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Perspectives of nuclear energy development in Ukraine on the global trends basis

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Abstract. The article examines global trends in the development of the nuclear power industry. It includes the following: extending the operating life of nuclear power units; development of atomic energy in the context of the Paris Agreement; development of nuclear-hydrogen energy; synergistic interaction of renewable energy sources and nuclear power plants; introduction of new reactor technologies. The attitude of different countries of the world to atomic energy is described. It is determined that China and India are the leaders in developing nuclear power. It was determined that small modular reactors are considered transformative reactors that will contribute to the further development of atomic energy in the world. The advantages of small modular reactors in comparison with reactors of large capacity are described, and recommendations for selecting small modular reactors for Ukraine are formulated. Installation of small modular reactors at the operational sites of the NPPs of Ukraine can reduce the financial costs of their construction. Therefore, it will contribute to the sustainable development of the nuclear energy industry of Ukraine.

1. Introduction

The complex problem should be solved to ensure the long-term development of humankind. The issue includes the maintenance of energy and economic and environmental security. Therefore, it is necessary to unite world efforts in the search for innovative directions of technological development that ensure a stable and secure future to solve the outlined problems [1]. Currently, the international energy community emphasizes the global revival of nuclear energy and the rapid

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development of renewable energy sources. The situation is evidenced by the active construction of new and modernization of existing nuclear power plants (NPP) in many countries [2].

Further digital transformation of society is essential to ensure the sustainable development of humankind. Such change requires an increase in energy consumption due to the need to process ever-increasing volumes of data. At the same time, growth in energy consumption leads to:

1) depletion of energy sources (problem of energy conservation and diversification of energy production types);
2) climate change (the problem of reducing carbon footprint involves transforming the electricity generation sector against the background of reducing the operational resource of existing energy capacities).

Azarov and Zadunaj [1] indicates various international initiatives in the global field of nuclear energy aimed at developing new projects to combine the efforts of many countries in creating innovative nuclear energy technologies. These initiatives are designed to ensure energy security, reduce atomic materials' distribution risks, and solve the problem of radioactive waste. Also, these ideas became the basis of the international project INPRO operating under the International Atomic Energy Agency (IAEA).

Interest in small modular reactors (SMRs) and their applications is growing worldwide. The main driver for SMR development is to meet the need to produce electricity for a broader range of users and applications, replace aging large-capacity reactors, and improve safety. SMRs include new-generation reactors designed to produce electricity up to 300 MW according to the accepted definition of the IAEA. Their components can be manufactured at the factory and transported as modules to the installation site. SMRs can be deployed as a single or multi-module installation. In addition, many SMRs have increased protection properties and safety functions [3].

Hussein [4] emphasized that SMRs are the next stage in developing nuclear reactors and are transformative by many criteria. SMRs are seen as a way to overcome cost overruns and construction delays where sizeable atomic power reactors were supposed to operate. SMRs can play an essential role in addressing climate change by providing a low-carbon source of electricity. They can also help alleviate the problem of nuclear waste disposal by burning spent fuel and nuclear waste.

Examining government documents regarding the regulation of nuclear energy issues in Ukraine for 2018-2019, we see the following:

1) SE "NAEK "Enerhoatom" and Holtec International signed a Memorandum of Understanding on cooperation in the use of SMR-160 in Ukraine. The Memorandum states that it is planned to license SMR-160 technology in Ukraine further to build these reactors at Ukrainian nuclear power plants and to localize production of SMR-160 equipment at Ukrainian enterprises partially;
2) SE "NAEK "Enerhoatom", State Scientific and Technical Center for Nuclear and Radiation Safety and Holtec International signed an agreement on the creation of an international consortium for "introduction of the small modular reactor (SMR) SMR-160 technology in Ukraine" [2, 5].

Therefore, we state that SMR use is also lobbied at the state level in Ukraine.

It was planned to end the operation period of some power units of the NPP of Ukraine between 2030 and 2040. Such power units already had an extended operation period. The fastest choice of the reactor type technology for the construction of replacement and new NPP power units is relevant [6], taking this into account and taking into account the duration of the creation of a nuclear installation.

Four nuclear power plants in Ukraine (15 power units with water-water power reactors) were operating in Ukraine at the beginning of 2022. Their capacity was 13,835 GW. Zaporizhzhya

NPP (6 power units, the largest nuclear power plant in Ukraine) is still under the control of the invaders in the occupied territory for the end of 2022 due to military operations on the part of Ukraine. The construction of SMR on the territory of Ukraine is still updated by the need for a stable electricity supply for the post-war reconstruction of Ukraine and its economy.

2. Literature review

Azarov and Zadunaj [1] analyzed nuclear energy development in the world and the impact of large-scale accidents at nuclear power plants ("Fukushima-1") on it. The need to improve the security of nuclear power plants is emphasized. Innovative technologies of the III-generation reactors are described. It was noted that atomic energy is the most critical component of the world's energy balance, and there is no severe alert.

Analysis of the materials of international organizations (International Project on Innovative Nuclear Reactors, International Atomic Energy Agency, Nuclear Energy Agency, etc.) [7–9] and scientific literature showed that only a few countries in the world started construction of SMRs by the end of 2022. Various concepts and project licensing are still discussed in other countries.

Nosovskyi [10] determined that there currently needs more technical, economic, and scientific justification for the SMR's operation. SMRs are only being developed worldwide, and their operation benefits still need to be confirmed in practice. Furthermore, the analysis showed that SMR technologies used for electricity production are more expensive than power units with a 500-1000 MW capacity.

