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STRUCTURAL AND FUNCTIONAL MODEL OF "BIOMETHANE" TRANSFORMATION OF THE ENERGY SECTOR OF UKRAINE

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Abstract. *The aim* of the article is to theoretically substantiate and develop a comprehensive structural and functional model of biomethane transformation of the energy sector of Ukraine. The research is aimed at overcoming the existing fragmentation of scientific approaches by forming a holistic concept that ensures systematicity, sectoral coherence and adaptability of transformation processes within the framework of the global decarbonization strategy. *Methodology*. The study is based on a systems approach and tools of structural-functional analysis, which allowed interpreting the energy transformation as a complex socio-technical-economic system. To visualize synergistic effects, conceptual and spatial modeling methods were used, which provide a reflection of the interaction between key subsystems. The methodological basis was expanded by a comparative analysis of traditional and modern energy models, taking into account the transition to renewable energy sources. Special attention was paid to nonlinear relationships between subsystems, which allowed adapting the logic of the inter-sectoral model "input-output" by W. Leontief to explain the dynamic structural exchange of resources, capital and knowledge within the energy cluster. *Results*. A three-vector structural-functional model of biomethane transformation has been developed, which is based on the hierarchical interaction of institutional (regulatory "rules of the game"), economic (motivational and financial levers) and technological (production and infrastructure contour) components. It has been proven that the efficiency of transformation is nonlinear: any asymmetry in the development of subsystems – for example, technological renewal without institutional stability or financial incentives – levels the systemic result. It has been established that the critical condition for maximizing the integral effect is the spatial and temporal synchronization of the above factors, which allows for the formation of a sustainable energy ecosystem. At the same time, it is shown that the introduction of innovative technologies for cleaning and enriching biogas to the level of biomethane, as well as its integration into the existing gas transportation infrastructure, provide a multiplicative effect, which is manifested in increasing energy efficiency, diversifying energy sources and stimulating the development of related industries, primarily the agricultural sector of the economy. *Practical implications*. The proposed model forms a reliable conceptual basis for the development of effective state policies, investment programs and strategies for the post-war restoration of the energy sector of Ukraine. The practical application of the model will allow optimizing the regulatory environment, reducing investment risks and increasing the predictability of the functioning of the biomethane market. An important aspect is the possibility of using the model as a decision-making support tool for the development of public-private partnerships, which will contribute to the activation of investment activities and the acceleration of the implementation of innovative technologies. *Value/Originality*. The originality of the research lies in the departure from the fragmentary study of the «biomethane» transformation and the formation of a single concept that combines institutional, economic and technological aspects within a holistic model. The proposed approach expands the theoretical foundations of the study of energy transformations, substantiating them as a process of forming a new system of sustainable and renewable value creation. This

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allows us to consider biomethane not only as an alternative energy source, but also as a strategic resource for the structural modernization of the Ukrainian economy in the face of global climate challenges.

Keywords: biomethane, energy transformation, structural-functional model, sustainable development, energy security.

JEL Classification: Q42, Q56, D02, Q55, C67

1. Introduction

The transformation of the energy sector of Ukraine towards the development of the biomethane industry is a complex multi-level process, which is formed on the basis of the principles of sustainable development and innovative transformation of the economy. In this context, the need to form a holistic scientific approach to modeling the relevant transformation processes becomes particularly important. An analysis of modern scientific sources indicates a significant interest of researchers in individual aspects of this issue, while comprehensive approaches remain insufficiently formed.

The theoretical basis of the study is formed by scientific works devoted to the development of a "green" economy as a basis for sustainable economic growth. In particular, the works (Tomashuk et al., 2023) substantiate the role of greening economic processes, while (Kaletnik & Lutkovska, 2020a) emphasize the need to implement innovative environmental strategies as a tool for ensuring long-term sustainability of the economy.

An important area of research is the adaptation of these approaches to the functioning of the agro-industrial complex as a key supplier of raw materials for biomethane production. The work (Tokarchuk, 2025) formed a concept for the development of the agro-industrial complex on the basis of a "green" economy, which involves the ecologization of production and increased resource efficiency. In this case, the determining factors are rational land use and investment support. Thus, the study (Zaremba et al., 2025) carried out modeling of capital investments in the sustainable development of land resources, and the work (Kaletnik et al., 2020b) summarized the world experience in regulating land relations in the context of sustainable development.

The formation of biomethane energy is directly related to the activation of innovative and digital transformations. The works (Tomashuk et al., 2025a) explore the tools of economic stimulation of innovative development of the agricultural sector, while (Tomashuk et al., 2025b) reveal the role of digital technologies in increasing the efficiency of agribusiness. In this context (Okhota et al., 2024) propose a multi-component model of the innovation mechanism for increasing the competitiveness of enterprises, which can be adapted to the conditions of biomethane transformation. Additionally, the use of expert systems to substantiate strategic decisions (Chikov & Titov, 2025) and the integration of ESG criteria into the management system (Honcharuk et al., 2025) form a methodological basis for building effective management models.

The relevance of the study is significantly enhanced under martial law and the need for post-war reconstruction of Ukraine. The paper (Tokarchuk et al., 2024) substantiates the feasibility of using the principles of the "green" economy as a basis for the recovery of the national economy. At the same time, "green" cooperatives can act as an important organizational tool for the implementation of biomethane projects (Shpykuliak & Bilokinna, 2019), which ensure the consolidation of resources and increase the efficiency of the introduction of alternative energy.

Despite the significant amount of scientific research, it should be noted that there is no systematic approach to the formation of a structural and functional model of biomethane transformation of the energy sector of Ukraine. Existing scientific developments are mostly focused on individual elements – environmental, investment, innovative or institutional – without their proper integration into a single model. This necessitates the development of an integrated approach that would take into account the relationships between structural components and functional mechanisms of transformation.

