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Roman ZVARYCH,
Bohdan KHARKOVSKYI

SMART INTEGRATION OF UKRAINE'S ENERGY SYSTEM INTO THE SINGLE ENERGY MARKET OF THE EU: CHALLENGES AND PROSPECTS

Abstract

This article is devoted to analyzing the process of Ukraine's energy market integration into the single energy space of the European Union. It examines the current state of this integration, key challenges, and future prospects. A comprehensive methodological approach was employed, including a comparative analysis and, for the first time, a SWOT analysis, to identify the Ukrainian energy system's strengths, weaknesses, development opportunities, and threats—particularly those arising from military actions and environmental challenges. Special focus is placed on the synchronization of the Ukrainian power system with Europe's ENTSO-E grid, its modernization, and implementation of new technologies, which create new opportunities for electricity exports and imports as well as for attracting international investment. A Pearson correlation analysis was also conducted for the first time to evaluate electricity import volumes and their impact

Zvarych Roman, Doctor of Economic Sciences, Professor, Head of Department of International Economic Relations, West Ukrainian National University, Ternopil, Ukraine. ORCID: 0000-0003-3741-2642 Email: r.zvarych@wunu.edu.ua
Kharkovskyi Bohdan, PhD student, Department of International Economic Relations, West Ukrainian National University, Ternopil, Ukraine. ORCID: 0009-0006-4030-4991 Email: kharkovskyibohdan@gmail.com

on the country's energy security. The study concludes that for Ukraine to achieve full integration with the EU energy market, it must implement extensive technological modernization, expand international partnerships, harmonize its legislation, and adopt new environmental standards.

Key Words:

energy market, energy sector, environmental transformation, Eurointegration, European Union, smart grid, Ukraine.

JEL: F15, Q40, Q48, Q58, O38.

3 figures, 1 table, 30 references.

Problem Statement

The integration of Ukraine's energy system into the single energy market of the European Union is a strategic task of modern energy policy that reflects global challenges of energy security, economic stability, and environmental sustainability. Current trends in the integration of international energy markets provide evidence for the need to harmonize technical, economic, and regulatory frameworks to ensure the competitiveness and efficiency of energy systems. Having operated within an integrated power system for a long time, Ukraine has focused its efforts on modernizing its infrastructure to comply with European standards and to ensure independence from outdated technologies (Mykhailova et al., 2023).

The modernization of Ukraine's energy sector has gained particular relevance due to the full-scale war and environmental challenges. Implementing innovative technologies, such as «smart grid» systems, together with integrating renewable energy sources, aims to increase energy efficiency and reduce environmental impact. The harmonization of national legislation with EU standards has become a prerequisite for creating conditions in which Ukraine's energy system can effectively compete in the European market while simultaneously ensuring the energy security and sustainable development of the country.

Literature Review

The integration of Ukraine into the European Union's energy market has been explored across a broad spectrum of studies, highlighting the technical and institutional aspects of the process. In particular, Böttcher et al. (2023), in their study titled «Initial analysis of the impact of Ukrainian power grid synchronization with Continental Europe», demonstrate that despite a slight increase in fluctuations in power grid stability indicators, the integrated system can be considered stable. This finding confirms the effectiveness of technical synchronization measures. However, a purely quantitative focus does not always account for the normative, legal, and institutional challenges that accompany the transformation of the power system.

Studies on green energy and its role in Ukraine's modern-day realities emphasize the need for a multifaceted approach to achieving energy independence while integrating with European standards. Mykhailova et al. (2023) suggest decentralization as a key mechanism for enhancing the resilience of the power system amid wartime challenges. However, they do not elaborate on the technical aspects of integrating with the European grid. Lutkovska et al. (2023) build on this idea, stressing the need to harmonize legislation to promote the development of renewable energy sources within the context of European integration. Yet, their analysis overlooks specific technologies, such as intelligent grids.

