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ECONOMIC ASPECTS OF NUCLEAR ENERGY EXPANSION IN THE CONTEXT OF ACHIEVING LONG-TERM SUSTAINABLE DEVELOPMENT GOALS

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ЕКОНОМІЧНІ АСПЕКТИ РОЗШИРЕННЯ ЯДЕРНОЇ ЕНЕРГЕТИКИ В КОНТЕКСТІ ДОСЯГНЕННЯ ДОВГОСТРОКОВИХ ЦІЛЕЙ СТАЛОГО РОЗВИТКУ

This article examines the economic and strategic importance of nuclear power in relation to long-term development goals, with a focus on its role in meeting the world's growing demand for electricity while reducing environmental impact. As some nations restrict nuclear energy due to safety concerns such as radiation pollution and the complexities of managing spent nuclear fuel, others embrace it as a low-carbon energy resource with potential economic benefits. This divergence underscores the dynamic role of nuclear power in global energy systems, with countries like France, China, and the United States investing in nuclear infrastructure to secure energy independence and reduce greenhouse gas emissions.

The article explores the present state of nuclear power development and the environmental, economic, and regulatory factors influencing its trajectory. A comparative analysis of different national approaches provides insights into the economic benefits of nuclear energy, including its lower fuel costs and stability over the long term, which make it an appealing option amid climate change imperatives. Additionally, nuclear power's potential to lessen dependency on fossil fuels positions it as a viable contributor to international decarbonization efforts.

Nevertheless, nuclear power faces substantial challenges, particularly in the areas of reactor construction costs, technological upgrades, and safety concerns heightened by geopolitical risks, such as military conflicts exemplified by Russia's invasion of Ukraine. Addressing these challenges necessitates robust government support, international partnerships, and a concerted focus on developing advanced, more sustainable nuclear technologies.

In conclusion, nuclear power's continued evolution remains central to the future of global energy policy. To ensure its viability, this study emphasizes the importance of enhancing safety measures, securing financing, and fostering international collaboration to develop efficient and environmentally responsible nuclear technologies. The findings underscore nuclear power's role not only in

achieving energy security but also in advancing sustainable development objectives globally.

У статті розглянуто економічні та стратегічні аспекти розвитку атомної енергетики, зокрема її значення для задоволення зростаючого попиту на електроенергію та зменшення негативного впливу на довкілля з метою забезпечення довгострокових цілей сталого розвитку. У той час як деякі країни обмежують використання ядерної енергії через ризики, пов'язані з радіаційним забрудненням і складнощами зберігання відпрацьованого ядерного палива, інші бачать у ній низьковуглецевий та економічно вигідний енергетичний ресурс. Такий підхід демонструє мінливу роль атомної енергетики в сучасних енергосистемах, де Франція, Китай і США активно інвестують у розвиток атомної інфраструктури для підвищення енергетичної незалежності та скорочення викидів парникових газів.

У статті наводиться аналіз поточного стану розвитку атомної енергетики, а також екологічних, економічних та регуляторних факторів, що впливають на її подальший розвиток. Порівняльний аналіз різних підходів різних країн дозволяє виділити економічні переваги атомної енергетики, до яких належать низькі витрати на паливо та довготривала стабільність. Саме ці характеристики роблять атомну енергетику привабливим варіантом на тлі зусиль зі скорочення викидів вуглецю. Крім того, атомна енергетика потенційно сприяє зниженню залежності від викопних видів палива, що підсилює її важливість для міжнародних ініціатив щодо декарбонізації економіки.

Попри значні перспективи, розвиток атомної енергетики супроводжується численними викликами. Серед них – високі витрати на будівництво нових реакторів, необхідність модернізації застарілих технологій, а також забезпечення високих стандартів безпеки, що особливо актуально на

тлі геополітичних ризиків і конфліктів, таких як агресія Росії проти України. Вирішення цих питань вимагає підтримки з боку держави, розвитку міжнародного співробітництва та спрямованості на впровадження передових та більш екологічно чистих ядерних технологій.

