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WORLD EXPERIENCE IN ENSURING ENERGY SECURITY

The article substantiates that each state strives for the effective implementation of its own holistic and interconnected system of measures to ensure energy security, focused on national interests and strategic priorities. The analysis showed that countries around the world (in particular, China, Germany, France, Norway, Great Britain, the USA) have defined and are implementing their own concepts of energy security, which are transformed under the influence of challenges and threats, modern technologies and the needs of the energy sector development on the principles of sustainability. It was found that the majority of global electricity production continues to be based on the use of hydrocarbons, but there is an increase in the share of low-carbon generation, in particular renewable energy sources (wind, solar, hydropower), and energy generation projects using small modular nuclear reactors are also developing. It was noted that the development of these types of energy generation allows reducing the carbon intensity of the electricity industry, which is critically important in the context of ensuring sustainable energy development. The author notes that Ukraine needs to take into account the best practices of global experience in energy security management to increase energy independence, reduce carbon footprint and ensure the stability of the energy sector. At the same time, it is noted that Ukraine, in war conditions, has generated its own practical experience in ensuring the functioning of the energy system, which is valuable for countries around the world in the context of responding to large-scale challenges and threats to energy security.

Keywords: energy security, world experience, management, nuclear energy, renewable energy sources, strategy, energy efficiency, innovation.

Problem statement. Each state strives for the effective implementation of its own holistic and interconnected system of measures to ensure energy security, focused on national interests and strategic priorities. In this context, it is important to form an independent, consistent and adaptive energy policy as a component of the paradigm of guaranteeing sovereignty, economic stability and geopolitical subjectivity of the state. Such a policy should determine the directions of development of the energy sector, mechanisms for responding to external and internal threats, and also ensure the integration of the country into global energy processes on the basis of parity, mutual benefit and security. Therefore, it is relevant to analyze the world experience in energy security management and determine the basic approaches to ensuring the effective functioning of the energy systems of the countries of the world.

Analysis of recent research and publications. The state and trends, problems of the functioning of the energy industry, models and mechanisms of energy security management are covered in publications by domestic and foreign scientists.

Energy security is influenced by many factors. In this context, M. Voynarenko et al [1] developed a mathematical model of the hierarchy of factors' influence on the energy security of an enterprise using graph theory tools. The developed model is relevant, because the use of an iterative procedure to determine the levels of the hierarchy of factors allows assessing the importance/priority of their influence in systems of different levels (global, national, regional, local).

The Russian Federation's war against Ukraine has caused challenges and threats to the energy security of Ukraine and other countries in the world. In particular, A. Lisovyi [2] investigated the current state and challenges for Ukraine's energy security. A. Atamanenko & V. Piddubnyi [3] highlighted the impact of the Russian-Ukrainian war on the EU's energy security.

In the author's publications [4; 5] the key problems in the energy sector of Ukraine are highlighted in the light of the war, and the feasibility of modernizing the energy sector, developing renewable energy, and implementing mechanisms for the functioning of the energy market, taking into account the requirements of integration into European energy markets, is substantiated. The publication [6] highlights the features of energy generation by type and substantiates the conceptual vision of the development of the energy generation market.

K. Sonowal & B. Ao [7] noted that energy security is a multifaceted and dynamic issue that affects economic, social, and environmental aspects of human life.

Q. Wang et al [8] investigated the impact of geopolitical dynamics on energy security. The role of primary energy supply in the economic

growth of the EU-27 was investigated by A. Deka et al in the publication [9].

Decarbonization measures in the energy sector are important, especially considering that greenhouse gas emissions by economic sector in the world are highest in the energy sector, as described in publications [10; 11]. A. Rao at al in article [12], based on the results of a study of 20 countries and modeling relationships, described the impact of decarbonization and government effectiveness (fairness, regulatory policy) on energy security.

Energy security is a critically important component of the national security of any country, therefore it is important to investigate the current state of energy security and the experience gained in energy security management, **which determines the purpose of the article.**

Presentation of the main research material. To develop effective approaches, institutional models, mechanisms and practices for energy security management, it is important to study global experience that countries can adapt to the national context. Studying experience contributes to the formation of national models for increasing the sustainability of the energy sector, building an effective system of public administration and forming a long-term strategy for ensuring energy independence.

One of the key strategic priorities of China's energy policy is the development of balanced approaches to ensuring energy security, which include the diversification of supply sources, the introduction of innovative technologies, and the reduction of dependence on energy imports.