Thus, the formation of a structural and functional model of biomethane transformation of the energy sector of Ukraine, which will ensure the systematic, coherence and adaptability of transformation processes, is an urgent scientific task and determines the direction of further research in this area.

2. Results

2.1. Conceptual Foundations of Biomethane Transformation

Biomethane transformation as a process of large-scale transition to the use of biomethane is an important element of the global strategy of decarbonization and energy modernization. In our opinion, it is advisable to consider this process not as a set of individual innovations, but as a complex socio-technical-economic system, within which the spread of technologies is determined by the synergistic interaction of three fundamental groups of factors: institutional, economic and technological.

A comprehensive analysis of their structure, functional content and relationships creates the basis for the formation of a conceptual model capable of explaining the mechanisms of development of this area. The focus on these groups of factors is justified by their system-forming and complementary role in the formation of an ecosystem that ensures the commercialization and integration of biomethane into the country's energy system.

Each of the components performs a separate, but interrelated function: the institutional factor provides regulatory certainty, stability of regulatory conditions and long-term predictability of market development; economic determines the investment attractiveness and financial feasibility of the production and commercial use of biomethane; technological forms the material and technical basis for the transformation of biomass into an energy product with high added value (Figure 1).

The institutional component is of particular importance in this system, since it determines the parameters of the functioning of technological and economic mechanisms, setting the general conditions for their implementation. Through the establishment of formal norms, procedures and organizational mechanisms, the institutional environment structures the interaction of all market entities and forms the basis for the stable development of the industry.

Institutional factors act as a system-forming basis for biomethane transformation, forming the regulatory and organizational framework for the functioning of all participants in the relevant market. Within the framework of the proposed model, they are considered as "rules of the game" that determine the permissible limits of economic interaction, the level of incentives and the nature of responsibility of business entities – from biomass producers to consumers and gas infrastructure operators.

Conceptually, institutional factors should be structured according to several interrelated subsystems:

– firstly, the legislative and regulatory subsystem, which includes national acts and international regulatory documents that determine the strategic guidelines for the development of renewable energy. Such documents form long-term goals, establish quantitative indicators and determine mechanisms for supporting the energy sector. In particular, European Union regulations create a coherent legal framework for incentivising the use of energy from renewable sources by laying down binding targets and rules for the operation of support schemes. Such regulatory initiatives play the role of catalysts, as they form predictable conditions for market development and create regulatory demand for biomethane as an energy product (Shpykuliak et al., 2019; Shpykuliak et al., 2023);

– secondly, the regulatory and procedural subsystem, which directly determines the conditions for the implementation of investment projects in the field of biomethane production and transportation. It includes rules for connecting to gas transmission and distribution infrastructure, mechanisms for distributing connection costs, procedures for obtaining permits, quality standards and requirements for product certification. It is this component that forms the operational environment for the functioning of projects and significantly affects their economic feasibility. Clarity, transparency, and stability of regulatory procedures are key prerequisites for attracting long-term investment, as institutional uncertainty increases transaction costs and reduces the attractiveness of the industry to investors (Uddin et al., 2023; Dotsiuk et al., 2024);

– thirdly, the institutional and infrastructural subsystem, which covers the efficiency of the functioning

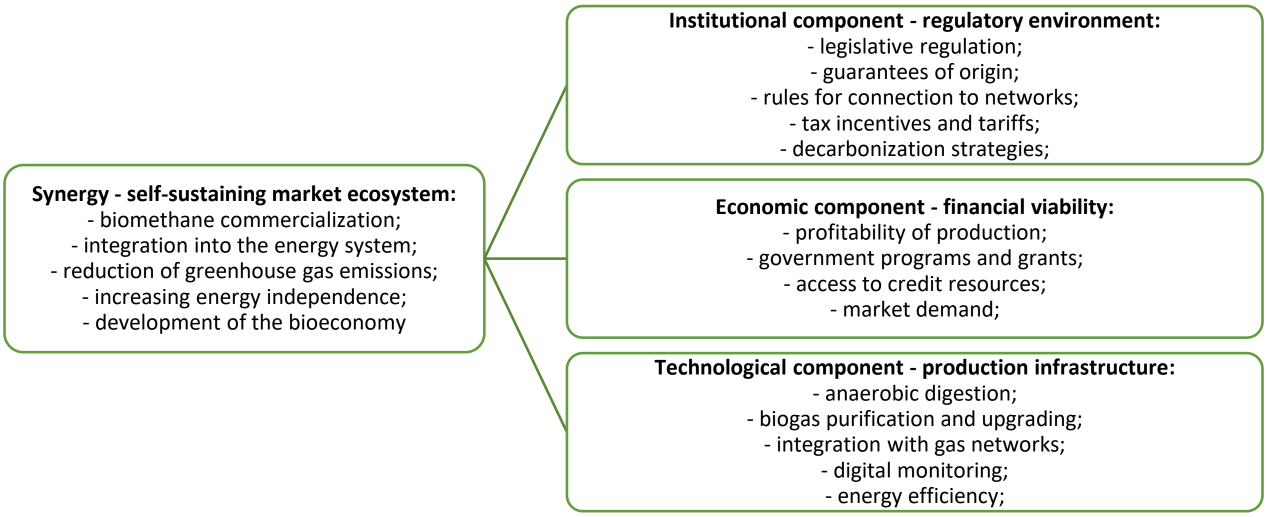

Figure 1. Structural model of components of biomethane transformation

Source: compiled by the authors based on (Kaletnik et al., 2025; Dotsiuk et al., 2024; Tokarchuk et al., 2024; Tomashuk, et al., 2025b) of state governing bodies, the level of coordination between institutions, mechanisms for supporting innovations, as well as the general characteristics of the institutional environment – in particular, political stability, the level of corruption risks and the quality of governance. This component determines the ability of the system to ensure the implementation of normative decisions and turn strategic goals into practical results (Kaletnik et al., 2022; Zakharchenko et al., 2024).