Meanwhile, Maksymova and Nastase (2024) propose digitalization as a means of achieving climate neutrality, but their ideas seem somewhat disconnected from the current situation, as they do not consider the damage to infrastructure caused by the war. Shnyrkov and Chugaiev (2023) expand this perspective by introducing an economic context to EU integration and noting that the war impedes investment. However, they omit specifics on how to overcome these impediments. Ohdanska and Chernobryvets (2024) revisit the concept of decentralization, proposing the use of renewable energy sources to restore infrastructure; nonetheless, they overlook the importance of smart grids, which could render their approach more practical. Oriekhova et al. (2024) focus on managing alternative energy sources during wartime and advocate for increased state support; yet, their recommendations remain general and lack technical detail. Kharin et al. (2024) propose an innovative path toward decarbonization through hydrogen technology, though their failure to connect this approach with the broader process of European integration weakens their contribution in the context of Ukraine's strategic objectives. Finally, Baidala and Nahornyi (2023) draw attention to the potential of wind energy, but their analysis does not engage with the technical or integrative challenges of connecting to the European grid. Taken together, these studies emphasize the importance of a comprehensive approach to developing

Ukraine's energy sector. However, their limited focus on technical details and wartime realities leaves considerable room for further research.

Abnet and Strzelecki (2022), in turn, offer a plan for synchronizing the Ukrainian and European power grids, addressing both technical and political aspects of the process. Their work outlines a detailed roadmap for connection to ENTSO-E and provides accessible context to garner international support, which is an essential factor in ensuring successful synchronization of the Ukrainian grid with the European one.

Researchers from the Organization for Economic Cooperation and Development (OECD, 2019) conducted a comprehensive analysis of Ukraine's energy sector, providing recommendations on energy efficiency and environmental sustainability. This report lays the foundation for understanding the ecological and technical challenges of integration, although it gives little attention to new technologies, such as smart grids.

A study by the Ukrainian Centre for European Policy (2023) considers Ukraine's integration with the EU market under wartime conditions, with an emphasis on the role of international support and the modernization of the energy sector. While shedding light on opportunities and threats, the report less thoroughly covers technical dimensions, such as smart grids.

Research by DiXiGroup and the Clingendael Institute (Cretti et al., 2024) outlines strategic plans for infrastructure modernization, with a focus on implementing renewable energy sources and harmonizing the legislation. However, their conclusions tend to be overly general and often fail to account for specific features of the local Ukrainian market.

The purpose of this study is to conduct a comprehensive analysis of SMART integration of Ukraine's energy system into the single energy market of the European Union, taking into account environmental and technological challenges. The study seeks to evaluate the current state of the energy sector, identify barriers and prospects for harmonization with European standards, and develop recommendations for infrastructure modernization to ensure energy security and sustainability.

Methodology

This study provides a comprehensive analysis of Ukraine's energy system integration into the European Union's single energy market, employing several research methods. First, a literature review was undertaken, during which scientific publications and reports on Ukraine's energy sector integration into the EU market were systematized and analyzed. A comparative analysis was then conducted, enabling the identification of key differences and common trends between the Ukrainian energy system and those of EU countries, as well as the assessment of the prospects for harmonizing Ukraine's legislation with European standards. To assess the relationship between electricity import volumes and time, a Pearson correlation coefficient was calculated using data from January 2023 to December 2024, which enabled us to determine the impact of electricity imports on national energy security. In addition, a SWOT analysis was performed to identify the strengths and weaknesses of Ukraine's power system, as well as the opportunities and threats related to its integration into the European energy market.

Research Results

At its current stage of development, Ukraine's energy system is characterized by a complex structure that incorporates both legacy infrastructure and modernized components. Analysis of the existing system reveals significant shortcomings, including outdated technological solutions, suboptimal energy efficiency in certain segments of the grid, and limited compliance with modern environmental standards. These factors significantly affect Ukraine's potential to integrate into the European Union's single energy market, as successful adaptation requires the harmonization of the national regulatory framework with EU requirements and standards.

The integration processes, meant to align Ukraine's energy system with European standards, encompass technical and regulatory aspects. Within this process, work is underway to modernize infrastructure, implement innovative technologies, and develop partnership projects with EU countries (Ukrainian Centre for European Policy, 2023). Significant attention is paid to harmonizing safety, efficiency, and environmental standards, which enable the joint operation of power systems of different countries within a single market. A comparative analysis (Razumkov Centre, 2020) drawing on the experience of neighboring countries that have already integrated or are in the process of doing so indicates the need for comprehensive reforms to improve the legal framework, develop a competitive environment, and enhance cooperation at the international level.

One key aspect of integration processes is the need to consider global environmental challenges, which are becoming the driving force behind the transformation of the energy sector. Against the backdrop of Russia's full-scale invasion and the growing urgency of addressing climate change, reducing greenhouse gas emissions, and decreasing dependence on fossil fuels, the integration of Ukraine's energy system into the EU's single market has become particularly relevant (Ministry of Energy of Ukraine, 2023). The shift towards clean, renewable energy sources and energy-efficient technologies is viewed as a strategic direction that will not only help mitigate negative environmental impacts but also enhance national energy security. Furthermore, the implementation of European environmental standards requires substantial investment in the modernization of production capacities, the adaptation of existing technologies, and the development of new approaches to energy resource management (OECD, 2020).

