ENERGY WARS
AND SAFETY POLICIES FOR NUCLEAR POWER FACILITIES

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ABBREVIATION LIST

CERN – European Organization for Nuclear Research;

CIF – Critical Infrastructure Facilities;

EAES – European Association for Energy Security;

EC – European Commission;

ENSREG – European Nuclear Safety Regulators Group;

EPR – Emergency Preparedness and Response;

EU – European Union;

EURATOM (EAEC) – European Atomic Energy Community;

FA – Fuel Assemblies;

FORATOM – European Atomic Energy Trade Association (European Atomic Forum);

HAW– Highly Active Waste;

IAEA – International Atomic Energy Agency;

ICRP – International Commission on Radiological Protection;

ICT – Information and Communication Technologies;

IEA – International Energy Agency;

INES – International Nuclear Event Scale (international scale of nuclear and radiological events);

IPCC – Intergovernmental Panel on Climate Change;

IPPAS – International Physical Protection Advisory Service (International Advisory Group on Physical Protection);

NATO – North Atlantic Treaty Organization;

NFC – Nuclear Fuel Cycle;

NM – nuclear materials;

NPP – Nuclear Power Plant;

OECD – Organization for Economic Co-operation and Development;

OECD NEA – the Nuclear Energy Agency of the Organization for Economic Co-operation and Development;

OSCE – Organization for Security and Co-operation in Europe;

PNM – Physical Nuclear Security;

PSR – Periodic Safety Review;

R&D – Research and Development work;

RAW – Radio-Active Waste;

RCF – Regulatory Co-operation Forum of IAEA;

RES – Renewable Energy Sources;

SIR – Sources of Ionizing Radiation;

SMR – Small Modular (nuclear) Reactors;

SNF – Spent Nuclear Fuel;

UN – United Nation;

UNECE – United Nation Economic Commission for Europe;

WANO – World Association of Nuclear Operators

WANO NPP – World Association of Nuclear Operators for Nuclear Power Plants;

WEC – World Energy Council;

WENRA – Western European Nuclear Regulator's Association (Association of Western European Nuclear Regulatory Authorities or Western European Association of Nuclear Safety Regulators);

WNA – World Nuclear Association.

INTRODUCTION

An important trend of diversification of the global fuel and energy balance is the development of nuclear energy. In the medium term, nuclear energy can become one of the leading drivers of economic growth, ensuring the fulfillment of key tasks on energy safety. Nuclear power plants have already played an invaluable role in reducing air pollution, reducing greenhouse gas emission and reducing dependence on fossil fuels, and their future potential in the global energy sector is huge. In addition to providing clean and low-carbon energy, nuclear power makes a significant contribution to the stability of the entire energy system and its sustainability.

The energy crisis of 2021-2022 has shown that it will be problematic to implement ambitious plan to achieve carbon neutrality without nuclear energy. RES-based energy turned out to be more of a political, rather than an economically sound decision. If the share of nuclear generation in the EU continues to decline, according to a number of independent experts, plan for the development of wind and solar generation and energy efficiency measures will never ensure the replacement of retiring nuclear capacities. The disadvantages of the energy strategy of many European countries are becoming obvious, in which too many hopes were pinned on unstable wind and solar energy technologies. Accordingly, countries are again turning their attention to the nuclear energy.

The transition from hydrocarbons to more environmentally friendly energy carriers is an obvious argument in favor of the advantages of nuclear energy used in combination with renewable energy sources. In particular, the integration of nuclear power with other low-carbon energy sources, such as renewable sources with variable generation mode and fossil fuels in combination with carbon capture and storage technologies, has been deepening recently. There are opportunities to integrate the nuclear power system with renewable energy and electricity storage systems, which contributes to the development of hybrid integrated energy systems with low CO_2 emissions at the national and international levels, which can significantly reduce greenhouse gas emissions compared to fossil fuels.

The combination of nuclear energy with renewable sources makes the rapid and long-term decarbonization of electricity production an achievable goal. The volatility of some RES remains a problem for power supply systems, as they require increased flexibility and additional costs due to storage, balancing and transmission of electricity. Nuclear power is capable of providing reliable supplies of low-carbon electricity, which is crucial for the stability of the entire energy system.

However, along with the bright prospects for the development of global nuclear energy, it is important to note that one of the critical factors for the growth of this industry is ensuring the safe operation of nuclear facilities within the framework of the development and improvement of nuclear energy. Nuclear power is associated with particular risks, such as radiation accidents and radioactive waste management, which must be properly anticipated and eliminated. Some countries prefer not to develop nuclear power because they consider the risks of nuclear incidents and accidents unacceptable, or because of problems associated with the long-term disposal of radioactive waste.

Therefore, the nuclear power industry must develop safely, reliably and responsibly. At the same time, it is important to demonstrate the commitment of all countries of the world to comply with international legal documents, safety standards, guidelines in the field of physical security, and nuclear safety in the nuclear energy industry.

The safety of nuclear facilities is the key to the stable development of national programs related to the use of nuclear energy in electricity generation, as well as the key to the energy security of regions where the share of nuclear energy in the energy balance is significant.

Ensuring the safety of nuclear facilities for the peaceful use of atomic energy is a complex task and includes many aspects. To solve it, various protection systems are being created at nuclear facilities, each of which is designed to prevent safety threats of a certain nature. Examples of such systems are nuclear and radiation safety systems, a system of accounting and control of nuclear materials, and a system of physical protection of nuclear materials, and nuclear installations – nuclear security systems, as well as a Cybersecurity system.

The issues of ensuring nuclear safety, ensuring the safety of nuclear waste and transportation of nuclear materials, as well as the readiness of the nuclear energy industry for emergency situations and rapid response are particularly important. The development and continuous improvement of Cybersecurity systems of nuclear facilities are relevant, which is associated with the growing role of computer technologies, and systems in the management of technological processes of a nuclear facility, handling information relevant to the safety of a nuclear facility, and in the management of other security systems. Cyber-attacks on nuclear power installations are becoming increasingly common, and pose a serious threat to international and national security.