Summing up, institutional factors form the basis of biomethane transformation, since they determine the rules of market functioning, the level of trust of participants and the predictability of economic conditions. Their consistency and stability are a necessary prerequisite for the activation of economic incentives and the effective implementation of technological solutions within the framework of a holistic structural and functional model.

Economic factors play the role of a motivational and financial mechanism for biomethane transformation in the structural-functional model. They determine the ability of the energy sector to generate economic value, ensure the reproduction of investments and form competitive advantages compared to traditional energy resources. In systemic logic, the economic component is the element that transforms institutional capabilities and technological solutions into a sustainable market result.

The economic component of biomethane transformation has a multi-level nature and covers both the parameters of the general economic environment and the internal characteristics of the effectiveness of specific projects. Accordingly, it is advisable to consider these elements through the prism of their influence on the transformation process, which makes it possible to distinguish the external conditions for the functioning of the energy sector from its internal economic indicators. A generalized characteristic of macro-, meso- and microeconomic components is given in Table 1.

The above decomposition demonstrates that the economic subsystem functions as an integrated mechanism for the interaction of external conditions and internal characteristics of projects. The consistency of macro-, meso- and microeconomic parameters determines the overall level of resilience of the energy sector and forms the prerequisites for its scaling (Okhota et al., 2024).

Within the framework of the proposed model, economic mechanisms of state and supranational regulation, which perform the function of correcting market imbalances, are of particular importance. These include tax incentives, subsidy instruments, guaranteed buyback mechanisms, and premium support models. Their systemic role is to reduce investment risks, increase the predictability of income and create conditions for scaling up production (Tomashuk et al., 2025a; Zaremba et al., 2025).

At the same time, the effectiveness of economic instruments depends on their consistency with the institutional environment and technological potential. Excessive or unsystematic stimulation can lead to distortion of market signals and a decrease in the long-term effectiveness of transformation (Dotsiuk et al., 2024; Uddin et al., 2023).

Within the framework of the structural-functional model, the economic component forms the motivational circuit of biomethane transformation, providing a transition from potential opportunities created by the institutional environment and technological innovations to real market results. Therefore, economic factors should not be considered in isolation, but as an element of an integrated

Table 1
Structure of economic factors of biomethane transformation by levels of influence

Main purpose	Key economic factors	System role
Macroeconomic level		
Formation of the external environment and national conditions	– price dynamics of energy resources; – cost of capital (discount rate); – investment climate; – tax and customs policy; – inflation expectations.	Determines the general conditions for strategic investment decision-making and the level of systemic risk
Mesoeconomic level		
Formation of local value chains and infrastructure conditions.	– concentration of the raw material base; – development of local infrastructure; – the state of related industries; – logistics potential of the region	Determines the spatial (geographical) and infrastructural capacity of project implementation in a particular region
Microeconomic level		
Ensuring the internal efficiency of specific investment projects.	– cost structure, technology productivity; – capacity utilization; – the cost of attracting raw materials; – management level	Forms the immediate financial viability, profitability and competitiveness of the enterprise

Source: compiled by the authors based on (Chikov et al., 2022; Tomashuk et al., 2023; Kaletnik et al., 2025) system that provides a balance between stimulation, competitiveness and sustainability of development (Shpykuliak & Bilokinna, 2019; Kaletnik et al., 2025).

Technological factors form the production basis of biomethane transformation and ensure the effective conversion of biomass into an energy product. In this logic, the technological component acts as a mechanism of implementation that transforms institutional prerequisites and economic incentives into the final production result (Kaletnik et al., 2022; Tomashuk et al., 2025b).

The technological dimension of biomethane transformation is formed as a coordinated set of interrelated components that determine the internal logic of the production process. Their interaction ensures not only the technical implementation of biomass transformation, but also stability, reproducibility and scalability of the results. In this context, it is advisable to conceptually outline the main components of the technological circuit, which systematize its structure and functional purpose (Table 2).

As you can see, the technological component of biomethane transformation is complex and is not reduced to separate engineering solutions. Its elements form a single production system, within which there is a consistent transformation of raw materials into a standardized energy product.

The basic element of the biomethane transformation process chain is the combination of the processes of anaerobic conversion of biomass and subsequent purification of the resulting gas to a level suitable for integration into the gas network or use as a transport fuel. In the system interpretation, it is the purification stage that determines the final parameters of the product, its market suitability and competitiveness (Kaletnik et al., 2022; Tokarchuk, 2025).

Technological development in this area is characterized by a variety of methods and approaches, differing in energy efficiency, capital intensity and scalability. The choice of a specific technology affects not only the production indicators, but also the economic structure of the project, which emphasizes the close relationship between the technological and economic subsystems of the model (Kaletnik et al., 2025; Sakhno et al., 2023).

The infrastructural dimension of the technological factor acquires special importance. It includes: access to gas transmission and distribution networks; availability of compressor capacity; storage and transportation capabilities; technical compatibility with end users. The lack of the necessary infrastructure can create systemic barriers to the development of Ukraine's energy sector, even if effective production technologies are available. Thus, the technological component in the model is not limited to the level of equipment, but covers the entire production and infrastructure ecosystem (Tokarchuk et al., 2024).

In addition, in the long term, the human and organizational dimension of technological development plays a decisive role – the level of qualification of personnel, the ability to maintain maintenance, innovative susceptibility and readiness for modernization. A low level of competence or insufficient service support can neutralize the advantages of even advanced technological solutions (Shpykuliak et al., 2023).

Within the framework of the proposed structural and functional model, technological factors form the executive circuit of the biomethane transformation system. Their efficiency determines the scale of production, the stability of functioning and the potential for the integration of biomethane into the energy infrastructure, and therefore directly affects the value of the integral transformation indicator (Okhota et al., 2024).

In order to structurally generalize these provisions and reflect the multidimensionality of the influence of factors, a systematization of their components is presented below, taking into account the nature of the action and applied indicators (Table 3).