The report [11] describes the main problems that should be overcome for the large-scale implementation and achievement of economic competitiveness of SMR. An overview of financial and technical aspects, issues of licensing, and legal regulation are presented. Expanding international cooperation in all directions is essential to create a sustainable global SMR market.

Features of SMR modularity and design are described in [4]. The economic advantages of SMRs and flexibility allow them to be used for various purposes. SMRs are considered a means to reduce greenhouse gas emissions. SMR designs incorporate features that were tested and proven in early reactors. They are also relatively safe for the surrounding population.

Azarova and Zadunaj [1] considered existing plans and programs to develop promising "IV generations" reactor technologies. It is necessary to consider several additional factors: principles development for ensuring the acceptability, efficiency, and economic competitiveness of nuclear energy, stability, nuclear and radiation safety, non-propagation, and physical protection.

Currently, SMR concepts can be conditionally divided into five main groups [11]:

1. *Single-module light-water reactors.* Their design uses the proven technology of light-water reactors (LWR) and appropriate types of fuel to create autonomous units suitable for deployment within the concept of distributed generation or capable of replacing small power units operating on fossil fuels;
2. *Multi-module light-water reactors.* They are based on the LWR technology and can be operated as sources of electricity within the framework of the concept of distributed generation or replace medium-sized power units that provide base load;
3. *Mobile/movable reactors.* They are based on LWR technology and allow easily implemented installation movement from one site to another. This category includes reactors of floating power units;
4. *"IV generations" SMRs.* They are based on modern technologies that differ from those used in LWR;
5. *Micromodular reactors.* Their capacity is at most 10 MW. Such reactors can operate in semi-automatic mode, as a rule. Also, they have characteristics that facilitate easily realized transportation compared to larger SMRs; Micro-modular reactors are designed primarily

for off-grid operation in remote areas where they can be competitive with mainstream electricity sources.

Demianiuk [12] defines the characteristics of SMR and the synergy of SMR with renewable energy sources. Progress of SMR projects in the short term and an overview of leading in technical and economic indicators of SMR are described. Finally, a list of priority measures for implementing SMR in Ukraine is outlined.

Classification of SMR projects depending on the novelty of their technical solutions was proposed by Dybach and Plachkov [13]. In addition, a comparative analysis of SMR (SMR-160 Holtec International project) with NPPs operating in Ukraine was made.

Currently, the most developed type is LWR installations with pressurized water among the existing SMR projects. Steam generators are one of the main elements of them. The preferred design is a functional-flow steam generator with functional body movement in tubes with coiled surfaces [14].

Niearonov et al [6] describes the algorithm for choosing reactor technology type based on a comparative evaluation of existing and promising reactors. Adaptation of the KIND-ET toolkit of the IAEA INPRO project on a multi-criteria comparative assessment of nuclear power plants was carried out for the obtained results ranking. Proposals for reactor technology type choice for constructing NPP power units in Ukraine after 2035 are described. Finally, recommendations for optimal reactor technology choices for creating NPPs in Ukraine for 2050 are defined.

The energy of Ukraine, will be endangered unless the country has time to replace NPP power units with new ones within 2040-2050. At the same time, a significant share of the country's human capital will be lost because nuclear energy is a high-tech industry. It requires specialists with a high level of training in various scientific fields. Therefore, developing and implementing programs to transfer nuclear technological knowledge at the state level is essential. The outlined understanding is a vital resource that will determine Ukraine's political and economic realities shortly. Renewal of Ukraine's nuclear power plants is possible in the following directions: construction of SMR and new "large" NPPs [2].

We analyzed the websites of international organizations dealing with nuclear energy issues and scientific literature during working on this research. Functioning of nuclear fuel cycle facilities are considered in publications [1, 2, 4, 15–18], issue of developing mathematical and software tools for assessing the impact t of energy facilities on the environment is considered in works [19–31]. Specifics implementing of alternative and renewable energy sources are described in publications [32–40]. Advanced training of specialists in nuclear energy is discussed in publications [41–44]. The literature review was performed based on open sources and the websites of international organizations [7–9].

Aim is to consider world trends regarding the development of the nuclear power industry and to substantiate the possibilities of building SMR in Ukraine, given their environmental friendliness and safety.

3. Results

We support the opinion of Kilnytskyi [45] that the principles of sustainable development have determined mainly the evolutionary directions of world energy since the beginning of the 21st century. Bet on energy efficiency, energy security, and low-carbon energy with the active construction of renewable energy sources allowed the industry to enter its development's revolutionary and innovative stage. Everything is changed dynamically on the energy map of the planet: the structure of generating capacities, the configuration of energy systems, and the arrangement of national energy markets.

Investments in nuclear energy were stable and promising for a long time. However, the accident at the Japanese NPP "Fukushima 1" (2011) made the world think about security and question the future of atomic energy. Later, talks about global climate change began, and advanced countries took a course on renewable energy. The question arose: will there be a place for nuclear energy in the new "green" world? NPPs do not emit CO_2 and fully fit the carbon bond neutrality policy. At the same time, atomic power plants leave harmful nuclear waste, and the risk of accidents still makes people distrust even high-tech reactors. Therefore, the USA, Germany, Japan, South Korea, and other world powers gradually reduced investments in this industry; the gas crisis occurred in 2021. So, nuclear energy received a chance for revival and a new future [46].

Currently, 440 nuclear reactors are operating in 32 countries. Another 50 are under construction, mainly in Asia. However, the IAEA does not give precise predictions role of nuclear power plants in electricity production worldwide. It depends on whether it will be possible to build new capacities to replace the stations that will be decommissioned. More than half of the active reactors in the world have been operating for more than 30 years. Today, nuclear energy accounts for 10% of global electricity production. According to the low forecast of the IAEA, this share will decrease to 6% by 2050. According to the high estimates, the percentage of nuclear electricity will increase to 12% [47].