The increasing use of digital technologies in the nuclear power industry, as well as the automation of power grids, make nuclear power plants more vulnerable to cyber-attacks. Therefore, the subjects of nuclear energy should treat the growing cyber threats in this area with maximum seriousness and responsibility.

As the amount of nuclear and radioactive materials in use around the world increases, the possibility of their malicious use is also a growing concern. In this regard, countries should ensure physical security at their nuclear installations and radioactive facilities, based on the assessment of threats to physical security, in order to prevent risks emanating, in particular, from terrorists, criminals and extremists. Now a similar situation has developed at the Zaporizhska NPP in Ukraine, which was captured by the Russian military and which is regularly shelled, creating a threat of a nuclear catastrophe, since the attacks are carried out in close proximity to reactors and storage facilities with spent nuclear fuel.

Given the dynamism and variability of the modern world, nuclear security systems must be prepared at a high level for new tests and threats.

In addition, the most important conditions for ensuring nuclear and radiation safety in the use of nuclear power plants, but also one of the necessary conditions for improving the efficiency and competitiveness of nuclear energy is a comprehensive solution to the problems of decommissioning nuclear and radiation-hazardous facilities, as well as the associated safe handling of used nuclear fuel and radioactive waste.

Nuclear security specialists have also been actively engaged in countering internal violators for a long time. Many recommendations developed by the IAEA and the requirements of individual states are devoted to how to hire personnel, how to identify violators, how to create a safety culture at nuclear facilities that reduces the danger of insiders.

In general, nuclear energy should be considered as a critical infrastructure, the disruption or destruction of which leads to extreme situations, disastrous consequences and violation of the national security of the country. The protection of the most important objects of the energy infrastructure of nuclear power is not only a national, but also a global task.

The most important task of the world's nuclear industry in the next 30 years will be the technological improvement of nuclear power plants to ensure their best performance in terms of safety, economy and maneuverability.

Since nuclear energy is a part of the future energy sources in a number of EU Member States along with renewable sources, it will need to modernize the safety system to extend the life of aging plants and replace obsolete nuclear power plants. It is necessary to ensure that new nuclear power plants use the most advanced technological solutions resulting from technological progress and increasing the level of energy security at the national level.

This book, which covers the abovementioned issues in detail, has been in progress during a period of high uncertainty about the future development of energy in European countries due to geopolitical processes, global energy conflicts caused by the acute global energy crisis of the end of 2021 – 2022 in the EU countries, transformations of the world economy and the energy industry, a change in paradigms in the field of ways to achieve a carbon-free economy, technological shifts in nuclear power.

This book is a matter of interest to researchers and analysts, government officials and business representatives dealing with the current and strategic development of nuclear energy, and will also be effective for educational purposes.

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1. NUCLEAR ENERGY AS AN ESSENTIAL COMPONENT FOR SOLVING ISSUES RELATED TO GLOBAL ENERGY CRISIS, CLIMATE CHANGE, AND SUSTAINABLE DEVELOPMENT GOALS ACHIEVMENT. NUCLEAR ENERGY AS A MATTER OF PRIORITY ON THE ENERGY AGENDA OF THE WORLD LEADING COUNTRIES

1.1. The role of nuclear energy in the future global energy balance. The economic advantages of nuclear power in the process of decarbonizing of the world economy and achieving carbon neutrality. Potentiality of nuclear energy synergy with renewable energy sources. Key factors of uncertainty in the nuclear power industry.

Nuclear energy is a source of low-carbon electricity and heat, which can contribute to achieving carbon neutrality, and therefore nuclear energy plays an important role in preventing carbon dioxide (CO_2) emissions [172, p. 1]. Nuclear energy generates electricity through a uranium fission reaction, leading to the generation of heat without burning any substance which makes it one of the most environmentally friendly sources of electricity [232]. Over the past 50 years, the use of nuclear energy has reduced global CO_2 emissions by about 74 Gt, which is equivalent to the total volume of global energy-related emissions in almost two years [172, p. 4]. Only hydropower has played a more significant role in reducing emissions in the past. Therefore, the leading countries of the world make a choice in favor of the development of nuclear energy with the expectation that it will be able to play an important role in the energy balance as an important element of decarbonization. Nuclear power plants already provide energy to residents of 32 countries.

Compared to power generating plants powered by fossil fuels, nuclear power plants have a very light carbon footprint. For example, when burning biomass, 230 g of CO_2 is released per kWh and only 12 g of CO_2 per kWh is released during the production of electricity at a nuclear power plant [209].

According to the IAEA, nuclear energy can contribute to mitigating the effects of climate change in a number of countries around the world [149]. Nuclear energy is a low–carbon energy source that plays an important role in preventing carbon dioxide emissions. According to the IAEA experts, nuclear energy is well suited for ensuring economic growth, maintaining the security of energy supply by reducing dependence on imports, ensuring the reliability and flexibility of the electric power system, and supporting the implementation of sustainable development goals on a broader scale [149].

Experts believe that nuclear energy should be considered as a part of measures' set aimed at implementing the Paris Climate Agreement and the 2030 Agenda for Sustainable Development [98]. Thus, the emergency climate situation in the world, which the UN has recognized, requires the use of all low-carbon technologies. Considering that energy production and use are the source of about 75% of global anthropogenic emissions of CO_2 and other greenhouse gases, to successfully achieve this goal, a radical transformation of the world energy system will be required [172, p. 3]. As you know, nuclear technologies are environmentally friendly energy technologies. Therefore, nuclear energy is an important element in solving the problem of climate change in the world.

In general, nuclear power can be used along with the introduction of other sustainable technologies with low or zero CO_2 emissions to decarbonize the global energy system and energy-intensive industries.

Thus, nuclear power can help humanity to solve two key problems at once: to ensure the reliability of energy supply and to limit greenhouse gas emissions. Today, there are 439 nuclear power reactors in operation in 32 countries, which account for more than 10% of all electricity generated in the world and a third of all so-called low-carbon energy [176, p. 1; 56]. In the coming decades, nuclear energy will retain its key role in the global structure of low-carbon electricity generation.