The presented systematization demonstrates that each group of factors has an internal structure and a different nature of influence on the transformation process. At the same time, their significance is

Table 2
System of technological factors of the structural-functional model of biomethane transformation

Process loop component	Systemic role in transformation	Key content of influence	Level of manifestation
Level of technological maturity of processes	Basic feasibility parameter	Determines the readiness of the technology for industrial scaling	Strategic
Raw material conversion efficiency	Efficiency of the production cycle	Characterizes biomethane yield and resource productivity	Operating
Equipment reliability	Stability of the system functioning	Affects production continuity and downtime risks	Technical
Innovative potential for improvement	Development dynamics	Determines the possibility of technological modernization and increasing competitiveness	Promising
Infrastructural provision of production and transportation	Integration function	Provides network connectivity, storage, and logistics	System

Source: compiled by the authors based on (Kaletnik et al., 2020b; Tomashuk et al., 2025a; Honcharuk et al., 2025)

Table 3
Multidimensional matrix of structural and functional criteria for the development of the biomethane industry

Subsystem	Nature of influence	Key criteria and practical dimension	System connections
Institutional (I)			
Legislative support	Strategic-stimulating	Framework laws, target indicators, harmonization with international law.	Creates regulatory demand (E); sets basic standards (T).
Regulatory environment	Barrier or supportive	Grid connection rules, transparency of permitting procedures.	Affects project speed and operational attractiveness (E, T).
Institutional infrastructure	Organizational-coordinating	State registries, guarantees of origin, protection of investors' rights.	Legitimizes processes for market monetization (E).
Economic (E)			
Macroeconomic conditions	Systemic	Cost of capital, energy prices, inflation, sovereign risks.	Determines the cost of financing for infrastructure (T).
Mesoeconomic conditions	Local (regional chains)	Logistics, local network capacity, raw material availability.	Limits production scale (T); forms logistics costs (E).
Microeconomic conditions	Endogenous	Unit cost, ROI, profitability, commercialization of by-products.	Relies on tech efficiency (T); regulated by tax framework (I).
Economic mechanisms	Motivational	State credit programs, grants, tax and customs incentives.	Compensates high costs of innovations (T); driven by (I).
Technological (T)			
Production technologies	Basic	Energy efficiency, biomass yield, modern generation technologies.	Forms CAPEX and OPEX structure (E).
Cleaning (Upgrading)	Transformational	Final product purity, biogas upgrading systems, loss minimization.	Ensures compliance with standards (I) for market entry (E).
Tech. infrastructure	Integrative	Pipeline capacity, network reliability, commercial metering.	Physically connects production (T) with end markets (E).

Source: authors' development

determined not only by individual parameters, but by the cumulative interaction within a single system environment. It is this multi-level configuration that creates the prerequisites for building an integrated structural and functional model that reflects the mechanism of interconnection between the institutional, economic and technological components of biomethane transformation.

2.2. Three-vector Structural and Functional Model of Biomethane Transformation

To adequately reflect the complex systemic nature of biomethane transformation, a three-vector structural and functional model has been developed, which interprets the process as an integrated multi-level system with mechanisms of direct and reverse influence. Conceptually, the model abandons the linear interpretation of transformation and considers it as a dynamic structure with iterative relationships between elements.

Thus, within the framework of the model, three functional subsystems are distinguished: technological, economic and institutional. Their interaction forms a closed circuit of the transformation process, in which the output parameters of one subsystem become input conditions for others. Such a structure ensures the circulation of resources, financial flows, information and regulatory impulses (Figure 2).

The technological subsystem performs the function of material implementation of biomass transformation and the formation of the final product. Its parameters are determined by technological factors and directly affect production volumes, the quality of biomethane and the possibility of its integration into the infrastructure (Kaletnik et al., 2022; Tomashuk et al., 2025b).

The economic subsystem provides a mechanism for financial interaction, the formation of incentives and the rational distribution of resources within the system. Its functioning is determined by the interaction of institutional and technological conditions that form the cost structure, affect the level of profitability and determine the investment attractiveness of projects. The economic circuit plays the role of a transformational intermediary between the production subsystem and the sphere of final consumption, ensuring the coordination of production volumes with solvent demand and strategic development goals (Tomashuk et al., 2025a; Zaremba et al., 2025).

The institutional subsystem forms regulatory frameworks, standards and regulatory mechanisms that determine the permissible parameters of the functioning of other elements of the system. Its role is to establish the rules of interaction, ensure the stability of the environment and reduce systemic uncertainty. Institutional influence has the character of an external regulator that sets the structure of possible economic

