CONCEPTUAL GOVERNANCE FRAMEWORK AND GAME-THEORETIC COORDINATION FOR COUNTRIES' DECARBONIZATION MANAGEMENT

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Abstract. This study examines the role of game theory and cooperative governance structures in macroeconomic decarbonization governance systems across countries. A conceptual framework for Decarbonization – Collaborative Planning, Forecasting and Replenishment (D-CPFR) is considered to support coordinated climate-related decision-making across countries with different assemblies as a solution to structural heterogeneity and uncertainty. The proposed method integrates three analytical levels: country clustering based on macroeconomic, energy and environmental indicators; artificial intelligence (AI)-based forecasting to identify nonlinear dependencies and structural patterns; and finally cooperative governance mechanisms that support coordinated policy interaction between countries. Thus, countries are grouped into homogeneous clusters that function as mutual governance units supporting coordinated planning, information exchange and climate strategy alignment. From a theoretical perspective, the study proposes a conceptual extension of the CPFR paradigm from supply chain coordination to global decarbonization governance. The interaction between countries is formally proposed to be interpreted as a cooperative game, where agents seek to maximize collective outcomes through coordination rather than independent optimization. This representation reflects the interdependence between policy decisions, investment flows, and technological transitions in the process of global low-carbon transformation. The main contribution of the study is the conceptual combination of clustering methods, AI-based forecasting tools and cooperative game-theoretic reasoning into a single analytical framework for decarbonization governance. The practical significance of the model is its potential application to support international climate coordination, improve the coherence of green investment strategies, and develop adaptive low-carbon development pathways at the macroeconomic level.

Keywords: decarbonization; game theory; cooperative governance; machine learning; clustering; neural networks; AI-based forecasting; CO_2 emissions.

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Introduction

Global decarbonization is increasingly becoming not only a technological or energy challenge, but also a problem of international collaboration, strategic interaction and multi-level governance. The high economic diversity of economies, differences in energy systems, uneven access to technologies and institutional imbalances significantly complicate the implementation of universal climate strategies. Under such conditions, decarbonization can be viewed as a multilateral cooperative game in which countries form their own strategies taking into account the behavior of other participants in the global system.

The effectiveness of climate policy largely depends on the ability of countries to coordinate low-carbon activities, transfer technologies, agree on investment decisions and form cooperative management mechanisms. This necessitates the transition from isolated national planning models to cooperative management systems based on network interaction, information exchange and cooperative decision-making between countries. At the same time, the development of technologies based on AI and machine learning methods offers new opportunities for forecasting complex climatic and economic processes. The use of self-organizing maps (SOM) may allow identification of structurally homogeneous groups of countries, while a multilayer perceptron may support modeling of complex dependencies between economic, energy and institutional factors of decarbonization.

In this context, the proposed Decarbonization – Collaborative Planning, Forecasting and Replenishment concept shows particular importance, which combines clustering, forecasting, collaborative management and elements of game theory into a single decision support system. Unlike traditional approaches, the model can allow formalization of both intra-cluster coordination between countries with similar structural characteristics and inter-cluster interaction, which includes the transfer of technologies, investments and management practices.

Within this approach, countries can coordinate decarbonization scenarios, form cooperative investment strategies and minimize transformational risks through collective decision-making mechanisms. At the same time, authors proposed the game-theoretic interpretation of the model to consider decarbonization processes as a task of finding a balance between economic costs, environmental goals and strategic interests of participants.

However, it is important to mention that this paper is a conceptual study and focuses on the development of an integrated support management system. Thus, the proposed D-CPFR architecture aims to provide a theoretical and methodological framework for future validation, empirical implementation, and testing.

Literature Review

The theoretical framework for international climate governance and decarbonization is based on research on the coordination of collective action and global environmental governance. Modern research increasingly conceptualizes

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decarbonization as a multi-level socio-technical transition that requires coordination among governments, firms, and international governance networks.

