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# MODELING REGIONAL ENERGY CLUSTERS IN THE CONTEXT OF UKRAINE'S INTERNATIONAL ECONOMIC SECURITY

**The article examines the modelling of regional energy clusters in the context of Ukraine's international economic security. The relevance of the study is determined by the large-scale destruction of Ukraine's energy infrastructure caused by the full-scale war, the increasing vulnerability of the centralized energy system, and the need to strengthen the energy resilience of territorial communities. According to the International Energy Agency, since the beginning of the full-scale invasion, nearly two-thirds of Ukraine's dispatchable power capacity has been occupied, damaged or destroyed. At the same time, Ukraine's total reconstruction and recovery needs are estimated at almost USD 588 billion, of which nearly USD 91 billion is required for the energy sector. The significant potential for decentralized renewable generation is also confirmed by the estimated rooftop photovoltaic potential of Ukraine, which reaches 238.8 GW, or 290 TWh per year. The purpose of the article is to substantiate an economic and mathematical model for assessing the effectiveness of a regional energy cluster in terms of energy availability, demand coverage, autonomy and dependence on centralized energy infrastructure. The proposed model includes the indicator of total available electricity, the energy coverage coefficient, the energy autonomy coefficient, and the coefficient of dependence on the centralized power grid. This approach makes it possible to quantitatively assess the capacity of a territorial community to meet its electricity demand through local generation, energy storage systems and centralized supply, taking into account technological losses. The study demonstrates that regional energy clusters can become an important tool for strengthening Ukraine's international economic security. They reduce the vulnerability of communities to attacks on centralized energy infrastructure, support the functioning of critical facilities, stabilize local production and create conditions for more resilient post-war economic recovery. The proposed modelling approach can be used as a**

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**decision-support tool for local authorities, policymakers and energy managers in developing decentralized energy strategies and improving the resilience of regional energy systems under crisis conditions.**

***Keywords:*** regional energy cluster; international economic security; energy resilience; decentralized energy system; territorial communities; local generation; energy storage systems; economic and mathematical modelling.

**Formulation of the problem.** The current energy crisis in Ukraine has revealed the structural vulnerability of the existing centralized energy supply model. Large-scale damage to generation facilities, transmission lines and distribution infrastructure has led to a chronic shortage of electricity, prolonged power outages, reduced industrial consumption and increased pressure on households, businesses and social infrastructure. Under such conditions, the restoration of the energy system within the traditional centralized framework does not fully ensure its resilience, flexibility and ability to respond effectively to military, technological and socio-economic challenges.

The problem is not limited to the physical destruction of energy infrastructure. It is also related to the insufficient adaptability of the existing energy management model, which is based on large-scale generation facilities, complex hierarchical coordination and a high dependence on centralized networks. In wartime conditions, such a system becomes highly vulnerable to targeted attacks and is unable to guarantee stable and equitable access to electricity for all categories of consumers.

At the same time, energy supply is becoming not only an economic and technical issue, but also an important component of international economic security. The instability of the Ukrainian energy system affects the country's industrial capacity, investment attractiveness, foreign trade potential, integration into European energy markets and overall economic resilience. Therefore, the search for new models of energy supply should be considered in the broader context of Ukraine's international economic security.

In this regard, there is a need to develop and scientifically substantiate decentralized energy models based on regional energy clusters, local generation, smart microgrids, energy storage systems and alternative technologies. Such models can reduce dependence on centralized infrastructure, strengthen the energy autonomy of territorial communities and increase the resilience of the national economy to external and internal shocks.

Thus, the scientific problem of the study lies in the need to model regional energy clusters as an instrument for transforming Ukraine's energy system and strengthening its international economic security under conditions of war, global energy instability and post-crisis recovery.

**Analysis of recent research and publications.** Theoretical and applied aspects of energy security, energy resilience and the transformation of energy systems have been widely studied by both Ukrainian and foreign researchers. Among Ukrainian scholars, considerable attention to the issues of energy security, strategic development of the energy sector and resilience of critical energy infrastructure has been paid by O. Sukhodolia, Ye. Bobrov and other researchers whose works focus on the institutional, economic and security dimensions of Ukraine's energy policy. Their studies emphasize the importance of energy independence, diversification of energy sources, infrastructure protection and adaptation of the national energy system to external threats.

