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STRATEGIC MANAGEMENT OF THE TRANSFORMATION OF THE GLOBAL ENERGY SECTOR: ANALYSIS OF INTERNATIONAL TRENDS IN NUCLEAR ENERGY IN THE CONTEXT OF GLOBAL DECARBONISATION

The paper considers the transformation of the energy sector in the context of general decarbonisation and the prospects for the use of nuclear energy to achieve global climate goals. The nuclear renaissance is considered as a process of renewed interest in nuclear energy. The strategies of the EU and leading countries of the world regarding the use of nuclear energy are examined. The problem of cost overruns, which often arises in the construction of new nuclear reactors, is investigated. Small modular reactors are considered as an alternative to large traditional reactors. The model of nuclear-industrial clusters as an element of decarbonisation is examined, and a cluster model around a small modular reactor is proposed. The role of nuclear energy in achieving Net Zero objectives and the risks associated with the widespread use of nuclear reactors are described.

Keywords: *nuclear energy, nuclear reactor, decarbonization, nuclear renaissance, SMR, nuclear-industrial cluster.*

JEL Classification: Q40, Q43, Q54, F01

Statement of the problem. Climate change is a global issue that requires immediate action. Many governments see nuclear energy as key to achieving climate goals while meeting electricity needs, drawing attention to this energy sub-sector. The nuclear industry is gradually transforming, and new technologies offer more versatile and affordable solutions than traditional large reactors. At the same time, the risks associated with the use of nuclear technologies remain, and the problems associated with radioactive waste are becoming more acute.

An analysis of recent studies and publications. Various aspects of nuclear energy are widely covered in the literature. The phenomenon of nuclear renaissance has been discussed by many authors, including William J. Nuttall [1], Zohuri B., Mossavar-Rahmani F. [2], Peters B. [3], and DUȚU D. M. [4]. These authors have examined nuclear energy primarily in the context of energy security, climate change, and as a response to current energy crises. They also devote considerable attention to small modular reactors and Generation IV reactors, which may increase the attractiveness of nuclear energy.

The problem of cost overruns in the construction of nuclear reactors has been studied by researchers such as Guaita N., Spangler R., Hansen J. [5], Islam M. S., Nepal M., Skitmore M. [6], Eash-Gates P., Klemun M. M., Kavlak G., McNerney J., Buongiorno J., Trancik J. E. [7]. Research in this area examines costs and data, describes sources of unplanned costs, and emphasises the need for comprehensive approaches to financial risk management in such projects.

Further research is needed on modern nuclear industrial clusters as a tool for decarbonisation and achieving net zero targets.

Statement of the article's objectives. The purpose of the study is to analyse the transformation of the global energy sector in the context of decarbonization, determine international trends in the development of nuclear energy and their role in ensuring low-carbon energy development.

Presentation of the main research findings.

1. Analysis of the global "nuclear renaissance" and international trends in nuclear energy.

The nuclear energy sector remains one of the most controversial sectors of the economy. Full of advantages and risks, nuclear energy continues to divide countries into its supporters and opponents. In recent years, there have been discussions about the so-called "nuclear renaissance".

According to the World Nuclear Industry Status Report, construction of the first nuclear power plants began in the 1950s, and the number of reactors under construction peaked in the 1980s at around 200 units. In the following years, this number plummeted, becoming almost seven times smaller by the mid-1990s. Two major events in the field influenced this decline. The first was the Three Mile Island accident, which had a significant impact on nuclear plant design and future construction projects. The second was the Chernobyl disaster in 1986, which severely affected nuclear programs, particularly in Eastern Europe.

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The overall number of reactors under construction remained largely unchanged until the late 2000s. After that, a noticeable increase in construction activity can be observed, driven primarily by Asia. Projects in Asia account for more than half of all reactors under construction through 2026 [8].

In recent years, there has been what is often referred to as a "nuclear renaissance," characterized by renewed interest in nuclear energy. According to Morgan Stanley, global nuclear capacity is expected to increase by 2050, with cumulative nuclear power capacity projected to reach approximately 586 gigawatts, compared to 395.4 GW in 2024. In addition, potential investments across the nuclear value chain are estimated to rise to $2.2 trillion by 2050, as reported by Morgan Stanley [8–9].