In this context, Barrett (2003) has emphasized that effective international environmental cooperation requires stable coordination mechanisms that can reduce incentives for free-riders in climate agreements. Also, Ostrom (2010) has emphasized the importance of multi-level institutional coordination to address complex environmental problems in the face of heterogeneity and uncertainty. Similarly, Nordhaus (2015) has demonstrated that coordinated international climate policy instruments and climate clubs can support more effective pathways to global decarbonization and reduce strategic asymmetries between countries.

Salimian and Salimian (2026) employ a game-theoretic framework to analyze carbon pricing and clean energy subsidy mechanisms, demonstrating that the effectiveness of low-carbon policies depends on strategic interaction and coordination among economic agents and regulatory authorities. Their results support the relevance of multi-level decision-making models in climate governance systems.

Belhadi (2026) examines blockchain-enabled carbon transparency in supply chains and finds that transparency mechanisms can improve signaling efficiency and reduce information asymmetry, thereby enhancing the effectiveness of decarbonization-related governance. This highlights the importance of reliable information flows in distributed sustainability systems.

Musonda et al. (2026) investigate the interconnected roles of digitalization, decentralization, and infrastructure decarbonization. The authors show that digital platforms and data-driven systems can support more coordinated investment and planning processes within energy transition governance structures.

Chen et al. (2026) analyze how supply chain ownership structures influence corporate CO_2 emissions, providing evidence that inter-firm relationships and governance structures affect emission outcomes. Similarly, Burzynska et al. (2026) demonstrate that board interlocks and corporate network structures may contribute to emission reductions through the diffusion of governance practices across firms.

Ben Belgacem et al. (2026) highlight the importance of green finance development and technological innovation in improving environmental outcomes under regulatory pressure. At the same time, Cheng and Jiang (2026) show that carbon trading systems may alter firms' risk perceptions, contributing to changes in carbon-related financial risk pricing. These findings indicate the importance of incorporating risk and financial dimensions into decarbonization governance frameworks.

Su et al. (2026) examine the trade-offs between carbon reduction policies and household welfare, demonstrating that climate mitigation policies may generate distributional and social welfare effects that must be considered in policy design.

Zhang et al. (2026) provide empirical evidence that supply chain digitalization contributes to reductions in corporate carbon intensity by improving information integration and operational efficiency. Wei and Wang (2026) further show that environmental regulation influences ESG performance through the mediating role of

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green innovation, emphasizing the importance of innovation-driven compliance mechanisms.

Overall, conducted literature review indicates that decarbonization is not only a technological or economic challenge but also a complex coordination problem involving information asymmetry, governance networks, financial mechanisms, and multi-level decision-making structures. Despite substantial progress in AI-driven and digital governance approaches, the integration of country-level clustering, nonlinear forecasting, and game-theoretic coordination within a unified macroeconomic decision-support framework remains insufficiently explored. This gap motivates the development of the proposed D-CPFR model as an integrated system for cooperative decarbonization governance.

Methodology

The aim of the article is to explore the possibilities of using the D-CPFR co-governance model and game theory tools to coordinate decarbonization processes and form adaptive international climate strategies. In accordance with the set goal, the study is aimed to accomplish tasks:

1. introducing the author's D-CPFR co-management model, which combines country clustering, nonlinear forecasting and mechanisms for coordinating decarbonization processes at the macroeconomic level;
2. reviewing and justifying the possibilities of using game theory tools to formalize intra-cluster and inter-cluster interaction of countries for the process of forming international climate strategies.

The general logic and sequence of implementation of the proposed approach are presented in Figure 1. This approach reflects the functional dependence between sets of input parameters and management decisions towards the low carbon transitions. The proposed structural model integrates cluster analysis methods, nonlinear forecasting, multi-criteria optimization and cooperative collaboration mechanisms, taking into account the structural heterogeneity of economies.