Отже, на сучасному етапі розвиток атомної енергетики залишається ключовим напрямом енергетичної політики багатьох країн світу. Для забезпечення її стабільного майбутнього необхідно зосередитися на підвищенні стандартів безпеки, залученні додаткового фінансування та активізації міжнародних зусиль для розробки нових ефективних технологій. Результати дослідження підкреслюють важливість атомної енергетики не лише для досягнення енергетичної безпеки, а й для сприяння реалізації цілей сталого розвитку на глобальному рівні.

Keywords: *nuclear energy, economic aspects, prospects, development of nuclear energy, environmental friendliness.*

Ключові слова: *атомна енергетика, економічні аспекти, перспективи, розвиток атомної енергетики, екологічність.*

Introduction. In the context of economic globalization, climate change, resource scarcity and environmental degradation, nuclear power, which is capable of generating large amounts of electricity with minimal greenhouse gas emissions, plays a key role in achieving the UN Sustainable Development Goals. By contributing to the decarbonization of the energy sector, nuclear power supports global efforts to reduce climate risks (Goal 13) and transition to cleaner energy systems (Goal 7) [1]. In addition, the introduction of nuclear power can provide economic benefits by stabilizing energy prices and reducing dependence on fossil fuel imports, making it an attractive option for countries seeking to transition to sustainable low-carbon energy systems while maintaining economic growth and competitiveness.

It is worth noting that internationally, the development of nuclear energy differs significantly in different regions due to differences in economic potential, energy demand, and regulatory frameworks. Thus, while countries with developed nuclear infrastructure, such as France, Japan and the United States, focus on extending the life of existing plants and developing advanced reactor technologies to achieve energy independence, emerging economies, especially in Asia and the Middle East, use nuclear energy as a means of diversifying their energy portfolio and stimulating industrial growth.

At the same time, the use of nuclear energy poses significant economic, environmental and geopolitical challenges. On the one hand, the significant capital costs associated with the construction, operation and maintenance of nuclear power plants, as well as the long-term financial commitments required for waste management and decommissioning, require careful economic planning and political support. However, the long-term benefits of stable energy production, low operating costs, and minimal greenhouse gas emissions compared to fossil fuel-based energy sources favor the development of nuclear power.

Analysis of publications. Recently, the scientific community has been increasingly focusing on the economic aspects of nuclear energy development with a special emphasis on the feasibility, economic efficiency and sustainability of nuclear energy in the context of growing environmental problems related to climate change.

In particular, Kessides (2010) examines the economic risks and factors of uneven development of nuclear power, including market volatility, affordability and development of small modular reactors (SMRs). The results of this analysis indicate the lack of a complete understanding of the integration of nuclear energy within liberalized energy markets and the possibility of using small reactors to diversify nuclear assets [2]. A similar opinion is shared by Kopishynska and Shyrokova (2019), who discuss key trends and innovations in the Ukrainian nuclear power industry through the introduction of innovative technologies and the development of small

modular reactors (SMRs), such as the SMR-160 model with their low initial costs and flexible deployment, may be important for achieving Ukraine's goals of sustainable nuclear energy production while meeting safety standards [3].

Nuclear power, in particular pressurized water reactors (PWRs), is an effective low-carbon solution, as emphasized by Fernández-Arias, Vergara, and Orosa (2020) [4]. The authors note the prevalence of European PWR designs, especially in North America and France, and draw attention to the fact that without preventive modernization or lifetime extension programs, the number of these reactors could decrease significantly by 2050.

As for our country, the Report on the State of Nuclear and Radiation Safety in Ukraine (2023) addresses specific regulatory issues and safety measures in response to current geopolitical risks and notes that nuclear energy remains a fundamental factor in Ukraine's energy security, especially as the country tries to achieve energy autonomy. At the same time, the report also emphasizes weaknesses, such as dependence on a limited number of fuel suppliers and deteriorating reactors, which require urgent government intervention and international cooperation [5].