These are not the only indicators of a nuclear renaissance observed worldwide. In 2023, the United Nations Climate Change Conference was held, representing one of the largest events of its kind and bringing together representatives from more than 150 countries and governments. During the conference, progress under the Paris Agreement in addressing climate change was assessed. However, the improvements achieved were deemed insufficient, leading to revisions of the agreed decisions and a renewed commitment to accelerate action across all relevant sectors by 2030. One of the key aspects of this agenda is a call for an accelerated transition to renewable energy sources [10].

The COP28 Declaration on tripling global nuclear energy capacity by 2050 was endorsed by more than 20 countries, including the United States, Moldova, Mongolia, Morocco, Bulgaria, Romania, Slovakia, Slovenia, Canada, the Czech Republic, Finland, France, Ghana, Hungary, Japan, the Republic of Korea, the Netherlands, Poland, Sweden, Ukraine, the United Arab Emirates, and the United Kingdom. As noted by the then Minister of Energy of Ukraine, nuclear energy can play a key role in ensuring reliable electricity supply during the energy transition. In addition to energy-related objectives, the declaration also emphasized the importance of responsible operation of nuclear power plants by all parties.

According to the declaration, the advantages of new nuclear technologies extend beyond their contribution to decarbonization, as they also require relatively small land areas for deployment [11].

Particular attention should also be paid to the inclusion of nuclear energy in the EU "green taxonomy." The EU taxonomy refers to a classification system that defines environmentally sustainable economic activities. The criteria established within this framework are intended to guide investments and financial flows toward sustainable projects [12].

According to the EU Taxonomy, nuclear power generation is excluded from "green" activities; however, it is not explicitly excluded from "enabling" or "transition" activities. On this basis, in 2022 the European Commission adopted a Complementary Climate Delegated Act, which includes certain nuclear energy-related activities within the category of "transitional" activities, subject to specific conditions. Article 10(2) of the Taxonomy Regulation defines transitional activities as those for which no technologically and economically feasible low-carbon alternatives are yet available, but which contribute to climate change mitigation and may play a role in the transition toward a climate-neutral economy.

The following nuclear energy-related activities meet the Commission's criteria:

– modification and modernization of existing nuclear installations aimed at extending their operational lifetimes, recognized until 2040;

– new nuclear power plant projects employing best available Generation III+ technologies, recognized until 2045;

– advanced technologies involving a closed fuel cycle (Generation IV), aimed at fostering innovation, particularly with regard to safety standards and waste minimization [13, p. 5–6].

One of the reasons for the occurred change regarding nuclear energy may be the energy crisis, which was a result of russia's full-scale invasion of Ukraine. Nevertheless, nuclear energy is still a debatable topic. Advantages and disadvantages of nuclear power are highlighted in Table 1.

Let us consider the positions of leading countries worldwide with regard to nuclear energy.

The United States is the largest producer of nuclear power globally. With 94 operational reactors, it accounts for approximately 30% of global nuclear electricity generation. At the same time, no new reactors are currently under construction in the United States, while a total of 41 reactors have been permanently shut down. The majority of operating U.S. nuclear reactors are located in the eastern part of the country.

The Inflation Reduction Act, enacted in August 2022, introduced a range of financial and fiscal mechanisms aimed at supporting both existing nuclear facilities and future nuclear development. These measures include investment support and tax incentives for large operating nuclear power plants, as well as for advanced reactor technologies. The Act also promotes the development of high-assay low-enriched uranium (HALEU) and the production of hydrogen.

In parallel, policy objectives have been articulated to expand U.S. nuclear generating capacity to approximately

Table 1 – Advantages and disadvantages of nuclear power

Advantages	Disadvantages
low carbon emissions	high risks in cases of emergency
low price volatility	nuclear waste (e.g. polluted water)
reliable baseload energy source	possible negative impact of uranium mining on the environment
the ability to locate the plant close to the consumer	difficult and costly construction
strict regulation and control	vulnerability
no scientific evidence of nuclear power, causing greater harm to human health than other sources (under normal conditions)	dubious public perception
can boost economic growth in particular areas	

Sourses: [14–15]

400 GWe by 2050 and to facilitate the deployment of advanced reactor technologies [16]. According to the World Nuclear Association, there are no new reactors planned in the US, but the number of reactors proposed is 25 [17].