Thus, the current state of Ukraine's energy system, its integration into the EU's single energy market, and environmental challenges together form an interconnected field of research that demands a comprehensive approach to addressing existing problems. Harmonizing national energy standards with European requirements, modernizing infrastructure, and actively implementing environmentally friendly technologies are key conditions for successful integration. These measures will contribute to achieving energy security and economic efficiency while ensuring the preservation of the natural environment in the face of global challenges.

To effectively identify critical components for power grid integration and develop clear strategies and action plans, it is worth conducting a SWOT analysis of the Ukrainian power grid in order to identify its weaknesses as well as opportunities for improvement.

Figure 1

SWOT analysis of Ukraine's power grid

Source: created by the authors.

The SWOT analysis of Ukraine's energy sector integration with the EU's single energy market revealed several key factors that determine the prospects of this process. Strengths include technical modernization, adoption of modern technologies, infrastructure modernization, increased system efficiency, international partnerships, support from international financial institutions, and power grid synchronization. However, weaknesses also persist, such as outdated infrastructure, low energy efficiency, dependence on fossil fuels, financial and human resource constraints, insufficient investment in modernization, a shortage of skilled specialists, problems with reform management, and critical damage to Ukraine's power grid caused by Russian missile strikes.

Main opportunities include technological advancements, implementation of renewable energy sources, digitalization of management and optimization of production, full integration with the EU market, expanded export opportunities, access to new investments, diversification of energy supply, participation in EU programs, international partnerships, and the creation of a favorable investment climate. However, the process faces threats, including geopolitical instability, Russian invasion, external pressures, risks of political crisis in the region, environmental challenges, tightening of EU environmental standards, climate change, additional investment needs for infrastructure adaptation, instability in global energy prices, economic crisis, and the high cost of power grid restoration. The analysis demonstrates the need for a comprehensive approach to energy sector reform, including adaptation to EU standards, diversification of energy sources, and attracting investment to support sustainable development.

One of the major accomplishments for Ukraine's energy sector in recent years has been the synchronization of Ukraine's power grid with the European ENTSO-E grid in March 2022. Although preparations for the synchronization had been ongoing for many years, it was the Russian Federation's full-scale invasion that prompted maximum efforts to finalize the process of synchronization in the shortest possible time and connect Ukraine's power grid to ENTSO-E (Abnet & Strzelecki, 2022).

At the strategic level, the synchronization with ENTSO-E plays a decisive role in Ukraine's integration into the single European energy market. It opens up opportunities for expanding electricity exports and imports, ensures access to advanced technologies, and promotes infrastructure development in line with European standards. In addition, this process facilitates regulatory framework harmonization and the creation of a stable investment climate, both of which are essential for economic growth and strengthening national energy security (Ukrainska Pravda, 2024).

Amid sustained missile attacks by the Russian Federation in recent years, synchronizing Ukraine's power grid with ENTSO-E has been central to ensuring the country's energy security. According to statistics (Energy Map, n.d.; DiXi-Group, 2024), the largest volumes of imports were recorded in June and July, when shelling coincided with abnormally high temperatures. In June, imports reached 858.4 thousand MWh, which was 6% higher than the total imports for all of 2023 (806.4 thousand MWh) and the highest monthly figure in 2024 (see Table 1).

Table 1

Volumes of electricity imports in 2023-2024, thousand MWh

Month	Volume of imports in 2023 (thousand MWh)	Volume of imports in 2024 (thousand MWh)
January	62,453	122,831
February	141,720	84,094
March	7,110	168,281
April	4,201	223,848
May	23,605	448,163
June	43,704	858,378
July	73,298	842,842
August	115,596	472,832
September	23,824	437,855
October	17,207	181,794
November	60,678	162,397
December	232,914	433,295

Source: compiled by the authors based on Energy Map (n.d.).

