence-based approaches, as well as scenario analysis of long-term decarbonization trajectories taking into account financial, technological and geopolitical factors.

Key words: *decarbonization, environmental externalities, sustainable finance, clustering, machine learning, climate governance.*

Statement of the problem. Climate change has emerged as one of the most important challenges affecting eco-nomic stability, financial systems, geopolitical security and sustainable development. Continues rising greenhouse gas emissions, increasing climate disasters, geopolitical instability and disruptions in energy markets continue to pose significant environmen-tal and macroeconomic risks worldwide [1].

Climate change is increasingly affecting not only environmental sustainability but also financial market stability, energy security, inflation, public debt, investment flows and international economic competitiveness [2, 3]. In this context, decarboniza-tion has become not only an environmental goal, but also a strategic economic, finan-cial and geopolitical priority.

The importance of this study is the comprehensive integration of ecological economics, macroeconomic transformation, sustainable finance and geopolitical cli-mate governance in the context of global decarbonization. This study considers decar-bonization not only as an environmental goal, but also as a strategic economic mecha-nism to improve resource allocation efficiency, reduce long-term financial risks, strengthen energy security and ensure sustainable economic development. It also em-phasizes the importance of international joint governance. Since climate change is a global problem that requires collective action, isolated national policies remain insuf-ficient to achieve long-term climate neutrality. Accordingly, the identification of common decarbonization centers is of strategic importance for the development of technological cooperation, the integration of renewable energy, climate finance and policy harmonization between countries with similar structural characteristics.

Analysis of recent research and publications. The academic literature on decarbonization, sustainable finance and the green econo-my can be broadly divided into six main research areas: environmental externalities and market failures; carbon pricing and climate policy; sustainable finance and ESG investments; macroeconomic consequences of decarbonization; geopolitical and cli-mate risks; and clustering methods for analyzing climate governance.

The theoretical foundations of environmental externalities were established by Pigou [4], who argued that environmental damage creates a divergence between pri-vate and social costs, leading to market failures. Later, Coase [5] emphasized the im-portance of institutional arrangements, property rights, and transaction-cost minimiza-tion in addressing environmental problems. In contemporary environmental econom-ics, Stiglitz [6] argued that both price and non-price climate-policy interventions play a central role in correcting climate-related market failures.

Research on carbon pricing and climate policy demonstrates that carbon taxes and emissions trading systems (ETS) significantly improve the efficiency of emission reduction policies. Nordhaus [7] emphasized the importance of internationally coordi-nated carbon pricing mechanisms for effective climate governance. Böhringer, Fisch-er, Rosendahl & Rutherford [8] further showed that harmonized border carbon ad-justment mechanisms contribute to reducing carbon leakage risks and improving the competitiveness balance of international climate policies.

The sustainable finance literature highlights the growing role of ESG invest-ments, green bonds, climate funds, and sustainable banking systems in supporting low-carbon transitions. Friede, Busch & Bassen [9] in a meta-analysis of more than 2,000 empirical studies, identified a positive relationship between ESG indicators and corporate financial performance. Similarly, Pedersen, Fitzgibbons & Pomorski [10] demonstrated that ESG-oriented investment strategies may improve long-term portfo-lio efficiency under ESG-constrained investment strategies. Bolton, Després, Pereira da Silva, Samama & Svartzman [2] further emphasized that climate-related risks sig-nificantly affect financial stability, asset valuation, and long-term investment de-ci-sions. Recent reports by the NGFS [11] also indicate that climate-related litigation and transition risks may increasingly affect banking-sector resilience and financial-system stability.

Research on macroeconomic transformation demonstrates that green invest-ments generate positive long-term economic multipliers. Hepburn, O'Callaghan, Stern, Stiglitz & Zenghelis [12] suggested that green recovery investments may gen-erate stronger long-term employment and productivity effects than carbon-intensive fiscal measures. Similarly, Acemoglu, Aghion, Bursztyn & Hemous [13] demonstrat-ed that policies supporting directed technological change can facilitate long-term tran-sition toward cleaner production technologies.

