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Assessing the Role and Viability of Nuclear Power in Ukraine's Post-War Energy Strategy

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Abstract
Ukraine's nuclear power industry is partially under russian occupation, which poses a significant energy threat. This applies to both Ukraine and European countries. Nuclear power plants in Ukraine operate on imported uranium. The article analyses trends in the development of nuclear energy in the world and in Ukraine. The energy system of Ukraine depends on imported uranium. The article presents an assessment of the exhaustibility of uranium resource. Steps to improve the safety of nuclear energy are presented and the necessity of transition to green energy is substantiated. The problems of atomic energy of Ukraine in conditions of sustainable development are analysed.

Keywords: energy, uranium, resource exhaustibility, energy strategy, nuclear power plants

1. Introduction

In recent years, the world has been experiencing a downward trend in nuclear energy consumption. According to IAEA estimates, the share of nuclear power will remain between 12.4% and 14.4% of global energy production until 2030. As of 2023, more than 30 countries produce nuclear electricity. Their share in the total global balance is 15%. The decline in the use of nuclear power is primarily due to the high level of danger and lack of environmental friendliness.

However, the United States, France, Finland, and a number of Asian countries (China, India) have decided to build new nuclear power units. This is primarily due to the rise in global oil and gas prices, the need to strengthen the country's energy security, reduce greenhouse gas emissions, etc. Moreover, recent years have shown their prospects due to Russia's political and military manipulation of energy resources.

For Ukraine, nuclear power is cheaper. The country has a network of reactors (however, due to Russia's terrorist attacks, the largest of them has not been operating normally since 2022).

Domestic nuclear power accounts for 55% of consumption. A possible way to develop hydrogen energy is to use nuclear power for electrolysis to produce hydrogen. Renewable energy in Ukraine accounts for 7% of the total. However, Ukraine has no fossil reserves of uranium enriched enough to be used.

Previously (before the Russian war), a significant share of it was exported from Russia. After the military events, the country will face a choice of developing renewable energy,

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which requires considerable time and investment, or investing in the nuclear industry and gradually switching to renewable sources. At the same time, the fact of exhaustibility of resources (uranium depletion time) should also be taken into account.
The main goal is to forecast the development and assess the prospects of investing in the nuclear industry in Ukraine.
One of the main tasks for Ukraine's economic policy in the post-war period to restore the national economy and the country as a whole will be to ensure highly efficient functioning of its energy sector.
It is clear that the issue of energy supply is significantly relevant to the resource crisis, as the exhaustion of energy resources promotes energy saving and diversification of energy production, including by increasing the share of nuclear energy in Ukraine's energy balance.
The aim of the article is to analyse trends in the development of nuclear energy in the world and Ukraine, to assess problems and threats to the development of nuclear energy in Ukraine, to assess the exhaustibility of uranium, to substantiate the necessity of transition to green energy.

2. Previous research

President of the Academy of Sciences of Ukraine Borys Paton, who was its president for 60 years. He promoted the nuclear energy complex and paid little attention to renewable energy. His achievements were incorporated into the development strategy of the National Academy of Sciences of Ukraine. Therefore, most of the scientific developments were related to the support and development of nuclear energy (Paton, etc. 2006).
The future of the national nuclear power industry should be considered in the context of the development of this industry in the world and the need to create nuclear technologies of the XXI century. Recently, European countries, having recovered from the post-Chornobyl shock, have begun to critically rethink their refusal to develop nuclear power. This is driven not only by the inevitability of exhausting hydrocarbon resources (a distant prospect), but also by rising gas and oil prices and the need to diversify energy sources. zirconium is produced, structural steels are smelted, uranium is mined, a powerful pipe industry has been established, control equipment is being developed, and turbines adapted for use at nuclear power plants are being manufactured.
Scientists are working to create the physical foundations of reactor materials science, and radiation physics is successfully developing. Secondly, the existing international system of prohibiting the proliferation of nuclear technologies and materials divides the world into nuclear and non-nuclear states, the latter being controlled consumers of nuclear energy. Today, the international community is concerned about the possibility of unauthorised proliferation of these materials and technologies for the production of nuclear weapons" (Paton, etc. 2006).
Zhou Sh., Zhang X. define the priority of nuclear energy in China "At present, China's energy supply is dominated by coal consumption, and natural gas and oil are in relative shortage. At the same time, nuclear power is a relatively clean form of energy with no greenhouse gas emissions. Given the rising cost of fossil fuels and limited resources in

China, the security of oil supply, coal mining disasters, domestic environmental pressure and global climate warming, nuclear power is an inevitable strategic choice" (Zhou, etc. 2010).