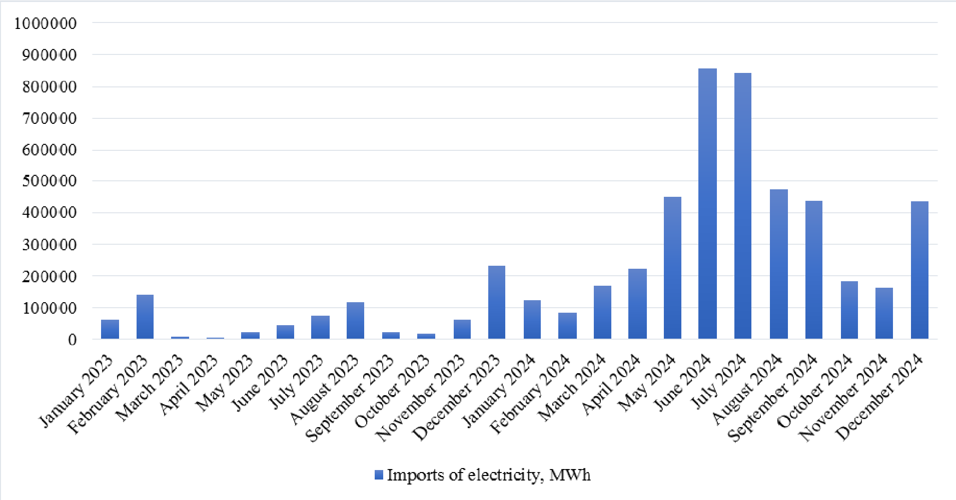
The data on electricity import volumes for 2023-2024, shown in Table 1, were used to create a chart that visualizes changes in electricity import volumes over time (see Figure 2).

As can be seen in Table 1 and Figure 2, the synchronization of Ukraine's grid with ENTSO-E was instrumental in maintaining the country's energy system stability during its most difficult times. Thanks to the work done on the modernization and strengthening of trunk interstate transmission lines, it has become possible to import enormous volumes of energy—a key indicator used to assess the integration of Ukraine's energy market into the single European market.

To examine in detail the increase in electricity imports and its role in ensuring the stability of Ukraine's energy system, a correlation analysis was conducted using the Pearson correlation coefficient. The analysis is based on data from Energy Map (n.d.), presented in Table 1, which illustrates monthly volumes of electricity imports for the period from January 2023 to December 2024.

Figure 2

Volumes of electricity imports in 2023-2024, MWh



Source: compiled by the authors based on data from Energy Map (n.d.).

The calculated correlation coefficient (*r* = 0.532) indicates a positive relationship between the passage of time and the volume of electricity imports, reflecting a gradual increase in the role of foreign energy supplies in ensuring the stability of Ukraine's energy system. This trend is clearly reflected in the sharp surge of imports during the summer of 2024, when their volumes reached 858.4 thousand MWh in June and an estimated 842 thousand MWh in July, compared to an average monthly volume of 67.2 thousand MWh in 2023. Such growth was made possible by Ukraine's power grid synchronization with the ENTSO-E system in March 2022—a strategic step toward ensuring energy security amid Russia's full-scale invasion and the resulting destruction of infrastructure.

The moderate correlation strength (0.5 < r < 0.7) indicates that, although the time factor plays an important role in import dynamics, other variables not included in the linear model also have a significant impact. Among these factors, it is worth mentioning the intensity and frequency of attacks on energy facilities, seasonal fluctuations in electricity demand (in particular those related to the abnormal heat of summer 2024), and technical limitations in the transmission capacity of interstate power lines. These aspects are consistent with the results of our SWOT analysis, which identifies outdated infrastructure, low energy efficiency, and significant war-related damage among the weaknesses of Ukraine's energy system.

From an energy security perspective, the correlation coefficient r = 0.532 underscores the dual nature of the current situation. On one hand, the increase in imports suggests a successful adaptation to critical conditions, where domestic production could not fully meet demand due to considerable losses in generating capacity (35% of operational capacity, according to data from the UN Human Rights Monitoring Mission in Ukraine, 2024). On the other hand, this points to a temporary vulnerability in the system, which is becoming increasingly dependent on foreign resources. The synchronization with ENTSO-E has demonstrated the stability of the integrated power network; however, it has not resolved institutional and technical barriers such as insufficient investment and a shortage of skilled personnel, which are key remaining impediments on the path to complete integration.

The findings of the correlation analysis directly relate to the strategic objectives of integrating Ukraine's energy market into the EU single market. The moderate increase in electricity imports reflects the initial stage of this integration, during which synchronization with ENTSO-E has opened access to European resources, but sufficient modernization of domestic infrastructure has yet to take place. A comparative analysis of neighboring countries' experiences (Razumkov Centre, 2019) corroborates these findings, highlighting the need for comprehensive reforms to harmonize the legislative framework and establish a competitive market.