China is one of the most promising players in the field of nuclear energy. The primary drivers of China's rapid nuclear power expansion are its climate commitments and concerns related to energy security, particularly in the context of air pollution caused by coal-fired power plants. China's nuclear policy is centered on a closed nuclear fuel cycle. As of 2023, the country operates 59 nuclear reactors, with an additional 38 reactors under construction. In 2023, nuclear power accounted for approximately 5% of China's total electricity generation [18].

The Chinese government's commitment to nuclear energy is supported by the 14th Five-Year Plan (2021–2025), which outlines the construction of 150 new reactors over the next 15 years, aiming to achieve a nuclear power capacity of 200 GW by 2035. China also targets a 15% share of electricity generation from nuclear power by 2050.

These developments are supported by government funding and subsidies, including "green tariffs," which help reduce the cost of nuclear energy. As a result, the cost of nuclear electricity in China is approximately half that of the European Union [19].

Among other countries noteworthy for their nuclear energy policies is France. Approximately 70% of France's electricity is generated from nuclear power. This strategy is primarily driven by energy security considerations. However, over the past 15 years, French nuclear policy has undergone several changes, ranging from efforts to reduce the share of nuclear energy to a complete abandonment of that objective. Currently, France operates 57 nuclear reactors, with an additional 14 permanently shut down. According to the World Nuclear Association, no new reactors are under construction in the country [20].

As in other countries, nuclear energy plays a key role in France's green transition. In particular, the "France 2030" plan identifies as a primary objective the development of small, innovative nuclear reactors with improved waste management, with an investment of €1 billion planned by 2030. Special attention is being given to small modular reactors (SMRs), which are expected to offer enhanced safety features [21].

Thus, global trends have once again shifted in favor of nuclear energy. Nuclear reactors represent one of the few viable options for countries to achieve their climate goals without disruptions to electricity supply. The development of nuclear energy is further supported by ongoing innovations in the sector, which have the potential to make this form of energy both safer and more accessible.

2. Research on the problem of cost overruns and the transition to SMR

Between 1970 and 2023, construction was abandoned on 92 nuclear reactors, 42 of which were located in the United States [22]. While some of these cases were related to changes in safety regulations, a substantial share resulted from financial difficulties, particularly cost overruns.

The problem of cost overruns can be attributed to several factors, one of the most common being inaccurate cost estimation at the project planning stage. Many projections take as a given the assumption that the construction of a subsequent, comparable nuclear power plant will be less expensive than that of the first-of-a-kind facility, and that costs will continue to decline as additional plants of the same type are built. Such expectations are often supported by assumed technological learning rates. Nevertheless, according to research by Philip Eash-Gates, Magdalena M. Klemun, and others, cost reductions following this trajectory are not an inevitable outcome of repeated construction of the same design. This discrepancy can be explained by the fact that each nuclear installation exhibits design variations in certain aspects of construction, and these differences may lead to unexpected cost increases, even when the same reactor model is deployed [7].

Cost overruns are primarily driven by indirect costs associated with the construction process of new nuclear power plants. As described by Philip Eash-Gates, Magdalena M. Klemun, and others, indirect costs account for more than 70% of total cost increases. These costs include expenditures incurred by home-office engineering services, expenses related to field supervision activities, and costs associated with temporary construction facilities, among others. According to the same study, the plant components that have the greatest impact on variations in both indirect and direct costs are the nuclear steam supply system (NSSS), the turbine-generator, and the containment structure [7].

There are several pathways to reducing investment costs in nuclear energy, which in turn could help address the issue of cost overruns. Since a substantial share of construction expenditures is related to labor costs – regardless of wage levels in the country of construction – greater emphasis should be placed on improving labor productivity. Priority should be given to activities that are the most labor-intensive, including construction works, engineering services, project management, and oversight.

