CHAPTER
INNOVATIVE MECHANISMS FOR THE DEVELOPMENT OF RENEWABLE ENERGY IN UKRAINE UNDER WAR AND ENERGY CHALLENGES

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Summary
The transformation of energy systems amid global instability and military challenges necessitates a rethinking of traditional approaches to renewable energy development. In Ukraine, this issue is particularly acute due to the simultaneous impact of structural energy transformation and large-scale military disruptions, which significantly constrain the energy sector's operations. The study aims to substantiate and develop innovative mechanisms for renewable energy development under conditions of high uncertainty and external shocks. The research finds that, despite significant natural potential, the renewable energy sector in Ukraine remains constrained by institutional instability, infrastructure constraints, and elevated investment risks. The findings demonstrate that traditional support models are insufficient to ensure the long-term sustainability and resilience of the energy system. A conceptual model of innovative mechanisms is proposed that integrates institutional, financial, technological, spatial, and managerial components. The study proves that their interaction generates a synergistic effect, enhancing system flexibility, investment attractiveness, and energy security. The results confirm that implementing these mechanisms contributes to the formation of a resilient, decentralized, and adaptive energy system capable of functioning effectively under wartime conditions. The study provides both theoretical justification and practical recommendations for improving state energy policy and ensuring sustainable development of the renewable energy sector.

Introduction

The transformation of energy systems in the 21st century extends beyond purely technological changes, evolving into a multidimensional process in which economic, security, environmental, and institutional factors are deeply intertwined. In this context, renewable energy is no longer a peripheral segment of the energy market but is transforming into a system-forming element of a new model of economic development. Its significance is determined not only by its capacity to support decarbonization but also by its potential to enhance energy autonomy, reduce geopolitical risks, and increase national economies' resilience to the impacts of crises.

For Ukraine, these processes acquire a fundamentally higher level of complexity, as the development of the energy sector occurs under the simultaneous pressure of two interrelated crises: structural energy transformation and a full-scale military conflict. The destruction of generation capacities, disruption of supply chains, instability of the regulatory environment, and elevated investment risks create qualitatively new constraints for the functioning of the energy market. At the same time, these conditions highlight the urgent need to transition toward more flexible, decentralized, and technologically integrated development models, in which renewable energy sources play a central role.

The previous stage of renewable energy development in Ukraine was characterized by rapid growth driven primarily by state support mechanisms and the active attraction of foreign investment. However, the established model demonstrated limitations in terms of long-term sustainability. Dependence on fixed tariff instruments, uneven development across different segments, insufficient integration into the energy system, and the lack of effective balancing mechanisms led to the accumulation of systemic dysfunctions. Wartime conditions have not only intensified these issues but also revealed the critical vulnerability of centralized energy models.

Under such circumstances, it becomes essential to reconsider the development of renewable energy not as an isolated sector but as a component of a broader system of economic and energy security. This implies a shift from direct support instruments toward the formation of comprehensive innovative mechanisms that integrate institutional, financial, technological, and managerial components. The distinctive feature of such mechanisms lies in their ability to ensure not only economic efficiency but also systemic resilience, flexibility in responding to external shocks, and long-term sustainability.

Despite the significant number of scientific studies devoted to renewable energy development, most focus primarily on technological aspects or environmental feasibility. At the same time, the issue of forming integrated innovative mechanisms for energy sector development under conditions of high uncertainty remains insufficiently explored. This is particularly relevant for countries undergoing structural transformations while simultaneously experiencing the effects of military conflict, where traditional economic policy instruments prove to be inadequate.

Thus, there is an objective need to develop a new conceptual framework for renewable energy development in Ukraine that addresses current challenges and supports a transition to a more resilient, adaptive energy system. The study aims to provide theoretical substantiation and develop innovative mechanisms for renewable energy development in Ukraine amid military and energy challenges.

To achieve this aim, the following objectives have been defined: to examine the theoretical foundations of renewable energy development; to conduct a comprehensive analysis of the current state of the renewable energy sector in Ukraine; to identify key systemic constraints and risks affecting its functioning; to determine the role of innovation factors in the transformation of the energy sector; to substantiate innovative mechanisms for renewable energy development; and to develop practical recommendations for improving the effectiveness of state policy in this field.

1. Fundamental principles of renewable energy development under global and security transformations

The modern energy system is undergoing a phase of structural transformation that cannot be reduced to the gradual substitution of fossil fuels with alternative energy sources. Rather, it involves a shift in the very logic of energy system functioning – from a centralized, inertial, and resource-dependent model to a decentralized, adaptive, and technologically integrated system. This transformation is driven by the simultaneous influence of several factors, including climate constraints, technological breakthroughs in energy generation and storage, and the growing importance of energy security as a component of national security [4; 9].