Studies on geopolitical risks emphasize the interrelationship between climate change, energy security, and international stability. According to the International En-ergy Agency [3], the transition toward renewable energy may reduce dependence on fossil fuel imports and strengthen long-term energy security. The IPCC [1] additional-ly stressed that limiting global warming requires rapid and deep decarbonization across all economic sectors. Steininger, Williges & Meyer [14] further emphasized the importance of coordinated climate governance and equitable burden-sharing mecha-nisms among countries within international climate policy frameworks.

In recent years, increasing attention has been devoted to the application of ma-chine learning and clustering methods in decarbonization research. Lee, Yun & Park [15] applied Kaya identity clustering analysis to identify heterogeneous drivers of carbon neutrality across countries with legislated decarbonization targets. D'Arcangelo, Kruse & Pisu [16] demonstrated that cluster-based climate-policy as-sessments improve the identification of adaptive emission-reduction pathways and in-teractions among climate-policy instruments.

Despite substantial progress across six major six research areas, the existing lit-erature remains fragmented across disciplinary boundaries. Each field has developed a strong theoretical and empirical foundation, however, interdisciplinary integration remains limited.

For example, environmental economics provides a robust explanation of market failures [4, 5] and climate-policy research offers advanced pricing mechanisms [6, 7], however these frameworks are rarely integrated directly with financial-system dynam-ics, including ESG-driven capital allocation and sustainable investment behavior. Consequently, the transmission mechanisms linking climate-policy instruments with financial-market responses remain insufficiently formalized within a unified analytical framework.

Although sustainable finance research has extensively documented positive re-lationships between ESG indicators and corporate performance [2; 9; 10] but it often examines financial systems independently of geopolitical constraints and macroeco-nomic transition risks. Similarly, macroeconomic studies [12–13] primarily focus on aggregate growth and innovation effects but without systematically incorporating in-stitutional coordination mechanisms and cross-country decarbonization dynamics.

Geopolitical studies emphasize energy security, international coordination and climate governance [1; 3; 14] but they are not systematically connected with quantita-tive clustering approaches capable of identifying structural similarities and divergence patterns among countries. Conversely, machine learning and clustering studies are primarily applied for classification and pattern recognition but often lack integration with environmental-economic and sustainable-finance theories, thereby limiting their policy interpretability.

Despite recent advances in data-driven climate governance research [15–16] ex-isting studies rarely integrate simultaneously environmental externalities, sustainable finance mechanisms, macroeconomic transformation processes, geopolitical risk structures and country-level clustering analysis into a unified model of decarboniza-tion pathways. In particular, the concept of common decarbonization hubs and coor-dinated climate-policy alignment among countries remains insufficiently developed in the existing literature.

Therefore, a key research gap is the absence of sufficient integrated multi-level framework combining green economy theory, sustainable finance, macroeconomic transformation, geopolitical risk analysis and machine learning clustering approaches. This study addresses this gap by proposing a hybrid conceptual and methodological framework for identifying decarbonization clusters and supporting coordinated cli-mate-governance strategies across countries.

The purpose of the study is to consider the integration of green economy relevant theoretical and methodological directions into a single conceptual model for the anal-ysis of decarbonization. Therefore, the author proposes to combine the theory of envi-ronmental externalities, principles of macroeconomic efficiency, concepts of sustaina-ble financing and ESG investing, analysis of geopolitical and climate risks, modern methods and mechanisms of clustering and machine learning for common manage-ment of decarbonization as the basis of the proposed concept of the approach.

The main objectives of the study are:

1) considering the economic theory of environmental externalities and mar-ket failures related to climate;
2) overview the role of sustainable finance and ESG investments in support-ing decarbonization;
3) taking into account the impact of geopolitical and macroeconomic risks on low-carbon transformations;
4) considering mechanisms for common climate governance;
5) exploring the application of clustering methods for identifying decarbon-ization hubs.

Materials and methods. This study considers principles of adopting a hybrid economics–machine learning framework to analyze decarbonization as a multidimensional structural transformation process. The methodology integrates environmental economics theory, macro-financial modeling, and unsupervised learning techniques for cross-country clustering.

