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ANALYSIS OF THE IMPACT OF CROSS-BORDER ENERGY TRADE ON THE ENERGY SECURITY OF EUROPEAN COUNTRIES

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Abstract:
The study is devoted to analyzing the impact of cross-border energy trade on the energy security of European countries and the management of energy flows at the international level. The main goal is to assess changes in the energy market structure and analyze management models for coordinating cross-border energy flows, mainly using the example of ENTSO-E. In the context of an unstable geopolitical environment, the problem of finding optimal mechanisms for ensuring energy security through international coordination of energy trade arises. It is precisely the lack of coordination of cross-border energy flows and the risks of supply disruptions that require systematic scientific analysis. To achieve this goal, the study employed system analysis, comparative and content analysis of regulatory documents, and economic-statistical analysis of the dynamics of cross-border energy trade. The main results indicate that cross-border trade plays a critical role in ensuring the region's energy sustainability, and the integration of the Ukrainian energy system into ENTSO-E contributes to the stability of the energy supply and the expansion of its role in the European energy market. At the same time, international mechanisms for managing energy flows, particularly the market and balancing mechanisms of ENTSO-E, ensure effective coordination between countries and increase energy security. The study visualizes the elements of the energy flow management process using the case of ENTSO-E, which allows us to clearly demonstrate the mechanisms for coordinating cross-border energy trade. It is concluded that further research in this area should focus on improving models for managing cross-border energy flows, providing financial support for integrating RES, and analyzing the impact of digital technologies on optimizing energy management.

Key words: management model, energy security, cross-border trade, renewable energy, energy policy

INTRODUCTION

Energy security is one of the essential elements of national security, especially for countries that are actively integrating into global energy markets and are influenced by geopolitical and economic factors. The world economy is becoming increasingly interconnected, and a stable supply of energy resources is one of the main factors determining the resilience of national economies to external crises and shocks. In particular, the countries of the European Union strive to achieve energy independence and reduce vulnerability to external threats, such as the monopoly of individual energy suppliers, political conflicts or economic sanctions.

Diversification of energy sources and developing renewable technologies are becoming strategically important policy areas. The abandonment of fossil fuels and the gradual transition to environmentally friendly energy sources allow countries to fulfill their obligations under international climate agreements and strengthen their energy independence. In particular, EU countries are investing significantly in developing infrastructure to support renewable energy [1] and creating a single energy network that would allow for efficient and secure energy trade between Member States.

Cross-border energy trade is one of the components of such an energy transformation. It allows countries to ensure stable energy supplies in the event of domestic disruptions or seasonal peaks in demand, using the resources of neighboring countries. At the same time, cross-border trade contributes to developing the European energy market, increasing competition and reducing the cost of energy resources for end consumers.

The system of cross-border energy flows in Europe already includes complex interaction schemes that allow countries to depend not only on their resources but also on mutual support in emergencies [2].

Ukraine, an essential link at the intersection of European and post-Soviet energy systems, plays a strategic role in ensuring energy security at both the national and European levels. The country's geographical location makes it one of the main transit routes for supplying energy carriers, such as natural gas and oil, from Central Asia to Europe. However, Ukraine's role in the international energy system is not limited to transit. The country is also gradually integrating into the European energy market, mainly through synchronizing its electricity system with the European ENTSO-E network, which ensures a more efficient and stable energy system operation.

Despite significant progress in the development of European energy integration, the problem of ensuring energy security through cross-border energy trade remains open. Supply instability due to political or technical factors, as well as insufficient adaptation of energy markets to changes in demand and supply, creates risks for the stability of energy systems.

Cross-border trade in energy carriers allows Ukraine to maintain the stability of its energy system and act as a strategic partner for other European countries, strengthening pan-European energy security. In the face of current geopolitical threats and challenges, such as military conflicts or economic instability, cross-border energy cooperation becomes crucial to ensuring uninterrupted supplies and strengthening the energy sustainability of the entire region.