At the same time, while these studies consider the general economic aspects of nuclear energy development, they do not take into account the additional impact of geopolitical and economic instability. Ukraine's experience in the context of hostilities emphasizes the vulnerability of nuclear energy infrastructure in terms of operational security, financing, and supply chain dynamics. The ongoing war has destroyed the energy infrastructure, limited the ability to sustain investments, and created additional safety concerns, making nuclear power both a potential asset and a risk in the context of the country's post-war recovery.

Problem statement. Thus, the purpose of this article is to provide an in-depth analysis of the economic aspects of nuclear energy development as a critical element in the transition to balanced and sustainable energy systems in the context of achieving long-term sustainable development goals.

The main part. The process of splitting the atoms of certain elements to produce energy was first developed in the 1940s during military campaigns. In the 1950s, attention turned to the peaceful use of nuclear fission, controlling it to produce electricity.

Currently, civilian nuclear power has experience in operating more than 400 reactors with a total operating time of about 20,000 reactor-years, and nuclear power plants are operating in 31 countries around the world [6]. In fact, thanks to regional transmission networks, many more countries are partially dependent on nuclear energy, especially in Europe. That is why, at the beginning of 2024, the European Commission took a clear position on nuclear energy, calling it a green energy source in its classification system, creating a list of environmentally sustainable economic activities [7].

Thus, according to the International Atomic Energy Agency, in 2023, fourteen countries generated at least a quarter of their electricity from nuclear power plants. It is worth noting that today the main producers of nuclear energy are the countries of Western and Central Europe, North America and Asia. Fig. 1 shows the amount of energy supplied from nuclear power plants in TWh in the period from 1970 to 2023.

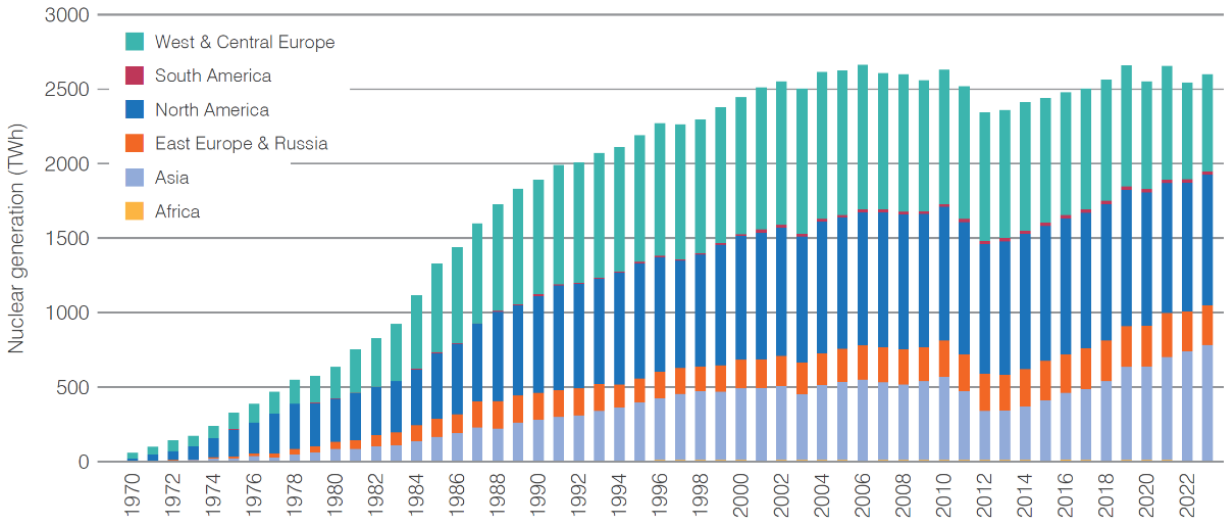

Fig. 1. Energy supplied from NPPs.