Therefore, methodological framework consists of four interrelated analytical steps described below.

Step 1. Theoretical economic foundation. The first step examines environmental externalities and the economic theory of decarbonization. It examines the market failures that arise from carbon-intensive production systems, as well as policy instruments aimed at internalizing environmental costs.

Considering that carbon taxes, emissions trading systems, renewable energy subsidies and carbon border adjustment mechanisms are assessed as tools to improve resource allocation efficiency and environmental performance [7]. We can suggest that from an analytical perspective, decarbonization contributes to economic efficiency by:

– reducing climate market distortions;
– optimizing resource allocation;
– stimulating technological innovation;
– minimizing long-term environmental damage.

Although, from the perspective of ecological economics, decarbonization is a mechanism for correcting market failures associated with negative environmental externalities. Negative externalities arise when economic activities create environmental and social costs that are not fully reflected in market prices [4]. Thus, carbon-intensive industries generate excessive emissions because producers and consumers do not bear full responsibility for the environmental consequences of their activities, leading to inefficient resource allocation and reduced social welfare [6].

In this context, decarbonization can be defined as a multidimensional process of economic transformation aimed at reducing carbon dependence through technological innovation, sustainable financing, the integration of renewable energy, carbon pricing mechanisms, and coordinated climate governance. In contrast to traditional approaches focused primarily on emission reduction, the modern concept of decarbonization includes economic sustainability, financial stability, energy security, and climate risk management. Matviychuk, Zhytkevych & Osadcha [17] emphasizes that decarbonization needs to be analyzed using multidimensional data sets that include macroeconomic, environmental, technological and energy indicators.

In line with Pigouvian environmental economics [4], marginal social costs can be conceptually represented as:

$$MSC = MPC + MEC, \tag{1}$$

where MSC is marginal social cost; MPC is marginal private cost and MEC is marginal external cost.

Equation (1) demonstrates that the real social costs of economic production include both private production costs and environmental losses caused by carbon emissions. According to Pigou [4], governments should implement corrective instruments that are able to internalize environmental costs.

Carbon taxes, emissions trading systems, renewable energy subsidies and border carbon adjustment mechanisms are used to align private incentives with broader public welfare objectives [8]. The optimal carbon tax corresponds to the marginal external damage generated by an additional unit of emissions, consistent with Pigouvian welfare economics [4, 7]. Therefore, carbon prices should reflect the marginal environmental damages caused by emissions in order to achieve socially optimal pollution levels. This principle forms the theoretical basis for the internalization of environmental externalities.

In this context, carbon taxes, ETS, renewable energy subsidies, ESG-oriented financial regulation, green investment coordination and climate cooperation mechanisms act as tools to correct market failures and form the basis for the transition to a low-carbon model of economic development. The internalization process improves the efficiency of resource allocation by integrating environmental damage into market prices, which in turn incentivizes the adoption of cleaner production technologies, more sustainable investments and a low-carbon transformation of the economy.

Step 2. Dataset and variable construction. The second step requires examining sustainable finance and investment system and geopolitical risks and macroeconomic stability in the context of decarbonization.

Climate risks are divided into three main categories: physical risks associated with climate disasters; transition risks caused by technological and regulatory changes and liability risks associated with environmental and legal liability. Although, climate risks have significant implications for portfolio management, investment allocation, banking stability and long-term economic growth [11].

From the perspective of financial economics, sustainable finance has become one of the key drivers of the low-carbon transformation. Therefore, green bonds, ESG investments, climate funds and sustainability systems increasingly channel financial resources into renewable energy, green infrastructure and low-carbon technologies [9].

The allocation of investments in sustainable development can be conceptually represented by the following optimization function:

$$GI_i = f\left(ER_i, CR_i, ESG_i, R_i\right), \tag{2}$$

where GI_i — green investment allocation in country i;

ER_i — expected return;

CR_i — climate-related risk;

ESG_i — sustainability performance indicators;

R_i — domestic regulatory incentives.