Nuclear energy has two advantages over other sources. First, it can provide heat for production processes and cheap and reliable electricity without releasing greenhouse gases. Secondly, nuclear energy currently avoids emissions of 200 million tons of CO_2 annually (equivalent to removing 400 million cars from all world's roads) [48].

Currently, nuclear energy is in trend again. Let's consider how the views of different countries of the world on nuclear energy were changed. Materials for analysis are taken from open sources of information: scientific publications, websites of international organizations, and analytical and reporting materials. Finally, continents and countries grouped the results of the analysis.

3.1. Europe

The **EU** still needs to make a final decision on the status of nuclear energy. There is an ongoing debate regarding including atomic energy in the "green" taxonomy. Taxonomy is a list of environmentally friendly activities. The European Union needs it to show "useful" companies and encourage investors to finance them. Companies with such markers will attract more loans and be supported by the EU authorities. In 2020 scientists from the European Commission recognized nuclear power plants as a safe, low-carbon energy source. But in 2021, the commission refused to include nuclear power plants in the "green" taxonomy due to the problem with nuclear waste disposal. However, the energy crisis in the EU intensified this debate. At the same time, 12 EU countries called the European Commission to recognize nuclear energy as "green" [46].

More than half of **Poland's** energy depends on coal. So, there is also a search for a stable alternative to reduce carbon emissions.

Germany decided to decommission its nuclear power plants after the Fukushima accident. However, seven reactors remain in operation and provide 12% of Germany's electricity. At the same time, renewable energy is successfully developing in the country [47].

Spain has gradually reduced its share of nuclear energy. Seven reactors remain in operation and supply about 20% of electricity. According to government directives, all reactors should be shut down between 2025 and 2035. It is planned to be replaced by stations with renewable energy sources. However, this may affect the timing of the planned shutdowns [47].

France is the informal leader in nuclear energy production in the world. The country's government is most interested in the approval of atomic energy. France operates 56 nuclear reactors. They provide more than 70% of electricity needs. The country is also the world's largest exporter of nuclear power. It also helps build atomic reactors around the globe. At the same time, 12 reactors coming to an end of service life are planned to be turned off.

Along with this, the construction of a new power unit at the Flamanville NPP is underway.

This will be the country's first EPR – a pressurized water nuclear reactor of the third generation with a capacity of 1,650 MW. Construction was delayed for ten years. Flamanville-3 is expected to be launched in 2023 [47, 48].

Slovakia is the country that is building new nuclear power plants in Europe. Four reactors provide half of the country's electricity, and two more are under construction. The situation with two new reactors at the Mohovets NPP demonstrates the general problem of NPP construction. The 2019 opening was delayed due to pressure from neighboring Austria and safety concerns for the power units, which were initially built to Soviet design and modified using "Western" elements [47].

Great Britain ranks tenth in the world for nuclear energy production. "Electricite de France SA (EDF)" began constructing the Hinkley Point C plant in Somerset in 2016. It is expected to be operational in the middle of this decade. Hinkley Point C is expected to supply around 7% of the UK's electricity once connected to the grid. In addition, it is currently underway for the 3,200 MW Sizewell C power station in eastern England. EDF plans to build it in partnership with China General Nuclear Power Group [48].

3.2. North America

Ninety-five reactors are actively operating in the USA, providing 30% of the world's nuclear electricity and remaining its largest producer. NPPs generate about 20% of electricity for the country's needs. From 1978 to 2013, new NPPs were not built. Only in 2012 were permits issued for constructing two new reactors at the Vogtle NPP in Georgia. It happened for the first time in 30 years. New projects began to appear in 2016 when the second power unit of the Watts Bar NPP in Tennessee opened. However, significant delays and rising construction costs led to the closure of two reactors at the V.C. Summer station in 2017 in South Carolina [47]. The development of nuclear power plants in the United States is part of the fight against climate change. The government allocated $1.85 billion to support the nuclear power industry in 2022. This value is 23% more than in 2021. Another $6 billion will be used to extend the service life of the NPP; 2.5 billion will be spent on the construction of experimental reactors [46]. President Biden spoke in favor of nuclear energy and emphasized the expansion of jobs and opportunities that will be created through the development of innovation and investment in the latest small modular reactors [48].

3.3. Asia and the Middle East

China plans to significantly increase the share of nuclear generation in the energy system from 3% to 7.7% in 2035. The country has 49 reactors, and 16 more are under construction. Preference is given to nuclear energy in the country due to excessive air pollution by coal-fired power plants. China is developing and planning to introduce new reactors and increase the number of plants and their capacity. For example, the first SMR may start operating on Hainan Island as early as 2025 [47]. China is ready to build many nuclear power plants on its territory and 30 reactors abroad, competing in this market with France and the USA [46]. In 2021 the President of China was directly present at the foundation laying ceremony of four new nuclear power units in the PRC. Power units 7 and 8 of the Tianwang NPP and 3 and 4 of the Xudapu station will be built using domestic equipment [48].

South Korea announced plans to withdraw from nuclear energy by 2040. As a result, the life of atomic power plants will remain the same, and new facilities will not be built [48].

Japan sees nuclear power as the key to achieving decarbonization goals and reducing greenhouse gas emissions. Therefore, Japan is also considering using nuclear energy by introducing small modular reactors. This is outlined in the country's Green Growth Strategy [48].