LITERATURE REVIEW

Cross-border energy trade plays a key role in ensuring the energy security of European countries. It is at the intersection of energy security, sustainability, and sovereignty, which creates several challenges and opportunities [3]. One of the main problems is the balance between these three aspects since strengthening one can threaten the others. The "green" transformation of the Polish energy sector is considered an example of the transition to renewable energy sources, which contributes to reducing dependence on fossil fuels and strengthening the country's energy security [4]. The transition to sustainable energy models is accompanied by profound socio-technical changes that require a comprehensive analysis of scientific approaches to transformation processes [5]. Studies of structural shifts in the energy sector's green transformation show that the industry's further development should be based on innovative technologies and effective, sustainable development policies [6]. However, public perception and support for energy reforms are essential factors for the success of these changes and the values of changing energy. This indicates consideration of social priorities and expectations when developing energy policy strategies [7].

The political context plays a significant role in shaping energy transformations, as green transformations require the coordination of interests of different influence groups [8]. At the same time, financial incentives remain essential in attracting investments in renewable energy, and other support schemes affect the economic feasibility of relevant projects in various ways [9]. In developing countries, a just energy transition is linked to the need to strengthen energy democracy, which implies the availability of clean energy for all social groups. In this context, energy justice becomes central to research in developing countries, as it concerns equal access to energy resources and the environmental consequences of the transformation [10, 11].

The global energy transformation is a long-term process that involves achieving a carbon-free economy by 2050 [12]. However, this transition is accompanied by challenges related to social justice and equitable distribution of benefits from the transition to clean energy [13]. Assessment of the energy-ecological efficiency of industry development strategies indicates the need to consider environmental consequences in forming energy policy [14]. At the same time, interdisciplinary studies emphasize the importance of integrating social and humanitarian aspects in energy research [15]. The impact of environmental innovations on the productivity of the energy sector is also of great importance, as they determine the future structure of renewable energy consumption [16]. Thus, the literature analysis shows that cross-border trade in energy carriers directly affects the energy security of European countries since ensuring a stable supply of resources, the development of renewable energy, and a fair energy transition remain essential elements of modern energy policy.

To conduct a retrospective analysis of cross-border energy trade and assess its impact on the energy security of European countries, including Ukraine, it is advisable to consider the key events and processes that shaped the energy system. Table 1 presents the main stages of the development of energy cooperation in Europe, starting from the 1990s, and their impact on the energy stability of the region.

Table 1

The main stages of the development of cross-border energy trade and their impact on the energy security of European countries

Stage	Important events and changes	Impact on energy security
Development of energy infrastructure (1990 – early 2000s) [17, 18]	Modernization of Ukraine's gas transportation system; conclusion of contracts between ukraine, Russia and the EU	Increasing energy dependence of EU countries on Russian supplies
The first gas crises (2006, 2009) [19, 20]	Disruptions in gas supplies to the EU due to gas conflicts between Ukraine and Russia	Emphasizing the vulnerability of EU energy systems, encouraging the search for alternative sources of supply
Beginning of supply diversification (2010s) [21]	EU development of strategic plans to reduce dependence on Russian gas; development of LNG infrastructure	Promoting diversification of energy supplies and strengthening energy security
The War in Ukraine and its impact on energy security (2014 – present) [22, 23]	War in eastern Ukraine, new energy supply projects	Intensification of EU efforts to reduce dependence on Russian gas, increase Ukraine's gas production
RePowerEU Plan (2022-2027) [24]	Response to Russian aggression; focus on diversifying energy sources and increasing the use of renewables	Potential change in the structure of cross-border energy trade, contributing to EU energy security

Source: developed by the author based on [17, 18, 19, 20, 21, 22, 23, 24].

In the post-Soviet period (1990 – early 2000s), Ukraine, as an essential transit route for Russian gas to Europe, received significant investments in modernizing its gas transportation system. During this period, active negotiations took place between Ukrainian, Russian and European energy stakeholders. It was these actions that created the basis for the formation of the energy dependence of EU countries on Russian supplies.

The gas crises that occurred in Ukraine had serious consequences for European consumers. In 2006 and 2009, there were significant interruptions in gas supplies, which led to a decrease in the volume of supplies to EU countries. The crises highlighted the vulnerability of the European energy system and prompted EU countries to seek alternative sources of supply.