Given the limited traditional energy resources in the world, the state is actively directing resources to the development of alternative and renewable energy, in particular hydropower, bioenergy, and nuclear energy. This determines the vector of the formation of an integrated concept of energy security, based on the principles of technological modernization, environmental sustainability, and energy independence [13].

The development of China's energy sector is characterized by a steady increase in demand for energy resources. According to the National Bureau of Statistics of the People's Republic of China [14], the average annual growth rate of energy consumption is expected to be at least 7.5% over the next two decades. This dynamics is due to the high rates of economic growth and industrial development.

China is actively investing in the development and implementation of modern coal-to-liquid fuel technologies, while focusing on changing the energy paradigm. The government is taking measures to support the efficient use of traditional energy sources, while developing renewable sources, strengthening national power grids and energy storage infrastructure.

The basis of Germany's energy strategy is the concept of Energiewende – "energy turnaround", which envisaged the abandonment of nuclear power by 2023, an increase in the share of renewables in the electricity sector to 80% by 2050 and a reduction of CO_2 emissions by 95% compared to 1990 [15]. One of the key elements of this policy is the support of decentralized electricity production, the involvement of households in the process of energy generation and the development of smart grids. Germany has focused on the gradual abandonment of nuclear and coal power in favor of the large-scale implementation of renewable energy sources (RES), which aims not only to achieve energy independence, but also to reduce greenhouse gas emissions.

On June 14, 2023, Germany's first-ever comprehensive National Security Strategy, entitled "Integrated Security for Germany", was published [16]. The document is based on three key principles: sustainability ("protecting peace and freedom"), resilience ("preserving values through internal strength"), and sustainable development ("protecting national resources").

The energy transition is seen as a dual-action measure: on the one hand, to increase resilience to climate change, and on the other, as a means of reducing energy dependence. Investment in critical infrastructure, its protection and strengthening its resilience are also important priorities for Germany.

In 2023, for the first time, more than half of Germany's total electricity consumption was covered by renewable energy sources. The most important source of electricity in 2023 was onshore wind power, with a share of more than 22% in electricity production [15]. The energy transition in Germany is defined as a key factor in stimulating energy efficiency, modernization, innovation and digitalization in electricity and heat supply. These processes cover not only industry, but also agriculture and the transport sector. At the same time, the German government emphasizes the need to maintain the country's international competitiveness as an important industrial region.

An important component of the strategy is increasing the efficiency of energy resources. During the period from 2008 to 2017, primary energy consumption in Germany decreased by 5.5%, which indicates the success of energy saving measures [15]. The goals and specific steps in this direction are systematized in special dossiers on energy efficiency.

Particular attention is paid to the energy transition in the building sector, which consumes around 35% of total final energy, mainly for heating and hot water. To support this sector, the Federal Ministry for Economic Affairs and Climate (BMWK) provides advisory support and financial incentives aimed at implementing energy-efficient technologies and measures.

Legislative initiatives, such as the Tenant Electricity Generation Act, aim to engage apartment building residents in the energy transition process. Funding includes solar installation projects that were commissioned after the adoption of the law that encourages the deployment of renewable energy sources in the residential sector [17].

Innovations in the electricity supply in Germany, linked to the decentralized production of renewable electricity, are creating new challenges, in particular for the transport networks. For example, electricity generated by wind turbines in the north of the country needs to be transported to consumers in the south. Therefore, the modernization of supra-regional transmission networks and local distribution systems is a priority to ensure the reliability and efficiency of the energy system. At the same time, increasing the flexibility of consumption and traditional energy production requires digitalization, in particular the introduction of smart meters. These technologies contribute to a more balanced relationship between production and consumption, opening up additional opportunities for energy savings and optimization of the system.

Thus, unlike China, where the main emphasis is on centralized regulation and strategic management, German energy policy is largely based on market mechanisms, public participation and transparent decision-making. An important place is occupied by the environmental component, which is due to the strong public demand for sustainable development.

It is important to note that the new German government led by F. Merz will no longer prevent nuclear energy from being recognized as "green" in the EU, changing the previous tough position (which was that only renewable sources should be included in green energy, which in 2024 provided more than 60% of the country's electricity consumption). Today, Germany plans to invest in modern nuclear technologies, such as small modular reactors and nuclear fusion, but does not plan to return traditional nuclear power plants [18].

Norway is consistently among the world leaders in terms of electricity production per capita, which is due to the high specific capacity of hydroelectric power plants, low domestic consumption, and efficient use of natural resources combined with the export orientation of the energy sector (Fig. 1).