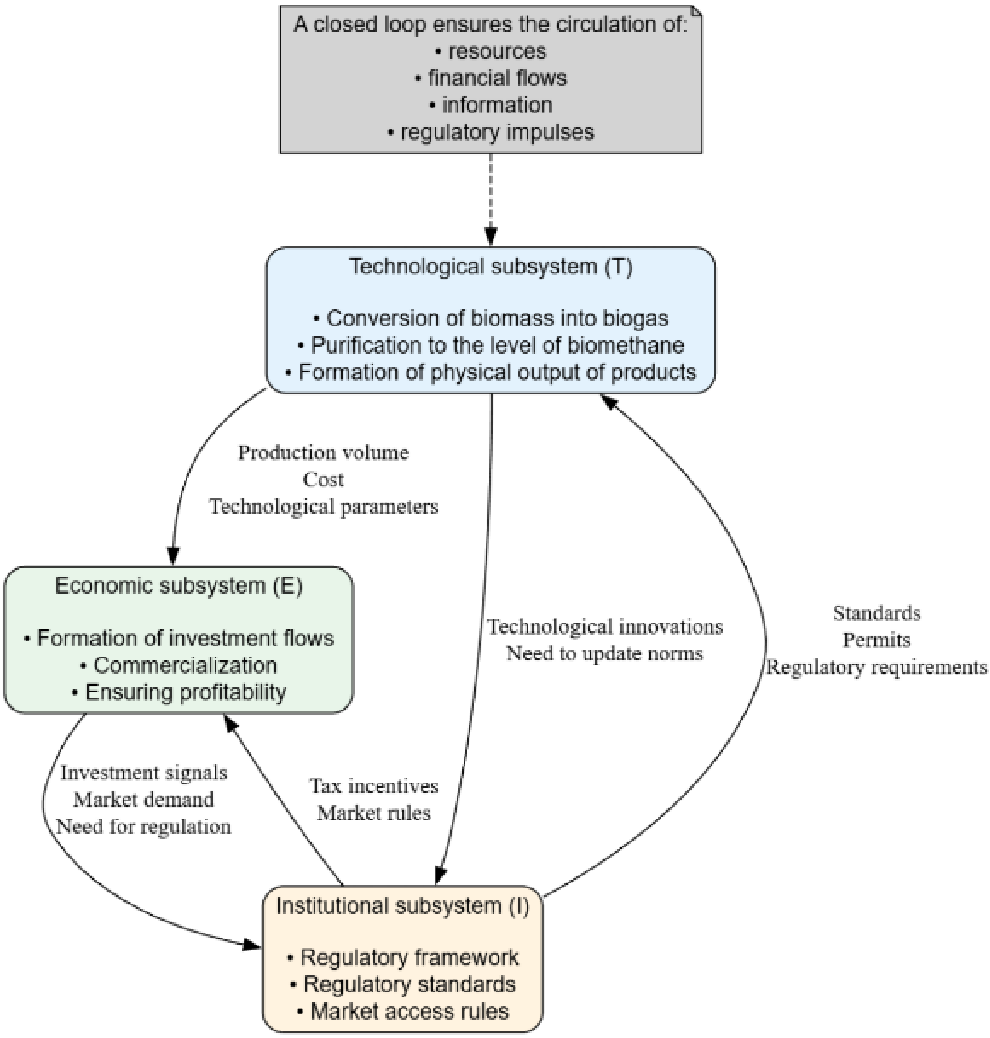

Figure 2. Three-vector structural and functional model of biomethane transformation

Source: authors' development

and technological decisions (Dotsiuk et al., 2024; Shpykuliak & Bilokinna, 2019).

Thus, the three-vector model reflects not a hierarchical, but a network type of organization, within which there is no dominant center, and systemic stability is achieved through balance and mutual consistency of functional relationships. The proposed approach allows us to interpret biomethane transformation as an integral, multi-level system of interconnected subsystems: the institutional subsystem sets the regulatory and strategic framework of functioning; economic forms a system of incentives and mechanisms for redistributing resources; technological provides material and technical implementation of production and conversion processes; And the contour of integration of consumption and infrastructure inclusion ensures the integration of the result into the overall energy architecture (Okhota et al., 2024; Honcharuk et al., 2025).

The totality of these interactions forms an integrated configuration in which each subsystem simultaneously affects the depth of transformational changes and is counteraffected by the entire system, forming the effect of mutual reinforcement or restraint of development (Sakhno et al., 2023).

Within the framework of the proposed architecture, biomethane transformation is interpreted as an integrated result of the interaction of institutional, economic and technological contours, which allows it to be presented in a functional form (1):

$$BT = f(I, E, T) \qquad (1)$$

where BT (Biomethane transformation) is an integral index of biomethane transformation, reflecting the generalized level of systemic integration of biomethane into the energy space. In the case of operationalization, it can be represented by the share of biomethane in the energy balance, the volume of its production or the degree of infrastructure integration; I (Institutional index) is an aggregate index of institutional quality, which characterizes regulatory stability, efficiency of regulatory mechanisms and the level of state support for the energy sector; E (Economic index) is a consolidated indicator of economic viability, reflecting the investment attractiveness, availability of financial resources and market feasibility of projects; T (Technological index) is an integral assessment of technological maturity, efficiency of production processes and infrastructural capacity for the integration of produced biomethane.

The proposed dependence reflects the synergistic nature of the transformation process, within which the overall result is formed not by simple aggregation of the influences of individual components, but through their structural interaction and mutual reinforcement. Thus, the formula performs a conceptual and analytical function and serves as a generalized expression of the integrative nature of the model.

The synergistic structure of the model allows us to consider it as a basis for the formation of managerial logic for the development of the biomethane sector. Since each of the components is potentially manageable within the framework of the relevant policies – through regulatory decisions, economic incentives or technological modernization – there is a possibility of purposeful influence on the parameters of the system in order to increase its integral result.

In this context, the model can be interpreted as a multifactorial system with a target function (2):

$$BT \to max \tag{2}$$

where max – is the achievement of the highest level of systemic integration of biomethane into the energy space under the existing institutional, economic and technological constraints.

2.3. Nonlinear Nature of Interaction and Synergistic Effect

The nonlinear nature of the $f(I,E,T)$ function emphasizes that the influence of each of the factors is not autonomous and deterministic in isolation from the general state of the system. The result of changing one parameter is formed in the context of the configuration of other components, which determines the presence of mutual reinforcement or, conversely, neutralization effects. In such a structure, the transformation process acquires the properties of systemic interdependence, where the key importance is not a separate influence, but their coordinated combination (Table 4).

As evidenced by the analysis of the multidimensional matrix (Table 4), institutional, economic and technological factors are closely intertwined. However, linear or tabular analysis of each subsystem allows you to evaluate only paired relationships, leaving out the integral (cumulative) result of their interaction. In practice, transformation processes often face the problem of asymmetric development. For example, the availability of advanced technological solutions (high level of the T-axis) in the absence of transparent institutional rules (low level of the I-axis) and effective financial incentives (low level of the E axis) does not lead to the launch of a full-fledged market, but only generates local, non-scalable projects with a high level of risk.