After the gas crises, active work began on diversifying energy supplies. The EU developed strategic plans aimed at reducing dependence on Russian gas. In 2014, the EU Energy Strategy was presented, which included the development of the internal energy market, expanding LNG (liquefied natural gas) supply infrastructure, and implementing projects such as the Southern Corridor.

The war in eastern Ukraine in 2014 was a significant factor in changing the energy security landscape. Europe began to look for ways to reduce its dependence on Russian gas, which led to the launch of new projects such as the Trans-Adriatic Pipeline and the Southern Gas Corridor. During this period, Ukraine also stepped up efforts to increase its own gas production and energy efficiency.

Introduced in response to Russian aggression in Ukraine, the RePowerEU plan envisages significant changes in the structure of energy supply in Europe. The main tasks are to diversify sources of supply, reduce gas consumption, and increase the use of renewable energy sources. The plan could significantly affect cross-border energy trade as EU countries seek to reduce their dependence on Russian gas.

The presented retrospective analysis shows that cross-border energy trade is critical for the energy security of European countries, particularly Ukraine. Historical experience shows that political and infrastructure development changes can significantly affect energy stability. In today's conditions, in the context of war and global challenges, it is necessary to continue diversifying supplies and invest in developing new energy technologies to ensure a stable energy future.

RESEARCH METHODOLOGY

Research sample

The study analyzed the energy security policies and strategies of the EU and Ukraine, including data on infrastructure development, cross-border energy trade volumes, and changes in the regulatory environment. Statistical data from official sources, such as ENTSO-E [29, 30, 31, 32, 33], the Ministry of Energy of Ukraine [25, 26], the European Commission [21, 24], and other open databases, were used for the analysis.

The methodological basis of the study includes the following methods:

- system analysis to assess structural changes in cross-border energy trade and their impact on energy security;
- comparative analysis to compare energy security strategies of different EU countries and Ukraine;
- content analysis to study regulatory documents, strategic plans, and international agreements in the energy sector;
- Economic and statistical analysis were used to study the dynamics of energy trade volumes, changes in the energy market structure, and assessment of the impact of external factors.

Analytical tools and procedures

The study uses secondary data from open sources, including official reports, scientific articles, energy publications, and analytical reviews. The primary analysis tool is the generalization and interpretation of the collected data to formulate conclusions on trends in cross-border energy trade and their impact on the energy security of European countries.

The results allow us to form substantiated conclusions on the current state of cross-border energy trade, its role in shaping the European energy market, and development prospects, considering the challenges associated with the transition to renewable energy sources and increasing the region's energy independence tendency.

RESULTS

Assessment of strategic plans in the field of energy security and adaptation to new challenges

In connection with the challenges of Ukraine's energy security, which arise in the context of growing interdependence with European markets, it is imperative to assess the extent to which national strategic plans contribute to strengthening the energy system's resilience and adapting to new conditions. Analysis of strategic documents and available data allows us to understand better Ukraine's energy system's current state and development trends in the context of its integration into European energy markets. A study of two strategic documents – the National Energy and Climate Plan for the period up to 2030 [25] and the Transmission System Development Plan for 2021-2030 [26] – allows us to identify Ukraine's approaches to integration into the European energy space.

According to the *National Energy and Climate Plan for the period up to 2030* [25], in terms of the development of natural gas infrastructure, Ukraine is significantly dependent on the infrastructure projects of other states.

The first direction is the Turkey-Greece-Bulgaria-Romania-Hungary-Slovakia gas corridor. Previously, this route transported gas via Ukraine to European countries, but with the construction of new gas pipelines such as BlueStream and TurkStream, this route is gradually shifting south. However, Russia's decline in gas volume is stimulating the development of alternative routes and sources. For example, Greece has increased its regasification capacity to 25.7 billion m³/year, significantly exceeding its domestic needs. It has allowed it to become an important transit hub for gas from Cyprus, the Middle East, and other regions.

The second direction is the Germany-Poland corridor, through which Russian gas also passed to Europe. The increase in the regasification capacity of LNG terminals in Germany and Poland strengthens their role in providing gas to the region, helping to reduce dependence on Russia. Ukraine, in turn, depends on Polish infrastructure projects to obtain alternative resources.