The problematics of nuclear power itself has been observed for the last 70 years (Hubbert, 1956). Hubbert M.K. discussed this issue in his research (Hubbert, 1956).

Besir Kok, Hüseyin Ben investigated the impact of nuclear and renewable energy utilisation on the economic growth of Turkey. Turkey's electricity sources are mainly thermal, renewable. It has been proved that nuclear power generation in Turkey will significantly reduce the dependence on energy imports (Kok, etc. 2017).

Most scientists were in favor of further growth of the nuclear complex. The reason is the cheapness and better availability of nuclear energy. However, uranium reserves are depleted and in the future it is necessary to develop renewable energy.

Some scientists have recognised the possibilities of raising the level of environmental friendliness of the use of atomic energy. Koning A.J., Rochman D. proposed a method of transferring uncertainties of fundamental nuclear-physical models and parameters to the design and operating parameters of future environmentally friendly nuclear power systems, which will increase the environmental friendliness of nuclear energy use (Koning, etc. 2008).

Nicholas Apergis, James E. Payne, Kojo Menyah, Yemane Wolde-Rufael investigate the causal relationship between CO_2 emissions, nuclear energy consumption, renewable energy consumption, and economic growth for a panel of 19 developed and developing countries for the period 1984-2008 using a panel error correction model. Long-term estimates show that there is a statistically significant negative relationship between nuclear energy consumption and emissions, but a statistically significant positive relationship between emissions and renewable energy consumption (Apergis, etc. 2010).

Some of the stations are not reliable and have some problems. The energy security problem facing energy-importing countries is equally daunting (Hedenus et al., 2010). The concentration of energy sources in the volatile region of the Middle East involves risks for many countries in terms of the reliability of the supply of energy (Apergis, etc. 2010, Gnansounou, etc. 2008). Energy security and environmental challenges are forcing many countries to find energy alternatives to fossil fuels. Both renewable and nuclear energy sources are believed to provide some solutions to the problems of energy security and environmental degradation. Consequently, many countries have made investments in nuclear and renewable energy as a means to reduce dependence on imported oil, increase the supply of secure energy, minimise the price volatility associated with imported fossil fuels, and reduce greenhouse gas emissions (Toth, etc. 2006).

Countries are choosing the energy mix and decarbonisation strategies that best suit their national circumstances.For example, nuclear power remains an important part of the low-carbon energy mix in many countries, including Bulgaria, Finland, France, France, Hungary, Romania, russia, Slovenia, Turkey and Turkey, with nuclear capacity increasing in some places. It is clear that the impact of hydrogen has grown significantly since last year's Issues Monitor, as it is seen as a solution for certain hard-to-reach sectors such as sectors such as high-temperature industrial processes. The adoption of the EU Hydrogen Strategy this year, as well as specific hydrogen strategies in many countries including Germany, the Netherlands, Portugal and Spain, illustrate the growing interest in hydrogen potential. The tipping point The tipping point of hydrogen innovation will require finding economic applications where scaling up and creating a scaling up and creating a market is essential. International cooperation is key to both of these processes, as well as to initiatives to create "hydrogen highways" in different countries. hydrogen highways" in different countries, potentially extending to North Africa, are under development (Association "Ukrainian Nuclear Forum", 2021, World Energy. Issues Monitor, 2021, Humanising Energy, 2024).

The world has not developed a unified approach to the development of nuclear energy and the transition to renewable sources. Each country is working out its own approach to building an energy system, taking into account the concept of climate change and the hazards of nuclear power. But the decisive factor is the cheap price of nuclear power. During the recovery period, Ukraine must work out a new concept for the development of the energy sector with a gradual transition to renewable sources. However, due to the significant share of nuclear power, it is advisable to keep the nuclear component, but to calculate the period of exhaustion of uranium sources.

3. Materials and methods

To analyse the prospects, we propose a model of the dynamics of exhaustion of limited resources. The dynamic model for calculating the depletion of a certain limited resource (resourcing) was proposed in 1956. Its developer was K. Hubbert. (Hubbert, 1956).