The formulation in Equation (2) aligns with portfolio allocation and sustainable finance literature [10], which demonstrates that investment decisions are jointly determined by expected financial returns, climate-related risks, ESG performance indicators and regulatory frameworks. It demonstrates that sustainable investment decisions depend not only on expected financial returns, but also on climate risks and regulatory and sustainability-related conditions.

Modern decarbonization processes are also closely linked to macroeconomic stability and the functioning of financial markets. Climate change increasingly affects inflationary processes, the sustainability of public debt, the allocation of capital, insurance markets, government spending and the resilience of financial systems [2].

The macroeconomic relationship between green investment and economic growth can be conceptually developed on the basis of the traditional Cobb–Douglas production framework [18] incorporating green investment capital as an additional production factor.

Such an approach is consistent with endogenous growth theory and literature emphasizing the role of green investment and technological transformation in sustainable economic development [12]. Thus, the model extends endogenous growth theory by incorporating green investment capital as a determinant of sustainable economic development.

The literature review suggests that sustainable finance improves the efficiency of capital allocation by directing investments to environmentally sustainable technologies and infrastructure [9].

Modern financial systems increasingly integrate climate risks into portfolio optimization and investment evaluation models. Climate stress testing, green taxonomies and ESG rating methodologies are becoming important elements of financial market regulation.

From the perspective of geopolitical risks and macroeconomic stability, climate shocks, energy dependence, inflationary pressures, geopolitical conflicts, sanctions and supply chain instability significantly affect the trajectories of global decarbonization [3].

Geopolitical instability also significantly affects decarbonization trajectories. Energy dependence, supply chain disruptions, geopolitical conflicts, sanctions, and competition for critical minerals affect countries' ability to transition to a low-carbon economy [3]. Recent geopolitical tensions have accelerated the development of renewable energy and increased attention to strategic autonomy and energy security.

Step 3. Latent decarbonization potential modeling. In this study, a country's decarbonization potential is conceptualized as the integrated capacity of a national economic system to reduce greenhouse gas emissions while ensuring sustainable economic growth, financial stability, energy security, technological competitiveness and social resilience. Decarbonization potential reflects a country's ability to implement effective low-carbon transformations through the interaction of environmental, macroeconomic, institutional, technological, financial and geopolitical factors.

Therefore, we can state that theoretically, a country's decarbonization potential depends on several interrelated components:
– structure and carbon intensity of the national economy;
– level of renewable energy integration;
– technological and innovation potential;
– effectiveness of climate policy and quality of institutions;
– access to sustainable finance and green investments;
– geopolitical conditions and state of energy security;
– adaptability of the economic system to the risks of climate transformation.

And formally, decarbonization potential can be represented as a multidimensional function which extends Equation (2):

$$DP_i = f\left(EI_i, RE_i, TI_i, ESG_i, CR_i, R_i, CP_k\right), \tag{3}$$

where DP_i — decarbonization potential of country i;
EI_i — emissions intensity;
RE_i — renewable energy integration;
TI_i — technological and innovation capacity;
ESG_i — sustainability performance indicators;
CP_k — collaborative policy framework at cluster level k.

Very important to mention that CP_kreflects the degree of collaborative decarbonization intensity within cluster k, including harmonization of climate policy instruments; cross-border energy cooperation; shared technological diffusion mechanisms and coordinated financial frameworks for green transition. Therefore, both investment allocation and decarbonization potential are not purely country-specific processes, but are also shaped by cluster-level collaborative mechanisms that capture policy harmonization, financial coordination, and cross-country technological spillovers within groups of structurally similar economies. So, Equation (3) demonstrates that the decarbonization potential of countries cannot be assessed solely by emissions indicators, but requires a comprehensive consideration of economic, financial, institutional, technological and geopolitical characteristics. This function is intended to serve as a latent construct estimated through clustering and dimensional reduction techniques. through clustering and dimensional reduction techniques.

Step 4. Clustering methodologies and identification of decarbonization hubs. The fourth stage proposes clustering methods as analytical tools for identifying common decarbonization hubs across countries.