In the short term, import growth serves to offset the deficit caused by the destruction of energy facilities, including thermal, hydro, and atomic stations, as well as high-voltage grids. According to estimates by the International Renaissance Foundation (2024), substantial infrastructure losses combined with the blockade of seaports have significantly limited the domestic production and supply of fuels, prompting Ukraine to reorient its logistics toward its western borders. In this context, imports not only emerge as a technical solution but also as a factor of economic stability, helping to avoid massive electricity outages, such as those in November 2022, when nearly 700 thousand customers were left without electricity.

In the medium and long term, however, reliance on imports may become an economic and political burden unless accompanied by a systemic transformation of the energy system. As noted in a study by DiXiGroup (2024), integration with the EU requires not only technical synchronization, but also the adoption of renewable energy sources (RES), digitalization of management, and harmonization of environmental standards. The moderate correlation coefficient (r = 0.532) suggests that, while the current crisis response model is effective under extreme circumstances, it is unsustainable without investment in modernization and diversification of energy sources.

In the coming years, electricity imports will likely continue to serve as a key mechanism for ensuring power grid stability, especially given ongoing geopolitical instability and the slow pace of infrastructure recovery. If the trend of increasing imports persists, volumes could reach 1 to 1.5 million MWh per month during peak periods (summer or winter), depending on the intensity of external factors and weather conditions. In this case, energy security will depend on the reliability of ENTSO-E partners and the government's capacity to respond promptly to new challenges—particularly through the development of backup grids and continuous modernization.

If modernization is delayed due to a lack of financing, political instability, or conflict escalation, imports will continue to be the dominant source of energy supply. This reliance will increase vulnerability to external economic factors, such as fluctuations in energy prices, and may complicate harmonization with the EU's increasingly stringent environmental standards. Under such a scenario, Ukraine's energy security will remain under threat, while its competitiveness in the European market will be constrained by low energy efficiency and an outdated technical base.

Thus, the synchronization of Ukraine's energy system with ENTSO-E is a fundamental step in the transformation of its energy sector, facilitating Ukraine's adaptation to modern global challenges and ensuring its integration into the EU's single market.

That said, power grid synchronization is merely one step on the path toward the full integration of Ukraine's energy market into the EU. The normal functioning of Ukraine's energy infrastructure is strategically important for the country's economic development, which is why ensuring its stability has become a priority objective in the context of security challenges. In recent years, in the absence of sufficiently effective air defense systems, massive ballistic and cruise missile strikes, along with multiple attacks by unmanned aerial vehicles, have caused substantial destruction to key facilities involved in the production, processing, transport, distribution, and storage of energy resources. As a result, the main elements of Ukraine's integrated power system – including thermal, hydro, and power stations, as well as all high-voltage electricity distribution facilities – have been damaged or taken out of operation (International Renaissance Foundation, 2024). Furthermore, in the temporarily occupied territories and combat areas, nearly 35% of operational power-generation capacity has been reported as lost, with the Zaporizhzhia Nuclear Power Plant—the largest in Europe by generation capacity—being a notable example; moreover, oil and gas refineries that supplied up to 30% of domestic oil product consumption are no longer operational; and more than 30 strategic fuel storage facilities have been destroyed (UN Human Rights Monitoring Mission, 2024). Due to the blockage of seaports, oil products have been supplied exclusively via railway and road crossing points at the western frontier and through three river ports, which has led to a considerable reduction in electricity consumption (e.g. nearly 700 thousand customers were cut off from power supply in November 2022) and a temporary suspension of gas supply to 230 thousand customers. The total economic losses in the energy and oil and gas sectors, estimated at $600 billion as of early December 2022 (UN Human Rights Monitoring Mission, 2024), are projected to increase further due to Russia's sustained strategy of massive missile attacks, creating uncertainty about the stabilization of the situation, a condition likely to persist at least until the war is over.

In this context, the following short-term tasks should be prioritized: preserving the integrity of Ukraine's integrated power system; ensuring the timely restoration of facilities after each attack; addressing territorial imbalances in the production and consumption of electricity and heat; restoring the supply of fuel and energy in regions with damaged infrastructure; developing backup networks and systems—both interstate and autonomous—for use in the event of a systemic failure; and guaranteeing the uninterrupted supply of energy resources through the western border and the safe operation of remaining functional energy infrastructure facilities (eu-ua.kmu.gov.ua, 2023).