From a game theory perspective, the “Collaborative D-CPFR and Coordination” stage of the proposed approach (Fig. 1) can be interpreted as a multi-level cooperative game with incomplete information, in which countries formulate decarbonization strategies taking into account their own economic constraints, expected benefits, and the behavior of other participants in the system. In this context, intra-cluster interaction tends toward a coalition-based model of cooperation, while inter-cluster coordination exhibits the features of an asymmetric dynamic game involving mechanisms of technology transfer, investment interaction, and risk sharing.

The methodological logic of the study is based on a sequential transition from basic econometric analysis to cluster-specific artificial intelligence modeling and further integration of the results into a cooperative management system.

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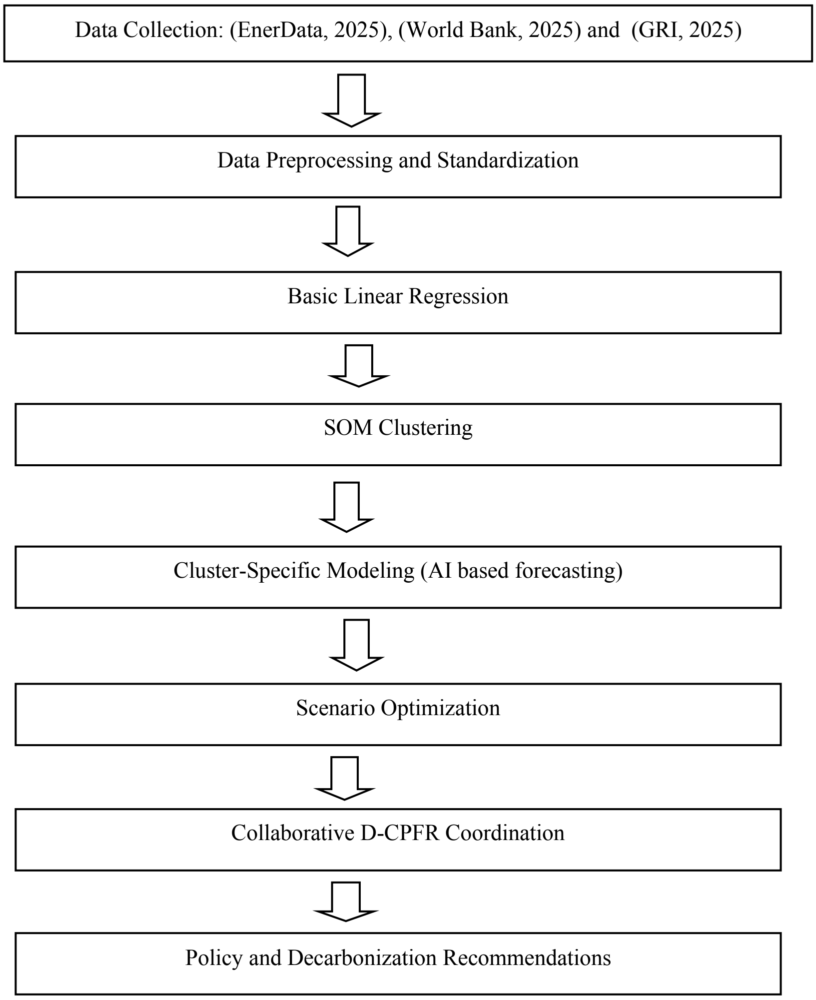

Figure 1. Conceptual architecture diagram of the D-CPFR collaborative governance model

Source: developed by author.

In this conceptual study, computational procedures may include modeling self-organizing maps, visualization of U-matrices, and agglomerative clustering of neuron weight vectors. These procedures are described as part of the methodological framework and can be implemented in Python using the MiniSom library, while visualization can be performed using Matplotlib and Seaborn, and hierarchical clustering can be performed using SciPy.