The country's unique energy structure is based on the wealth of hydropower resources,

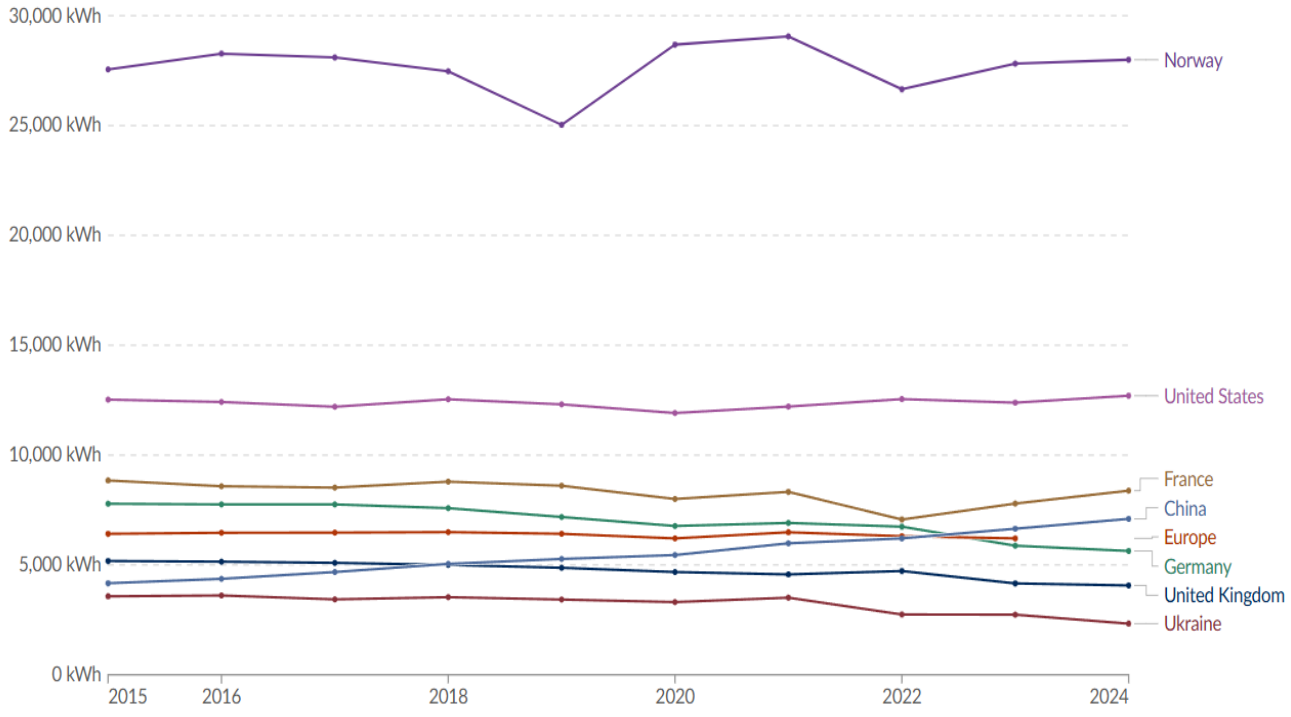

Figure 1. Comparison of energy production per capita by country, kilowatt-hours per person

Source: [19]

significant reserves of oil and natural gas, as well as the active development of new renewable energy sources, such as wind power and biomass. An important aspect is the complete absence of nuclear energy in the national energy system, which reflects the priority of environmental sustainability in Norway's strategic decisions [20].

In 2019–2020, Norway ranked ninth in the world in terms of net exports of oil and petroleum products and third in terms of natural gas exports, which emphasizes the country's importance as one of the leading energy suppliers in the international market. At the same time, oil and gas play a relatively small role in Norway's domestic energy consumption: over 95% of natural gas and over 75% of oil are exported, which indicates the country's export orientation and high level of energy efficiency in domestic consumption [21].

An analysis of Norway's energy balance shows that hydropower is the dominant source of electricity generation. Norway has over 1,240 hydroelectric power plants with a total capacity of 87 TWh. The 30 largest reservoirs provide approximately half of the capacity. The total capacity of the reservoirs corresponds to 70% of Norway's annual electricity consumption.

Over the past decades, Norway has been implementing a policy of increasing the efficiency of energy resources, which has allowed to reduce energy consumption per capita, despite the growth of economic activity (Fig. 2). Key measures have been the modernization of energy infrastructure, the introduction of energy-saving technologies in industry and everyday life, as well as the stimulation of the development of clean energy, in particular wind energy at sea and onshore facilities [22].