According to the analysis, another important aspect is the development of strategies for modernizing the energy sector that take into account international experience and advanced technological solutions. The adaptation of modern monitoring and control systems will not only optimize energy production and distribution processes but also ensure compliance with environmental requirements set at the European level. The practical implementation of these measures can rely on the use of innovative technologies, such as the digitalization of energy infrastructure, the application of smart grid systems, and the integration of renewable energy sources (IEA, 2017).

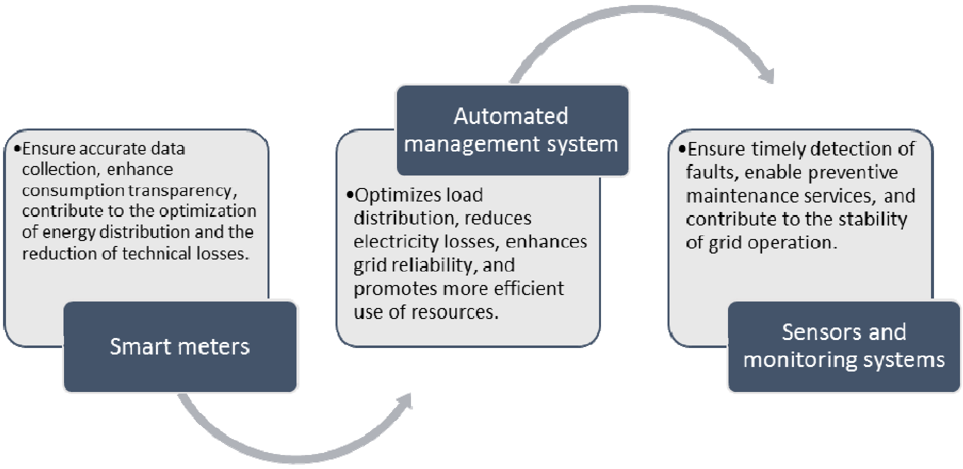
A *smart grid* is an intelligent, modernized power supply system that integrates modern information and communication technology (ICT) with conventional power grid infrastructure to enhance its efficiency, reliability, safety, and environmental sustainability (U. S. Department of Energy, n. d.). The core concept of the smart grid is to create a dynamic, self-regulating network capable of enabling two-way information exchange among producers, consumers, and grid operators. This is achieved through the deployment of various sensors, automated metering devices, monitoring systems, and high-speed communication networks, which together facilitate real-time analysis of electricity production and consumption data, load forecasting, and timely responses to changes in grid operation.

In the context of Ukraine's energy system integration into the European energy market, the deployment of smart grid technologies is instrumental in achieving national competitiveness and energy security. First, smart grids enable the efficient integration of renewable energy sources (solar, wind, and hydroelectric) into existing networks, ensuring the system's flexibility and adaptability in response to fluctuations in power production, which is especially relevant for Ukraine given its natural resources and the need to reduce dependence on fossil fuels. Second, advanced power distribution systems help reduce energy losses and increase the efficiency of electricity use by optimizing grid operation, thereby contributing to cost and resource savings (Zulhusni, 2024).

Starting in 2023, DTEK Merezhi, the distribution system operator, announced that it had begun actively testing and implementing key smart grid components into the Ukrainian power system. As of now, the company has successfully integrated three important components that improve grid efficiency during crisis situations (DTEK Merezhi, 2024).

Figure 3

Smart grid components integrated into the Ukrainian energy system



Source: (DTEK Merezhi, 2024).

As shown in Figure 3, the implementation of three key components of smart grid technology into the Ukrainian energy system has already produced tangible positive results, confirming the potential of smart grids to increase its reliability and efficiency. These elements, integrated by DTEK Merezhi since 2023, include advanced real-time monitoring systems, automated metering devices, and high-speed communication networks, which enable two-way information exchange between operators and consumers. As a result, several important advantages have been achieved. First, the stability of the power grid has significantly improved, even under crisis conditions caused by substantial infrastructure damage from massive missile attacks by the Russian Federation. Monitoring systems enable the rapid detection of fault areas, while automated controls facilitate the swift redistribution of energy flows, thereby minimizing the scale of outages. For example, during periods of peak load or damage to key power facilities, these components have helped to prevent total blackouts, which is an especially important factor during wartime.

Second, the integration of these technologies has contributed to improved energy efficiency by optimizing electricity distribution and reducing losses, which traditionally reached 10% to 15% in Ukraine's obsolete grid (IEA, 2017). This not only lowers operational costs but also helps conserve resources during periods of acute shortages in domestic production. Third, the deployed components have laid a foundation for more flexible integration of renewable energy sources (RES), such as solar and wind power generation. This constitutes an important step toward the ecological transformation of the energy system in accordance with European Union standards.