The **Indian** government plans to launch nine reactors in three years. The construction of another 12 was approved in 2020. This is the first time a nuclear power plant has been built in the country on such a scale [46]. It is planned to increase the number of nuclear power plants in India within the framework of large-scale infrastructure development programs. Currently, 23 reactors are operating in the country. In addition, 21 new reactors with a total capacity of 15 GW may be installed [48] up to 2031.

The **United Arab Emirates** launched the first Baraka NPP in 2020. It is planned that all four power units of the station, with a total capacity of 5.6 GW, will work already in 2023 and will provide up to 25% of the country's electricity needs [48].

Turkey is building its first Akkuyu nuclear power plant. One of the reasons is a desire to reduce energy dependence. The country imports about 75% of its electricity. The station will have four power units with a total capacity of 4.8 GW. Its first reactor is planned to be launched in 2023 [48].

So, we conclude that China and India became leaders in developing the nuclear energy industry based on the analysis above. Based on the analysis of scientific literature [14,45,47,48], the main problems of the development of nuclear energy in the world are outlined:

- decrease in the competitiveness of nuclear energy and premature shutdown of power units;
- exceeding terms and cost of construction of new NPPs;
- aging of operating power units and need for decommissioning;
- the negative attitude of society against the background of Fukushima and other nuclear accidents;
- the difference in licensing of nuclear reactor projects;
- the need to solve the problem of spent nuclear fuel and radioactive waste;
- the inability of energy markets to attract long-term investments.

We agree with the Lutska [47] that today's security issue remains the most crucial reason for refusing to build new nuclear power plants. It got tougher every time after the accidents at the Chornobyl and Fukushima stations. In 2011 anti-nuclear protests intensified significantly in Europe, where plants are often located near borders with neighboring countries. The next problem is the complex process of nuclear power plant construction. It is often delayed and stopped causing the cost of power units to rise. Also, the issue of handling atomic waste remains relevant. At the same time, some countries see nuclear energy as an opportunity to diversify energy sources, reduce dependence on other energy sources and replace coal-fired power plants [47].

An outline of the world trends in the development of nuclear energy is essential. The research was prepared based on the analysis of various sources [4, 14, 16, 45, 47–50]:

- an extension of the operating periods of nuclear power units;
- development of nuclear energy in the context of the Paris Agreement;
- development of nuclear-hydrogen energy;
- synergistic interaction of renewable energy sources and nuclear power plants;
- introduction of new reactor technologies.

Let's briefly describe the trends outlined above. The critical disadvantage of nuclear energy today is the high capital costs for constructing large atomic power units. Therefore, many countries with operating nuclear power plants are forced to extend the operating periods of their power units. The leading technologies that will ensure the fulfillment of the goals of the Paris Agreement include those with low levels of greenhouse gas emissions. Hydropower, wind, and nuclear power will play an important role. They produce the least amount of greenhouse gas emissions. Every year amount of hydrogen consumption increases. So, the development of hydrogen energy is taking place. Many countries developed their own "Hydrogen Strategy". The world public and scientists predict a significant effect from the operation of hybrid energy systems for the synergistic interaction of renewable energy sources and nuclear power plants. Such hybrid systems will make it possible to generate electricity and provide low-carbon thermal energy for the industry at a price lower than a traditional thermal generation (figure 1).

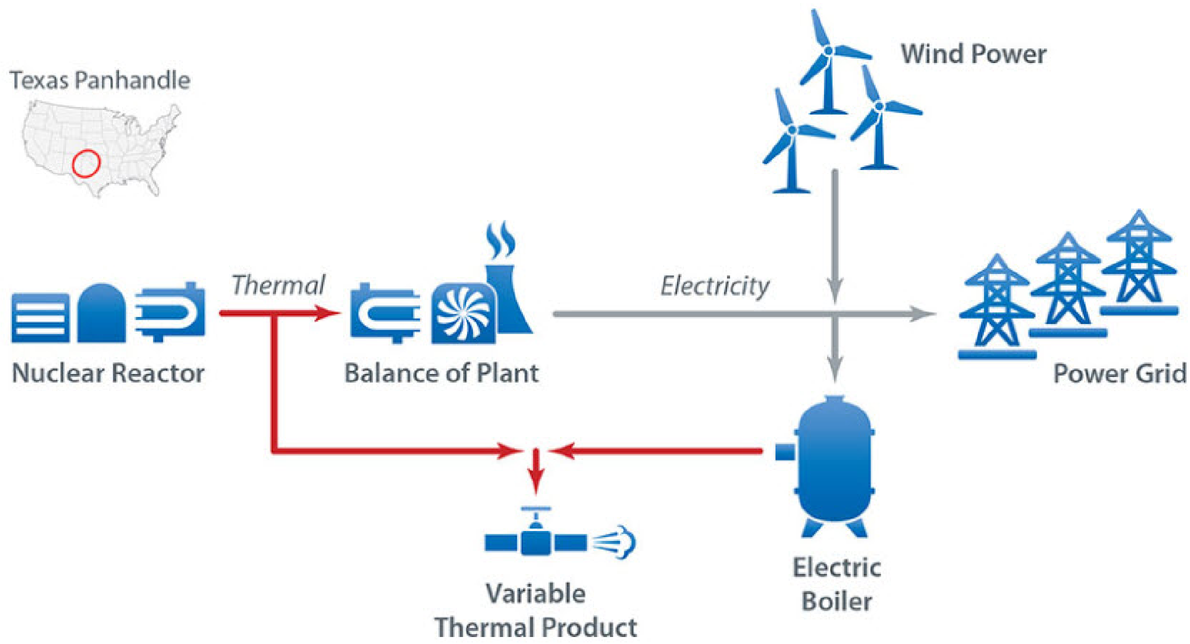

Figure 1. An example nuclear-renewable hybrid energy system configuration [51].