In addition, the plant design itself can be improved. Design optimization should primarily focus on key components such as the reactor and the turbine system, as these represent the most capital-intensive elements of a nuclear power plant.

Finally, overall financial costs can be reduced by lowering the cost of capital and shortening project implementation timelines [23, p. 43].

An alternative approach to reducing costs and mitigating the risks associated with construction is the shift from large-scale nuclear projects to small modular reactors (SMRs). While conventional large reactors typically have capacities exceeding 700 MW(e), SMRs are designed with capacities of up to 300 MW(e) per unit.

SMRs not only reduce construction time and resource requirements but also offer several advantages related to their design. As the name suggests, these reactors are modular, meaning that components can be manufactured at centralized facilities and subsequently transported to the deployment site for assembly. The land area required for SMRs is also significantly smaller, allowing them to be installed in locations where large conventional reactors would not be feasible. This, in turn, provides additional logistical benefits, such as the possibility of siting SMRs closer to end users, including urban areas or industrial facilities. Such characteristics may offer a viable response to growing electricity demand under conditions of accelerated global decarbonization.

Since a single power plant should not account for more than 10% of total grid capacity, SMRs may represent an effective solution for rural areas and remote regions, as they can be integrated into locations where supporting infrastructure is limited. In certain cases, a subset of SMRs – microreactors, with capacities of up to 10 MW(e) – may be deployed. These systems can also serve as backup power sources and as alternatives to diesel generators.

Small modular reactors have lower fuel requirements and require less frequent refueling. While conventional nuclear power plants typically undergo refueling every two to three years, SMRs may require refueling intervals of three to seven years, with some designs intended to operate for up to 30 years without refueling.

Safety considerations constitute another significant advantage of SMRs. Reactor shutdown does not require human intervention, external power supply, or applied force, as safety concepts often rely on passive systems. In certain designs, these enhanced safety margins reduce the likelihood of hazardous radioactive releases into the environment in the event of an accident [24].

3. ESG and decarbonisation through nuclear industrial clusters

Industry also perceives clear advantages in cooperation with the nuclear energy sector. The establishment of nuclear-generated energy sources as hubs for industrial clusters represents a mutually beneficial operational model for all participants involved.

Within such clusters, industrial facilities are located in close proximity to one or more nuclear reactors, which provides several advantages:

– industrial consumers gain access to a stable and low-carbon energy supply;

– reduced load on the local electricity transmission network;

– shorter distance between energy production and consumption;

– facilitated financing of nuclear energy infrastructure through contributions from industrial partners;

– the possibility for industrial consumers to receive heat supply from nuclear generation sources;

– the ability to meet growing energy demand (for example, from large data centers required for cloud computing and artificial intelligence);

– hydrogen production to meet industrial needs [25].

Accordingly, such a cluster operates as an ecosystem that enables the maximization of systemic advantages and benefits that individual participants would not be able to achieve if operating independently. It should be noted, however, that the development of nuclear-industrial clusters is not a universal solution. This type of ecosystem is most suitable for industrial facilities with demand for electricity, cooling water, hydrogen, and/or heat. Cluster participants must also be prepared to address associated regulatory challenges, although, in the context of the global nuclear renaissance, the resolution of such issues may become more feasible [26].

Let us consider a conditional model of a nuclear-industrial cluster (Fig. 1).

At the heart of the proposed model is a small model reactor with a capacity of up to 300 MW(e). Next to the reactor are two production facilities: a metallurgical plant and a construction plant. In addition to being consumers of the electricity produced by the reactor, both the construction and metallurgical facilities also use derivative resources.

The metallurgical plant can use cooling water from the reactor to harden metals and cool induction furnaces. Metallurgical facilities can also be consumers of hydrogen, which is a product of the nuclear reactor. The use of hydrogen is necessary for direct iron reduction technologies, which reduce carbon dioxide emissions, reduce intermediate processing and lower production costs. Thus, the use of hydrogen will allow for a simultaneous transition to coke-free production and, accordingly, a transition to green metallurgy [27, p. 131].