For a reproducibility-oriented design specification, the key parameters of the SOM are clearly defined, including a 16×12 neural network, an input dimension of 14 indicators(number may varies), a Gaussian neighborhood function, a learning

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rate of 0.5, a sigma of 1.0, and 5500 training iterations. The SOM initialization structure is illustrated as follows:

```
from minisom import MiniSom

som = MiniSom(
    x=16, y=12,
    input_len=14,
    sigma=1.0,
    learning_rate=0.5,
    neighborhood_function='gaussian',
    random_seed=42
)
```

The computational workflow and model specification are presented as a reproducible methodological design, consistent with the framework proposed by Matviychuk (2025) and Zhytkevych (2025a). Future empirical implementations of the D-CPFR framework may include a similar but updated dataset, model configurations, and computational scripts to support reproducibility, benchmarking and comparative validation. In this context, the framework assumes the integration of macroeconomic, energy, institutional, and environmental indicators including macroeconomic, energy, institutional and environmental indicators for 45 countries for the period 2015 – 2025 obtained from global open access datasets (EnerData, 2025; World Bank, 2025; GRI, 2025). To ensure statistical correctness, comparability of data, in accordance with the requirements of the employed software, and this procedure is integrated into the formalization of the model (Zhytkevych, 2025).

The framework conceptually incorporates multiple linear regression as a baseline analytical component, which is used as a basic model to assess the general dependencies between explanatory variables and the decarbonization potential indicator. Potential model evaluation should be based on indicators of R^2, MAE and MSE. However, linear specifications may have limited ability to capture hidden nonlinear dependencies due to complex hidden dependencies between factors, which necessitated the transition to more sophisticated approaches based on artificial intelligence.

However, in order to capture structural heterogeneity of economies, SOM can be applied at the next stage, which provide a nonlinear projection of the multidimensional feature space and allow the formation of structurally homogeneous groups of countries (Kohonen, 2013). The choice of SOM is justified by the algorithm’s ability to preserve topological relationships between observations, handle high-dimensional data and detect complex nonlinear structures. Prior to the application of SOM, the optimal number of clusters is determined using internal clustering validity metrics, in particular the Silhouette, Davies–Bouldin, and Calinski–Harabasz indices (Zhytkevych, 2025).

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After clusters formation, nonlinear forecasting using multilayer perceptron architectures was proposed for all clusters separately. This approach allows the model structure to be adapted to the characteristics of individual groups of countries and to increase the accuracy of forecasting decarbonization trajectories. The models were implemented in Python using the NumPy, Pandas, and Scikit-learn libraries, which ensures the reproducibility of results and the correctness of calculations (Zhytkevych O.V, 2025).

The main feature of the proposed approach is that clustering is considered not only as an analytical tool but also as a coordination and governance function. The resulting clusters are interpreted as an environment for collaborative interaction among countries with similar structural characteristics, which creates a basis for cooperative planning, information exchange, investment coordination, and alignment of decarbonization strategies. Countries are considered as interconnected agents within a unified network system, where forecasting processes are integrated with decision-making mechanisms grounded in cooperative game theory.

At the final stage of the structural model (Figure 1), a scenario space is constructed, encompassing political, investment, technological, and regulatory parameters of decarbonization. The selection of optimal scenarios is performed within a multi-criteria optimization framework, taking into account environmental, economic, social, and risk-related components. In this context, the interaction between countries and clusters can be interpreted as a cooperative game, in which participants form joint strategies to minimize total decarbonization costs, reduce risks, and achieve mutually agreed climate targets.

Thus, the proposed methodology forms an integrated approach architecture that combines tools of machine learning, econometric analysis, clustering, collaborative governance and game theory. This may support more adaptive and coordinated decision-making in the field of decarbonization at the macroeconomic level.

Results

A theoretical extension of the D-CPFR model is its interpretation through game theory, which allows the formalization of collaboration processes in decarbonization decision-making between countries both within and across formed clusters. Hence, countries do not operate in isolation but function as elements of an interdependent global system, in which decisions on climate policy, investments in green technologies, and energy sector transformation affect not only national outcomes but also the global dynamics of decarbonization.

In the proposed framework, decarbonization governance is considered as a multi-level coalition game in which countries coordinate strategies to reduce aggregate transition costs, share technological resources to achieve mutually beneficial climate outcomes.