The third direction is the Italy-Austria-Slovakia corridor. Italy continues to increase its regasification capacity and develop domestic gas production sources. By 2025, Alternative sources will fully cover Italy's need for Russian gas.

Such processes demonstrate the deep integration and cooperation between European countries in the field of energy security, which is an essential factor in maintaining the stability of energy supplies in the face of geopolitical changes. The map (Fig. 1) shows the main directions for developing energy projects that are important for Ukraine and related to gas transportation.

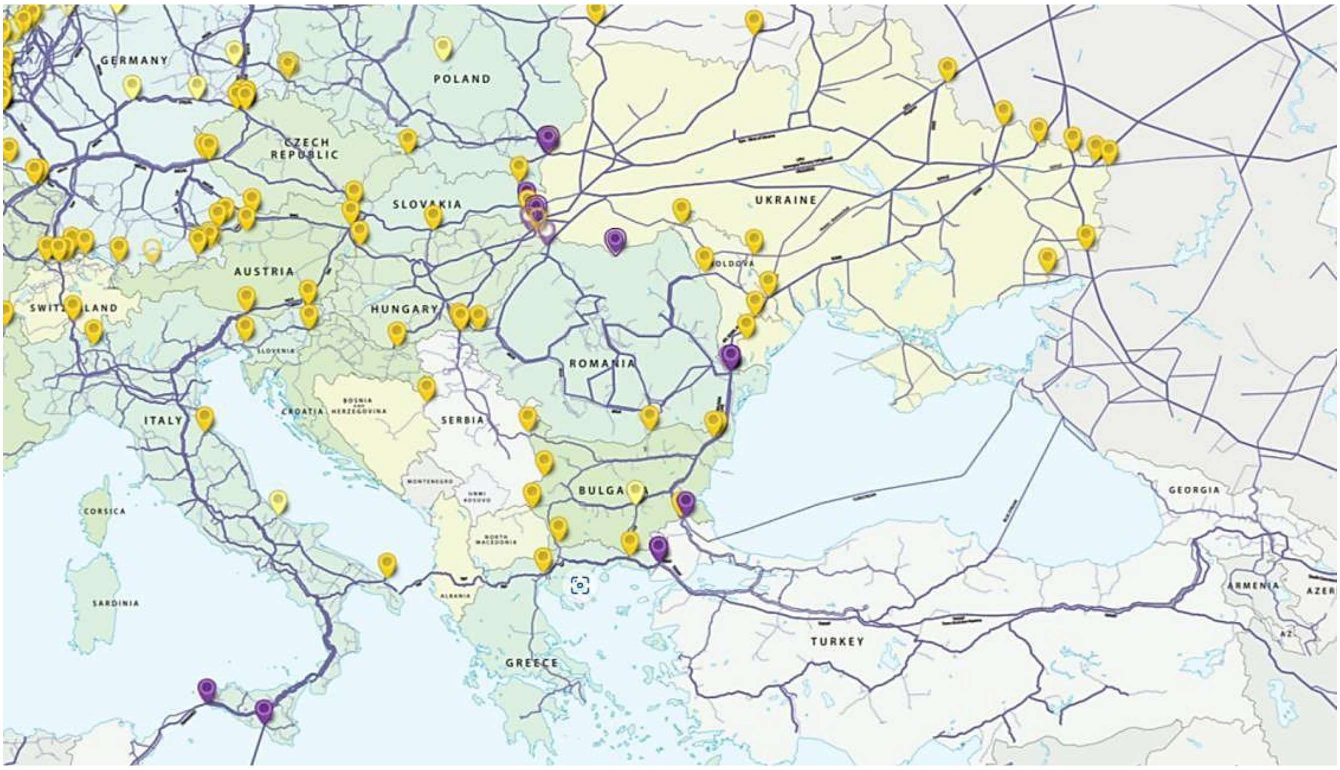

Fig. 1 Directions of Energy Projects for Gas Transportation in Ukraine
Source: ENTSOG Transparency Platform [25, 27].