Let's analyze the trend regarding the "introduction of the new reactor technologies" in more detached new reactor technologies caused by the following factors: risk of accident at the nuclear power plant and difficulty of disposal of radioactive waste. The publication [46] indicated that the factors listed above could be leveled by using new reactor technologies. One of the progressive ideas is thorium reactors. Uranium-233 is used for the operation of these systems. The substance is obtained through the irradiation of thorium-232. These reactors are predicted to leave behind less toxic waste. At the same time, there are more thorium reserves in nature than uranium, which is safer to produce. Currently, China decided to build an experimental thorium reactor that will work on an alloy of salts. The reactor will be filled with an alloy of salts. So, it will have a much lower risk of melting or exploding, making the leakage of radioactive components almost impossible. However, thorium is associated with the risk of nuclear propagation. It is hotly debated.

The TerraPower company plans to launch an experimental nuclear reactor in the remote town of Kemmerer (USA). The reactor will be cooled by liquid sodium. There will be no increased pressure in the reactor, So it minimizes the possibility of an explosion. The system will not require external energy sources for cooling. The creators of TerraPower promise to solve the problem of nuclear waste. Now they are stored in concrete containers. Spent fuel from TerraPower will take up two-thirds less space than waste from conventional reactors. Also, the construction of such an object costs much less than usual due to greater use efficiency. This reactor is small in size. It, in turn, reduces capital costs. It produces three times less energy than the average reactor, so it is more profitable to build it [46].

Today, companies and startups worldwide develop new models of nuclear power plants. They should be simpler and cheaper to build, safer, use less fuel, and operate more flexibly. They may influence global trends in the development of atomic energy [47] if the new reactors meet all these criteria.

NPPs with high-power reactors are designed to operate in the base mode. Therefore, it limits the possibilities of using nuclear potential due to the need for daily regulation of loads in the power grid. This drawback can be avoided by switching to SMRs (figure 2). SMRs are cheaper to operate, can be used in shift mode, do not require the construction of powerful underwater power lines, and have higher levels of safety [45].

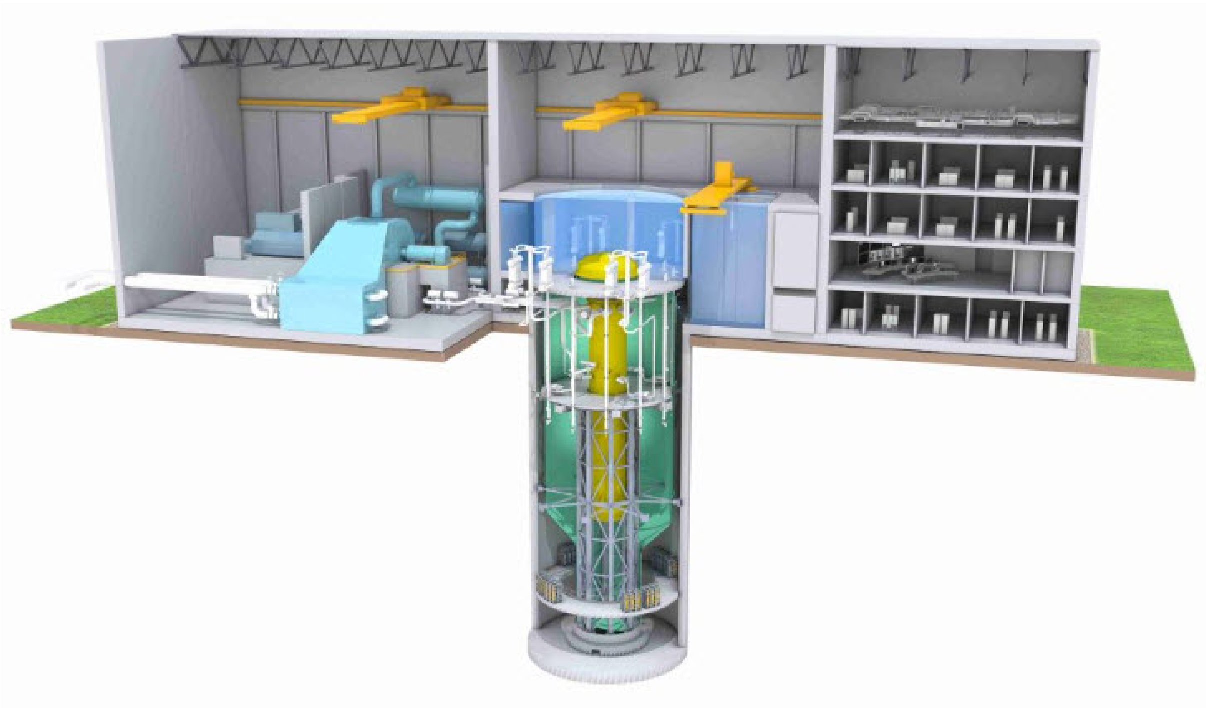

Figure 2. Example of BWRX-300 Small Modular Reactor [52].

Miroshnychenko [46] indicated that SMRs will produce three to four times less energy than conventional ones and will be affordable for underdeveloped countries. In addition, their low cost will make it possible to replace large nuclear power plant reactors that with ending their service life [45].