Classical approaches to the analysis of energy systems, traditionally based on cost efficiency and supply stability, are increasingly insufficient for explaining contemporary developments. As noted by Cherp et al. (2018), energy security cannot be understood solely in terms of the physical availability of resources [2]. However, it must be evaluated in terms of the system's ability to adapt to external shocks and maintain functional resilience under crisis conditions. In this context, renewable energy takes on a new meaning – not merely as an environmentally friendly alternative, but as a tool to enhance systemic flexibility.

A distinctive feature of the current stage is the shift in focus from energy generation to the management of energy flows. The development of smart grids, digital management platforms, and energy storage technologies is shaping a new architecture of energy systems in which the integration of diverse generation sources plays a central role [7]. Within this framework, renewable energy sources function not as isolated elements but as integral components of complex networked systems.

The economic specificity of renewable energy lies in the transformation of cost structures: high initial capital investments are combined with low marginal production costs. This creates the preconditions for a long-term reduction in electricity costs, while simultaneously increasing the importance of institutional conditions that determine access to capital and risk levels [5].

In traditional energy systems, the primary source of value is the resource itself, whereas in renewable energy systems, it is technology and infrastructure. This shift fundamentally alters the logic of investment decision-making and reinforces the role of public policy as a key determinant of project viability. As Polzin demonstrates, regulatory instability is a major barrier to renewable energy development, as it directly affects financing costs.

From the perspective of energy security, renewable energy has a dual effect. On the one hand, it reduces dependence on imported energy resources, which is particularly critical for countries with limited domestic reserves. On the other hand, it introduces new challenges related to generation variability and the need for system balancing [1]. This necessitates integrating renewable energy with other elements of the energy infrastructure, including energy storage systems and flexible generation capacities.

For Ukraine, this issue is particularly important, as its historically established energy model is characterized by a high dependence on centralized power generation and imported energy resources. Under such conditions, the development of renewable energy can be considered not only as an environmental initiative but also as a tool for economic and geopolitical stabilization.

The development of renewable energy is closely linked to innovation processes that extend beyond the technological sphere to include institutional and organizational transformations. As noted by Geels (2019), the energy transition is a socio-technical transformation in which change occurs at the intersection of technologies, markets, and political institutions [3].

Innovations in the renewable energy sector are inherently complex and encompass several dimensions:

- technological (new generation and energy storage technologies);
- digital (management systems, smart grids);
- financial (green bonds, power purchase agreements – PPAs);
- institutional (new market regulation models).

A key feature of the current stage is that institutional innovations largely determine the pace of sectoral development. Empirical evidence suggests that countries with more flexible regulatory systems demonstrate higher rates of renewable energy integration regardless of their natural resource potential [6].

Under conditions of military and crisis-related challenges, the role of innovation becomes even more significant. It serves not only to improve efficiency but also to ensure system resilience. In particular, the development of decentralized generation reduces the vulnerability of energy infrastructure to physical damage, which is critically important for Ukraine.

Thus, innovative mechanisms for renewable energy development should be understood as a multi-level system integrating technological solutions, institutional transformations, and economic instruments to ensure the long-term sustainability of the energy sector.

The development of renewable energy in leading countries has occurred within various institutional models that reflect differences in economic structures, technological advancement, and policy priorities. Despite these differences, international experience reveals common patterns, particularly the decisive role of state regulation, innovative financing mechanisms, and the integration of technological solutions into the energy system.

One of the most illustrative examples is Germany's energy transition, known as Energiewende, which involves a gradual phase-out of fossil fuels and the expansion of renewable energy generation. At the initial stage, feed-in tariffs served as the key policy instrument, providing long-term predictability for investors and stimulating rapid capacity growth. Subsequently, the system evolved toward competitive mechanisms, such as auctions, which helped reduce electricity costs and improve resource allocation efficiency.

A distinctive feature of the German model is the active participation of local communities and households in energy production. The development of energy cooperatives and the prosumer concept has contributed to the decentralization of the energy system and enhanced its social resilience. This approach not only diversifies generation but also creates additional economic incentives for local market development.

Another important case is Denmark, which has achieved significant success in wind energy development. A combination of state support, long-term strategic planning, and well-developed balancing infrastructure has enabled the high share of wind generation in the national energy mix. Integration with the European energy market is crucial, enabling fluctuations in generation to be compensated through cross-border electricity flows.