Overall, Norway's energy policy is an example of a balanced approach to ensuring energy security, environmental sustainability, and economic growth, based on the rational use of natural resources and the introduction of innovative technologies.

France is one of the key players in the European Union energy market, demonstrating a high level of energy independence, primarily due to a developed nuclear energy sector. About 70% of electricity in France is produced by nuclear power plants, which is one of the highest rates in the world [24] (Fig. 3). This power generation model has allowed the country to minimize its dependence on fossil fuel imports and at the same time achieve low levels of greenhouse gas emissions in the electricity sector.

At the same time, France's energy security in the 21st century is being transformed by new challenges. First of all, it concerns the need to modernize the nuclear fleet, most of which was built in the 1970s and 1980s. The French government has decided to extend the life of existing reactors and to invest in new projects for small modular reactors (SMRs) and EPR-2 generation reactors [26].

In addition, in accordance with the National Energy and Climate Plan (PPE), France is gradually expanding the share of renewable energy sources.

France's national security strategy is set out in the form of the National Strategic Review [27]. The need to update the previous document in 2021 was due to changes in the security sector caused by Russia's aggression against Ukraine. The French National Strategic Review 2022 focuses on achieving ten strategic objectives related to [27]: 1) nuclear deterrence; 2) state resilience; 3) economic security;

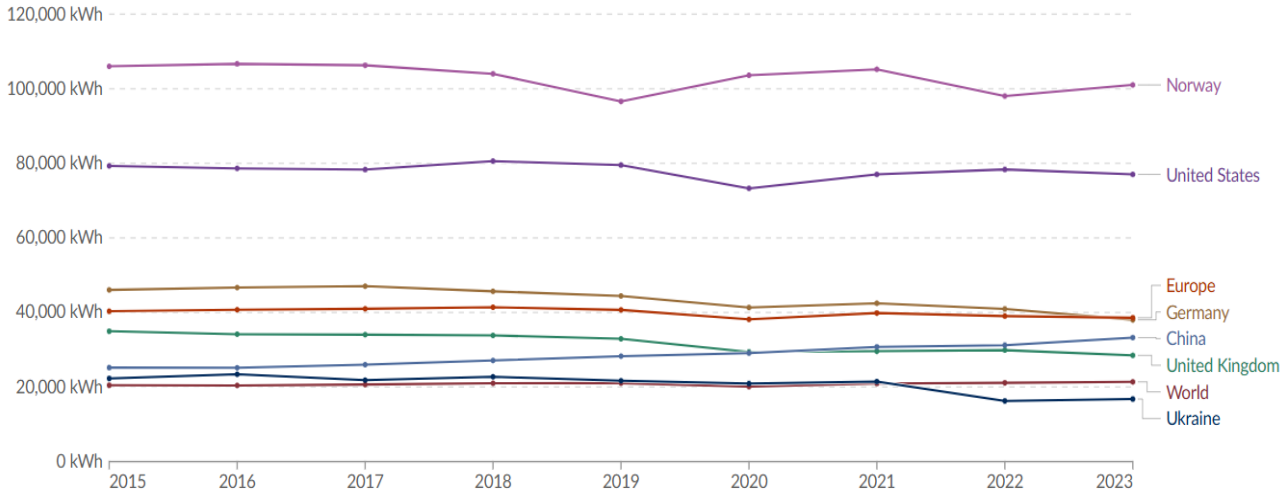

Figure 2. Comparison of energy consumption per capita by country, kilowatt-hours per person

Source: [23]