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Accordingly, countries are considered rational agents that make strategic decisions regarding decarbonization scenarios, taking into account economic interests, risk levels, resource availability, and expected environmental outcomes of the proposed model. Under such conditions, the decarbonization process exhibits the characteristics of a cooperative game, in which the payoff of an individual country depends not only on its own decisions but also on the degree of collaboration with other participants in the system.

Within the proposed game-theoretic interpretation, each country or cluster is associated with a loss function L_k.The loss function $L_k$conceptually includes environmental costs, transition risks, investment expenditures, technological adaptation costs, and potential macroeconomic instability associated with the decarbonization process.

Accordingly, the payoff (gain) function of cluster or country k can be represented as the inverse of the associated loss function adjusted by the cooperation effect between countries. In a simplified form, the payoff function can be expressed as:

$$U_k = -L_k + \lambda Coop_k, \quad (1)$$

where U_k denotes the payoff function of country or cluster k; L_k is the aggregate decarbonization loss function, $Coop_k$ represents the cooperation effect among countries and λ is the coefficient of collaboration intensity.

As per proposed framework, countries seek to maximize their long-term payoffs through cooperative coordination mechanisms that reduce aggregate transition losses and improve the effectiveness of climate-policy implementation. Thus, increasing the level of cooperation between countries allows reducing the costs of decarbonization, minimizing the risks of technological transition and increasing the effectiveness of the implementation of climate strategies. In this context, cooperation is considered as a mechanism for forming a collective win of the system. Hence, the proposed model (Figure 1) can be interpreted as a multi-level cooperative game with incomplete information, within which countries form decarbonization strategies taking into account their own economic constraints.

Considering intra-cluster cooperation of countries can be presented as a coalition of countries with similar structural characteristics. Since, within one cluster, countries have a similar level of energy dependence, economic structure, institutional features and decarbonization goals, which creates the prerequisites for the formation of cooperative strategies. Such coalitions provide an opportunity to coordinate investment decisions, exchange technologies, agree on regulatory mechanisms and jointly plan the energy transition. In particulary, countries can implement several types of cooperative strategies for the intra-cluster coordination (Table 1).

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Table 1. **Intra-cluster cooperative strategies of countries**

Strategy	Description	Expected effect of collaboration
Cooperative technological transition strategy	coordination of renewable energy deployment, energy storage systems, and digital energy platforms among countries within the same cluster.	Technology diffusion
Coordinated investment strategy	formation of cooperative financing mechanisms for green projects, energy infrastructure development, and industrial modernization.	Lower transition costs
Data-sharing and digital integration strategy	creation of a unified information space for sharing CO_2 emissions data, energy balances, ESG indicators, and climate risk information.	Better forecasting
Adaptive policy coordination strategy	harmonization of regulatory mechanisms, tax incentives, carbon pricing instruments, and decarbonization standards.	Reduced policy asymmetry
Transformation risk minimization strategy	collective management of social, energy, and financial risks arising during the green transition process.	Lower systemic risk

Source: Developed by author

Inter-cluster coordination is implemented between countries or even clusters with different levels of decarbonization development and is asymmetrical in nature, based on the principles of technological complementarity and resource transfer. In this case, clusters with countries of high level of technological development can act as donors of innovation and investment for clusters with high carbon intensity (Table 2).

Table 2. **Inter-cluster strategies of countries**

Strategy	Description	Expected long term effect
Technology transfer strategy	transfer of low-carbon technologies from highly decarbonized clusters to clusters with high carbon intensity.	Faster decarbonization
Investment partnership strategy	allocation of green investments, climate funds, and ESG financing to countries with insufficient technological modernization.	Capital equalization
Knowledge-sharing strategy	exchange of managerial practices, digital solutions, ESG governance models, and climate adaptation mechanisms.	Institutional convergence
Infrastructure integration strategy	development of cross-border energy networks, logistics systems, hydrogen corridors, and smart-grid infrastructure.	Energy sustainability
Global decarbonization convergence strategy	coordination of climate trajectories between clusters to reduce structural disparities among countries and achieve a more balanced global energy transition.	Reducing global inequality