Dybach and Plachkov described several potential advantages of SMR [13]:

1) higher protection of SMR from undue external influences of natural and artificial nature (possibility of underground placement of the reactor installation). Figure 3 shows this placement of Canada's first SMR;
2) high level of internal self-protection and wide use of passive systems. It allows reviewing (reducing) a set of technological systems necessary for safety, operating in standby mode;
3) modular principle ensures serial production, the possibility of complete factory production of the module and its delivery to the NPP site;
4) operation in power tracking mode (power shift) allows combining SMR with other renewable energy sources.

Figure 3. Example of underground placement of SMR [53].

SMRs can find applications in many areas of nuclear energy use. The steady development of SMRs was revealed as a result of the analysis of the current trends in the development of atomic energy. Currently, the most developed type is LWR installations with pressurized water among the existing SMR projects. Steam generators are one of the main elements of them. The preferred design is a functional-flow steam generator with functional body movement in tubes with coiled surfaces [14].

OECD [11] indicated that worldwide policy-making bodies, enterprises of the nuclear sector, and energy analysts show growing interest in the potential of SMR as a competitive element of low-carbon technologies used in integrated energy systems of the future. In addition, SMRs embody hopes for inherent safety, simplification, and standardization properties. All of this can significantly facilitate and make nuclear power more cost-effective.

SMRs can be placed directly in energy consumption centers. It eliminates the need for external power lines and maintenance in difficult climatic and terrain conditions. Significant reduction in network infrastructure costs allows for increased efficiency and competitiveness of SMR technologies [54].

Gaspar [55] emphasizes that SMRs are smaller and use innovative technologies with many built-in safety features. An important element of their design is minimizing accidents and radioactive emissions. A similar opinion was expressed by Zhou [14]: "SMR possess better safety characteristics and lower amount of radioactive materials (less potential for radioactive release); it is expected that iodine prophylaxis, shelter, evacuation will not be needed to protect public from the SMR".

Considering SMR according to various criteria characterizing their advantages, we will describe the "safety" criteria and its indicators based on [11]:

- reducing the level the severity of emergency modes (a combination of increased levels of simplification and structural integrity is expressed in a smaller number of emergency modes);
- efficiency of passive safety systems (need for active systems decreases, which in the long run simplifies safety assessment, reduces the number of emergency modes, and improves the reactor cooling mode using natural circulation. All this contributes to increasing the time provided for emergency response);
- reduced protective zone outside the site (less need for shielding means and a smaller area of the zone for planning protective measures).

Table 1, table 2 and table 3 compares SMR and high-power reactors according to the criteria "Operational safety," "Infrastructure," and "Personnel resources." This tables was compiled based on publications [6, 12, 54, 55] and open sources.

Ukraine promised to abandon coal burning by 2035. Consequently, the number of thermal power plants will decrease over the years, and domestic energy will gradually lose 30% of its capacity. The decline of thermal power plants will stimulate the development of nuclear power plants and renewable energy facilities. The problem is that 13 out of 15 reactors will become unusable by 2040. Therefore, fourteen power units should be built in the coming decades for the energy transition and replacement of old reactors. Three should be located at the Khmelnytskyi

Table 1. Comparison of SMR and high-power reactors ("Operational safety" criterion).

Indicators	SMR	High-power reactors
Physical safety	Possibility of hidden placement underground, underwater on the territory of military bases, etc. There needs to be more infrastructure, personnel, and length of heating lines.	Risks associated with the extensive infrastructure and territory of the station.
Energy security, infrastructure risks	Integration into the local power system. Flexibility to build up generating capacity. Low distance to the consumers.	Extensive network and consumer life support system risks.
Nuclear and radiation safety	Reduction of the risks and magnitude of caused damage. Absence of "serious accident" consequences.	Probabilistic methods estimate them.
Energy stability	There are no power unit stops due to common causes.	However, the power unit stop occurred due to familiar grounds.
Human factor	We make technical decisions on modularity, quality, and reliability – a minimum number of personnel, a personnel training system, and a department management structure.	The high number of personnel at all stages of the object's life cycle and workshop management structure.

Table 2. Comparison of SMR and high-power reactors ("Infrastructure" criterion).

Indicators	SMR	High-power reactors
Reliable energy supply	Organization of ensuring effective navigation of transit and sea routes, military facilities, etc.	Limited. It is possible with a developed structure of energy networks.
Technical competencies and infrastructure development	Development of competencies within the territory's economy. An educational center, scientific and technological complex, prospective studies of habitats. I am stopping the outflow and employment of the population, particularly the youth.	We were limited by the technology of the power unit (electricity production).
The wide contour of energy conversion and tariff stability	Electricity, heat, fresh water, steam, and hydrogen are modules for the region's infrastructure needs and a reliable life support system.	Limited to electricity production only.
Creation and provision of reliable hybrid energy systems	Ensuring stability, reliability, and quality of the energy carrier, design of hybrid energy systems in local areas, a wide range of capacity changes, and creation and development of industrial nuclear-hydrogen energy.	
Insurance	It is possible for various infrastructure objects.	Not available in its entirety.

NPP, one at the Zaporizhzhya, Rivne, and South Ukrainian NPPs, and eight at new stations. SE "NAEK "Enerhoatom" signed a memorandum with the American company Westinghouse which will participate in constructing five power units worth about 25 billion dollars. Cooperation with Westinghouse SE "NAEK "Enerhoatom" is positive. It is believed that Ukrainian specialists have enough experience to build power units [46].

The first energy cooperatives appeared in Ukraine: several community members united to provide themselves with energy resources. This practice is widespread worldwide, especially in the USA and Germany. In these countries, the total number is calculated in hundreds and thousands, and they unite millions of people. For example, in Germany, 47% of solar energy is produced by citizens and cooperatives. Energy cooperatives are common in Great Britain, Australia, the Netherlands, and Denmark. A Cooperative is also cheaper to administer than a joint-stock company or an investment fund. The primary meaning of energy cooperative for citizens is not to expect mercy from the state or industry monopolies in solving energy supply problems but to develop their energy businesses and earn money independently [45].