The year of 2021 was marked by a number of major events in the world for the nuclear industry. The Vienna Group was created under the auspices of the IAEA, which brought together key players of the nuclear market [41]. Nuclear energy also turned out to be one of the central items on the agenda of the UN Climate Change Conference in Glasgow [41]. The energy generated at the NPP was recognized as "green".

On one hand, there are no CO_2 emissions at nuclear power plants, which is important for achieving carbon neutrality. It is not surprising that nuclear energy has already been recognized as "green" in China, India, England, the USA, and the Russian Federation. For example, China expects to build 150 more nuclear reactors in the next 15 years [41]. To assess the scale of the task in China, it is enough to say that there are now 439 of them in the world. The total installed capacity of China's nuclear power industry will reach 70 GW by 2025 [237]. Even in Japan, where public opinion is against nuclear power plants after the Fukushima accident, it was decided to increase the share of nuclear energy in the total structure of the country's energy consumption to 20-22% [41].

On the other hand, nuclear power is denied the "green" status due to hazardous waste and catastrophic consequences in case of an accident. Especially heated debates are taking place in the EU, where there is no unity on the issue of the status of nuclear power plants.

So, in the history of nuclear power, there have been three major accidents at reactors – at nuclear power plants located on Three Mile Island, in Chornobyl and Fukushima. These are the only major accidents that have occurred in more than 17 thousand cumulative reactor years of commercial operation of nuclear power plants in 33 countries [209].

Today nuclear power plants are technically safe: In modern nuclear power plants, safety systems account for about a quarter of the capital costs of reactor construction.

The energy crisis of 2021-2022 has shown that it will be problematic to implement ambitious plans to achieve carbon neutrality without nuclear energy. Wind and solar power plants cannot meet the needs of the economy. Against this background, the decision in the Netherlands to allocate 500 million euros for new nuclear power plants looks indicative [41].

In general, the attitude towards nuclear energy in the world is changing positively. It is associated with the achievement of climate goals. And for this, by 2050, it is necessary that nuclear power plants around the world generate 2 times more energy than they do now [41]. Thus, the IAEA assumes that the share of nuclear energy in global electricity production will double, to 12%, by 2050 [123, p. 8]. The IPCC Report on global warming by 1.5°C, published at the end of 2018, also predicts that by 2050 electricity production at nuclear power plants will increase by an average of 2.5 times compared to today's level [172, p. 4]. In turn, the International Energy Agency (IEA) also states that in order to achieve zero greenhouse gas emissions by 2050, it is necessary to double the capacity of nuclear power worldwide [232]. At the same time, according to the statistical analysis of world energy conducted by the British oil and gas company BP, in 2020 the share of nuclear energy in energy consumption was only 4% [232].

The IAEA experts believe that in the future nuclear power will continue to play a serious role in the production of low-carbon energy. Unlike traditional hydrocarbon energy sources, nuclear power plants do not emit carbon dioxide, which is vital for efforts to achieve zero emissions. Thus, when burning 1 ton of coal or 1 thousand cubic meters of gas, about 2 tons of carbon dioxide and various impurities, including radioactive, are emitted into the atmosphere, not to mention the combustion of oxygen [123, pp. 7-8]. And when burning 1 kg of uranium fuel, there are practically no emissions.

The creation of a carbon–free economy, which will be necessary to avoid the worst consequences of global climate change – many governments in the world have set such goals for themselves - will require a complete transformation of the energy system, including a much greater contribution of nuclear energy [86]. The operating nuclear power plant fleet in the world plays a significant role in achieving energy security, economic growth and mitigating the effects of climate change.

In particular, according to the analysis of the World Energy Council [52, p. 12], the contribution of nuclear energy technology to the achievement of the UN Sustainable Development Goals is high, since nuclear energy:

- offers desalination technologies;
- it is a reliable, affordable, and low-carbon energy supply 24 hours a day;
- contributes to the elimination of hunger – improves crop varieties and nutrition with the help of radiation technologies – avoids up to 20-25% of food losses;
- promotes the development of high-quality education and training of highly qualified engineers and workers, especially in emerging economies;
- provides economic growth – 2 GW nuclear power plant provides 400,000 years of operating life;
- promotes industrialization, innovation, and the development of other industries;
- does not contribute to climate change by generating electricity with low carbon dioxide emissions;
- contributes to the preservation of terrestrial ecosystems – contributes to the control of agricultural pests using radiation technologies; detection of soil erosion using radionuclides;
- it promotes partnership through supranational organizations within the global energy sector in the interests of sustainable development to ensure the energy security of the industry.

The new IEA report, “Nuclear Energy and Safe Energy Transition: From Today's Challenges to Tomorrow's Clean Energy Systems” for July 2022, identified nuclear energy as the key in achieving climate goals [169; 23]. According to this report, nuclear power can improve energy security by reducing dependence on fossil fuel imports, reduce carbon dioxide emissions and help countries transition to energy systems with a predominance of renewable energy sources [169]. The IEA report also states that nuclear power is the second largest source of low-emission energy after hydropower, and that in the period from 2020 to 2050, nuclear power capacity will double as a part of the global path to achieving zero emissions [169].

According to the special report of the Intergovernmental Panel on Climate Change (IPCC) on global warming by 1.5 °C, by 2040 the share of nuclear energy in the total volume of electricity produced will be up to 19% (a three-fold increase relative to the same indicator in 2010), which will contribute to the fulfillment of obligations under the Paris Agreement and the achievement of the UN Sustainable Development Goals [52, p. 6].

As of July 2022, 439 nuclear power units (NPP) have the status of operating in the world, and 54 units have the status of under construction [56].

According to the PRIS database supported by the IAEA, in 2022, five power units were launched in the world (two in China, one each in Pakistan, Finland and South Korea), construction of three units was started (all in China) and three power units were finally stopped (two in Britain and one in the USA) [56]. So, on July 6, 2022, the “Hinkley Point B-2” block (Britain) was finally stopped [56]. The unit has been in commercial operation since September, 1976. The total number of reactor years of operation of nuclear power units in the world is 19392 [56].