Therefore, for a successful biomethane transformation, it is critically important not just the parallel development of individual components, but their spatial synchronization. To clearly demonstrate this hypothesis and visualize the concept of nonlinear growth, it is advisable to move from matrix deconstruction to spatial modeling (synthesis).

Figure 3 proposes a spatial 3D model of the synergistic effect of biomethane transformation. In this coordinate system, each axis is responsible for the state of development of a particular component, and the volume and color of the sphere at the corresponding points in space reflect the scale of the resulting effect.

This visualization proves the key thesis of the study: maximization of the integral effect is achieved exclusively at the point of absolute intersection (1, 1, 1), where technological readiness, economic feasibility and institutional support

Table 4
Nonlinear nature of the interaction of factors in the model *BT*

Change of one factor	Status of other factors	Probable effect on *BT*	System interpretation
Decrease in technological costs ($T\downarrow$)	Low level of (E) or presence of institutional barriers (I)	Limited or no growth (BT)	Technological progress without economic and institutional support does not generate a systemic effect
Decrease in technological costs ($T\downarrow$)	High (E) and favorable (I)	Significant growth (BT)	Synchronized development of components generates synergy
Strengthening of economic incentives ($E\uparrow$)	Low level of (T) or weak coordination (I)	Market imbalances, inefficient investments	Excessive incentives without technological readiness may cause structural distortions
Improvement of institutional environment ($I\uparrow$)	Insufficient level of (E) or (T)	Slow or incomplete transformation	Institutional stability is a necessary but not sufficient condition
Coordinated growth (I, E, T)	System balance	Maximization of the integral effect (BT)	A synergistic effect is achieved

Source: authors' development

form a self-sustaining synergy. Any other scenarios (isolated movement along only one or two axes) lead to structural imbalances, slow transformation or inefficient allocation of investments.

The above interaction scenarios demonstrate that biomethane transformation has a pronounced nonlinear character and is determined not by isolated changes in individual parameters, but by their structural coherence. Each of the factors – institutional, economic and technological – is capable of influencing the level of the integral indicator BT, but its effectiveness significantly depends on the state of other components of the system. In case of imbalance between subsystems, the effects of partial compensation or structural constraints that restrain the overall result. Instead, under the conditions of synchronous development of all three components, a synergistic effect is formed, which ensures the maximization of the integral level of transformation.

On the basis of the above provisions, it is possible to draw a methodological parallel with Leontief's intersectoral model of "input-output" (Tsirimokos, 2025). Just as in the intersectoral balance each industry simultaneously acts as a producer and consumer of resources from other sectors, institutional, economic and technological subsystems within the biomethane transformation are in a state of mutual structural exchange (Lach et al., 2025). Here, none of them functions autonomously: the development of one element inevitably creates the need for adaptation of others, forming a system of internal dependency coefficients. In this context, it is advisable to interpret the three-vector model as a simplified intersectoral system, where each component simultaneously generates a transformational impulse and acts as a condition for the implementation of the effects of other subsystems (Okhota et al., 2024).

To formalize the structure of biomethane transformation, in our opinion, it is advisable to present it as a set of interconnected components in vector form, which allows you to reflect the internal configuration of the system without losing its integrity (3).

$$X = \begin{pmatrix} I \\ E \\ T \end{pmatrix} \qquad (3)$$

where X is the vector of the state of the system, I is the institutional subsystem, E is the economic subsystem, T is the technological subsystem.

Since the development of each component depends on the state of other subsystems, it is advisable to take into account the internal coefficients of mutual influence. This allows the effects of synergy, coherence and structural balance between subsystems to be reflected (4).

$$X = AX + Y \qquad (4)$$

where $X = (I, E, T)^T$ is the vector of the state of the system, A is the matrix of structural interdependencies, Y is the vector of external impulses of development

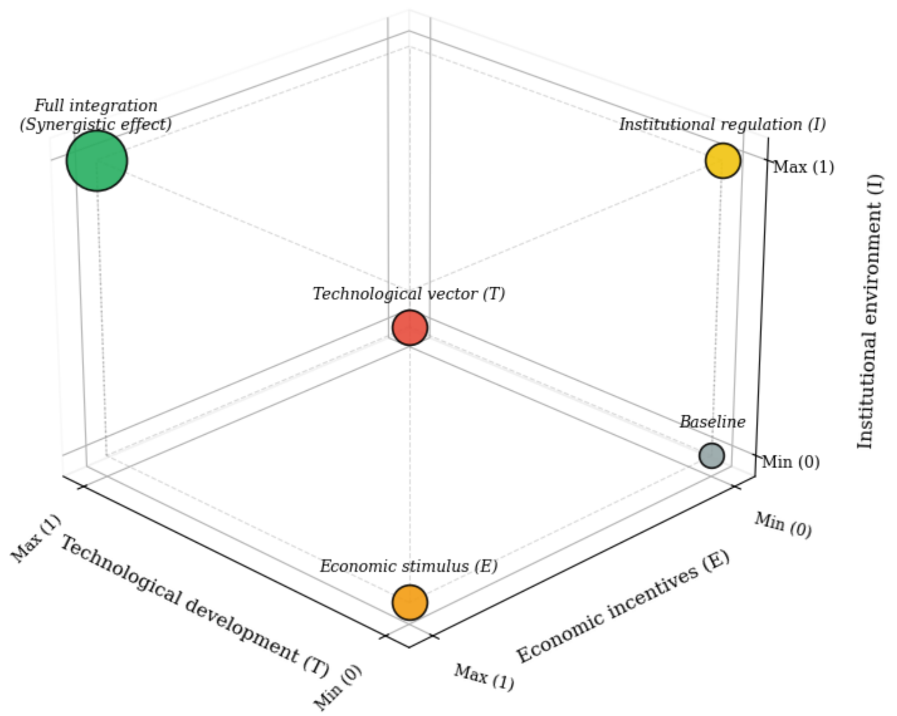

Figure 3. 3D model of the synergistic effect of biomethane transformation

Source: authors' development

(state support, investments, international incentives, etc.