The country's energy security and the possibility of further digital transformation of the economy will be endangered if Ukraine does not have time to replace the existing NPP units with new ones during 2040-2050. Also, a significant share of the country's human capital will be lost. Nuclear energy is a high-tech industry and requires specialists with a high level of training in various scientific fields. The "nuclear energy knowledge of Ukrainian specialists" can be classified as a national strategic resource. Therefore, at the state level, it is necessary to develop and implement programs to preserve and transfer nuclear technological knowledge as a resource that will determine Ukraine's political and economic realities shortly [2].

Activities on analyzing prospects for the introduction of SMR technology in Ukraine were also

Table 3. Comparison of SMR and high-power reactors ("Personnel resource" criterion).

Indicators	SMR	High-power reactors
An alternative approach to reloading nuclear fuel	The zone is active for 10-15 years. Filling together with a radioactive installation at notable enterprises. Absence of dose loads on personnel.	Reload every two years. Availability of spent nuclear fuel and radioactive waste infrastructure. Radioactive waste removal. Dose load.
Risks at the decommissioning stage	Large modular dismantling. Reducing the likelihood of exposure to personnel at risk.	Large modular disassembling. They are reducing exposure probability to personnel.
Environmental safety	Local energy system transformation into an ecologically clean system. Significant reduction of emissions (liquid, solid, gaseous) and oxygen combustion. Reduction of environmental consequences.	Placement and assignment restrictions.
Application of waste-free technologies	Development of unavailable resources. Deep processing of minerals, water desalination, waste disposal, etc.	Limitation by purpose.
Social acceptance.	Possibility of visual proof of increased security.	Psychological barriers (after the Chornobyl and Fukushima accidents).

started: working cooperation with potential SMR suppliers (NuScale Power) was established, and work on studying the technical and economic aspects of these reactors is ongoing. In addition, SE "NAEK "Enerhoatom" and "Holtec International" signed a "Memorandum of Understanding" on cooperation in the use of SMR-160 in Ukraine (figure 4).

The work of Demianiuk [12] contains a generalization of SMR safety indicators: frequency of damage to the active zone, the frequency of early/significant release, and the size of the emergency planning zone. In addition, a combination of SMR and renewable energy sources is considered.

Niearonov et al [6] emphasized that using SMR in Ukraine is the most promising direction for developing nuclear energy in Ukraine. At the same time, it is necessary to conduct additional research on determining the optimal ratio of SMR and PWR reactor technologies, considering prospects for deploying renewable energy sources. Priority measures for SMR implementation in Ukraine are described [12]:

1) in-depth strategic analysis of the United Energy System of Ukraine according to international methods (IAEA, OECD);
2) detailing needs of the United Energy System of Ukraine in balancing (maneuvering) capacities and developing technical requirements for SMR;
3) execution of preliminary technical and economic substantiation of SMR construction;
4) development of optimal financial models for the implementation of SMR projects in Ukraine based on public and private partnership.

It is essential to take into account the following aspects [6] during the comparative evaluation of reactor technologies:

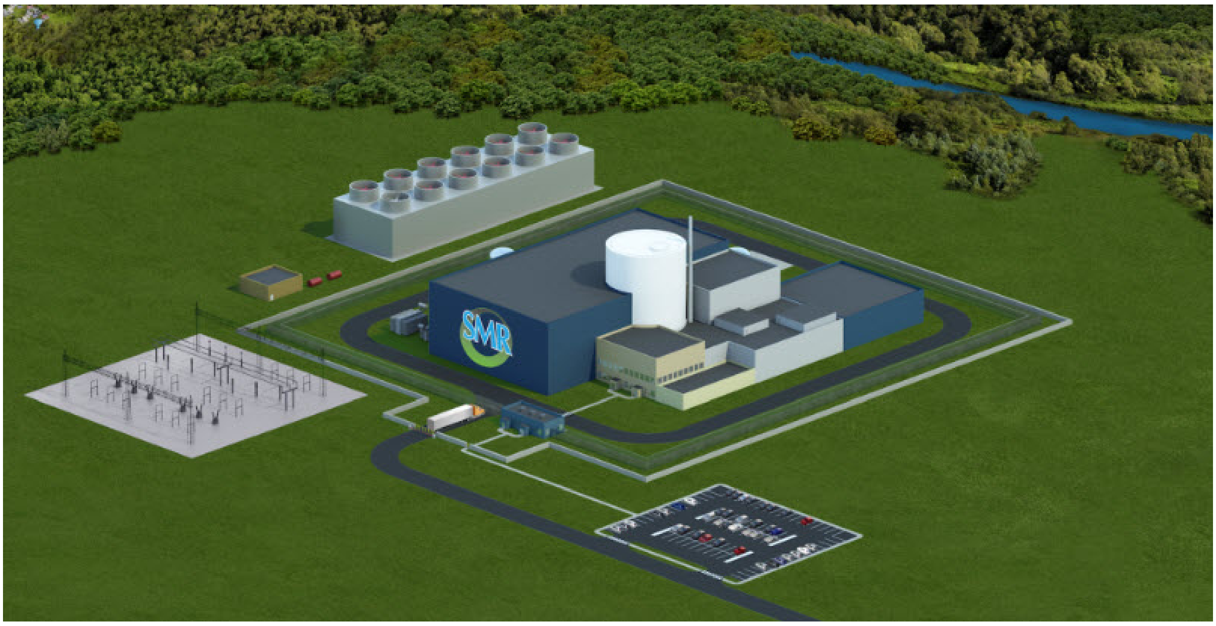

Figure 4. Holtec SMR-160, a 160 MW Electric Nuclear Power Plant [56].