According to the IAEA, 32 countries of the world have nuclear power plants today, but 63% of these nuclear power plants have been operating for more than 30 years [169; 73]. Another 50 states have nuclear installations with research reactors [73]. Thus, nuclear energy is the largest source of low-carbon generation in many countries, including Belgium, Bulgaria, Croatia, Czech Republic, Finland, France, Hungary, Slovakia, Slovenia, Spain, Sweden, Ukraine and the USA [172, p. 4]. In eleven countries (Belgium, Bulgaria, Czech Republic, Finland, France, Hungary, Slovakia, Slovenia, Sweden, Switzerland, Ukraine) it provides more than 30% of electricity generation [98].

Currently, 20 UNECE Member States operate nuclear power plants, and 15 countries are building or actively planning to build new nuclear reactors [172, p. 4; 98]. In addition, 7 UNECE Member States are in the process of developing programs in the field of nuclear energy for the first time [172, p. 4; 98]. A number of ECE member countries, such as Canada, the Czech Republic, Finland, France, Hungary, Poland, Romania, Slovakia, Slovenia, Russia, Ukraine, the United Kingdom, and the United States, clearly state that in the future nuclear power will play an important role in reducing national CO_2 emissions [172, p. 4; 98].

In turn, the European Union operates 127 nuclear power reactors in 14 states, producing about 27% of the total electricity [122]. France (72%), Slovakia (54%), Belgium (52%) and Hungary (51%) have the largest shares of electricity produced at nuclear power plants in the EU in national generation [122].

Plans for the development of nuclear energy in the UNECE member countries are presented in Table 1.

Table 1.

Plans for Nuclear Energy Development in the UNECE member countries
(As of May, 2021) [172, p. 20-21].

ECE countries with operating power reactors or planning to develop nuclear power	*Number of operating power reactors*	*Installed capacity of nuclear power facilities (MW)*	*Percentage of electricity generated (2019)*	*Reactors under construction*	*Current plans for the development of nuclear energy*
Armenia	1	375	28	0	It is proposed to build 1 new reactor. Long-term operation of the operating reactor
Belgium	7	5930	48	0	Decommissioning by 2025
Bulgaria	2	2006	38	0	It is planned to build at least 1 new reactor. The expediency of the construction of SMR type reactors is being studied
Canada	19	13554	15	0	Licenses for several SMR reactors are being actively issued
Czech	6	3932	35	0	It is planned to build at least 1 new high-power reactor. The expediency of the construction of SMR type reactors is being studied
Finland	4	2794	35	1	It is planned to build at least 1 new high-power reactor. The expediency of the construction of SMR type reactors is being actively studied
France	56	61370	71	1	It is proposed to build 6 new reactors. The government intends to reduce the share of nuclear energy in the energy balance to 50%
Germany	6	8113	12	0	Decommissioning by 2023
Hungary	4	1902	49	0	It is planned to build 2 new high-power reactors
Netherlands	1	482	3	0	Consultations are being held on the construction of new reactors
Romania	2	1300	19	0	It is planned to build 2 new high-power reactors. The expediency of the construction of SMR type reactors is being studied
Slovakia	4	1814	54	2	It is proposed to build at least 1 additional high -power reactor
Slovenia	1	688	37	0	It is proposed to build 1 new high-power reactor
Spain	7	7121	21	0	Construction of new reactors is not planned
Sweden	6	6859	34	0	Construction of new reactors is not planned

Switzerland	4	2960	24	0	The construction of any new nuclear facilities is currently prohibited
Ukraine	15	13107	54	2	It is proposed to build at least 2 new reactors
Great Britain	15	8923	16	2	It is planned to build at least 4 new high-power reactors. The development of SMR projects is funded
USA	93	95523	20	2	Permits have been issued for the implementation of projects for the construction of 10 new high-power reactors. Several projects of SMR type reactors are being developed. A license has been issued for one SMR type reactor design
Russia	38	28578	20	2	It is planned to build 25 new reactors. It is proposed to build another 21 (SMR type reactors and high-power reactors)
Belarus	1	1110	0	1	There is 1 new high-power reactor under construction. The first reactor has been put into industrial operation
Estonia	0	0	0	0	The expediency of introducing SMR type reactors is being actively studied
Kazakhstan	0	0	0	0	It is proposed to build at least 1 high-power reactor. The expediency of the construction of SMR type reactors is being studied
Lithuania	0	0	0	0	It is proposed to build 2 new high-power reactors (suspended)
Poland	0	0	0	0	It is planned to build 6 new reactors by 2040.
Canada	0	0	0	3	It is proposed to build 8 additional high-power reactors
Uzbekistan	0	0	0	0	It is planned to build 2-4 new high-power reactors. The expediency of the construction of SMR type reactors is being studied

Outside the ECE region, the use of nuclear energy is expanding in Asia, the Middle East, South America and Africa.

Recently, countries with developed economies have lost their leadership in the global nuclear power industry, since 27 of the 31 power units whose construction began in 2017 are Russian or Chinese projects [169].

Currently, nuclear power plants are being built in 19 countries, and it is expected that even more of them will be stimulated by the recent price hikes for oil, gas and electricity [169]. The Czech Republic, Slovakia, Bulgaria, Hungary and Finland are among the countries planning to build new nuclear power plants and have local supply chains of equipment and services in the industry, as well as highly qualified personnel [52, p. 20].

At the beginning of February 2022, the European Commission (EC) has presented in its final version, the Complementary Delegated Act (CDA) for the EU Taxonomy Regulation[1], in which defined nuclear energy as a transitional energy technology, but at the same time imposing strict conditions for its future development [97]. The EC noted that, taking into account scientific recommendations and current technological progress, private investment in the nuclear industry plays an important role in the energy transition process. The CDA states that the nuclear industry meets the EU's climate and environmental goals and allows accelerating the transition from more polluting activities, such as coal production, to a climate-neutral future based mainly on renewable energy sources [97].