The experience of Spain and several other European Union countries demonstrates the effectiveness of auction-based support mechanisms for renewable energy. Competitive bidding enables the identification of the most cost-efficient projects and reduces the financial burden on consumers. However, the effectiveness of this model depends critically on regulatory stability and investor confidence.

Particular attention should also be paid to integrating renewable energy into complex energy systems through digital technologies and energy storage solutions. In many countries, implementing smart grid concepts enhances system flexibility, improves energy flow management, and minimizes losses associated with generation variability.

A summary of international experience in renewable energy development is presented in Table 1

Table 1

Comparative characteristics of renewable energy development models in different countries

Country	**Main Support Mechanism**	**Model Features**	**Result**	**Applicability to Ukraine**
Germany	Feed-in tariff → auctions	Decentralization, cooperatives, prosumers	High RES share (>40%)	High (gradual transition to auctions)
Denmark	State support + market integration	Wind energy development, cross-border flows	Leader in wind energy	Moderate (requires EU integration)
Spain	Auctions	Competitive pricing	Reduced cost of RES	High
USA	Tax incentives (PTC, ITC)	Private investment stimulation	Rapid market growth	Partial
China	State planning	Large-scale investments, centralized model	Global leader in capacity	Limited

Source: compiled by the author based on international experience

The analysis of international experience yields an important conclusion: the development of renewable energy is not solely the result of technological progress but is shaped by the complex interaction of institutional, economic, and social factors. Successful development models are based on a combination of state regulation and market mechanisms, along with a gradual transition from direct support instruments to competitive frameworks [8].

In the context of Ukraine, adapting international experience requires consideration of the specific features of the national energy system and wartime conditions. Direct replication of foreign models is inappropriate, as the effectiveness of policy instruments largely depends on the institutional environment [3].

At the same time, several approaches demonstrate high potential for implementation in Ukraine:

- gradual transition to competitive support mechanisms for renewable energy;
- development of decentralized generation and energy cooperatives;
- integration into the European energy market;
- implementation of digital energy management technologies;
- development of energy storage systems as a balancing tool [7].

Particular importance is attached to adapting international experience with consideration of the security factor. While countries operating under stable conditions primarily focus on economic efficiency, in Ukraine, the priority is ensuring system resilience and an uninterrupted energy supply. This necessitates a reorientation of renewable energy policy toward decentralization, redundancy, and rapid infrastructure recovery.

Thus, international experience in renewable energy development demonstrates the importance of a comprehensive approach to energy policy formation that integrates institutional reforms, innovative financial mechanisms, and technological solutions. Its adaptation in Ukraine should take into account national specificities and current challenges in order to ensure the effective and sustainable development of the energy sector.

2. Dynamics of renewable energy development in Ukraine

The development of renewable energy in Ukraine over the past decade has been characterized by high growth intensity; however, this dynamic has been largely driven by institutional factors rather than by internal energy system transformation. The introduction of state support mechanisms, particularly the feed-in tariff model, created favorable conditions for attracting investment and led to a rapid increase in installed capacity.

As of the end of 2021, Ukraine's total installed capacity of renewable energy facilities reached approximately 9.6 GW, ranking it among the fastest-growing renewable energy markets in Europe. However, by 2023–2024, due to the impact of military actions, this figure declined to approximately 8.5–8.7 GW, reflecting both physical infrastructure losses and partial loss of control over energy assets [5].

Structurally, the renewable energy sector in Ukraine is characterized by significant asymmetry. Solar energy dominates, accounting for more than 60% of installed capacity, while wind energy represents approximately 20–25%, and bioenergy and small hydropower remain underdeveloped. This structure is not the result of organic development but reflects the nature of institutional incentives. In particular, the feed-in tariff mechanism encouraged investment in projects with shorter payback periods and lower technological complexity, leading to a concentration of capital in the solar segment [8].

Over the past few years, more than USD 12 billion has been invested in the renewable energy sector, with a significant share from foreign investors. This indicates a high level of integration of Ukraine’s energy market into global financial flows. At the same time, this development model has proven vulnerable to regulatory changes and external shocks.

Notably, even during the full-scale war, the renewable energy sector has shown signs of adaptation. In 2023, new generating capacities were commissioned, albeit at a significantly lower level than in the pre-war period. This indicates a transformation in investment behavior – from large-scale centralized projects to more flexible, decentralized solutions.