Construction companies located nearby can benefit from both other participants in the cluster. Firstly, construction companies can use heat from the nuclear reactor in processes such as brick production, concrete drying, dry mixes and ceramics. They can also be direct consumers of the metallurgical partner's products, as well as consumers of its waste. The construction industry is one of the largest consumers of metallurgical slag, which is used

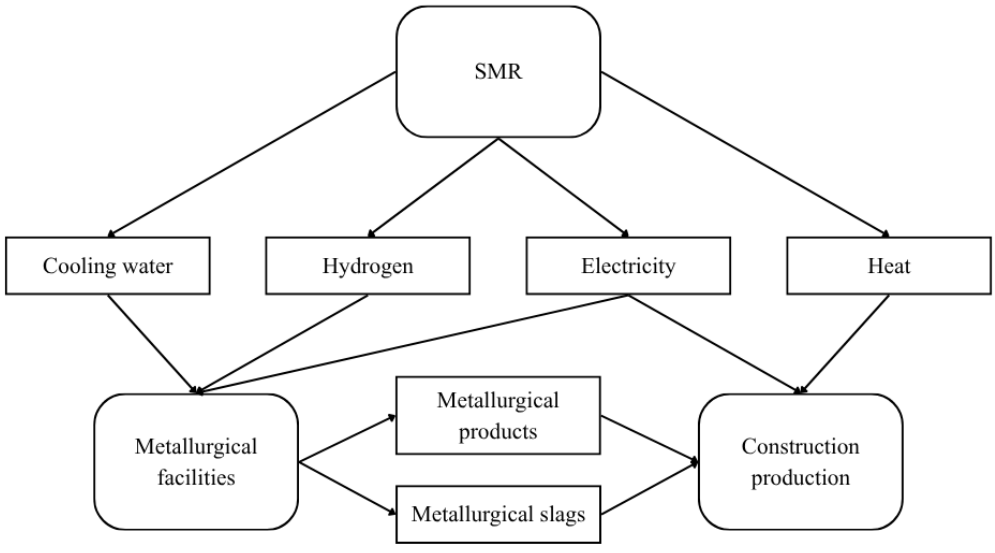


Fig. 1. Model of a nuclear-industrial cluster

in the production of bricks, thermal insulation mixtures, concrete, cinder blocks, dry construction mixtures, cement, foam concrete, roofing felt, aerated concrete, abrasives, paving slabs, and slate [28].

Such a cluster not only maximises the benefits of using nuclear energy derivatives, but also incorporates elements of green metallurgy and the circular economy. At the same time, the challenges of creating such a cluster may include complex organisation and design, limited space suitable for the simultaneous location of a large number of production facilities, significant initial investments, and regulatory restrictions.

The development of nuclear energy, the transition toward small modular reactors, and the utilization of synergistic advantages with other facilities connected to nuclear power generation should be regarded as key elements in achieving Net Zero objectives. It can be expected that, as a result of regulatory policies aimed at meeting global climate targets by 2050, energy sources associated with high carbon emissions and significant environmental harm will increasingly face restrictions, while renewable energy sources and nuclear power will, conversely, be encouraged. In line with these trends, companies that are participants in nuclear-industrial clusters or consumers of electricity generated by nuclear power are likely to be more attractive to investors, as they will not require costly transitions to alternative energy sources, unlike their competitors.

Meanwhile, ESG risks associated with the use of nuclear energy should also be taken into account. Firstly, the problem of nuclear waste must be considered. Although nuclear energy does not cause carbon dioxide emissions and smog, which are often the negative side effects of fossil fuel use, the need for nuclear waste disposal remains urgent. Liquid nuclear waste is usually simply stored in special repositories, often for centuries, so the growth in the number of nuclear power generation sources may exacerbate this problem. As a result, there is a risk of contamination of significant areas of land allocated for the storage of such waste.

Secondly, nuclear reactors carry the risk of accidents. Although past disasters have led to improvements in nuclear reactor design, and small modular reactors are considered less risky, nuclear disasters are still possible. This creates the risk of contamination of large areas of land, casualties, disruption of local ecosystems, as well as damage to nearby facilities (for example, in nuclear industrial clusters) and significant financial losses.