As countries differ significantly in economic structure, institutional quality, financial systems, and environmental characteristics, international cooperation is a prerequisite for effective climate governance [14]. Cross-border cooperation facilitates technology diffusion, climate finance, policy harmonization, and the integration of renewable energy. Hence, the decarbonization is increasingly emerging not only as an environmental imperative, but also as a strategic economic security mechanism that can strengthen national resilience and reduce geopolitical vulnerability.

Machine learning methods, in particular self-organizing maps, allow researchers to identify structurally similar decarbonization trajectories and form adaptive climate strategies. Clustering methods increase the accuracy of identifying structurally similar decarbonization trajectories [19].

It is proposed to consider the concept of common decarbonization hubs as a mechanism for coordinating regional low-carbon transformations. Consequently, countries can be grouped according to the set of following criteria:

– emission intensity;
– integration of renewable energy;
– energy dependence;
– ESG indicators;
– financial market structure;
– macroeconomic indicators;
– institutional quality;
– geopolitical risks.

This interpretation is consistent with modern multidimensional approaches to climate governance and adaptive economic transformation proposed in recent studies of decarbonization [19]. In this study, common decarbonization hubs can be defined as networks of countries with structurally similar economic, environmental, financial and energy characteristics that cooperate to achieve low-carbon transformation goals.

After obtaining clusters with composition of countries, it requires economic interpretation of clusters and diving into further categories as: high decarbonization efficiency economies to be names hubs, collaborative transition hubs, fossil-dependent economies, etc. These clusters may create analytical foundations for inter- and intra-cluster collaboration, facilitating green finance allocation strategies and regional or multiregional cooperation frameworks.

Therefore, analytical advantages of clustering methods are: identification of structurally similar countries, supporting adaptive climate policies between countries or clusters, optimizing the allocation of climate finance for countries in cluster or between clusters, improving international policy coordination among countries and forming common decarbonization hubs.

Discussion. Modern approaches for analysis of decarbonization demonstrate a transition from classical models of ecological economics to integrated interdisciplinary frameworks that combine the theory of externalities, financial mechanisms for sustainable development, macroeconomic approaches and machine learning methods. Therefore, decarbonization is considered not only as a tool for internalizing environmental externalities, but also as a systemic structural transformation of the economy.

The question of the sufficiency of traditional climate policy instruments (carbon taxes, ETS) to ensure long-term transformations remains debatable, since their effectiveness depends on the institutional quality and financial capabilities of countries. At the same time, the role of ESG investments and green financing as channels for accelerating the low-carbon transition is growing, therefore should be incorporated into analytical approaches.

The results of the study represent decarbonization as a systemic transformation process shaped by the interaction between financial systems, institutional capacity, technological development and geopolitical constraints. The clustering methods proposed to be used to identify major groups of countries, such as countries with highly efficient decarbonization economies and countries with economies in transition, etc. These clusters can provide a basis for identifying common decarbonization hubs that enhance the effectiveness of climate governance, technology diffusion and financial coordination between countries.

Conclusions and prospects for further research. Given the significant differences between countries in terms of economic development, institutional capacity, technological readiness and energy structure, the formation of common governance mechanisms that implement technology transfer, expand renewable energy, mobilize climate finance and coordinate policies is critical.

The study integrates the provisions of ecological economics, macroeconomic theory, sustainable finance and geopolitical analysis into a single analytical framework, allowing to consider decarbonization as both an environmental imperative and a strategic mechanism for economic transformation.

The proposed cluster approach allows to identify centers of common decarbonization among countries with similar environmental, financial, economic and geopolitical characteristics. The application of instrumental learning methods, in particular self-organizing maps, provides a fundamental basis for more adaptive and evidence-based climate policy-making and support for international cooperation.

At the same time, it is necessary to acknowledge the limitations of the study, which is largely conceptual in nature and does not include empirical validation on large data sets. Further research should be aimed at quantitative testing of the proposed model, the application of dynamic forecasting and artificial intelligence-based approaches, as well as scenario analysis of long-term decarbonization trajectories taking into account financial, technological and geopolitical factors.