- compliance of reactor technology with international safety standards, criteria of IAEA, WENRA3, EUR4, and comparability with requirements of regulatory documentation of Ukraine on nuclear and radiation safety;
- economy, reliability, the possibility of NPP power units operating in different modes;
- involvement of NPP power units in ensuring conditions of reliable functioning of the unified energy system of Ukraine;
- the possibility of reliable provision of nuclear fuel taking into account own uranium reserves, diversification of suppliers and manufacturers;
- ensuring a non-propagation regime by the legislation and international obligations of Ukraine;
- the possibility of serial construction, further operational support of power units, and production localization of their systems and components.

We agree with the opinion of Vyshnevskyi and Mykytenko [2] that it is impossible to give absolute priority to SMR construction to meet the needs and conditions of functioning of the nuclear energy industry of Ukraine. It is essential to stimulate the entrepreneurial initiative of businesses with the necessary technology and capital. The state's role should remain leading and adequately respond to the existing risks related to the main aspects of private nuclear energy: safe operation of nuclear facilities, countering propagation of atomic weapons, and disposal of nuclear waste.

4. Author contributions

The research results provided in the publication are presented in the aggregate of the joint contribution of individual authors:

- **Oleksandr O. Popov**:
  - Idea and preparation of the draft article.
  - Organization of the authoring team's work and task assignment for article preparation.

  - Analysis and synthesis of global trends in nuclear energy development.
  - Description of the advantages of small modular reactors (SMR) compared to large reactors.
  - Justification of the possibilities of small modular reactors construction in Ukraine considering their environmental friendliness and safety.
  - Formulation of article conclusions.
- **Anna V. Iatsyshyn**:
  - Justification of the research relevance and article project preparation.
  - Analysis of scientific publications and websites of international organizations dealing with nuclear energy issues.
  - Analysis of literature sources on the training and qualification improvement of specialists in the energy sector.
  - Identification of important aspects regarding the specialized training of personnel for SMR operation and maintenance.
  - Substantiation of the possibilities of small modular reactors construction in Ukraine considering their environmental friendliness and safety.
  - Formulation of article conclusions.
- **Maryna A. Deineha**:
  - Analysis of literature sources on the operation of nuclear fuel cycle facilities.
  - Examination of how different countries' views on atomic energy have evolved, the results of the analysis are grouped by continents and countries (Poland, Germany, Spain, France, Slovakia, Great Britain, China, South Korea, Japan, Indian, United Arab Emirates, Turkey).
- **Tamara S. Novak**:
  - Analyzed state documents on the regulation of nuclear energy issues in Ukraine.
  - Reviewed how the views of different countries on nuclear energy have evolved. The results of the analysis are grouped by continents and countries.
  - Conducted a comparison of SMRs and large-scale reactors based on the criteria of "operational safety," "infrastructure," and "human resources" using scientific publications and open sources.
- **Dmytro V. Taraduda**:
  - Analyzed materials from international organizations (International Project on Innovative Nuclear Reactors, International Atomic Energy Agency, Nuclear Energy Agency, etc.).
  - Conducted a comparison between SMRs and large-scale reactors based on the criteria of "operational safety," "infrastructure," and "human resources" using scientific publications and open sources.

5. Conclusions

We analyzed scientific publications and websites of international organizations dealing with nuclear energy issues and concluded that nuclear energy is again in trend. Also, the attitude of governments of different countries of the world to atomic energy was considered. It was determined that China and India are the leaders in developing nuclear power.

Global trends regarding the development of the nuclear power industry were considered as a result of the research. They include an extension of the operating life of nuclear power units; the development of atomic energy in the context of the Paris Agreement; the development of nuclear-hydrogen energy; synergistic interaction of renewable energy sources and nuclear power plants; introduction of new reactor technologies.

SMRs are considered transformative reactors that will contribute to the further development of nuclear energy globally. The advantages of SMR compared to high-power reactors include lower time and financial costs for construction and implementation; significant potential for maneuvering energy capacities; higher safety indicators for the environment and personnel; quick response to the needs of the energy market; synergy with renewable energy sources and increasing their efficiency within the framework of a hybrid energy system, etc.

At the same time, SMRs are still under discussion regarding the feasibility of such construction. Only a few countries started their construction. Another vital aspect is the special training of personnel to manage and maintain the SMR.

Military operations on the territory of Ukraine since the beginning of 2022 have confirmed the importance and expediency of the construction of SMR to ensure the energy needs of the state and opportunities for post-war reconstruction and restoration of various sectors of the economy. At the same time, Ukraine's tragic experience with the accident at the Chornobyl NPP requires ensuring environmental safety [57]. Therefore, it uses safe, energy- and resource-saving, low- and zero-waste technologies. Also, preference should be given to light-water (evolutionary) SMR projects. Their technical solutions use the accumulated experience of operation and safety analysis of operational NPPs with VVER. Furthermore, SMRs that can already be installed at the active sites of the NPPs of Ukraine should be chosen. Such actions will contribute to the reduction of financial costs for the construction of SMR and contribute to the sustainable development of the nuclear energy industry of Ukraine.

Therefore, the construction of SMR on the territory of Ukraine will make it possible to reach a new level of development of nuclear energy, ensure a faster transition to the digital economy, and contribute to occupying a key position among countries in the modern atomic energy world space.

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