Foreign researchers have also made a significant contribution to the development of the scientific foundations of energy security and energy system resilience. In particular, B. Sovacool, A. Cherp, J. Jewell, R. Schmitz, F. Flachsbarth, L. S. Plaga, M. Braun and P. Härtel consider energy security and resilience as multidimensional concepts that combine technical reliability, economic stability, environmental sustainability and institutional adaptability. Their studies show that modern energy systems should be able not only to withstand shocks, but also to adapt to long-term geopolitical, technological and climate-related changes.

A separate group of studies is devoted to the resilience of power systems, smart grids and microgrids. M. Panteli and P. Mancarella analyze the resilience of critical power infrastructure and emphasize the need for modeling approaches that allow assessing the impact of external disturbances on electricity systems. S. Mishra, K. Anderson, B. Miller and other researchers examine microgrids as flexible local energy systems capable of improving reliability, reducing vulnerability and supporting critical consumers during disruptions.

Recent analytical reports of international organizations also confirm the relevance of decentralized energy models for Ukraine. The

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International Energy Agency emphasizes that distributed energy resources, renewable generation, storage systems and smart grids can play an important role in rebuilding and modernizing Ukraine's electricity sector. This approach is particularly important under conditions of military threats, large-scale infrastructure damage and the need to strengthen the resilience of territorial communities.

At the same time, despite the considerable number of studies on energy security, energy resilience, renewable energy sources, microgrids and post-war reconstruction, the problem of modeling regional energy clusters in the system of Ukraine's international economic security remains insufficiently developed. Existing publications mostly focus either on technical aspects of energy infrastructure recovery or on general energy policy measures. Less attention is paid to the integrated modeling of regional energy clusters as complex socio-economic and technological systems that combine local generation, energy storage, smart microgrids, economic optimization, community governance and international economic security priorities.

Thus, the analysis of recent research and publications shows that the transformation of Ukraine's energy system should be considered not only as an engineering or infrastructural task, but also as an important component of international economic security. This creates a scientific basis for developing a conceptual model of regional energy clusters aimed at strengthening Ukraine's energy autonomy, reducing infrastructure vulnerability and increasing the resilience of the national economy under conditions of war, global energy instability and post-crisis recovery.

**Formulating the article goals.** The purpose of the article is to substantiate the theoretical and methodological foundations for modelling regional energy clusters as an instrument for strengthening Ukraine's international economic security under conditions of war, global energy instability and post-crisis recovery.

**The current energy** crisis in Ukraine has demonstrated that the problem of energy supply should be considered not only as a technical issue, but also as an important component of international economic security. Large-scale damage to generation facilities, transmission lines and distribution infrastructure has reduced the stability of the national energy system and created additional risks for industrial production, foreign trade, investment activity, regional development and the functioning of critical infrastructure.

The scale of the problem is confirmed by a number of quantitative indicators. According to the International Energy Agency, since the beginning of the full-scale invasion, nearly two-thirds of Ukraine's dispatchable power capacity has been occupied, damaged or destroyed. The IEA also emphasizes that distributed energy resources, including solar PV, wind, batteries and small modular gas turbines, can reduce vulnerability to targeted attacks and strengthen energy resilience [1]. The World Bank, together with the Government of Ukraine, the European Commission and the United Nations, estimates that Ukraine's total reconstruction and recovery needs reached almost USD 588 billion as of December 31, 2025, while the energy sector alone requires nearly USD 91 billion [2].

The presented data show that Ukraine's energy crisis has a systemic rather than purely infrastructural character. The destruction of a significant part of dispatchable power capacity, the projected electricity deficit and the high financial needs for recovery indicate that rebuilding the energy system within the previous centralized model is not sufficient. At the same time, the estimated rooftop photovoltaic potential of 238.8 GW and 290 TWh per year confirms the significant opportunities for the development of decentralized renewable generation in Ukraine [3] (Table 1).