Thus, the development of renewable energy in Ukraine is characterized by high potential and structural imbalances that limit the sector's efficiency.

The full-scale war has become a systemic shock for Ukraine’s energy sector, leading to transformations not only in production processes but also in the institutional foundations of market functioning. Unlike previous crises, current challenges are complex and include physical destruction of infrastructure, loss of generating capacity, disruption of supply chains, and a sharp increase in uncertainty [4].

A key feature of the situation is the spatial concentration of renewable energy facilities in regions most affected by military actions. A significant share of solar and wind power plants is located in the southern and southeastern regions of Ukraine, resulting in substantial losses of generating capacity. As a result, electricity production from renewable sources declined by more than half compared to pre-war levels.

According to estimates by international organizations, a significant portion of Ukraine’s energy infrastructure was damaged or taken out of service during 2022–2024, posing a serious threat to the stability of the entire energy system [4]. Under such conditions, the priorities of state policy shifted toward ensuring the basic reliability of the energy supply, temporarily limiting the development opportunities for renewable energy.

At the same time, the war has revealed new functional capabilities of renewable energy. Decentralized generation systems have proven more resilient to physical damage and can ensure local energy supply. This highlights the need to reconsider the traditional model of energy system development and transition toward more flexible, distributed systems [7].

In 2024, the share of renewable energy in Ukraine's electricity production was approximately 10–11%, indicating the continued relevance of this sector even under crisis conditions [5]. Thus, renewable energy serves not only as an object affected by wartime risks but also as a potential tool for enhancing the resilience of the energy system.

The analysis of the current state of the renewable energy sector in Ukraine identifies several systemic barriers that constrain its development and are complex in nature.

The first key barrier is institutional instability, manifested in frequent changes in market rules and insufficient predictability of state policy. This significantly increases investment risks and limits access to financial resources [1].

The second factor is the structural imbalance of the energy system. A high share of intermittent generation, combined with insufficient development of energy storage systems and balancing capacities, increases costs to maintain system equilibrium and reduces overall market efficiency.

The third barrier is financial dysfunctionality, particularly the accumulation of debt by renewable energy producers and the imperfections in compensation mechanisms. This creates additional risks for investors and hinders further development of the sector [8].

The fourth aspect is the spatial concentration of generation capacity, which increases the energy system's vulnerability to localized risks, including military actions. The lack of territorial diversification limits the potential of renewable energy to enhance energy security.

At the same time, strategic policy documents envisage a significant increase in the role of renewable energy in the future. In particular, it is planned to achieve approximately a 27% share of renewable energy in final energy consumption by 2030, which requires substantial investment resources and structural reforms.

It should also be noted that Ukraine has considerable potential for decentralized generation, particularly solar, which significantly exceeds current utilization levels. This indicates that the main constraints on renewable energy development are not resource-related but rather institutional and infrastructural.

Thus, the further development of renewable energy in Ukraine depends on the state's ability to establish effective governance mechanisms that ensure the integration of renewable energy into the energy system, reduce investment risks, and enhance market flexibility.

The assessment of renewable energy development potential is a key element in shaping long-term energy policy, as it enables the determination of expansion limits, investment priorities, and opportunities for structural transformation of the energy sector. In the case of Ukraine, this issue is particularly relevant given the combination of a substantial resource base and a relatively low level of utilization.

The potential of renewable energy should be considered across several interrelated dimensions: technical, economic, and institutional. Such an approach avoids the simplified assumption that the mere availability of natural resources automatically translates into effective utilization.

From a technical perspective, Ukraine has significant potential for solar energy development, given its geographic location and ample solar radiation. The most favorable conditions are observed in the southern and central regions, where solar irradiation levels support stable electricity generation. At the same time, solar potential is not limited to large-scale power plants; there are considerable opportunities in rooftop installations and distributed generation, which are particularly relevant to energy system decentralization.

Ukraine also has substantial wind energy potential, especially in coastal areas of the Black and Azov Seas and in steppe regions. However, its realization is significantly constrained by both infrastructural limitations and wartime risks, as many of the most перспективні areas are located in high-risk regions.

This creates the need to redirect investments toward safer regions or to develop new technological solutions, including offshore wind energy in the long term.

A significant but underutilized segment is bioenergy. Ukraine has substantial agricultural and forestry resources that can be used for energy production. The development of this sector is important not only for electricity generation but also for heat supply, particularly amid rising fossil fuel costs. In addition, bioenergy contributes to waste management and supports local economic development.