Source: Developed by author

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Discussion

From a game theory perspective, the interaction between countries or clusters within the D-CPFR approach cannot be adequately represented only as a zero-sum game, since the decarbonization process generates both individual benefits and aggregate system effects through technological transfers effects, knowledge transfer, and risk-sharing mechanisms (Nash, 1951). Nevertherless, due to country heterogeneity, information asymmetry and differences in technological readiness, some elements of international decarbonization interactions may partly reflect the characteristics of iterative coordination processes and environments with incomplete information. In this study, such interpretations are treated as additional extensions of the cooperative coalition structure, rather than as independent game-theoretic specifications.

Therefore, we cannot exclude that countries may face a classic conflict between short-term individual rationality and long-term collective efficiency, where non-cooperation may provide temporary benefits but worsens the aggregate welfare of the system. The presence of repeated interactions, reputational effects, and institutional pressure mechanisms creates the prerequisites for the formation of cooperative equilibria in the long run. Formally, such a system can be characterized by a multiplicity of Nash equilibria, including both non-cooperative equilibria and Pareto-optimal cooperative outcomes (Nash, 1951; Fudenberg & Maskin, 1986). In repeated games, the use of strategies such as “tit-for-tat” or “trigger strategies” can support cooperation and guide the system towards more socially efficient outcomes (Axelrod, 1984; Fudenberg & Maskin, 1986).

In addition, the presence of incomplete information about the costs, opportunities, and political preferences of other participants may lead to a Bayesian game formulation (Harsanyi, 1967–1968). In this case, the concepts of equilibrium refinement become relevant, in particular subgame perfect equilibrium, which describes the stability of strategies in dynamic interactions (Fudenberg & Tirole, 1991). Thus, D-CPFR can be viewed as a mechanism that structurally facilitates the transition to cooperative and Pareto-efficient equilibria by reducing information asymmetry and increasing the payoffs from coordinated strategies.

Overall, integration of game theory into the D-CPFR approach enables a transition from traditional forecasting to a model of AI-driven strategic decision-making, in which forecasting outputs serve as a basis for the coordination of management decisions. This shift increases the accuracy of decarbonization trajectory assessment and establishes a theoretical foundation for developing multi-level mechanisms of international climate cooperation. Accordingly, the game-theoretic interpretation extends the functionality of the D-CPFR model, positioning it not only as an analytical and forecasting tool but also as a framework for supporting collective decision-making, coordinating climate strategies, and managing global decarbonization processes.

Refering to the Table 1, five fundamental strategies are identified, however, the strategy’s quantity and specific configuration may vary depending on the participating countries and the nature of their cooperation. Collectively, these mechanisms enable countries to operate as a cooperative network, within which collaborative planning contributes to the reduction of the loss function (L_k) for all participants in the cluster, thereby avoiding zero-sum outcomes.

As shown in Table 2, the main mechanisms of inter-cluster interaction are strategies of technology transfer, investment partnership, knowledge exchange, infrastructure integration, which in the long term form the basis for the implementation of the strategy of global decarbonization convergence aimed at harmonizing climate trajectories between clusters and reducing the structural gap between countries.

Therefore, inter-cluster interaction can be interpreted as a dynamic cooperative game in which countries maximize collaborative gains by reducing the total costs of decarbonization, reducing risks and increasing the resilience of energy systems. At the same time, the effectiveness of such interaction depends on the level of institutional readiness, technological potential and the ability of recipient countries to adapt innovative solutions.

Conclusions

The article considers the D-CPFR model which combines methods of cluster analysis, machine learning, elements of game theory and cooperative management mechanisms for assessing and forecasting the decarbonization potential of countries. This approach takes into account the structural heterogeneity of economies, hidden dependencies between decarbonization factors and the scenario nature of climate transformations of countries.