The main routes include corridors through Turkey, Greece, Bulgaria, Romania, Hungary, and Slovakia, which play a key role in ensuring the diversification of gas supplies to Central Europe, minimizing dependence on traditional routes through Ukraine. Another important direction is the Germany-Poland corridor, which strengthened ties between Western and Central Europe. The Italy-Austria-Slovakia corridor also plays a significant role, allowing for the supply of energy carriers through the Southern and Northern gas corridors to Italy and Central Europe. The projects are essential for increasing the region's energy security and reducing dependence on Russian resources.

According to the Transmission System Development Plan for 2021-2030 [26], cross-border electricity trade and the effective use of interstate energy intersections are crucial elements in ensuring the energy security of Ukraine and Europe. Interaction with the energy systems of neighboring countries contributes to increasing the stability of energy systems and allows Ukraine to integrate into the European energy market.

The connection with ENTSO-E is an integral part of the interaction of the Ukrainian Electricity System with the energy systems of Hungary, Slovakia, Poland, and Romania, emphasizing the integration processes between Ukraine and the European energy market [28]. Such connections allow Ukraine to ensure stable electricity exports to EU member states and contribute to increasing Europe's energy security, especially at critical moments of electricity shortage in EU countries. Power flows through energy corridors play an essential role in Hungary, where the capacity of the flows can reach up to 650 MW, as well as to Slovakia and Romania, with figures of about 400 MW.

Energy transmission to Poland is carried out through the Dobrotvirska TPP, which has a 220 kV transmission line connecting it to the city of Zamość in Poland. The line allows the exporting of up to 210 MW of electricity in the directional transmission mode, thereby ensuring the stability of the electricity supply in Poland. Such energy connections are of strategic importance for Ukraine and Central Europe.

The Moldovan power system also actively interacts with the Unified Power System of Ukraine, and power flows can reach up to 400 MW. This is an essential factor in regional energy security, as it satisfies Moldova's needs for electricity, providing additional stability in a politically sensitive region.

Ukraine's integration into the European energy system is critical from the point of view of increasing the energy security of the country itself and the entire European continent. The use of powerful cross-border energy corridors allows for the effective export of electricity, increasing the stability of energy supplies to EU countries and reducing dependence on traditional energy sources. That is, cross-border trade in energy carriers is an essential factor in ensuring the energy stability of the region.

Table 2 below illustrates the number of interstate power transmission lines (PTLs) between Ukraine and neighboring countries by voltage class, which is a factor in maintaining reliable energy connectivity.

Table 2
Interstate power transmission lines

Country	Number PTL by voltage class (kV), pcs.							
	750 kV	500 kV	400 kV	330 kV	220 kV	110 kV	35 kV	6+10 kV
Poland	1	-	-	-	1	-	-	-
Slovakia	-	-	1	-	-	-	1	-
Hungary	1	-	1	-	2	-	-	-
Romania	1	-	1	-	-	-	-	-
Moldova	-	-	-	7	-	11	1	1
Total connections with ENTSO-E countries	3	-	3	7	3	11	2	1

Source: own elaboration based on [25].

Table 2 shows the cross-border electricity crossings and flows between Ukraine and neighboring countries and the distribution of power transmission lines (PTLs) by voltage class connecting Ukraine with Poland, Slovakia, Hungary, Romania, and Moldova.

The total number of connections between Ukraine and ENTSO-E countries is 26 PTLs, different in voltage class, among which the most significant number are 110 kV and 330 kV PTLs, which ensures substantial electricity flows and stable operation of the power system. Ukraine has the largest PTL with a voltage of 750 kV, one of the most potent lines for transmitting electricity to Poland. This indicates the strategic importance of energy relations with this country. Romania and Hungary also have significant connections through 400 kV and 330 kV PTLs, which means a high level of interaction between the power systems of these countries. Although Moldova does not have 750 kV high-voltage lines, it has 11110 kV and 7330 kV transmission lines, ensuring a moderate electricity exchange between these countries.

The data in the table demonstrate a wide range of opportunities for cross-border electricity trade and interstate cooperation in the energy sector. High-voltage lines transmit large volumes of energy, thereby increasing Ukraine's and its neighbors' energy security and stability.