Source [8]

As the figure shows, nuclear energy production has hardly changed over the past 20 years. This was influenced by several factors. First, after the Fukushima Daiichi accident in Japan, the local population's trust in the peaceful atom was shaken, and local authorities suspended the operation of all nuclear power plants to check their safety. Secondly, some Central European countries have banned the use of energy from nuclear power plants by law.

At the same time, France gets about 70% of its electricity from nuclear power, while Ukraine, Slovakia and Hungary get about half of their electricity from nuclear power. Japan is used to relying on nuclear power for more than one quarter of its electricity and is expected to return to about this level. At the same time, the total share of electricity generated by nuclear power plants in the world in 2023 is 10%, and the total capacity of all installed reactors as of 2023 is about 400 GW [9] (Fig. 2).

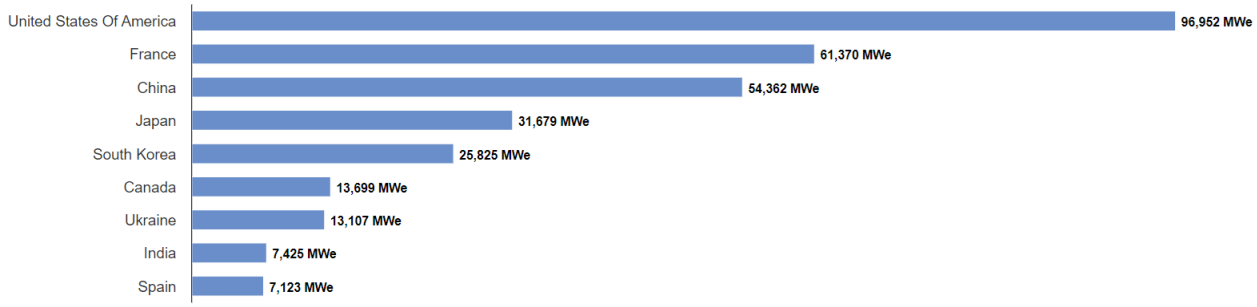

Fig. 2. Total installed reactor capacity by country.

Source [9]

At the same time, according to the World Nuclear Organization, as of 2020, the share of electricity generated by nuclear power plants in the United States is up to 20%. Currently, there are still many conventional power plants in operation due to the availability of significant amounts of raw materials in the form of gas and oil. It is estimated that by 2030 the amount of energy consumed will increase by 10%, and by 2050 by 25%. As for energy production at nuclear power plants, it is projected to

increase by 15% by 2030 and by 23% by 2050 to cover the demand for consumption and gradually abandon fossil fuel plants [10].

As for France, which ranks second in terms of electricity produced by nuclear power plants, back in 2012, the country launched a program aimed at reducing electricity production at nuclear power plants to 60% of total production by 2020, and to 50% by 2025. Subsequently, the program was abandoned, and as of 2024, the country is considering the completion of 8 new nuclear power plants and 6 additional power units due to the aging of the nuclear reactor fleet [11]. Thus, as of 2024, nuclear energy production accounts for 63% of total electricity production, which is the highest in the world. The country has 19 NPPs with 57 operating power units of various capacities. Thanks to nuclear power, France is largely independent of energy imports, especially oil, and produces a larger share of electricity without using coal. It has also become the largest exporter of electricity in the world.