In this case, matrix A reflects the degree of influence of each subsystem on the other components of the system. Its structure allows us to interpret the biomethane transformation by analogy with the "input-output" model of intersectoral relations, where each element of the system simultaneously acts as both a consumer and a generator of impacts (5).

$$A = \begin{pmatrix} a_{II} & a_{IE} & a_{IT} \\ a_{EI} & a_{EE} & a_{ET} \\ a_{TI} & a_{TE} & a_{TT} \end{pmatrix} \quad (5)$$

where a_{ij} are the coefficients that characterize the proportion of the influence of the *j*-subsystem on the *i*-th. For an analytical demonstration of the cumulative effect of internal connections, it is advisable to move on to a generalized expression that reflects the propagation of external impulses through the structure of the system. Solving (4) with respect to *X*, we get (6):

$$X = (I - A)^{-1} Y \quad (6)$$

The resulting expression can be interpreted as a structural multiplier of transformation: the matrix $(I - A)^{-1}$ reflects the cumulative (direct and indirect) effect of external stimuli on all components of the biomethane development system.

Thus, the revealed nonlinearity of the interaction of factors and the need for their coordinated development have a wider macroeconomic dimension, since they relate not only to the internal configuration of the model, but also to changes in the general logic of the functioning of energy systems. It is at this level that the biomethane transformation goes beyond technological renewal and acquires the character of a structural restructuring of the economic architecture of the energy sector of Ukraine.

2.4. Energy Paradigm Change: Comparative Analysis of Models

A comparative analysis of the traditional model of fossil gas supply and the proposed biomethane structural-functional paradigm allows us to demonstrate fundamental differences in the nature of the systemic organization, mechanisms for creating added value, the institutional role of the state and approaches to environmental impact management (Table 5).

The comparison demonstrates that the traditional gas model and the proposed biomethane structural-functional design belong to different economic paradigms, which differ not only in the source of energy, but also in the architecture of the system, mechanisms of value formation and the logic of institutional management. The first is based on a centralized, linear and resource-extractive development model, while the second is based on a decentralized, circular and regenerative logic of value creation.

Table 5

Comparative analysis of the traditional energy and proposed biomethane models

Comparison Criterion	Traditional Energy Model	Biomethane Structural-Functional Model
Resource lifecycle	linear: exploration → extraction → transportation → combustion → CO_2 accumulation	circular: waste collection → anaerobic conversion → energy + biofertilizers → return to the agricultural sector
Source of value creation	– natural resource rent; – dependence on geopolitics and resource concentration	– technological processing; – intellectual property; – premium for decarbonization and sustainability
Role of institutions	– regulation of natural monopolies; – licensing of subsoil use; – tariff administration	– formation of a guarantees of origin market; – sustainability standards; – equal access to infrastructure
Environmental externalities	– predominantly negative; – external costs not fully internalized in prices	– overall positive; – emission reduction; – substitution of mineral fertilizers; – environmental benefits
Energy security	– dependence on imports and external supplies	– localization of production; – reduced import dependence; – increased autonomy
System resilience	– high asset concentration; – risk of a single point of failure	– distributed generation; – diversification of sources; – increased resilience
Socio-territorial effect	– limited local impact; – concentration of income in extraction regions	– rural development; – job creation at the local level; – regionalization of value added
Innovation dynamics	– slow modernization; – low dependence on innovation	– high dependence on research and development; – continuous technological improvement and digital monitoring

Source: authors' development

The revealed differences confirm that the biomethane transformation is not a partial technological modernization, but a structural restructuring of the energy system, which involves a change in institutional mechanisms, economic incentives and approaches to managing external effects. Thus, the proposed model forms a conceptual basis for the transition to a new paradigm of energy development, focused on sustainability, circularity and system integration.

3. Conclusions

Based on the conducted research, it can be concluded that the biomethane transformation of the energy sector of Ukraine is a complex, multidimensional process that requires a holistic and balanced approach to management.

The developed three-vector structural and functional model proves that the formation of a full-fledged biomethane market is possible only under the condition of simultaneous and coordinated interaction of three fundamental subsystems: institutional, economic and technological. The institutional environment sets the necessary "rules of the game" and stability, the economic vector generates financial motivation and investment attractiveness, while the technological circuit ensures the physical implementation of the process and compliance of products with quality standards.

The study established the nonlinear and synergistic nature of the influence of these factors of biomethane transformation. It is proven that asymmetric development, in which advanced technological solutions are introduced without proper adaptation of regulatory procedures or the creation of financial incentives, does not create a systemic effect, but only leads to market imbalances. Maximization of the result is achieved exclusively through spatial synchronization of all three vectors of transformation.

The proposed model creates a reliable conceptual basis for the development of state policies, investment programs and strategies for the post-war restoration of the energy sector of Ukraine. Further scientific research in this direction should be focused on the empirical (quantitative) assessment of the impact of individual components of the model and the development of scenario forecasts for the development of the biomethane industry in the context of European integration.

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References:

Chikov, I., Radko, V., Marshalok, M., Tepliuk, M., Petrenko, O., Sharko, I., & Sitkovska, A. (2022). Economic development of agricultural food enterprises on an innovative basis. *Financial and Credit Activity: Problems of Theory and Practice*, 1 (42), 98–106. https://doi.org/10.55643/fcaptp.1.42.2022.3672

Chikov, I., & Titov, D. (2025). Expert system for determining strategic directions for ensuring the stable functioning of agricultural enterprises and rural areas. *Baltic Journal of Economic Studies*, 11 (4), 238–251. https://doi.org/10.30525/2256-0742/2025-11-4-238-251

Dotsiuk, S., Chikov, I., Shevchenko, O., Nitsenko, V., Gerasymchuk, N., & Demydova, M. (2024). Evaluation of the institutional development of innovative activities to ensure the economy of the state. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 3, 171–180. https://doi.org/10.33271/nvngu/20243/171