The potential of small hydropower and geothermal energy in Ukraine is more limited than that of other renewable energy sources; however, it can play an important role in ensuring regional energy autonomy. The use of these sources is most appropriate at the local level, where they can complement other forms of generation.

At the same time, the assessment of potential cannot be limited to natural resources alone. The realization of renewable energy opportunities largely depends on the condition of the energy infrastructure. Limited grid capacity, insufficient development of energy storage systems, and the lack of flexible generation capacities constrain the integration of renewable energy into the energy system [7].

The economic dimension is equally important. Although declining costs for renewable energy technologies increase their competitiveness, a high level of investment risk – driven by regulatory instability and wartime factors – significantly limits the realization of this potential. Under such conditions, access to financial resources and risk mitigation instruments becomes a critical determinant of sectoral development [8].

Institutional constraints also play a significant role. Imperfect regulatory mechanisms, complex grid connection procedures, and insufficient coordination among market participants create additional barriers to renewable energy development [1].

At the same time, strategic policy frameworks envisage a substantial increase in the share of renewable energy in Ukraine’s energy balance. This indicates political will to realize the potential of renewable energy; however, achieving these targets requires systemic changes in governance.

A distinctive feature of the current stage is the shift of renewable energy development potential toward decentralized generation. The expansion of local energy systems, rooftop solar installations, and microgrids enhances the energy system's resilience and reduces dependence on centralized infrastructure [4].

In summary, Ukraine has significant renewable energy potential that far exceeds current utilization levels. However, the primary constraints are not resource-related but rather institutional, economic, and infrastructural. This implies that the realization of renewable energy potential depends primarily on the effectiveness of state policy and the ability to create a favorable environment for investment and innovation.

The transformation of the energy sector under contemporary global and national challenges necessitates a rethinking of approaches to renewable energy development. Traditional models that stimulate electricity generation through financial support instruments are insufficient to ensure the long-term sustainability of the energy system. This is particularly evident under conditions of wartime instability, where, alongside economic factors, security risks, infrastructural constraints, and high levels of uncertainty, these factors play a decisive role [3; 9].

In this context, renewable energy development should not be considered as an isolated economic sector but as a component of a broader system of energy security and economic stability. This approach implies a transition from a linear model focused on maximizing generation volumes to a systemic model in which adaptability, flexibility, and recovery capacity become the key criteria of effectiveness [2].

Particular importance is attached to the concept of energy resilience, which reflects an energy system's ability to maintain functionality or rapidly recover after external shocks. Within this framework, renewable energy serves not only as a source of clean energy but also as a tool for diversification, decentralization, and strengthening the resilience of energy infrastructure.

Taking this into account, innovative mechanisms for renewable energy development can be defined as an integrated system of interrelated institutional, economic, technological, and managerial instruments aimed at ensuring the sustainable, secure, and efficient functioning of the energy sector amid transformational change.

A key characteristic of such mechanisms is their complexity and interplay, which enable a synergistic effect that cannot be achieved with isolated instruments. It is precisely the coherence of different system components that determines the effectiveness of renewable energy policy implementation [6].

3. Innovative mechanisms for renewable energy development in Ukraine under military and energy challenges

Based on the conducted research, a model of innovative mechanisms for renewable energy development in Ukraine is proposed, taking into account the specifics of contemporary challenges and aimed at forming a resilient energy system.

The proposed model is based on the integration of five interrelated mechanisms operating within a multi-level governance system.

The first component is the institutional mechanism, which ensures the formation of a stable regulatory environment, predictability of state policy, and transparency of market functioning. Its implementation involves a transition to market-based support instruments, such as auctions or Contracts for Difference, which reduce regulatory risks and enhance investment attractiveness [8].

The second component is the investment and financial mechanism, designed to ensure access to financial resources and reduce capital costs. Under current conditions, particular importance is attached to the development of green financing instruments and mechanisms for insuring war-related risks, which are critical for stimulating investment activity [8].

The third element is the technological mechanism, which encompasses the implementation of innovative technologies for energy generation, storage, and management. Its role is to ensure the integration of renewable energy sources into the energy system and to reduce the negative impact of generation variability [8].

The fourth component is the spatial-diversification mechanism, which involves the development of decentralized generation and local energy systems, as well as the balanced distribution of generation capacities. Its implementation reduces the vulnerability of energy infrastructure to localized risks and enhances overall system resilience [4].

The fifth element is the managerial mechanism, which ensures coordination across different levels of governance, integration of energy and security policies, and the implementation of adaptive management approaches under conditions of uncertainty [3].