China ranks third in the world in terms of total installed nuclear capacity, accounting for about one-tenth of the world's nuclear energy. Back in 2019, the China National Nuclear Corporation announced that it would begin construction of the ACP100 demonstration small modular reactor by the end of the year. The development of the ACP100 began in 2010, and it was the first project to undergo an independent safety assessment by the International Atomic Energy Agency in 2016. At the same time, despite the fact that China tripled its nuclear energy production to 417 TWh between 2014 and 2023, the share of domestic production is only 5%. [12]

It is also worth noting that Japan, before the 2011 disaster, produced 30% of its electricity from nuclear reactors and planned to increase the share to 40%. Until 2011, all nuclear reactors in Japan successfully withstood earthquakes and other natural disasters. After the March 11, 2011, tsunami and the failure of the cooling system, all Japanese nuclear power plants were suspended for safety checks. However, in 2017, Japan announced that if the country wants to fulfill its obligations under the Paris Climate Agreement, nuclear power should account for 20 to 22% of the nation's

portfolio. As of 2020, Japan had 54 reactors, of which only 9 were actually operating. 24 reactors are scheduled for decommissioning or are in the process of decommissioning. Others are undergoing modifications to improve disaster resilience, and Japan's energy goals for 2030 stipulate that at least 33 will be restored later [13].

As for Ukraine, it is worth noting that as of 2020, our country produced about half of its electricity at nuclear power plants with a total capacity of 14 GW. The largest nuclear power plant in Europe is Zaporizhzhia NPP with 6 power units with a total capacity of 6 GW [14]. At the same time, during the full-scale invasion in 2022, Zaporizhzhia NPP was seized and as of 2024, it is disconnected from the Ukrainian power grid and is in “cold” mode, when it needs backup power to cool the reactors. It is worth noting that since the beginning of the war, ZNPP has repeatedly experienced partial or complete power outages, which is one of the most difficult challenges to maintain nuclear safety. In total, the plant lost external power eight times, forcing it to temporarily rely on emergency diesel generators to generate electricity [15] That is why, against the backdrop of losing control over the country's largest NPP, Ukraine plans to complete 2 power units at Khmelnytsky NPP and one unit each at Rivne and South Ukraine NPPs.

However, in the context of war and the loss of control over the country's largest nuclear power plant, the importance of nuclear energy for energy independence and greenhouse gas emission reduction becomes even more critical. It is important to emphasize that despite numerous challenges related to safety and energy supply, nuclear power plants remain environmentally friendly sources of energy, as they do not pollute the environment with substances such as flue gases, ash, and discharge waters containing oil products, and therefore do not emit greenhouse gases. Nuclear power plants have a carbon footprint that is comparable to that of renewable energy sources such as solar and wind power plants and much lower than fossil fuels such as natural gas and coal. Nuclear power plants are one of the safest ways to generate electricity compared to solar and wind power plants [16].

At the same time, measures to mitigate global warming, such as a carbon tax or emissions trading, are increasingly favoring the economics of nuclear power. Further efficiency gains are expected to be achieved through improved reactor designs. Today, 3rd generation reactors are already being installed, which are 17% more fuel efficient and have lower capital costs. At present, 4th generation reactors are only being designed, which will be able to reprocess spent nuclear fuel, which will allow to completely close the nuclear fuel cycle. From the environmental point of view, this will close the controversial issue of nuclear waste storage in repositories and stop the construction of new storage facilities. At the same time, the construction of a nuclear power plant often takes five to ten years, which can entail significant financial costs, depending on how the initial investment is financed. The total cost should also include the costs of spent fuel extraction, processing, use, and storage [17].

Due to the high construction cost and lower operation, maintenance and fuel costs, nuclear power plants are typically used for baseload generation, as this maximizes the hours during which the fixed construction cost can be amortized. Despite the fact that the construction of nuclear power plants is more expensive and complex than other plants, this is offset by the lower price of fuel. In particular, according to the World Nuclear Association, as of 2023, nuclear power is cost-competitive with other forms of electricity generation, except when there is direct access to inexpensive fossil fuels. This is due to the fact that the average cost of energy from a nuclear power plant is 0.4 euro-¢/kWh, approximately the same as for a hydroelectric power plant. For a coal-fired power plant, this figure is 4-7 euro-¢/kWh, for a gas-fired power plant - 1.3-2.3 euro-¢/kWh. Only solar energy is cheaper than thermal energy - 0.1 - 0.2 euro-¢/ kWh [18].