He showed the following: for a given geographical area (a single field, an entire planetary field), the graph of the production rate U(t) of a given resource in period t should have a bell-shaped bell-shaped graph.

Production first increases rapidly, then reaches a peak (maximum) Umax at some time tmax and then decreases until the resource is finally exhaustion of the resource. US oil production did indeed peak in 1972.

Hubbert's prediction was broadly fulfilled, and his work has since been widely recognized widespread recognition. The disadvantages of model include the symmetry of the U(t) curve, its divergence from the current value of production with strong volatility of past data (Hubbert, 1956). At the beginning of time t = 0 we choose the present moment from which we need to make a forecast moment from which it is necessary to make a forecast. Previous production will correspond to negative values, while future production will be positive. The total amount of the given resource still remaining in the subsoil, we denote by Max (Hubbert, 1956).

The model used in this paper makes three assumptions about the smoothed production characteristics: - the equation of the remaining resource (t is greater or equal to zero)

$$Max = \int_0^\infty U(t)dt \tag{1}$$

- the rate of change of extraction dU/dt (proportional to the level of extraction.
Accordingly, it is received:

$$dU/dt = c(t)*U(t), \tag{2}$$

where the coefficient c(t) – trend production rate, it depends on time (sometimes is called resource utilisation efficiency, because the higher value c(t), the higher rate of production is growing similarly);
- the production rates decrease with forecasting

$$c(t) = c0 * (1 – t/tmax), \quad (3)$$

where c0 – the rate at the beginning of the forecasting period (at t = 0), rather than at the beginning of resource development (Hubbert, 1956). The level of production c0 at the beginning of the forecasting period reflects the existing demand for this mineral. it also indicates the amount of investment in future production. As a result, the analytical expression for the dynamics of resource production takes the form of a Gaussian curve located to the right of the point t = 0

$$U(t \geq 0) = Umax* \exp[c0*tmax*(1 – t/ tmax)^2/2]. \quad (4)$$

The relationship between the peak production volume (per year) UM, its initial value U0= U (at zero t), c0, tmax of maximum production is determined by the expressions

$$Umax = U0 * \exp(c0*tmax/2) \text{ or } tmax=2*k0–1ln(Umax/ U0). \quad (5)$$

Substituting (7-8) into the balance equation gives the connection between c0, tmax, Umax, which establish dynamics, U (the amount of extractable fossil resource remaining in the subsurface):

$$U = Umax\ tmax\varrho(\varepsilon). \quad (6)$$

By introducing a dimensionless parameter ε, ϱ(ε) looks like this (Hubbert, 1956)

$$\varepsilon = \sqrt{\frac{k_0 * t_{max}}{2}} = \sqrt{ln \frac{U_{max}}{U_0}};\ \varrho(\varepsilon) = \sqrt{\pi} * \frac{1+U(\varepsilon)}{2*\varepsilon};\ U(\varepsilon) = \frac{2}{\sqrt{\pi}} \int_0^{\varepsilon} \exp(-z^2)\, dz \quad (7)$$

This function has following increment monotonically from «0» to «1» as ε increases from «0» to ∞ (Hubbert, 1956, Ul'yanin, Yu. A., 2018).
For the purpose of practical application of the dynamical model, the main results are presented (4) - (7), «3» values are required.
Option C is convenient at what time the initial extraction rate c0 is known (or set), i.e. M, U0 and c0 are known. If the initial level of production is not determined, it can be estimated by averaging over several years preceding the forecasting period, taking into account the volatility of production. Given the known values of c0, U0, the dimensionless complex c0 M/U0 is determined. From the transcendental equation, we will calculate the dimensionless parameter ε (Hubbert, 1956).

$$c_0 * \frac{Max}{U_0} = \rho_c(\varepsilon); \quad \rho_c(\varepsilon) = 2\rho(\varepsilon) * \varepsilon^2 \exp(\varepsilon^2) = \sqrt{\pi}(1 + U(\varepsilon) * \varepsilon * \exp(\varepsilon^2); \quad (8)$$

accordingly, the necessary parameters to obtain the maximum production volume

$$\mathrm{U}U_{max} = U_0 \exp(\varepsilon^2); \quad t_{max} = 2 * \varepsilon^2 / c_0. \quad (9)$$

Variant G is convenient when the limitation on the value of GM production peak is known, the value is 〖 ε = (ln(U_max/U_0))〗 1/2. The other estimated parameters c_0, t_max, characterising the forecast of dynamics, calculate by:

$$t_{max} = \mathrm{M}/(U_{max}\varrho(\varepsilon)); \qquad c_0 = 2\varepsilon 2/t_{max}. \quad (10)$$

An analysis of uranium deposits in Ukraine has revealed a sufficient level of security. As of January 1, 2024, uranium reserves and resources that can be obtained at a cost of up to 260$/kg amounted to 185,389 tU (Moroz, 2024).