Honcharuk, I., Chikov, I., Okhota, Y., & Biletska, N. (2025). Strategic Management and ESG Impact Assessment in Sustainable Agribusiness Development Model. *Economics Ecology Socium*, 9(4), 109–128. https://doi.org/10.61954/2616-7107/2025.9.4-8

Kaletnik, G., & Lutkovska, S. (2020a). Innovative environmental strategy for sustainable development. *European Journal of Sustainable Development*, 9 (2), 89–98. https://doi.org/10.14207/ejsd.2020.v9n2p89

Kaletnik, G., Honcharuk, I., Yemchyk, T., & Okhota, Y. (2020b). The world experience in the regulation of the land circulation. *European Journal of Sustainable Development*, 9 (2), 557–568. https://doi.org/10.14207/ejsd.2020.v9n2p557

Kaletnik, G., Sakhno, A., Pryshliak, N., Lutkovska, S., & Kolomiiets, T. (2025). Economic evaluation of environmental protection activities in the context of sustainable development: the experience of Ukraine. *Polityka Energetyczna-Energy Policy Journal*, 28 (3), 217–236. https://doi.org/10.33223/epj/207022

Kaletnik, G., Pryshliak, N., Khvesyk, M., & Khvesyk, J. (2022). Institutional capacity building on waste management as a secondary resource in Ukraine on the path to European integration. *Polityka Energetyczna*, 25(3), 105–122. https://doi.org/10.33223/epj/153932

Lach Ł., Kopeć S., Heller K., Zyśk J., Adamiec E., Kisiel-Dorohinicki M., Brzoza-Zajęcka A., & Gaska K. (2025). Input-output model for forecasting economic and environmental effects of smart meters deployment in Poland. *Energy*, 328, 1–14. https://doi.org/10.1016/j.energy.2025.136504

Okhota, Y., Chikov, I., & Bilokinna, I. (2024). Conceptual polycomponent model of an innovative mechanism for improving the competitiveness of agro-industrial complex enterprises. *Baltic Journal of Economic Studies*, 10 (2), 196–210. https://doi.org/10.30525/2256-0742/2024-10-2-196-210

Sakhno, A., Salkova, I., Abuselidze, G., Yanchuk, T., & Buha, N. (2023). Evaluation of efficiency of small agricultural enterprises economic activity under sustainable development conditions. *Lecture Notes in Networks and Systems*, 575(2), 2262–2271. https://doi.org/10.1007/978-3-031-21219-2_254

Shpykuliak, O., & Bilokinna, I. (2019). "Green" cooperatives in the formation of an institutional mechanism of development of alternative power engineering in the agrarian sector of the economy. *Baltic Journal of Economic Studies*, 5 (2), 249–255. https://doi.org/10.30525/2256-0742/2019-5-2-249-255

Shpykuliak, O., Diuk, A., & Balaniuk, I. (2023). Management of organizational-institutional and resource potential of social enterprises in the development of rural areas: theoretical concept of analysis. *Digital Economy and Economic Security*, 7(07), 136–140. https://doi.org/10.32782/dees.7-22

Tokarchuk, D. (2025). The concept of the development of the Ukrainian AIC on the principles of the "green" economy. *Herald of Khmelnytskyi National University. Economic sciences*, 6, 12–19. https://doi.org/10.31891/2307-5740-2025-348-6-1

Tokarchuk, D., Pryshliak, N., Berezyuk, S., & Tokarchuk, O. (2024). Advancing sustainable reconstruction in Ukraine after full scale invasion: utilizing a «green» economic approach and essential guidelines for successful implementation. *Polityka Energetyczna*, 27 (2), 71–88. https://doi.org/10.33223/epj/185209

Tomashuk, I., Baldynyuk, V., & Boltovska, L. (2023). Green economy as a factor of sustainable development. *Baltic Journal of Economic Studies*, 9 (3), 194–206. https://doi.org/10.30525/2256-0742/2023-9-3-194-206

Tomashuk, I., Koliadenko, S., & Burdiak, M. (2025b). The impact of digital innovations on the development of agricultural businesses. *Baltic Journal of Economic Studies*, 11 (1), 361–375. https://doi.org/10.30525/2256-0742/2025-11-1-361-375

Tomashuk, I., Mazur, K., Alieksieieva, O., & Shvets, V. (2025a). Transformation processes of formation and implementation of instruments of economic stimulation and innovative development in the agricultural sector of the economy. *Economy, finances, management: Topical issues of science and practical activity*, 4 (74), 75–92. https://doi.org/10.37128/2411-4413-2025-4-5

Tsirimokos, C. (2025). A Comprehensive Input–Output Analysis Model for Quantifying Environmental Linkages and Leakages: Evidence from Greece. *Biophysical Economics and Sustainability*, 10 (2). https://doi.org/10.1007/s41247-025-00124-8

Uddin, I., Ahmad, M., Ismailov, D., Balbaa, M., Akhmedov, A., Khasanov, S., & Haq, M. (2023). Enhancing Institutional Quality to Boost Economic Development in Developing Nations: New Insights from CS-ARDL Approach. *Research in Globalization*, 7, 100137. https://doi.org/10.1016/j.resglo.2023.100137

Zakharchenko, V., & Zabolotnyi, H. (2024). Decentralization Reform in Ukraine as a Factor and Institutional Component of Sustainable Development of Territorial Communities. *Ukrainian Geographical Journal*, 1 (125), 49–62. https://doi.org/10.15407/ugz2024.01.049

Zaremba, O., Sakhno, A., Chesnik, N., Nitsenko, V., Chikov, I., Zakharova, T., & Boltovska, L. (2025). Capital Investments in Sustainable Development of Land Resources of Ukrainian Agrarian and Industrial Complex Enterprises: Assessment, Modeling, Optimization. *Rocznik Ochrona Srodowiska*, 27, 722–737. https://doi.org/10.54740/ros.2025.058

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