Under such conditions, the restoration of the energy system within the traditional centralized model is not sufficient. The centralized model remains vulnerable to targeted attacks, technological failures, high transmission losses and management delays. Therefore, the transformation of Ukraine's energy sector requires the development of decentralized models based on local generation, smart microgrids, energy storage systems and community-level governance.

In this study, a regional energy cluster is considered as an integrated socio-economic and technological system that combines local energy generation, storage facilities, smart microgrid infrastructure, digital energy management and institutional mechanisms of community-based control. The purpose of such a cluster is to increase the autonomy of territorial communities, reduce dependence on centralized infrastructure and strengthen the resilience of the national economy under conditions of war, global energy instability and post-crisis recovery.

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Table 1

**Selected indicators confirming the need for decentralized energy solutions in Ukraine**

| Indicator | Value / trend | Relevance to the study |
|---|---|---|
| Dispatchable power capacity occupied, damaged or destroyed | two-thirds | Confirms the vulnerability of centralized generation |
| Projected winter power deficit in 2024/2025 | 6 GW | Demonstrates the need for rapid deployment of distributed energy resources |
| Increase in damaged or destroyed energy assets compared with RDNA4 | about 21% | Shows the growing scale of energy infrastructure destruction |
| Recovery and reconstruction needs of Ukraine | USD 588 billion | Confirms the macroeconomic scale of post-war recovery |
| Recovery and reconstruction needs in the energy sector | USD 91 billion | Shows the strategic importance of energy transformation |
| Estimated rooftop photovoltaic potential in Ukraine | 238.8 GW and 290 TWh/year | Demonstrates the potential of decentralized renewable generation |

*Source:* developed by the author based on [1-3]

The conceptual structure of the proposed regional energy cluster is presented in Figure 1.

The proposed model represents a regional energy cluster as an integrated decentralized system designed to ensure resilient, autonomous and socially accessible energy supply at the community level. The central element of the model is the *Regional Energy Cluster,* which combines three functional blocks: ambient and wireless energy sources, local generation facilities and energy storage systems.

The first block *(ambient and wireless energy sources)* forms the basic level of the model. It includes atmospheric power systems, Tesla resonant transformers and wireless power receivers based on laser or microwave transmission. These technologies are considered as prospective solutions that may contribute to reducing dependence on traditional centralized energy infrastructure.