ДОДАТКОВА ІНФОРМАЦІЯ

ФІНАНСУВАННЯ: Автори не отримували фінансування для цього дослідження.
ЗАЯВА ПРО ДОСТУПНІСТЬ ДАНИХ: Не застосовується.
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ЕКОНОМІЧНІ ОСНОВИ ДЕКАРБОНІЗАЦІЇ: ІНТЕРНАЛІЗАЦІЯ ЕКОЛОГІЧНИХ ЗОВНІШНІХ ЕФЕКТІВ ТА ВИЗНАЧЕННЯ ЦЕНТРІВ СПІВПРАЦІ З ДЕКАРБОНІЗАЦІЇ

Анотація. *Вступ. Дослідження розглядає концепцію розробки гібридного економіко-аналітичного підходу на основі машинного навчання для аналізу декарбонізації як багатовимірного процесу структурної трансформації, що інтегрує екологічні екстерналії, макрофінансову динаміку, геополітичні ризики та міжкраїнову неоднорідність країн. Запропонований підхід ґрунтується на теорії екологічної економіки, розширюючи її за допомогою методів кластеризації на основі даних для визначення структурно подібних шляхів декарбонізації та спільних центрів декарбонізаційного переходу для інтерналізації екологічних екстерналій.*

Мета. Метою дослідження є розгляд інтеграції відповідних теоретичних та методологічних напрямків зеленої економіки в єдину концептуальну модель для аналізу декарбонізації. Тому запропоновано поєднати теорію екологічних екстерналій, принципи макроекономічної ефективності, концепції сталого фінансування та ESG-інвестування, аналіз геополітичних та кліматичних ризиків, сучасні методи та механізми кластеризації та машинного навчання для спільного управління декарбонізацією як основу запропонованої концепції підходу.

Матеріали і методи. Методологічна основа складається з чотирьох взаємопов'язаних аналітичних етапів. Перший етап полягає у визначенні теоретико-економічної основи на базі теорії екологічних екстерналій Пігу, де декарбонізація інтерпретується як механізм корекції ринку, що враховує розбіжність між граничними приватними та соціальними витратами. На другому етапі пропонується скласти структурований міжкраїновий набір даних, що включає ключові показники, пов'язані з інтенсивністю викидів, інтеграцією відновлюваних джерел енергії, показниками ESG, розвитком фінансової системи, якістю інституцій та геополітичним ризиком. Третім етапом було запропоновано визначити інтегральну функцію потенціалу декарбонізації, яка охоплюватиме багатовимірні національні можливості переходу до низьковуглецевої економіки. Четвертим етапом запропоновано застосування методів машинного навчання без учителя, включаючи самоорганізовані карти (SOM), для класифікації країн у групи зі схожими показниками декарбонізації.

Результати. Емпірична логіка цієї структури свідчить про те, що декарбонізація – це не лінійний процес скорочення викидів, а системна трансформація, що формується взаємодією між фінансовими структурами, інституційним потенціалом, технологічним розвитком та геополітичними обмеженнями. Результати кластеризації здатні забезпечити таксономію країн, що характеризуються різними профілями переходу, включаючи держав із високоефективними економіками декарбонізації, держав з перехідними економіками та держав, економіки яких залежать від викопного палива. Ці кластери слугуватимуть аналітичною основою для визначення структурно подібних траєкторій декарбонізації та формування спільних центрів переходу до низьковуглецевого розвитку країн.

Дослідження робить внесок у літературу, інтегруючи економічну теорію екстерналій з класифікацією класифікації країн у групи зі схожими показниками декарбонізації на основі машинного навчання, пропонуючи єдину аналітичну основу для кліматичного врядування на основі доказів та сталої економічної трансформації.

Перспективи. Подальші дослідження мають бути спрямовані на кількісне тестування запропонованої моделі, застосування підходів на основі динамічного прогнозування та штучного інтелекту, а також сценарний аналіз довгострокових траєкторій декарбонізації з урахуванням фінансових, технологічних та геополітичних факторів.

Ключові слова: *декарбонізація, екологічні екстерналії, стале фінансування, кластеризація, машинне навчання, кліматичне врядування.*