Among other things, the CDA states that the technical selection criteria for economic activities related to nuclear energy should ensure that there is no significant damage to other environmental purposes due to potential risks arising from long-term storage and final disposal of nuclear waste [97]. It also states that, although reactors of generation IV are not yet commercially viable, technical selection criteria should be established for such reactors "in the light of their potential contribution to achieving the goal of decarbonization and minimization of radioactive waste" [97]. The CDA will come into force and will be applied in the EU from January 1, 2023.

Proponents of nuclear energy, including 12 EU Member States that publicly supported its inclusion in the "green" taxonomy, believe that it is a low-carbon energy source that should be a part of any energy balance to solve the problem of climate change, and does not cause more significant harm than other energy technologies included in the taxonomy [165]. They argue that science and science-based policy support the inclusion of nuclear power in the taxonomy. Opponents of nuclear power argue that it should not be turned on because radioactive waste makes it unstable.

For the European Union, it was one of the most resonant issues in recent times, where France, the most actively supporting nuclear energy, was in confrontation with Germany. In this regard, the German government has not ruled out a lawsuit against the decision to include nuclear energy in the "green" taxonomy of the European Union [196]. According to German Foreign Minister, Annalena Baerbock, nuclear energy is "risky and expensive, and also not environmentally friendly, and with new nuclear reactors conception" [196]. In turn, the Minister of Energy and Climate, of Austria Leonore Gewessler called the inclusion of nuclear energy in the taxonomy "green brainwashing" and threatened with legal proceedings [165]. The European branch of the World Wildlife Fund (WWF) called on the European Parliament to vote for the rejection of the plan [165].

The Complementary Delegated Act (CDA) of the EU Taxonomy Regulation sets out such mandatory for performance proposals for the further development of the nuclear industry:

[1]The European Commission is developing a ***"green taxonomy"*** – a classification of energy resources that meet the requirements of the EU environmental safety label, aimed at redistributing financial flows towards decarbonization [26, p. 20]. The EC Regulation on Taxonomy provides investors with guidance on economic activities that can be considered environmentally sustainable [64]. It also obliges European companies to report on the level of their activities corresponding to the taxonomy. Any activity excluded from the list may be excluded from sustainable financing products and will be in conflict with the long-term objectives of EU policy.

- advanced nuclear power technologies with a closed nuclear fuel cycle ("Generation IV") are recognized to stimulate research and innovation in the field of future technologies in terms of safety standards and waste minimization (there is no end date for this direction);
- projects of new nuclear power plants for energy production that will use the best available existing technologies ("Generation III+") will be recognized until 2045 (the date of approval of the permit for their construction);
- modifications and modernization of existing nuclear power units for the purpose of extending the service life will be recognized until 2040 (date of approval by the competent authority) [165].

In fact, the CDA adopted by the EC establishes acceptance of criteria that can limit the number of nuclear projects that meet these requirements [97].

At the same time, unfortunately, ***nuclear power was included by the EC in the taxonomy only on a temporary basis***, with expiration dates for both existing reactors (2040) and new reactors (2045).

The EC also put forward a requirement for the future use of nuclear fuel: that all operating and new designed reactors use "accident-resistant fuel" by 2025, and starting from 2025, operating already and new NPP construction projects must use tolerant fuel that has been certified and approved by the national regulator. However, according to the Head of the World Nuclear Association, such a requirement goes beyond the existing national and European nuclear regulation and will be difficult to implement, and in some cases impossible [97]. For example, according to FORATOM, tolerant fuel is still at the testing stage and, therefore, will not be commercially available (it will not be certified and approved) by 2025, which will make it impossible for nuclear power projects to meet these criteria [97].

At the same time, nuclear fuel cycle activities are not currently included in the CDA as stimulating activities, and nuclear investments outside the EU remain excluded from the taxonomy [165].

The arguments of the World Nuclear Association were supported by FORATOM CEO, Yves Desbazey, who stated that FORATOM is "disappointed that nuclear power continues to be considered as a transitional technology" [97]. FORATOM firmly believes that nuclear power contributes to the achievement of climate change mitigation goals and does not cause more harm than any other electricity generation technology already considered to meet the requirements of the EU taxonomy [97].

But, despite some mutual misunderstandings regarding the further development of nuclear energy in the EU, between individual international organizations, there is a clear understanding that nuclear energy will remain a part of the EU energy balance after 2050 in accordance with the EC's own forecasts.

This is due, in particular, to the fact that the costs of fuel, operation, maintenance and repair of nuclear power plants are usually lower than those of fossil fuel power plants, which is a key economic advantage of nuclear power. By implementing a standardized reactor construction program and following other best practice recommendations, countries can expect to significantly reduce the cost of nuclear power plant construction projects.

The potential for synergy of nuclear energy with RES is high. The volatility of some RES remains a problem for power supply systems, as they require increased flexibility and additional costs due to storage, balancing and transmission of electricity. Nuclear power is capable of providing reliable supplies of low-carbon electricity, which is crucial for the stability of the entire energy system.

In recent years, the integration of nuclear power with other low-carbon energy sources, such as renewable sources with variable generation mode and fossil fuels in combination with carbon capture and storage technologies (CCS), has been deepening. According to industry experts, the combination of nuclear energy with renewable sources makes the rapid and long-term decarbonization of electricity production an achievable goal [93].

The experience of France and Germany has well demonstrated the ability of nuclear power plants to adapt to the energy system and the ability to increase the production of renewable energy at lower costs [52, p. 12]. Nuclear power in this role reduces the need for more power plants to provide peak load, such as gas-fired power plants with carbon capture, use and storage technologies [52, p. 12]. The joint placement of facilities of different types of generation – nuclear and renewable energy – makes it possible to increase the efficiency of the distribution of labor resources and infrastructure, including networks, as well as reduce the socio-economic costs associated with significant land use for generating wind and solar energy.