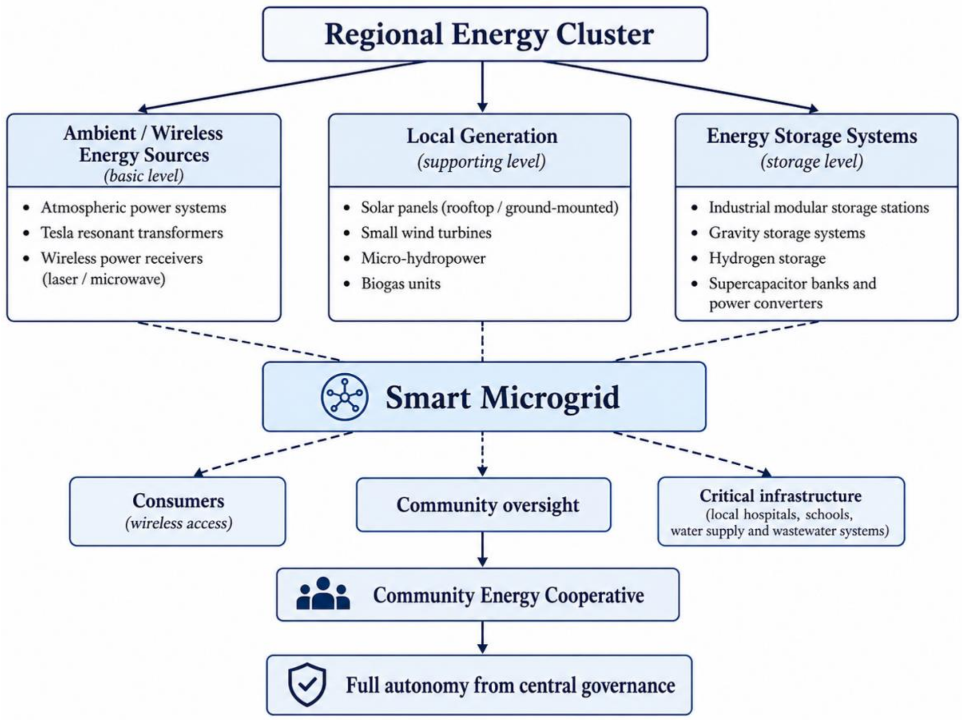


Figure 1. **Conceptual model of a regional energy cluster in the system of Ukraine's international economic security**

*Source:* developed by the author.

The second block ***(****local generation****)*** performs a supporting function and includes solar panels, small wind turbines, micro-hydropower plants and biogas units. These sources provide distributed electricity production within the territory of the community and increase the flexibility of the local energy balance.

The third block ***(****energy storage systems****)*** ensures the stability of the cluster. It includes industrial modular storage stations, gravity storage systems, hydrogen storage, supercapacitor banks and power converters. This component allows the accumulation of surplus energy and its use during peak demand, emergency situations or interruptions in centralized supply.

All three blocks are connected to the *Smart Microgrid****,*** which acts as the technological core of the model. The smart microgrid manages energy flows, balances generation and consumption, optimizes electricity distribution and reduces losses. Through this system, energy

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is supplied to three main groups of users: consumers, critical infrastructure facilities and community-level institutions.

A specific feature of the model is the presence of *community oversight* ***and a*** *community energy cooperative****.*** These elements provide institutional coordination, public control and transparent management of local energy resources. The cooperative model allows households, businesses, local authorities and social infrastructure institutions to participate in the organization and use of the regional energy system.

The final expected result of the model is the achievement of a high level of regional energy autonomy. In the context of Ukraine's international economic security, such a model can reduce the vulnerability of territorial communities to attacks on centralized infrastructure, support the functioning of critical facilities, stabilize local economic activity and strengthen the resilience of the national economy under conditions of war, global energy instability and post-crisis recovery.

For the purposes of formalizing the proposed model, the regional energy cluster can be considered as a local energy system in which electricity supply is formed through the combination of local generation, energy storage systems and, if necessary, electricity received from the centralized power grid. At the same time, part of the generated and supplied electricity is lost during transmission and distribution. Therefore, the effectiveness of the regional energy cluster can be assessed through several key indicators: available energy supply, energy demand coverage, regional energy autonomy and dependence on the centralized power grid.

The first stage of the model is to determine the total amount of electricity available within the regional energy cluster during a specific period. This indicator forms the basis for further assessment of energy sufficiency, autonomy and dependence on centralized infrastructure.

$$\boldsymbol{E_{av(t)} = E_{loc(t)} + E_{st(t)} + E_{grid(t)} - E_{loss}(t)}$$

where:

$E_{av(t)}$ - the available amount of electricity in the regional energy cluster during period t

$E_{loc(t)}$ - electricity generated by local sources;

$E_{st(t)}$ - electricity obtained from energy storage systems;

$E_{grid(t)}$ - electricity supplied from the centralized power grid;

$E_{loss}(t)$ - technological losses during electricity transmission and distribution.

This formula shows that the energy capacity of a territorial community depends on local generation, stored energy, centralized supply and technological losses. The increase in local generation and storage capacity directly strengthens the stability of the regional energy cluster. After determining the total available amount of electricity, the next step is to assess whether this amount is sufficient to meet the actual electricity needs of the community. For this purpose, the energy coverage coefficient is introduced.

**Energy Coverage Coefficient**

$$\boldsymbol{K_{cov}(t) = \frac{E_{av}(t)}{D(t)}}$$

$K_{cov}(t)$ - the energy coverage coefficient;

$E_{av}(t)$ - the available amount of electricity in the regional energy cluster;

$D(t)$ - the total electricity demand of households, local businesses, social infrastructure and critical facilities.