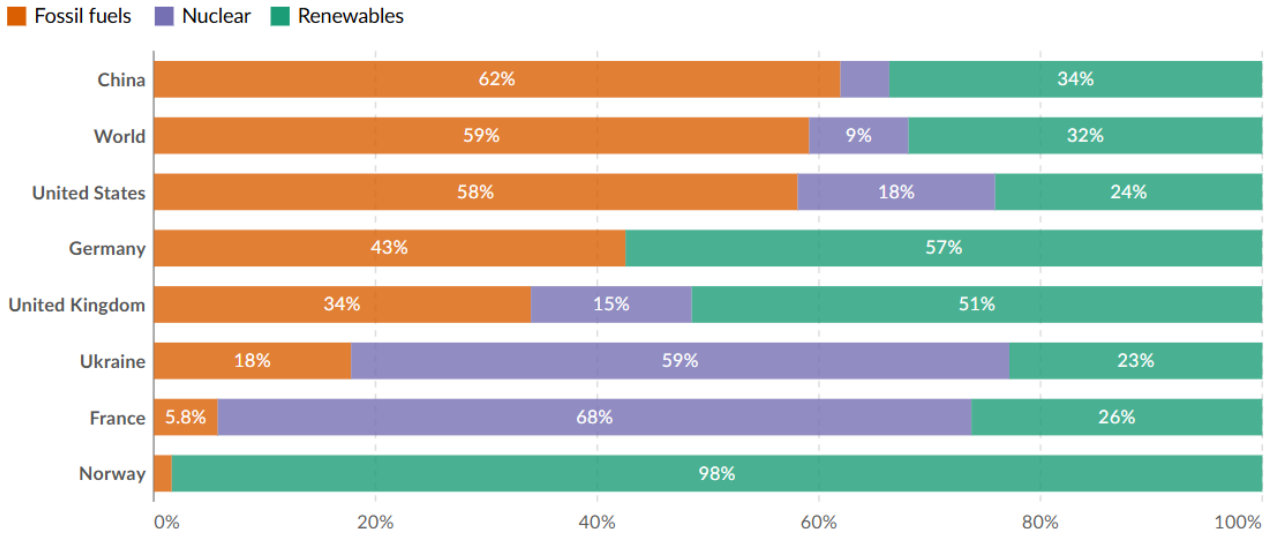

Figure 3. Electricity production per person from fossil fuels, nuclear and renewable energy in 2024

Source: [25]

4) cyber resilience; 5) Euro-Atlantic cooperation; 6) development of European strategic autonomy; 7) international security cooperation; 8) ensuring autonomy of assessment and decision-making; 9) defense in hybrid scenarios; 10) conducting military operations.

In strategic terms, France places great emphasis on the stability of gas supplies. In response to current challenges, the country has stepped up the expansion of LNG infrastructure and the strengthening of energy interconnectors with Spain, Germany and Italy. It is also considering the possibility of increasing the flexibility of the system through smart grids and energy storage systems, which is especially relevant in the context of the growing role of unstable renewables. The key challenge for France remains the balance between the nuclear strategy and the EU climate policy, which provides for a stronger role for renewable energy. France has consistently advocated for the recognition of nuclear energy as "green" in the EU taxonomy, which allows it to attract funding for relevant projects [26].

The United Kingdom is demonstrating a consistent transformation of its energy system aimed at increasing energy security, reducing dependence on fossil fuel imports, and achieving climate neutrality by 2050. The country's energy policy is based on an integrated approach that combines decarbonization, innovative technology development, and ensuring security of supply.

By 2024, more than 50% of the UK's electricity will be generated from renewable sources, with the largest share coming from wind (both onshore and offshore), solar and biomass (Fig. 3). The UK is a world leader in offshore wind, with a total installed capacity of over 14 GW and the government aims to reach 50 GW by 2030 [4]. At the same time, gas-fired power plants continue to play a significant role in ensuring energy stability, serving as a flexible reserve in the event of fluctuations in renewable generation. Natural gas accounts for around a third of electricity generation, but its use is gradually being reduced in line with decarbonisation targets. Nuclear power plays an important role in ensuring the basic functioning of the system. The UK government has approved a strategy to expand nuclear generation: it is planned to build new large reactors (Hinkley Point C, Sizewell C), as well as introduce small modular reactors (SMRs) in partnership with national and international companies [28].

The updated Comprehensive Security Review of the United Kingdom 2023 identifies four key strategic directions [29]: 1) shaping the international environment to support a stable world order and protect global public goods; 2) deterrence, protection and competition in all areas; 3) strengthening resilience to internal and external vulnerabilities; 4) enhancing competitive advantages in the context of geopolitical instability. The 2023 strategy builds on the provisions of the Comprehensive Review 2021 and is complemented by a number of functional strategies, in particular in the energy sector [30].

Europe is facing its largest military conflict since World War II, provoked by Russian aggression and exacerbated by migration and energy crises. These events have caused serious disruptions in global energy markets and heightened tensions over access to energy resources. In the United

Kingdom, the result has been a sharp increase in energy prices, requiring government intervention through the introduction of the Energy Price Guarantee and other support programs [31].

A significant factor determining the current energy policy of the United States is the strategic aspiration for energy independence, which intensified after the energy crises of the 1970s and has become particularly relevant in the conditions of geopolitical instability of the early 21st century. Since the 2010s, thanks to the active development of hydraulic fracturing and horizontal drilling technologies, the United States has significantly increased oil and natural gas production, becoming one of the world's largest producers of energy resources.