There are opportunities to integrate the nuclear power system with renewable energy and electricity storage systems, which contributes to the development of hybrid integrated energy systems with low CO_2 emissions at the national and international levels, which can significantly reduce greenhouse gas emissions compared to fossil fuels [52, pp. 12-13].

Since the number of renewable energy sources continues to increase, and restrictions are being imposed on generation facilities that are sources of CO_2 among the leading countries of the world, operating nuclear power plants can be considered as a valuable source of maneuverability of the energy system along with energy storage, demand management and reduction of renewable energy generation [172, p. 16].

Experts believe that improved flexible networks based on nuclear power plants in combination with long-term energy storage systems (for example, using "green" hydrogen) can ensure the energy security of EU countries [163]. Hydrogen as a low-carbon fuel can meet the requirements of Europe and, in the future, other countries pursuing a policy of decarbonization.

In the long term, taking into account the fact that the EU firmly adheres to the climate course, it would be advisable to invest in energy storage technologies from renewable sources [246, p. 86], which would contribute to improving the energy security of the EU Member States.

In addition to providing clean and low-carbon energy, ***nuclear power makes a significant contribution to the stability of the entire energy system and its sustainability.*** Currently, this contribution is not taken into account when comparing the cost of electricity generation [52, p. 4]. Projects of small and medium-power reactors, which are currently under development or construction in different countries and are expected to be fully commercialized in the next 10-15 years, could open up significant opportunities for synergy when using hybrid energy systems with combined use of RES and nuclear reactors [52, p. 4]. Reducing the costs of electrolysis at nuclear power plants also opens up opportunities to promote the development of global hydrogen trade.

At the same time, the disadvantages of the energy strategy of many European countries become obvious, in which too much hope was pinned on unstable wind and solar energy technologies. Accordingly, countries are again turning their attention to the nuclear energy.

Along with the high potential for the development of nuclear energy in the world, it should be noted that a number of countries have decided not to use nuclear energy for various reasons: some due to the high availability of natural resources, others due to concerns related to safety and handling of nuclear waste (see Figure 1). In particular, Belgium and Germany have announced the cessation of the use of nuclear energy in the coming years.

Currently, Belgium has 7 operating nuclear power units at two nuclear power plants – 4 at the "Doel" NPP, and 3 at the "Tihange" NPP (commissioned in the period from 1975 to 1985) [153]. According to the Belgian Federal Law of 2003 (as amended in 2013 and 2015), only 3 of them were to remain in operation until 2025 [153]. In July 2022, the Belgian government requested permission from the energy company "Engie" to extend the operation of Unit No. 2 of the "Tiange" NPP until the end of the winter peak of energy consumption in 2022 [194]. The unit was put into commercial operation in June 1983. The planned deadline for the final shutdown of the block is the beginning of February 2023. According to the "Bloomberg", the operating organization "Engie" has previously reported that the extension of this power unit is not possible due to technical limitations and restrictions on nuclear safety [194].

It should be noted that safety incidents regularly occurred at the "Tiange" NPP in Belgium – previously, the operation of the "Tiange" NPP power unit stopped due to cracks in the reactor vessel [74]. Eco-activists claimed that the cracks found at the reactor in 2012 could have existed since the beginning of the construction of the NPP from 1975-1983 [74]. The reactor was temporarily shut down in March, 2014 after thousands of microcracks were found on its steel vessel earlier [203]. Earlier, in 2011, a total of 14 incidents occurred at a nuclear power plant in Belgium. Eleven of them were classified as first–level incidents (technical incidents without consequences), and two more were classified as second-level incidents (incidents with a significant violation of security measures) according to the INES international seven-point scale of nuclear incidents [238]. In 2012, at the "Tiange" NPP, a leak of weakly radioactive water occurred in the holding pool, in which spent nuclear fuel from the NPP reactor is placed for cooling [238]. At the end of 2015, the "Tiange" NPP in Belgium was restarted after a fire [104]. And in 2016, in Belgium, an agent of the security service of the "Tiange" NPP was killed, and his pass (document) was stolen [217]. At that time, as the EU anti-terrorism coordinator, Gilles de Kerschow stated, there was a high level of “risk of terrorist cyber-attacks against Belgian nuclear power plants” [217].

As you know, new technologies allow even individuals to commit large-scale terrorist acts against nuclear power plants. In 2011, attempts were already made to introduce remote monitoring and information collection systems for managing nuclear power plants in Belgium.

In 2014, sabotage occurred at the second Belgian nuclear power plant, “Doel”, in the north of Belgium, the culprit of which was not identified, but during the investigation it turned out that the former technician of this station was among the Belgian Islamists fighting in Syria [217]. As a consequence, on August 5, 2014, the fourth power unit of the “Doel” NPP in the northern Belgium was urgently stopped as a result of the failure of a steam turbine. The investigation found that the incident was the result of “deliberate and well planned actions” in other words, sabotage [217]. To this day unknown criminal leaked 65 thousand liters of oil from the steam turbine system into the emergency tank, which led to overheating of the turbine and its failure [217].

In December 2021, an agreement was reached in the ruling coalition of Belgium on the closure of all nuclear power units in the country until 2025 [195]. However, in January 2022, the Belgian National Regulators concluded that the “Doel-4” and “Tihange-3” units could continue to operate after 2025 in terms of their technical condition, while being subject to a number of modernization measures. In general, in March 2022, in order to reduce dependence on imported fossil energy resources, the Belgian government has allowed to extend the operation of two NPP units (unit No. 3 of the “Tiange” NPP and unit No. 4 of the “Doel” NPP) with a total capacity of 2 GW until 2035 [195]. The rationale for this decision is the need to “strengthen independence from fossil fuels in turbulent geopolitical times”. The government's decision to keep the two units in service until 2035 is due to the fact that Belgium lacks a clear understanding of how the country can replace the retiring nuclear power.