If:

$$K_{cov}(t) \geq 1$$

the regional energy cluster is able to fully cover local electricity demand.

If:

$$\boldsymbol{K_{cov}(t) < 1}$$

the region experiences an electricity deficit.

This coefficient makes it possible to determine whether the proposed cluster model can ensure stable electricity supply for the community. In the context of Ukraine's international economic security, this indicator is important because electricity shortages directly affect local production, business activity, critical infrastructure and the socio-economic stability of territories.

However, the ability to cover total demand does not fully reflect the level of energy independence of the region. Therefore, it is necessary to determine what share of electricity demand can be covered by local generation and storage without relying on the centralized power grid.

**Energy Autonomy Coefficient**

$$\boldsymbol{K_{aut}(t) = \frac{E_{loc}(t) + E_{st}(t)}{D(t)}}$$

where:

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$K_{aut}(t)$ - the energy autonomy coefficient;
$E_{loc}(t)$ - electricity generated by local sources;
$E_{st}(t)$ - electricity obtained from energy storage systems;
$D(t)$- the total electricity demand in the region.

This coefficient shows what share of local electricity demand can be covered without using electricity from the centralized power grid. The closer $K_{aut}(t)$ is to 1, the higher the level of regional energy autonomy.

For example, if:
$K_{aut}(t)$ =0,75
this means that the regional energy cluster is able to independently cover 75% of local electricity demand.

At the same time, energy autonomy should be analysed together with the degree of dependence on centralized electricity supply. This is especially important under crisis conditions, when centralized energy infrastructure may be damaged, overloaded or temporarily unavailable.

**Dependence on the Centralized Power Grid**

$$\boldsymbol{K_{dep}(t) = \frac{E_{\mathrm{grid}}(t)}{D(t)}}$$

$K_{dep}(t)$ - the coefficient of dependence on the centralized power grid;
$E_{\mathrm{grid}}(t)$ - electricity supplied from the centralized power grid;
$D(t)$ - the total electricity demand in the region.

This coefficient shows how dependent the territorial community is on centralized energy infrastructure. A decrease in $\boldsymbol{K_{dep}(t)}$ indicates a reduction in vulnerability to disruptions of centralized electricity supply and an increase in the resilience of the regional energy system.

Thus, the proposed system of indicators makes it possible to assess the effectiveness of a regional energy cluster from the standpoint of energy availability, demand coverage, autonomy and dependence on centralized infrastructure. In the context of Ukraine's international economic security, this approach allows determining the capacity of territorial communities to maintain stable electricity supply, support critical infrastructure, reduce energy vulnerability and ensure the continuity of local economic activity under crisis conditions.

The modeling of regional energy clusters confirms that decentralized energy systems can become an important tool for strengthening Ukraine's international economic security. Such clusters reduce the vulnerability of communities to attacks on centralized energy infrastructure, support the functioning of critical facilities, stabilize local production and create conditions for more resilient post-war economic recovery.

**Conclusion.** The study demonstrates that the modelling of regional energy clusters provides an effective theoretical and methodological framework for assessing the energy resilience of territorial communities under crisis conditions. In contrast to traditional approaches focused mainly on centralized energy supply, the cluster-based approach emphasizes the importance of decentralization, local generation, energy storage systems and reduced dependence on centralized infrastructure. This makes it possible to interpret regional energy security not only as the availability of electricity, but also as the ability of communities to maintain stable economic and social functioning during disruptions.

The proposed system of indicators allows the effectiveness of a regional energy cluster to be assessed through several interconnected dimensions: total energy availability, demand coverage, energy autonomy and dependence on the centralized power grid. The available energy indicator reflects the overall capacity of the cluster to accumulate electricity from local sources, storage systems and the centralized grid while taking into account technological losses. The energy coverage coefficient makes it possible to determine whether the cluster can fully meet the electricity demand of households, local businesses, social infrastructure and critical facilities. The energy autonomy coefficient shows the share of demand that can be covered without centralized supply, while the dependence coefficient reflects the vulnerability of the community to disruptions in the national power grid.