In 2019, the United States became a net energy exporter for the first time in decades, meaning that energy exports exceeded imports [32]. In 2022–2023, the country ranked first in the world in natural gas production and first in liquefied natural gas (LNG) exports, which is an important element of the US geoenergy strategy in the context of the energy crisis in Europe [33].

According to the US Energy Information Administration (EIA), as of 2023, the structure of primary energy consumption in the US is as follows: oil about 38%, natural gas – 33.85%, renewable energy sources – 13%, coal – 8.69%, nuclear energy – 7.77% [34]. Although fossil sources remain dominant, the share of renewable sources has doubled over the past decade, especially due to the development of solar and wind generation. At the same time, US federal energy policy is increasingly focused on decarbonization and the development of clean energy.

A key challenge for the United States remains the need to ensure the reliability and flexibility of electric power systems in the face of increasing decentralization and integration of unstable energy sources. To this end, smart grids, digital demand management technologies, and intelligent energy forecasting systems are being implemented.

The National Security Strategy of the United States of America is a key policy document that defines national interests, major threats and security challenges, as well as strategic approaches to overcoming them [35]. The strategy clearly positions energy security in the context of the global climate crisis, which has been defined as the "existential challenge of our time". It emphasizes the need for an energy transformation that should reduce the "collective dependence" on authoritarian states that use energy resources as an instrument of geopolitical pressure, in particular, Russia and its attempts to transform oil and gas exports into weapons.

In response to the worsening energy crisis, the document envisages the implementation of a "responsible global energy transition", the stabilization of energy markets and the introduction of innovative technologies in the energy sector. At the same time, the strategy recognizes the urgent need to accelerate the transition away from fossil fuels, as long-term energy security directly depends on the development of clean energy.

Renewable and low-carbon energy technologies have been identified as an investment priority of industrial and innovation policy. Relevant measures are implemented through [35]:

– investments in energy infrastructure and the development of clean energy technologies within the framework of the law on chips and science;

– reducing carbon emissions in accordance with the national biotechnology and bioproduction initiative;

– stimulating domestic energy production in accordance with the law on reducing inflation.

The Strategy pays special attention to integrated approaches to security (both military and civilian, including energy). The document emphasizes the importance of deepened cooperation with regional partners and allies, aimed at strengthening collective energy security and developing a joint response to modern transnational challenges.

Significant threats to the energy system of Ukraine are caused by Russian aggression, targeted missile strikes on energy facilities. Modern realities have led to changes in energy security management and the definition of strategic priorities taking into account modern challenges and threats. The "Energy Strategy of Ukraine until 2035" [36], taking into account the new challenges caused by the full-scale invasion of the Russian Federation into the territory of Ukraine, required significant changes. Therefore, on April 21, 2023, the Cabinet of Ministers of Ukraine approved the "Energy Strategy of Ukraine until 2050" [37], which provides for the restoration of the energy sector using the most modern technologies, strengthening the system's resilience and enhancing the energy security of Ukraine and the European continent as a whole.

Globally, fossil fuels, particularly coal and natural gas, remain the main sources of electricity generation. Hydropower and nuclear power dominate low-carbon sources, although wind and solar generation have shown rapid growth over the past decade.

In the world, more than a third of electricity is generated from low-carbon sources (Fig. 4).