However, according to the recognition of the Belgian Government, all procedures related to the extension of the operation of these power units cannot objectively be completed by the beginning of 2025 [153]. Therefore, experts of the International Energy Agency (IEA) in their report dated as of April 2022, having analyzed the consequences of the possible implementation of Belgium's plans for the phase–out of nuclear power plants, recommended that the Belgian government carry out all necessary work to modernize operating reactors no later than the deadline stated by the government - by 2026, after which they resume operation after forced annual downtime [153].

As noted in the IEA report, the rejection of nuclear power plants in Belgium will lead to an increase in greenhouse gas emissions even in the event of a significant transition to renewable energy sources. Although Belgium has joined the plan established in the European Union for the transition to achieving “climate neutrality” by 2050, however, according to experts, the government of the country does not have a clear strategy to achieve this goal.

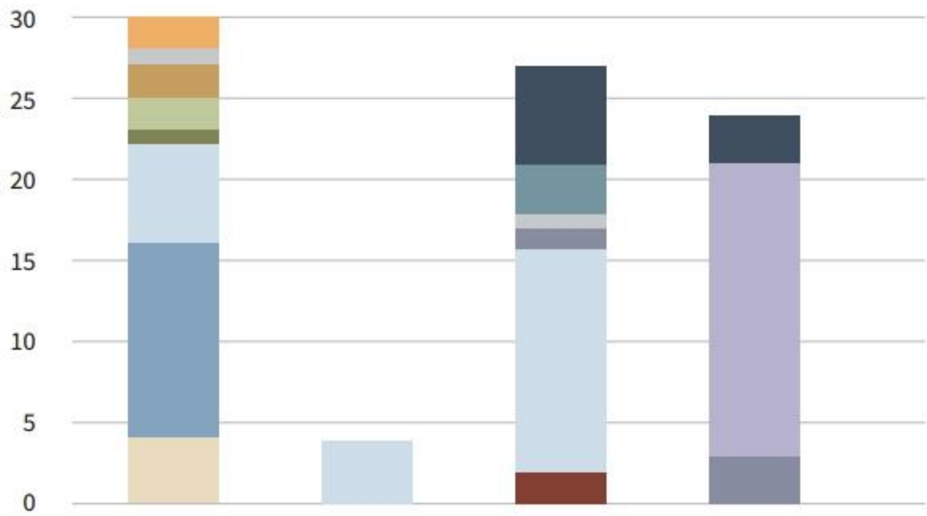
The IEA also recommended the Belgian government to formulate a long-term plan for the development of the country's nuclear industry.

According to the IAEA, in 2020, the share of nuclear generation in total electricity production in Belgium was 39.1% [195].

In turn, Germany, despite the current desire to ensure stable energy supplies and reduce dependence on Russian gas, has not yet changed its plan for decommissioning the last three operating power units at the end of 2022. Germany turned off three of the last six power units operating in the country on December 31, 2021 [196].

The UK also has six generating nuclear power plants, providing about 16% of the country's electricity, but most of them should also be decommissioned by the end of the decade [93].

Data on decommissioning of reactors in different countries and the reasons for such decommissioning are presented in **Fig. 1**.



Socio-political causes Accident Economic Problems with components

R E A S O N S F O R C L O S U R E

Symbols:

USA; Canada;

Great Britain; Lithuanian;

Taiwan; Korea;

Sweden; Japan;

Spain; Bulgaria;

Slovakia; Germany;

Russia.

Fig. 1. **Global decommissioning of reactors from 2000 to 2020 by main reasons (*number of reactors*).** Source: *World Nuclear Association, June 2020, the Enduring Value of Nuclear Energy Assets* [172, p. 17].

Reliability and safety are key factors for the successful development of nuclear energy. Moreover, these concepts are interrelated and interdependent. The reliability of nuclear power plants determines the safety of nuclear power, respectively; the high safety of nuclear facilities contributes to the reliability of the entire nuclear industry as a whole.

The most important criterion for the reliability of the global nuclear power industry is the number of accidents and emergency situations at peaceful nuclear facilities. In 1988, the IAEA developed a special scale of such events, which was called ***INES (International scale of nuclear and radiological events)*** [184, p. 370; 81]. INES includes seven levels: from level 7, where there is a serious threat to human health and life, as well as to the entire ecosystem due to a strong release of radioactive materials, to level 1, where what is happening at a nuclear facility is characterized as an abnormal situation associated with exceeding the norms [184, p. 370]. The INES scale, which is now considered a universal tool, emerged after and as a result of the Chornobyl disaster. After all, after the Chornobyl accident, the world realized that a simple and understandable tool for measuring radiation risks and informing about them was needed. Consequently, this scale classifies nuclear events into eight levels, where 0 is an “event below the scale”, and only two tragic events had the 7th level – the Chornobyl accident in Ukraine (1986) and Fukushima-1 in Japan (2011) [81]. And this proves that the reliability and safety of modern nuclear power plants are growing, as is growing the control over emergency situations.

According to the report of the International Atomic Energy Agency (IAEA), the main causes of the Chornobyl accident were: design flaws of the reactor; poor quality of the operating regulations in terms of safety; inefficiency of safety supervision in nuclear power, and staff errors [81].

As in 1986, the accident at the Fukushima-1 nuclear power plant became a catalyst for public discussions about the need to improve the reliability of nuclear facilities and the feasibility of using nuclear energy in general.

Now, against the background of the Russian military invasion of Ukraine and the seizure by the Russian occupiers of the Zaporizhska NPP in Ukraine, the ghost of the “second Chornobyl” has regained real outlines due to the constant shelling of the NPP.

At the same time, one of the main barriers to the further development of nuclear energy in many countries is public opinion. For example, the negative attitude of the country's population to nuclear energy is the main obstacle to the expansion of nuclear energy in a number of countries: Indonesia, Thailand, the Philippines [88, p. 54], and this is despite the fact that in the Asia-Pacific region, nuclear energy is developing at the fastest pace in the world.

Public opinion polls regularly show that the highest level of support for nuclear energy falls on areas located in the immediate vicinity of nuclear energy facilities [52, p. 16]. There is a concentration of knowledge about the nuclear industry in these areas. The highest levels of support are noted in those countries where a significant part of the energy is generated by nuclear power plants with some exceptions, such as Germany and Japan. Polls show a lower level of support in areas remote from nuclear facilities, where most of the population is not familiar with nuclear energy, and the opinion is formed mainly by the media [52, p. 16].