Thus, Ukraine is actively developing cooperation with European countries in the energy sector, which increases energy security and ensures the stability of the energy system in conditions of war and restructuring. An essential role in this process is integrating the Ukrainian energy system into the European ENTSO-E network, which allows Ukraine to participate in cross-border electricity trade.

Energy flow management model at the level of international institutions (using the example of ENTSO-E)

Effective management of energy flows at the international level is crucial for ensuring the stability and security of electricity systems. The European Network of Transmission System Operators for Electricity (ENTSO-E) coordinates the work of national operators, ensuring the balancing of energy flows, the development of market mechanisms, and the response to crises. Thanks to an integrated approach, ENTSO-E contributes to increasing resource efficiency, reducing the risks of energy crises, and developing renewable energy. Digital technologies, consumption forecasting, infrastructure modernization, and planning are essential roles in the process. Figure 2 shows the energy flow management process elements using the example of ENTSO-E.

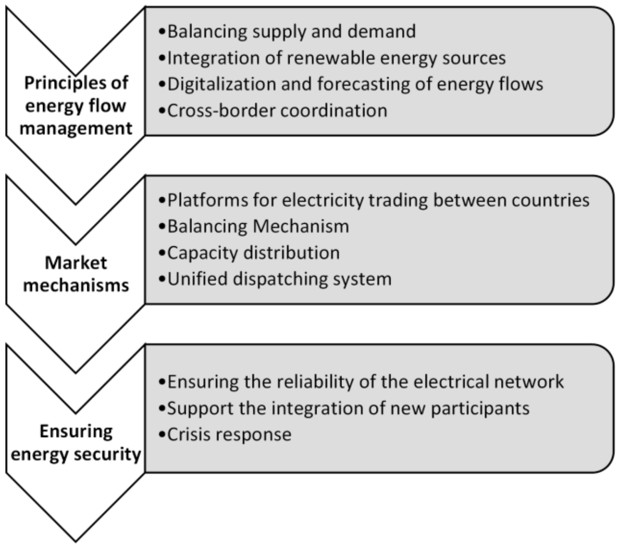

Fig. 2 Main elements of energy flow management in ENTSO-E
Source: own elaboration based on [29, 30, 31, 32, 33].

According to Figure 2, energy flow management within ENTSO-E is based on three essential elements: the basic principles of energy management, market mechanisms, and measures to ensure energy security. ENTSO-E uses modern management models based on several key principles. Firstly, it is the balancing of demand and supply, which involves the coordination of energy supply between countries to minimize energy imbalances. Secondly, integrating renewable energy sources (RES) allows for a more efficient distribution of capacity between Member States and contributes to the transition to sustainable energy. Digitalization and forecasting of energy flows play an essential role in this process – artificial intelligence and big data analytics help transmission system operators (TSOs) optimize loads and avoid critical situations. Last but not least, cross-border coordination is an aspect of ENTSO-E, which implements common standards and procedures to ensure efficient interoperability between European energy systems.

Cross-border electricity flows within ENTSO-E are regulated by market mechanisms that optimize energy resource use. One of the key elements of this model is the Day-Ahead Market (DAM) [29] and the Intraday Market (IDM) [30], which create platforms for international electricity trading and facilitate the operational balancing of the energy system. The Balancing Mechanism [31] is an additional tool that allows centralized real-time energy consumption balancing. Another vital model component is the Capacity Allocation Model [32], which determines the available cross-border capacities and provides for the auction allocation of electricity network capacity. The last element is a single dispatching system (Coordinated Security Analysis), which offers centralized load forecasting and modern analysis methods to prevent emergencies. [33]

ENTSO-E strategically forms a single European energy market, ensuring energy supply stability and security. Transmission system operators constantly monitor energy flows, allowing prompt response to possible challenges. ENTSO-E also promotes the integration of new participants, particularly Ukraine, into the pan-European energy system, which expands the market and increases the reliability of the energy supply.

In addition, ENTSO-E develops rapid response mechanisms for crises, such as energy shocks or supply disruptions. This provides an additional level of protection and minimizes risks for end consumers. Thus, international cooperation in the field of energy flow management not only improves economic efficiency but also strengthens Europe's energy security.