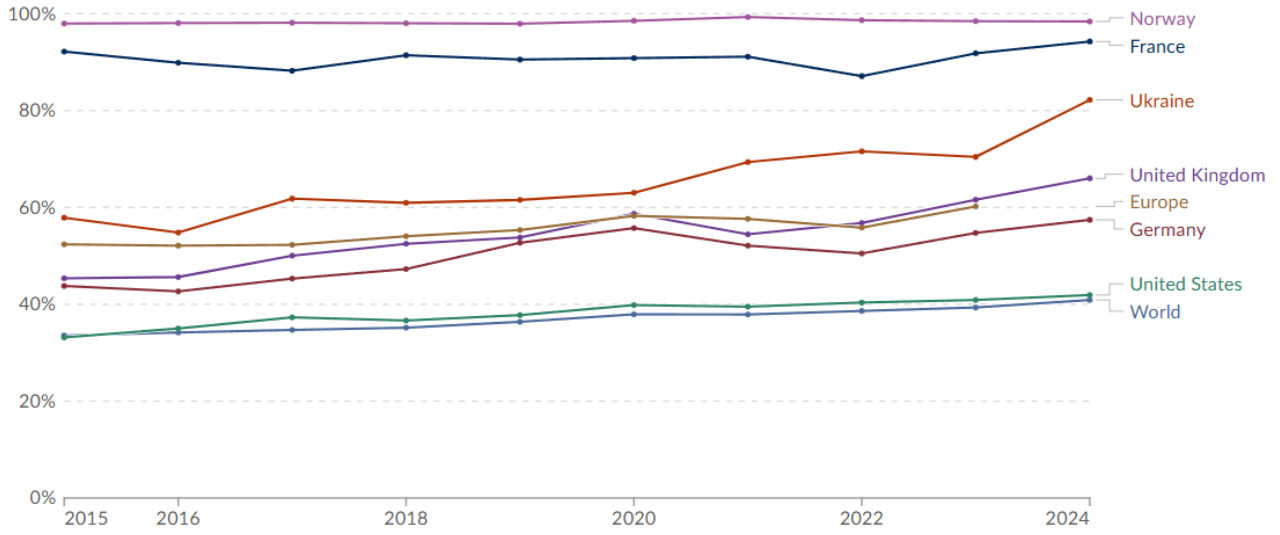

Figure 4. Share of electricity generated from low-carbon sources, 2015–2024

Source: [25]

Global trends in the field of nuclear energy reflect significant differences in national energy strategies. In particular, France, Ukraine, the USA are among the leaders in terms of nuclear electricity production. Unfortunately, the largest nuclear power plant in Ukraine, Europe and the third in the world (Zaporizhzhia Nuclear Power Plant) is currently occupied by the Russian Federation. A number of countries are completely abandoning the use of nuclear energy or are in the process of phasing out nuclear generation, while other countries are focusing on the development of other low-carbon energy sources.

In Europe, there was a 1% decrease in nuclear energy production, due, on the one hand, to the gradual restoration of France's nuclear fleet after large-scale failures in 2022, and, on the other hand, to the final decommissioning of the last three nuclear power units in Germany in early 2023.

China remains the world leader in the pace of nuclear generation expansion, having built about 60% of all new nuclear power units in the world since 2000. In late 2023, China began commercial operation of the world's first demonstration small modular reactor (SMR), based on fourth-generation technology and equipped with built-in passive safety systems.

Japan has been gradually restarting its nuclear power plants since the Fukushima accident in

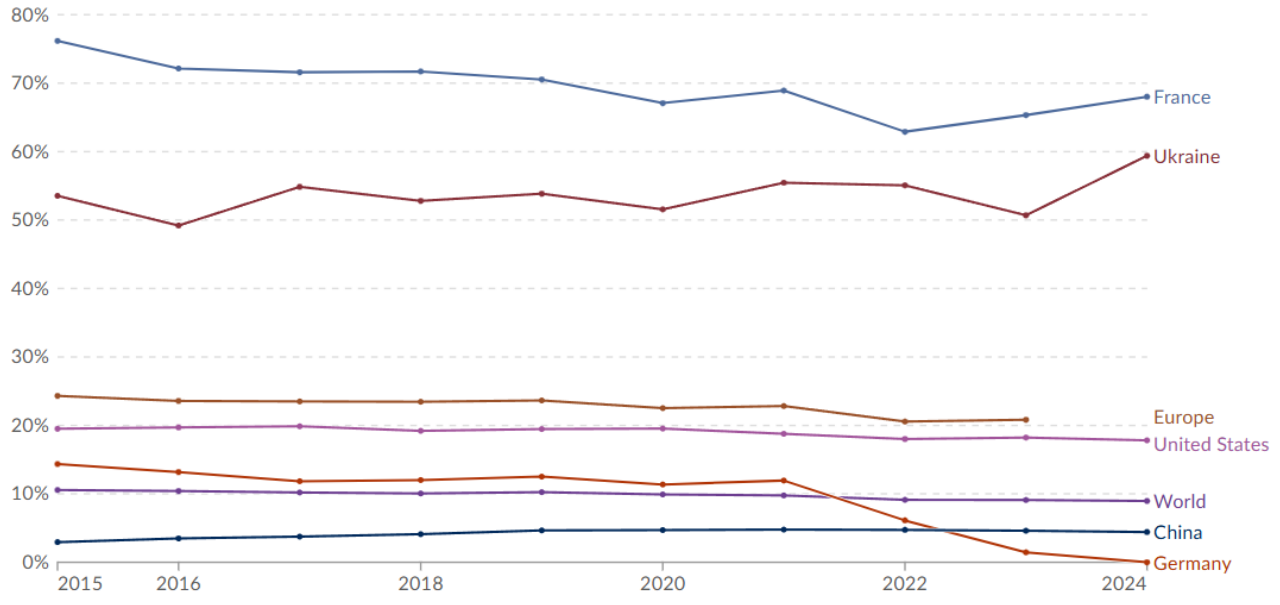

Figure 5. Share of electricity production from nuclear energy in total energy generation, 2015–2024

Source: [38]

2011. In 2023, the country's nuclear power generation increased by 50%, indicating a strengthening of the national energy stabilization policy. In the United States, production levels remained stable, but total nuclear generation was comparable to the combined production of China and France, the countries with the second and third largest nuclear power plants in the world.