Also, taking into account the negative public opinion related to the concern of the general public about the reliability and safety of nuclear power plants, it was decided in Germany to gradually (until 2022) abandon the use of nuclear energy on a national scale, although before that German nuclear energy was one of the most promising and efficient on the European market.

Therefore, as an energy solution, nuclear power remains extremely dependent on the political, social and economic conjuncture.

Thus, in today's conditions of the global energy crisis, the rapid rise of fossil fuel prices, energy security problems and ambitious commitments to protect the climate, nuclear power has a unique opportunity to return to new key positions in the global energy balance. According to the IEA, the future of low-carbon, sustainable, affordable and safe energy needs nuclear energy [169].

According to the Director General of the World Nuclear Association, Sama Bilbao y Leon, nuclear energy is necessary for the transition to low-carbon energy and will become a part of the future energy landscape of the EU for many decades to come [97].

At the same time, along with the bright prospects for the development of global nuclear energy, it is important to note that ensuring the safety for operation of nuclear facilities within the framework of the development and improvement of nuclear energy is one of the key factors for the growth of the industry. Since nuclear energy is a part of the future energy sources in a number of EU Member States along with renewable sources, it will need to modernize the safety system to extend the life of aging plants and replace obsolete nuclear power plants. It is necessary to ensure that new nuclear power plants use the most advanced technological solutions resulting from technological progress.

It is obvious that nuclear energy will be part of the global energy balance over the coming decades, but its share and growth rates will depend on a number of factors [52, p. 6]. Some of them are largely determined by the development of the nuclear industry itself, for example, the speed of innovation in the field of new nuclear technologies and the formation of a policy regarding the management of accumulated nuclear waste. At the same time, other factors, such as energy policy, the structure of markets and financing mechanisms, are formed and influenced by a wider range of stakeholders outside the nuclear industry [52, p. 6].

At the same time, understanding major changes in the global picture of world energy, including those related to geopolitical factors, will help determine the role of nuclear energy in the new trajectories of world economic development until 2060. Uncertainty factors are extremely important in shaping the trajectory of global nuclear energy development: the spread of new technologies and digitalization, the development of supranational governance and geopolitics, geostrategic competition, regionalization, priorities for governments, business and the public in the field of climate change, environmental protection and sustainable development, an approach to energy sector management.

In general, the prospects for nuclear and other forms of energy production are determined by the complex and unpredictable interaction of global factors such as decentralization, decarbonization, digitalization and geopolitics [52, p. 2].

The world is facing a shift in market forces toward the non–OECD countries, mainly in the Asian region, among which India and China are the main engines of economic growth. The geopolitical agenda goes beyond the sphere of oil and gas, covering technologies and non-primary energy resources. It is no longer clear what form and direction the rivalry between states will take, and whether a cohesive system of supranational governance can be built, including in the global energy market [52, p. 18].

In addition to the above-mentioned wide range of uncertainties, there are certain factors that will affect the future of nuclear power and the amount of NPP capacity commissioned by 2060 [52, p. 20]. Much will depend on reaching consensus on the role of nuclear power in the energy transition, extending the service life of existing nuclear power plants and policies regarding the construction of new nuclear power plants.

1.2. Modern technologies for nuclear energy use.

Along with other low-carbon technologies, nuclear power can meet the growing demand for electricity and non-electric energy applications for the period up to 2050 within the framework of the conception of transition to sustainable energy [174, p. 15]. In particular, the use of modern nuclear reactors is increasing in all regions of the world, as they are regarded as nuclear power systems capable of contributing to the global transition to more sustainable, affordable and reliable energy systems. They are suitable for integration into future carbon-free power systems, the important components of which will be a variety of energy sources, including small and medium-power reactors or Small Modular Reactors (SMR) [174, p. 2]. In particular, SMR can meet the needs for clean energy in a basic mode, and at the same time, working flexibly, so that it is possible to provide a combination with a variety of alternative energy sources and respond to demand [174, p. 32].

It should be noted that currently there are three main technologies of power reactors: pressurized water reactors (PWR), boiling water reactors (BWR), and pressurized heavy water reactors (PHWR) [172, p. 9]. PWR is the most widespread technology of nuclear power reactors in the world, having 70% of the world fleet of nuclear power plants [39]. There are also other types of reactors, in addition to the above, which are currently in operation; these are graphite reactors with light water (LWGR), gas–cooled reactors (GCR), and fast neutron reactors (FBR) (Fast Breeder Reactor) [39].

Water-cooled reactor technologies occupy a dominant position in the global market. However, there are many possible design options for reactors based on the use of various types of nuclear fuel, structural materials and heat carriers. ***Six so-called Generation IV nuclear power systems are identified*** as priorities for further research: a gas-cooled fast reactor (GFR), a lead-cooled fast reactor (LFR), a molten salt reactor (MSR), a supercritical water reactor (SCWR), a sodium-cooled fast reactor (SFR), and an ultra-high temperature reactor (UHTR) [172, p. 9].

The reactors of the new, fourth generation assume a qualitatively new level of safety and ease of operation, as well as the closure of the nuclear fuel cycle (NFC) [52, p. 21].

Currently, several designs of water-cooled reactors (WCR) are also being constructed, commissioned or operated around the world, in which evolutionary and innovative technologies are used [174, p. 32]. Among the latest achievements in WCR technologies are improvements to existing and the development of new designs with common goals of improving safety, more efficient use of resources and improving economic performance [174, p. 32]. In most evolutionary concepts, security systems have passive functions that do not depend on power supply and provide for the presence of large water reserves, which allows in case of unplanned situations, such as prolonged de-energization of the station, to have a time reserve calculated not in hours, but in days. Another important area of WCR development is the design, testing, and construction in a factory of modular integrated reactors with low-power pressurized water reactor (PWR) [174, p. 32].

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