Nonetheless, the current level of smart grid integration represents merely the initial phase of a much broader transformation of Ukraine's power grid. Further development will require substantial investment, which remains limited due to economic constraints stemming from ongoing military actions and their aftermath. The prospective rollout of additional smart grid components, such as smart meters, power load forecasting systems, and expanded energy storage, offers significant opportunities to enhance the grid's adaptability and resilience. For example, smart meters can provide consumers with detailed information about their energy consumption, thereby encouraging energy-saving behavior and reducing peak loads – an especially important factor amid seasonal fluctuations in demand, as seen during the summer of 2024 due to abnormal heat (Energy Map, n. d.). Load forecasting systems, in turn, will enable grid operators to optimize electricity production and imports, which is crucial for reducing reliance on foreign supplies that reached record levels in 2024 (Cretti et al., 2024). In addition, the integration of energy storage systems – such as high-capacity batteries – can play a decisive role in stabilizing naturally intermittent renewable energy sources, as well as in creating reserves for emergency use.

To realize these prospects, DTEK Merezhi has been actively developing a plan to attract financing from international partners, such as the European Bank for Reconstruction and Development and the World Bank. A successful implementation of a full-cycle smart grid would not only enhance the competitiveness of Ukraine's energy system on its path toward the European market, but also contribute to achieving energy independence by diversifying energy sources and reducing vulnerability to external factors. In the medium term (through 2035), this will enable Ukraine to transition from a crisis-response model to proactive energy resource management, which is a prerequisite for integration into the EU's single energy space. Thus, the initial success of integrating smart grid components lays a solid foundation for future transformation – one that will combine technological innovation, economic efficiency, and environmental sustainability to address the global challenges of the modern era.

Additionally, when integrating Ukraine's energy system into the EU's unified market, it is crucial to take into account social and economic aspects, in particular their impact on employment, regional infrastructure development, and social stability (National Institute for Strategic Studies, 2014). Developing the energy sector within the framework of European standards could be a powerful catalyst for economic growth; however, this requires strong political will and active engagement from all stakeholders. Effective cooperation among government bodies, academia, and the private sector will foster the synergy necessary to implement comprehensive solutions that promote not only technical modernization and environmental sustainability, but also social responsibility within the energy sector (Committee on Ukraine's Integration into the European Union, Verkhovna Rada of Ukraine, 2020).

Therefore, the implementation of integration processes in Ukraine's energy sector requires a comprehensive approach that combines modernization of technical infrastructure, reform of the legislative system, and active adoption of innovative technologies, all while taking into account environmental and socio-economic aspects. The systematic rollout of these measures will facilitate the harmonization of national standards with EU requirements, enhance the competitiveness of Ukraine's energy system, and foster conditions for sustainable development in the face of global environmental and economic challenges.

Key strategic directions for fully integrating Ukraine's energy market with that of the EU include comprehensive initiatives encompassing modernization, innovation, and harmonization of the regulatory framework.

1. Effective realization of Ukraine's nuclear energy export potential involves not only the modernization of existing reactor technologies, but also the implementation of new quality standards to ensure product compliance with European requirements, thereby expanding export opportunities.

2. Optimal utilization of Ukraine's gas transportation system, including underground gas storage facilities (Plakhotnyuk & Ikonnikova, 2018), is a key factor in ensuring reliable supply to both domestic and foreign markets, enabling price stabilization and diversification of energy sources.

3. The development of distributed electricity generation, with a special focus on renewable energy sources, includes not only augmenting the proportion of clean energy within the overall energy balance but also incentivizing the production of highly efficient equipment capable of competing in the global market.

4. The production and export of hydrogen, in particular «green» and «pink», is a promising direction that promotes the transition to a low-carbon economy and the reduction of greenhouse gas emissions.

5. The joint use of energy resources, especially hydrocarbons, with a focus on developing the Black Sea shelf's potential, will optimize natural resource use and strengthen the country's energy independence.

6. Leveraging advanced expertise in technologies for exploring and developing unconventional and offshore hydrocarbons will facilitate the efficient use of resources and foster innovative development in the extractive sector.

Finally, implementing a closed-loop production cycle for energy storage systems will secure the stability of supply, optimize the production-consumption balance, and enhance overall energy efficiency—factors critical for adapting Ukraine's energy sector to the EU's single market.