The proposed model is implemented across three levels – national, regional, and local – enabling it to account for the specific features of energy system functioning and to ensure effective coordination among various stakeholders.

A distinctive feature of the model is the presence of interconnections between individual mechanisms, which generate a synergistic effect. In particular, a stable institutional environment facilitates investment inflows, which in turn enable the implementation of new technologies that enhance the efficiency of the energy system [8].

The proposed model requires further conceptual clarification to reveal its internal structure and the logic of interaction among its components. It should be understood as a holistic and dynamic system in which renewable energy development is not treated as an isolated sectoral process, but rather as the result of interactions among external drivers, internal capacities, and coordinated policy mechanisms.

External factors, including global energy transition processes, European climate and energy policies, economic and energy instability, military risks, and rapid technological progress, shape the model's functioning. These factors define both the constraints and opportunities for renewable energy development, creating a complex and unstable operating context that requires adaptive, flexible policy responses [4; 2].

At the input level, the model is grounded in a combination of resource and institutional capacities, including natural resource potential, energy infrastructure, financial and investment resources, and human capital and institutional maturity. The interaction among these elements determines the initial conditions for implementing innovative mechanisms.

A key feature of the model is its systemic nature, evident in the interactions among the five core mechanisms. These mechanisms do not operate independently; instead, they reinforce each other through feedback loops. For instance, improvements in the institutional environment enhance investor confidence, thereby stimulating financial flows and enabling technological innovation. In turn, technological advancement supports system flexibility and facilitates the expansion of decentralized energy systems.

A set of cross-cutting enabling factors, such as digitalization, innovation and research, human capital development, international cooperation, and public engagement, further strengthen the model. These elements act as catalysts, increasing the effectiveness of the mechanisms and supporting their coordinated implementation [8].

At the same time, the model incorporates potential constraints and risks, including regulatory instability, financial limitations, technological barriers, structural imbalances in the energy system, and security threats associated with military conditions. Accounting for these factors is essential for ensuring the feasibility and robustness of the proposed mechanisms [1].

The implementation of the model results in a synergistic effect across multiple dimensions, including enhanced energy resilience and security, economic growth, environmental sustainability, and social development. In addition, it contributes to Ukraine's integration into the European energy space and strengthens its strategic positioning [2].

The practical implementation of the proposed innovative mechanisms for renewable energy development in Ukraine requires a comprehensive approach that combines public policy reform, the introduction of new financial instruments, and the advancement of the technological base.

One of the key directions is improving the state regulatory system, particularly the transition to competitive support mechanisms, which will enhance resource allocation efficiency and ensure a more balanced development of different renewable energy segments [8].

Equally important is the development of decentralized energy systems, which enhance the energy system's resilience. In this context, local energy systems capable of operating autonomously in the event of disruptions to centralized energy supply play a crucial role [4].

Another important direction is the implementation of digital technologies, which enhance the efficiency of energy flow management, ensure system balancing, and reduce operational costs. The integration of smart energy solutions significantly increases system flexibility and reliability [7].

In addition, international cooperation is essential, as it facilitates Ukraine's integration into the European energy space, attracts investment, and promotes the adoption of advanced technologies.

In summary, the effective implementation of innovative mechanisms for renewable energy development is possible only under conditions of their comprehensive application and coordination across different levels of governance.

Unlike traditional approaches focused on the quantitative expansion of the renewable energy sector, the proposed concept emphasizes the formation of a qualitatively new energy system model in which renewable energy performs not only a generation function but also a role in ensuring systemic resilience, which becomes a decisive factor under conditions of military and energy challenges [2; 3].

4. Assessment of the effectiveness of innovative mechanisms

The assessment of the effectiveness of innovative mechanisms for renewable energy development is a necessary condition for substantiating their practical relevance and determining their potential impact on the energy sector. Unlike traditional approaches, which are primarily based on economic indicators, a comprehensive approach is required under modern conditions – one that also incorporates energy, security, and environmental dimensions [1].

The innovative mechanisms proposed in this study have a systemic nature, which necessitates their evaluation through an interrelated set of effects. In this context, effectiveness can be considered as an integral indicator reflecting the ability of these mechanisms to ensure stability, adaptability, and development of the energy system.

From an economic perspective, the implementation of innovative mechanisms enhances the investment attractiveness of the renewable energy sector. The formation of a stable institutional environment and the introduction of market-based support instruments reduce regulatory risks and ensure a more efficient allocation of financial resources. This, in turn, stimulates investment growth and the development of new projects [8].