The scientific novelty of the study lies in the conceptual integration of coordination principles based on CPFR with clustering approaches, artificial intelligence-based forecasting mechanisms and cooperative governance concepts within a single adaptive decarbonization management system. The proposed method conceptually demonstrates how the combination of clustering and complex modeling may lead to higher forecasting accuracy compared to traditional linear models and may support adapting models to the characteristics of individual groups of countries.

Within the proposed framework, clustering is interpreted as an analytical tool and a coordination mechanism , forming the basis for intra-cluster and inter-cluster interaction of countries in decarbonization processes. Based on the integration of game theory elements the decarbonization process is interpreted as a cooperative coalition-based coordination system in which countries align investment, technological and regulatory strategies in order to reduce aggregate transition costs, hence improving climate-policy effectiveness.

The practical significance of the model lies in the possibility of its use to support climate and energy policies, coordinate green investments, generate energy transition scenarios and develop collaborative management systems based on artificial intelligence. This approach is relevant for countries with transition economies, where a high level of structural instability requires adaptive forecasting and management tools.

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Prospects for further research are related to empirical validation of the model on extended panel data, development of digital platforms to support collaborative management of decarbonization and research into mechanisms of inter-cluster coordination in global climate policy.

Author Declarations

Conceptualization; Methodology; Formal analysis; Investigation; Writing – Olena Zhytkevych.

The author have read and approved the final version of the manuscript.

Conflict of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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Data Availability

This is conceptual study and does not rely on proprietary datasets. However, all data sources are supposed to be used in the future referenced in the manuscript are publicly available from international databases, including EnerData, the World Bank, and GRI.

Use of AI Tools

During the preparation of this manuscript, artificial intelligence tools (including ChatGPT and Google Translate) were used as supplementary instruments for language editing, text structuring and improving clarity of expression. No AI tools were used for generating research results or analytical outputs.

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КОНЦЕПТУАЛЬНА ОСНОВА УПРАВЛІННЯ ТА ТЕОРЕТИКО-ІГРОВА КООРДИНАЦІЯ ДЛЯ УПРАВЛІННЯ ДЕКАРБОНІЗАЦІЄЮ КРАЇН

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Анотація. У статті досліджується роль теорії ігор та кооперативного управління в системах макроекономічного управління декарбонізацією країнами. Запропоновано концептуальну основу для декарбонізації – спільного планування, прогнозування та компенсування (D-CPFR), а також концептуальну інтеграцію кластеризації країн, механізмів прогнозування на основі штучного інтелекту та структур міждержавної співпраці.

У рамках запропонованого підходу процеси декарбонізації формалізуються як багаторівнева система стратегічної взаємодії, яка поєднує аналітичне групування країн за допомогою кластеризації та нелінійного прогнозування на основі моделей нейронних мереж. Це дозволяє краще дослідити приховані структурні зв'язки між економічними, енергетичними та інституційними факторами, а також адаптувати моделі до конкретних груп країн.

З точки зору теорії ігор, модель пропонується інтерпретувати як багаторівнева кооперативна гра з неповною інформацією, в якій країни формують стратегії декарбонізації з урахуванням власних обмежень, очікуваних вигод та стратегічної поведінки інших учасників системи. Водночас внутрішньокластерна взаємодія країн набуває форми коаліційної співпраці, тоді як міжкластерна співпраця країн характеризується асиметричною динамікою, включаючи трансфер технологій, інвестиційні потоки та розподіл ризиків. Науковий внесок дослідження полягає в розширені концепції CPFR орієнтоване на глобальне управління декарбонізацією та формалізації внутрішньокластерної та міжкластерної взаємодії як кооперативної гри між країнами. Практичне значення моделі полягає в підтримці міжнародної координації кліматичних питань, підтримці інвестиційної співпраці та розробці адаптивних стратегій низьковуглецевого розвитку на макрорівні.

Ключові слова: декарбонізація; теорія ігор; колаборативне управління; машинне навчання; кластеризація; нейронні мережі; ШІ орієнтоване прогнозування; викиди CO_2.*)*

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