Conclusions. The next 20 years will be transformative for the energy sector. The transition to more active use of nuclear reactors for energy generation is perhaps the only way currently available to transition to low-carbon energy production and achieve global climate goals by 2050. Small modular reactors are gaining significant popularity as an alternative to large traditional reactors and a way to provide energy to remote regions or rural areas. An effective tool for maximising the effect of using nuclear reactors is the creation of nuclear-industrial clusters. At the same time, despite the advantages offered by nuclear energy, its development requires significant resources and exacerbates safety risks and nuclear waste disposal issues that require further reasearch.

Конфлікт інтересів: автор є членом редакційної колегії журналу. Для забезпечення незалежності редакційного процесу рукопис розглядався редактором, який не мав конфлікту інтересів з автором. Автор не брав участі у відборі рецензентів, процесі рецензування та прийнятті рішення щодо публікації статті. Рукопис пройшов стандартну процедуру подвійного сліпого рецензування.

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СТРАТЕГІЧНЕ УПРАВЛІННЯ ТРАНСФОРМАЦІЄЮ СВІТОВОГО ЕНЕРГЕТИЧНОГО СЕКТОРУ: АНАЛІЗ МІЖНАРОДНИХ ТРЕНДІВ ЯДЕРНОЇ ЕНЕРГЕТИКИ В УМОВАХ ГЛОБАЛЬНОЇ ДЕКАРБОНІЗАЦІЇ

Метою статті є трансформація енергетичного сектору в контексті глобальної декарбонізації та перспективи використання ядерної енергії для досягнення глобальних кліматичних цілей. Актуальність теми пояснюється зацікавленістю країн у зменшенні негативного впливу на зміни клімату та відповідними трансформаціями, що відбуваються у енергетичному секторі. Методи дослідження включають аналіз і синтез, дедукцію, абстрагування та моделювання, а також графічний метод. Дослідження фокусується на технологічних, економічних та організаційних аспектах глобальних тенденцій та перетворень у розвитку атомної енергетики та їхній ролі у забезпеченні розвитку енергетики з низьким рівнем вуглецю. Наведено коротку ретроспективу тенденцій будівництва ядерних реакторів починаючи від будівництва першого атомного реактора. Ядерний ренесанс розглядається як процес відновлення інтересу до ядерної енергетики та її потенціалу в умовах глобального енергетичного переходу. Наведено приклади подій, що сигналізують про ядерний ренесанс. Аналізуються стратегії ЄС та провідних країн світу щодо розвитку та використання ядерної енергетики, зокрема описується сектор ядерної енергетики у США, Китаї та Франції. Розглядається визнання ядерної енергетики трансформаційною технологією в межах Європейської таксономії. Описуються основні переваги та недоліки використання ядерної енергетики. Досліджується проблема перевищення витрат, яка часто виникає під час будівництва нових ядерних реакторів, а також визначаються її основні причини. Розглядаються особливості малих модульних реакторів як альтернативи великим традиційним реакторам та їхній потенціал для розвитку нових моделей енергопостачання. Аналізується модель ядерно-промислових кластерів як елемент декарбонізації. Визначаються переваги близького розташування різноманітних виробничих потужностей у межах промислових

кластерів. Запропоновано модель кластера, сформованого навколо малого модульного реактора та який поєднує металургійні та будівельні потужності. Визначаються переваги такого кластера в контексті максимізації використання ресурсів та підвищення ефективності виробничої взаємодії. Окрему увагу приділено ролі ядерної енергетики у досягненні цілей «Net Zero» та ризикам використання ядерної енергетики, зокрема пов'язаними з поводженням із ядерними відходами та загрозою аварій. Практична цінність дослідження полягає у можливості його застосування для обгрунтування рішень щодо формування ядерно-промислових кластерів, впровадження малих модульних реакторів та розвитку енергетики у контексті декарбонізації загалом.

Ключові слова: *атомна енергетика, ядерний реактор, декарбонізація, відродження атомної енергетики, малі модульні реактори (SMR), ядерно-промисловий кластер.*

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