Furthermore, the implementation of innovative financial instruments, such as green bonds and risk insurance mechanisms, helps reduce capital costs and increase access to financing. In the long term, this will reduce electricity production costs and enhance the competitiveness of renewable energy [8].

Table 2

Comparative characteristics of innovative mechanisms for renewable energy development

Mechanism	Essence	Advantages	Disadvantages	Relevance for Ukraine
Institutional	Regulatory policy	Risk reduction	Dependence on the state	High
Financial	Investments, green bonds	Access to capital	High risks	High
Technological	Smart grids, storage	Increased efficiency	High cost	High
Spatial	Decentralization	System resilience	Requires infrastructure	Very high
Managerial	Policy coordination	Flexibility	Complexity of implementation	High

Source: developed by the author

From an energy perspective, the effectiveness of the proposed mechanisms is reflected in increased flexibility and reliability of the energy system. The implementation of energy storage technologies and digital management systems minimizes the negative impact of generation variability and ensures system balancing [7]. The development of decentralized generation reduces the load on centralized infrastructure and enhances system resilience to external shocks.

A significant effect is also observed in the field of energy security. The diversification of energy sources and the reduction of dependence on imported energy resources increase the autonomy of the national energy system. Wartime conditions further reinforce the importance of this aspect, as decentralized generation systems are less vulnerable to physical damage [2].

The environmental effectiveness of innovative mechanisms lies in reducing greenhouse gas emissions and minimizing environmental impact. The development of renewable energy contributes to fulfilling international climate commitments and creates the preconditions for the transition to a low-carbon economy [4].

An important dimension is also the socio-economic effect. The development of renewable energy creates new jobs, stimulates regional development, and improves energy accessibility for the population. This is particularly relevant in rural areas, where renewable energy can drive local economic growth.

A key characteristic of the proposed mechanisms is their multiplicative effect. The interaction among institutional, financial, and technological components creates synergy, amplifying the overall impact. In particular, a stable regulatory environment stimulates investment, which in turn facilitates the implementation of new technologies that enhance the efficiency of the energy system [6].

At the same time, it should be noted that the effectiveness of implementing innovative mechanisms depends on several conditions. The most important among them include the stability of state policy, access to financial resources, the level of infrastructure development, and the capacity for institutional transformation. In the absence of these conditions, the potential benefits may only be partially realized.

In summary, the proposed innovative mechanisms for renewable energy development have a comprehensive positive impact across economic, energy, security, and environmental dimensions. Their implementation will contribute to the formation of a resilient and adaptive energy system capable of functioning effectively under conditions of military and energy challenges.

Thus, the effectiveness of the proposed innovative mechanisms is manifested not only in improving the performance of the renewable energy sector but also in shaping a new quality of the energy system oriented toward resilience, adaptability, and security.

As a result of the conducted research, the theoretical, analytical, and applied aspects of renewable energy development in Ukraine under military and energy challenges have been generalized, enabling the formulation of a comprehensive vision of the energy sector's transformation and the substantiation of innovative mechanisms for its development.

Based on an analysis of theoretical approaches, it has been established that modern energy transformation is systemic and extends beyond technological changes, encompassing institutional, economic, and security dimensions. Under such conditions, renewable energy acts not only as an alternative to traditional energy sources but also as a key element in ensuring energy resilience and economic security [2; 3]. It is substantiated that effective development of renewable energy is possible only through the integration of public policy instruments, financial mechanisms, and technological solutions.

The study of international experience has demonstrated that successful renewable energy development models are based on a combination of state regulation and market mechanisms, along with a gradual transition from direct support instruments to competitive frameworks. It has been determined that decentralization of energy systems, active participation of local actors in energy generation, and the use of innovative energy management technologies are essential elements of effective models [7; 8]. At the same time, it has been proven that adapting international experience to Ukraine requires consideration of national specifics, particularly wartime instability and institutional constraints.

The analysis of the current state of renewable energy in Ukraine has shown that the sector has significant development potential, which, however, remains underutilized. It has been established that the rapid growth observed in previous years was primarily driven by state support mechanisms, which led to structural imbalances, including the dominance of certain types of generation and insufficient development of integration infrastructure. It has been found that wartime conditions have intensified these problems while simultaneously highlighting the need to transition to more flexible, decentralized energy models [4].

The assessment of renewable energy potential in Ukraine has confirmed that the country possesses significant natural resources for the development of solar, wind, and bioenergy. It has been substantiated that the main constraints on realizing this potential are not resource-related but rather institutional, economic, and infrastructural barriers. This indicates the need to revise governance approaches and create a favorable environment for investment and innovation [1].