The results confirm that the development of local generation and energy storage capacity directly strengthens the resilience of territorial communities. A higher level of energy autonomy reduces exposure to attacks on centralized energy infrastructure, limits the risk of electricity shortages and supports the continuity of local economic activity. At the same time, the model shows that even partial decentralization can have a significant stabilizing effect, especially when critical infrastructure, small and medium-sized businesses, healthcare facilities, educational institutions and public services require uninterrupted electricity supply.

It is established that regional energy clusters should be considered not only as a technical solution, but also as an important component of Ukraine's international economic security. Stable electricity supply at the local level supports production processes, protects critical infrastructure, reduces socio-economic vulnerability and creates

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conditions for post-war recovery. In this context, decentralized energy systems contribute to strengthening national resilience, reducing dependence on vulnerable centralized infrastructure and increasing the adaptive capacity of the economy under conditions of military, energy and geopolitical instability.

The findings highlight the practical value of the proposed model as a decision-support tool for regional energy planning and crisis management. The system of indicators can be used by local authorities, policymakers and energy managers to assess the current level of energy resilience, identify vulnerable areas and justify investments in renewable energy sources, storage systems and local energy infrastructure. Further research should focus on the empirical testing of the model using data from Ukrainian territorial communities, as well as on the development of scenario-based assessments of regional energy cluster performance under different crisis conditions.

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# МОДЕЛЮВАННЯ РЕГІОНАЛЬНИХ ЕНЕРГЕТИЧНИХ КЛАСТЕРІВ У КОНТЕКСТІ МІЖНАРОДНОЇ ЕКОНОМІЧНОЇ БЕЗПЕКИ УКРАЇНИ

**У статті досліджено моделювання регіональних енергетичних кластерів у контексті міжнародної економічної безпеки України. Актуальність теми зумовлена масштабними руйнуваннями енергетичної інфраструктури внаслідок повномасштабної війни, посиленням ризиків для централізованої енергосистеми та необхідністю формування більш стійкої, гнучкої й децентралізованої моделі енергозабезпечення територіальних громад. За даними International Energy Agency, з початку повномасштабного вторгнення майже дві третини диспетчеризованих енергетичних потужностей України були окуповані, пошкоджені або зруйновані. Водночас загальні потреби України у відновленні та реконструкції оцінюються майже у 588 млрд дол. США, з яких близько 91 млрд дол. США припадає на енергетичний сектор. Додатково значний потенціал для розвитку децентралізованої енергетики підтверджується оцінкою rooftop photovoltaic potential України на рівні 238,8 ГВт, або 290 ТВт·год на рік.**

**Метою статті є обґрунтування економіко-математичної моделі оцінювання ефективності регіонального енергетичного кластера з позицій енергетичної доступності, покриття попиту, автономності та залежності від централізованої енергетичної інфраструктури. У дослідженні запропоновано систему показників, що включає загальний обсяг доступної електроенергії, коефіцієнт енергетичного покриття, коефіцієнт енергетичної автономії та коефіцієнт залежності від централізованої мережі. Такий підхід дозволяє кількісно оцінити спроможність територіальної громади забезпечувати власні потреби в електроенергії за рахунок місцевої генерації, систем накопичення енергії та централізованого постачання з урахуванням технологічних втрат. Доведено, що регіональні енергетичні кластери можуть стати важливим інструментом посилення міжнародної економічної безпеки України, оскільки вони знижують вразливість громад до атак на централізовану енергетичну інфраструктуру, підтримують функціонування критичних об'єктів, стабілізують місцеве виробництво та створюють передумови для стійкого післявоєнного відновлення економіки. Запропонована модель**

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**може бути використана органами місцевого самоврядування, державними інституціями та енергетичними менеджерами для оцінювання рівня енергетичної стійкості громад, визначення вразливих місць і обґрунтування інвестицій у відновлювану енергетику, системи накопичення та локальну енергетичну інфраструктуру.**

***Ключові слова:*** регіональний енергетичний кластер; міжнародна економічна безпека; енергетична стійкість; децентралізована енергетична система; територіальні громади; місцева генерація; системи накопичення енергії; економіко-математичне моделювання.

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