Energy flow management models at the level of international institutions, such as ENTSO-E, contribute to the effective functioning of cross-border trade and increased energy security integration of renewable energy sources. Ukraine's inclusion in ENTSO-E is a strategic step that allows the country to become a full-fledged participant in the European energy market, increasing its resilience to energy crises.

DISCUSSION

When considering the impact of cross-border energy trade on the energy security of European countries, it is worth paying attention to global trends in energy policy and risk management. In particular, the issue of energy sustainability and the integration of renewable energy sources (RES) is one of the key challenges for EU countries and Ukraine.

Recent studies indicate that the development of offshore wind energy in Poland [34] can be an essential step in increasing the region's energy independence. Implementing such projects contributes to strengthening the sustainability of energy systems, reducing the carbon footprint, and improving the role of the EU in the global energy transformation. Regarding risk management in the energy sector of Ukraine, the unstable geopolitical situation and economic factors are key threats to the sustainability of the Ukrainian energy sector [35, 36]. This confirms the need to diversify supply sources and integrate Ukraine into the European energy grid, which is already actively being implemented through cooperation with ENTSO-E.

The issue of energy taxation is also essential in the context of developing a sustainable energy policy. Applying energy taxes can promote the transition to clean energy and stimulate investment in renewable energy [37]. In this regard, the role of political and economic mechanisms is increasing, which should balance energy security and environmental sustainability. Financial mechanisms play a crucial role in the development of the energy sector. Researchers [38] consider integrated models of attracting grant and private financing in the energy sector of Ukraine based on public-private partnerships. This can contribute to energy infrastructure modernization and increase Ukraine's competitiveness in the European energy market. In general, the energy security crisis in Europe has a long history, which is confirmed by studies [39], which emphasize that the countries of Central and Eastern Europe continue to feel the impact of dependence on traditional energy resources, which complicates the process of transition to alternative energy sources. At the same time, the expansion of LNG infrastructure and the development of renewable energy sources help to reduce the impact of energy crises.

On the other hand, research results [40, 41] demonstrate that the future of energy infrastructure will depend on technological innovations, digitalization, and integration of distributed energy sources. This confirms the need for increased cooperation between countries in developing "smart" energy systems, which will optimize electricity flows and increase supply stability.

Thus, the analysis of modern literature indicates the need for an integrated approach to ensuring energy security. The combination of strategic planning, innovative financing mechanisms, and the development of renewable energy sources will allow European countries to reduce their vulnerability to external threats and increase the efficiency of cross-border energy trade.

CONCLUSIONS

Cross-border energy trade plays a key role in ensuring the energy security of European countries, contributing to the diversification of supply sources, increasing the resilience of energy systems, and reducing the risks of energy crises. An analysis of the development of energy cooperation in Europe shows that integrating regional energy markets and implementing sustainable energy strategies can significantly increase the efficiency of the functioning of energy systems.

Ukraine plays a strategic role in cross-border energy trade due to its geographical location and gradual integration into the European energy network. The synchronization of Ukraine's energy system with ENTSO-E stabilizes the energy market, opens new opportunities for electricity exports, and strengthens pan-European energy security.

Geopolitical challenges, such as military conflict and economic sanctions, have accelerated the EU's reorientation towards alternative energy sources and reduced dependence on Russian resources. The RePowerEU plan envisages the active development of renewable energy, which will determine the structure of cross-border trade in the future.

The assessment of strategic plans in the field of energy security demonstrates the importance of international cooperation, investment in infrastructure, and the implementation of mechanisms for managing energy flows. The experience of ENTSO-E proves the effectiveness of integrated market mechanisms in ensuring the stability of the energy supply.

Modern management models based on balancing supply and demand, digitalization of processes, load forecasting, and centralized market mechanisms create conditions for the stable functioning of energy systems even in the event of internal or external threats. Further research should focus on improving management models for coordinating cross-border energy flows, adapting to the growth of the share of renewables, developing crisis mechanisms, and actively using digital technologies to increase the reliability and efficiency of energy management within the global energy system.

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