In addition, achieving strategic integration necessitates a thorough analysis of the economic implications and potential benefits arising from aligning Ukraine's energy policy with the European model. In this context, it is imperative to assess the market's investment attractiveness, taking into account both opportunities for attracting foreign direct investment and risks posed by fluctuations in global energy prices and the Russian Federation's invasion (European Commission, 2023). Employing a systemic approach to the evaluation of economic indicators will help identify prospects for long-term economic growth, encourage the development of innovative technologies, and reinforce the country's energy independence.

Within the framework of digital transformation and the deployment of modern technologies, significant attention should be given to the development of integrated information systems for monitoring and managing energy flows. The integration of smart grid systems can not only decrease response time in volatile market conditions, but also optimize the distribution of energy resources, giving due consideration to energy efficiency and ecological security (Papadopoulou et al., 2021, Preprint). These technological solutions will help reduce electricity losses, improve the security of energy supply, and enable more efficient use of available resources.

Alongside technical considerations, the implementation of integration processes should be accompanied by the formation of a skilled human resource base capable of effectively managing modernization and innovation processes. Educational programs aimed at enhancing the professional training of specialists in the energy sector, alongside research and development projects in this field, form the foundation for building the intellectual capacity necessary for the successful transformation of the energy system. The engagement of international experts and cooperation with leading scientific centers will be instrumental in adapting cutting-edge experience to the specific conditions of the national energy sector, which, in turn, will facilitate the more efficient implementation of integration initiatives.

Thus, the systemic integration of Ukraine's energy system into the EU's single market is a multidimensional process that requires concurrent attention to technical, economic, environmental, and social aspects. The harmonization of the legislative framework, modernization of infrastructure, implementation of innovative technologies, and development of human capital constitute mutually complementing elements of this transformation. The synergy among these components will foster favorable conditions for integration, which will make Ukraine's energy system more competitive while enabling sustainable economic development and environmental security in the long term.

Conclusions

The study produced several important conclusions regarding Ukraine's integration into the European Union's single energy market amid global environmental challenges and wartime realities. First, the SWOT analysis of Ukraine's current energy system (see Figure 1) revealed the urgent need for comprehensive modernization of its aging and war-damaged infrastructure, since these deficiencies impede the system's ability to meet European standards for energy efficiency and environmental security. At the same time, the adoption of smart grid technologies and the transition to renewable energy sources were identified as critical pathways to reduce energy losses and mitigate environmental impact, thereby driving the sector's technological transformation.

Second, the integration processes aimed at synchronizing with ENTSO-E require not only technical reforms but also systemic improvements in the regulatory framework. Drawing on a comparative analysis of neighboring countries' experiences, it was determined that legislative harmonization, creation of a favorable investment environment, and development of international cooperation are critical for establishing a competitive energy market. The correlation analysis, yielding a coefficient of $r = 0.532$, confirmed a moderate positive relationship between time and electricity import volumes, reflecting the increasing role of foreign supply in maintaining the stability of the energy system; however, this also suggests the vulnerability associated with import dependency amid insufficient modernization.

Third, the environmental transformation of the energy sector constitutes an indispensable component of integration, as proven by the imperative to adopt the EU's stringent environmental standards in response to global challenges such as climate change. The shift to clean energy sources, supported by smart grid capabilities, will not only contribute to the preservation of the natural environment but also strengthen Ukraine's energy security and reduce its reliance on fossil fuels – benefits identified in the «Opportunities» section of the SWOT analysis.

Therefore, the integration of Ukraine's energy system into the unified energy market of the European Union is a multifaceted process that encompasses technical, economic, regulatory, and environmental aspects. A comprehensive approach to modernization, harmonization of standards, and active deployment of innovative technologies, such as smart grids, will establish the necessary preconditions for ensuring energy security, economic efficiency, and environmental sustainability. Achieving synergy among these components is a critical success factor in the transformation of Ukraine's energy sector, which, in turn, plays a decisive role in its integration into the European energy space.

Future research could focus on quantitative evaluations of the economic impacts associated with the implementation of smart grid technologies and the expansion of RES in Ukraine. This could include cost-benefit analyses of modernization efforts and their implications for consumer tariffs. It would also be feasible to explore the long-term consequences of reliance on electricity imports, taking into account potential geopolitical risks and volatility of energy prices. Another research trajectory involves examining the socio-economic effects of integration, such as job creation within the RES sector and its effects on regional development – both of which warrant deeper analysis to fully understand the prospects of this integration process.

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