Globally, approximately 10% of electricity is generated by nuclear power plants. At the same time, in a number of countries, such as France, Ukraine, and Belgium, the share of nuclear energy in the energy generation structure is significant and forms the basis for ensuring energy security.

In general, it should be noted that existing energy strategies indicate the existing approaches of states to ensuring energy security. At the same time, in the light of modern challenges and risks, countries around the world are making changes to existing strategic documents, implementing measures to mitigate and prevent threats, achieve climate neutrality, and increase energy efficiency.

Conclusions. Thus, despite the gradual expansion of the share of renewable energy sources, the majority of global electricity production continues to be based on the use of hydrocarbons. Over the past decades, the overall balance between fossil and low-carbon sources has remained relatively stable. The reduction in nuclear energy production in a number of countries has been partially offset by positive dynamics in the implementation of renewable energy generation technologies. An analysis of global experience shows a steady trend towards an increase in the share of low-carbon generation, in particular renewable energy sources (wind, solar, hydropower), and energy generation projects using small modular nuclear reactors are also being developed. The development of these types of energy generation allows reducing the carbon intensity of the electricity industry, which is critically important in the context of ensuring the development of energy on the principles of sustainability.

The successful implementation of energy transformation in all countries depends largely on strategic vision in the process of forming and implementing public policy, investments in the latest technologies, as well as on the effective management of critical energy infrastructure. Diversification and stimulation of the development of innovations in the field of green energy are of particular importance for strengthening the national energy security of countries.

Given the examples given, it is advisable to take into account the best practices of world experience in managing Ukraine's energy security, focused on increasing energy independence, reducing the carbon footprint, and ensuring the stability of the energy sector in the face of global challenges.

At the same time, Ukraine has generated its own practical experience in ensuring the functioning of the energy system in conditions of war and direct targeted missile attacks by the Russian Federation on its energy facilities. Such experience is valuable for countries of the world in the context of responding to large-scale challenges and threats to energy security. The characteristics of the features of the modern model of energy security management in Ukraine will be the subject of a separate study.

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СВІТОВИЙ ДОСВІД ЗАБЕЗПЕЧЕННЯ ЕНЕРГЕТИЧНОЇ БЕЗПЕКИ

У статті обґрунтовано, що кожна держава прагне до ефективної реалізації власної цілісної та взаємопов'язаної системи заходів із забезпечення енергетичної безпеки, орієнтованої на національні інтереси та стратегічні пріоритети. Проведений аналіз засвідчив, що країни світу (зокрема, Китаю, Німеччини, Франції, Норвегії, Великої Британії, США) визначили та реалізують власні концепції енергетичної безпеки, які трансформуються під впливом викликів та загроз, сучасних технологій та потреб розвитку енергетичного сектору на принципах сталості. З'ясовано, що більшість світового виробництва електроенергії й надалі базується на використанні вуглеводнів, але відбувається збільшення частки низьковуглецевої генерації, зокрема з відновлюваних джерел енергії (вітрової, сонячної, гідроенергетики), а також набувають розвитку проєкти генерації енергії з використанням малих модульних атомних реакторів. Зазначено, що розвиток цих видів генерації енергії дозволяє знижувати вуглецеву інтенсивність електроенергетики, що є критично важливим в контексті забезпечення сталого розвитку енергетики. Автором зазначено, що Україні необхідно враховувати кращі практики світового досвіду при управлінні енергетичною безпекою для підвищення енергетичної незалежності, зменшення вуглецевого сліду та забезпечення стабільності енергетичного сектору. В той же час зазначено, що Україна в умовах війни згенерувала власний практичний досвід забезпечення функціонування енергетичної системи, який є цінним для країн світу в контексті реагування на масштабні виклики та загрози енергетичній безпеці.

Ключові слова: енергетична безпека, світовий досвід, управління, ядерна енергетика, відновлювані джерела енергії, стратегія, енергоефективність, інновації.