A key result of the study is the development of a conceptual framework for innovative mechanisms of renewable energy development in Ukraine, integrating institutional, financial, technological, spatial, and managerial components. Unlike traditional approaches, the proposed model is oriented toward building a resilient, adaptive energy system capable of operating under high uncertainty and external shocks [3].

It has been substantiated that the effectiveness of innovative mechanisms is determined by their complexity and interaction, which generate a synergistic effect. In particular, a stable institutional environment promotes investment inflows, which enable the implementation of new technologies that enhance the efficiency and reliability of the energy system [6].

Conclusions

The evaluation of the effectiveness of the proposed mechanisms has demonstrated that their implementation produces a comprehensive positive impact across economic, energy, security, and environmental dimensions. It has been established that the introduction of innovative approaches contributes to increased investment attractiveness, reduced dependence on imported energy resources, improved system flexibility, and minimized environmental impact.

The practical significance of the obtained results lies in their applicability in the formation of state energy policy, the development of energy sector strategies, and decision-making processes at both enterprise and regional levels. The proposed mechanisms can serve as a basis for developing renewable energy programs to enhance the efficiency and resilience of Ukraine’s energy system.

The scientific novelty of the study lies in the development of a conceptual approach to renewable energy as a component of the energy security system, as well as in the formulation of a model of innovative mechanisms that account for the specifics of military and energy challenges. For the first time, the necessity of integrating institutional, financial, and technological instruments into a unified system designed to ensure energy sector resilience has been substantiated.

Prospects for further research include the development of quantitative models to assess the effectiveness of innovative mechanisms, scenario analysis of energy-sector development in the context of post-war recovery, and the exploration of Ukraine's integration into the European energy space.

References:

1. Azzuni, A., & Breyer, C. (2018). Definitions and dimensions of energy security: A literature review. *Wiley Interdisciplinary Reviews: Energy and Environment*, vol. 7(1), e268. DOI: https://doi.org/10.1002/wene.268
2. Cherp, A., Jewell, J., & Goldthau, A. (2018). Governing global energy: Systems, transitions, complexity. *Global Policy*, vol. 9(1), pp. 75–88. DOI: https://doi.org/10.1111/1758-5899.12544
3. Geels, F. W. (2019). Socio-technical transitions to sustainability: A review of criticisms and elaborations. *Research Policy*, vol. 48(3), pp. 896–913. DOI: https://doi.org/10.1016/j.respol.2018.12.005
4. International Energy Agency (IEA). (2023). World Energy Outlook. DOI: https://doi.org/10.1787/weo-2023-en
5. International Renewable Energy Agency (IRENA). (2024). Renewable capacity statistics 2024. DOI: https://doi.org/10.34892/8f5e-8k47
6. Johnstone, N., Haščič, I., & Popp, D. (2010). Renewable energy policies and technological innovation: Evidence based on patent counts. *Environmental and Resource Economics*, vol. 45(1), pp. 133–155. DOI: https://doi.org/10.1007/s10640-009-9309-1
7. Lund, H., Andersen, A. N., Østergaard, P. A., Mathiesen, B. V., & Connolly, D. (2015). From electricity smart grids to smart energy systems. *Energy*, vol. 42(1), pp. 96–102. DOI: https://doi.org/10.1016/j.energy.2012.04.003
8. Polzin, F., Migendt, M., Täube, F. A., & von Flotow, P. (2019). Public policy influence on renewable energy investments: A panel data study across OECD countries. *Energy Policy*, no. 127, pp. 124–136. DOI: https://doi.org/10.1016/j.enpol.2018.11.057
9. Sovacool, B. K. (2016). How long will it take? Conceptualizing the temporal dynamics of energy transitions. *Energy Research & Social Science*, no. 13, pp. 202–215. DOI: https://doi.org/10.1016/j.erss.2015.12.020
10. Geletukha, G. G., Zheliezna, T. A., & Bashtovyi, A. I. (2020). Renewable energy in Ukraine: Current state and prospects for development. *Tekhnichna Elektrodynamika*, no. 3, pp. 52–60. DOI: https://doi.org/10.15407/techned2020.03.052
11. Kudria, S. O. (2015). Renewable energy in Ukraine: State and prospects. *Tekhnichna Elektrodynamika*, no. 2, pp. 51–56. DOI: https://doi.org/10.15407/techned2015.02.051