The advantages of nuclear fuel also lie in the fact that uranium is a highly concentrated energy source that is easily and cheaply transported. The required quantities are much smaller than for coal or oil. At the same time, one kilogram of natural uranium provides about 20,000 times more energy than the same amount of

coal. It is worth noting that fuel costs for NPPs are a small share of total generation costs, although capital costs are higher than for coal-fired power plants and much higher than for gas-fired power plants. A 1 GW reactor requires about $5-6 billion to build. For coal-fired power plants, this figure is about 2 billion for the same capacity, and less than 1 billion for gas power plants [19].

At the same time, we note that regardless of whether a country has an existing nuclear power program or is developing nuclear power for the first time, it needs public funding to develop or maintain the necessary nuclear infrastructure.

The IAEA supports Member States planning to build new nuclear power plants by providing a roadmap for developing the necessary infrastructure and modeling tools and obtaining the necessary financing. The IAEA's approach aims to help Member States understand the obligations associated with developing a nuclear power program. The IAEA also publishes reports on financial management, for example, on the financing of new nuclear power plants.

According to the Nuclear Energy Assessment 2050 [4], published in 2020, to achieve net zero emissions by 2050, the amount of energy provided by nuclear power will have to almost double between 2020 and 2050. The 2020 Energy Technology Outlook report states that a combination of renewables and nuclear will meet most of the demand growth. Nuclear power has the advantage of low carbon emissions, and its share of global production will increase to 15% by 2060. To reach the projected level, about 23 GW of capacity will need to be built annually. At the same time, financing of nuclear power projects has become more difficult over the past three decades. In order to encourage nuclear development despite these difficulties, innovative approaches to financing and support policies are being applied, including partial investments or loan guarantees from the government. For this reason, a number of new financial instruments have been developed to better ensure a return on investment and attract investors to specific projects, such as phased financing to reduce risks at different stages of a project, from construction to the addition of

additional units. For example, the U.S. Department of Energy has allocated more than $3 billion to support reliable, affordable, and clean electricity in the Midwest. Of this amount, 1.5 billion has been allocated for the restoration of an 800 MW nuclear power plant in Michigan [20]

Ukraine also has its own nuclear energy support programs. In 2022, the Organization of the Canadian Nuclear Industry (OCNI) and Energoatom agreed to cooperate in the field of nuclear energy and related technologies. And in 2024, Energoatom and the Korean Hyundai Engineering and Construction Co., Ltd. (HDEC) agreed to cooperate in the design, construction and commissioning of new nuclear power units in Ukraine. As of 2024, the construction of new reactors at Khmelnytskyi NPP is financed by the US Export-Import Bank (Exim). According to Energoatom, the construction of one reactor costs approximately $5 billion. [21]

Conclusions. Thus, nuclear power continues to play a key role in global electricity generation due to its ability to ensure stable and environmentally friendly production. Having analyzed various aspects of the development of nuclear power plants in countries, several important conclusions can be drawn.

First, nuclear power remains competitive, especially in the face of increasing requirements to reduce greenhouse gas emissions. Its economic advantages, including relatively low fuel costs and long-term stability, make it attractive to many countries, especially France, China, and the United States. Second, nuclear power makes a significant contribution to reducing dependence on fossil fuels, contributing to the global fight against climate change.

However, the development of nuclear energy is accompanied by a number of challenges, including the high cost of building new reactors, the need to update outdated technologies and ensure safety, especially against the backdrop of military conflicts such as Russia's attack on Ukraine. Government support and international cooperation is also an important area of progress, which helps to ensure financing and implementation of new projects.

In summary, the development of nuclear power remains an important area of global energy policy. To ensure its successful future, it is necessary to address safety and financing issues, as well as to intensify international efforts to develop more efficient and environmentally friendly technologies.

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