With production costs of up to 80$/kg, U is 71,841 tU. This price level includes the cost of uranium ore mining and enrichment. There are two main types of deposits of economic interest in Ukraine (Moroz, 2024): metasomatite and sandstone types.

Metasomatite deposits are located within the Ingulsky block of the Ukrainian crystalline shield. The uranium ores consist of albite veins with complex morphology, ranging in thickness from 2-3 m to 50 m. Ore minerals of uranium ores are represented by uraninite, coffinite, and branerite. The uranium content in the ore is 0.1-0.2%. Deposits of this type are developed by underground mining. Deposits of this type include Novokonstantinovskoye, Michurinskoye, Central, Vatutinskoye, Severynivskoye, Zhovtorichenskoye, Pervomayskoye, and others (Moroz, 2024).

Sandstone deposits are located within the Dnipro-Bug metallogenic zone. This type of deposits includes industrial deposits, which are confined to coal-bearing deposits of the Buchach Formation and occur at depths of up to 70-90 m. The ore deposits consist of separate ore bodies of stratiform and lenticular shape with a thickness of 3-10 m. Uranium in ore bodies is contained mainly in coal and clay substances: uranium-bearing leucoxene and iron hydroxides, sulfides, usually accompanied by uranium black (marcasite, pyrite, melnikovite, sphalerite, bravoite, etc.). The uranium content in the ore is 0.02-0.06%. In addition to uranium, these ores contain molybdenum, selenium and rare earth elements of the lanthanide group. Deposits of this type are developed by underground leaching. This type of deposits includes: Sadove, Bratske, Safonivske, Devladivske, Novohurivske, Surske, etc. (Moroz, 2024).

Other types of domestic uranium deposits are still classified in Ukraine as non-industrial in terms of the scale of mineralization, mining, and other indicators (Moroz, 2024). Forecasting uranium production in Ukraine is impossible due to military operations in almost all areas of explored deposits.

4. Results and discussion

Since the end of the coal era in the 1950s, oil has become the dominant resource, but against a backdrop of significant growth in consumption of both coal and natural gas. Recently, renewable energy has grown so much in terms of production that it has become a competitor to nuclear power. In the future, consumption of natural gas (up to 193 exajoules, or 4,617 million tonnes of oil equivalent) and renewable energy (115 exajoules, or 2,748 million tonnes of oil equivalent) is expected to grow rapidly. According to forecasts, in 2040, the consumption of primary energy resources (PER) in total will reach 748 exajoules (1766 mtoe), which is 25% more than in 2019.4 In specific terms, the consumption of fuel and energy resources has grown non-linearly over time. While in 1990, the annual specific value was about 64 GJ per 1 person, in 2019 it was almost 76 GJ, i.e., this figure has increased by about 1.2 times in 30 years.

The energy intensity of global GDP has been decreasing nonlinearly, from 6.7 to 4.5 MJ/USD at purchasing power parity in constant 2017 prices.

The total volume of energy generation is 28,520 Terawatt hours. Nuclear power accounts for 10% of the global balance (Fig. 1) (Nuclear Power in the World Today, 2024).

The uses of nuclear technology extend well beyond the provision of low-carbon energy. It helps control the spread of disease, assists doctors in their diagnosis and treatment of patients, and powersour most ambitious missions to explore space. These varied us esposition nuclear technologies at the heart of the world's efforts to achieve sustainable development (Nuclear Power in the World Today, 2024). Moreover, Ukraine ranks 7th in terms of nuclear power generation in the world. Ukraine has 15 operable nuclear reactors, with a combined netcapacity of 13.1 GWe. In 2022, nuclear generated an estimated 58.7 TWh of electricity (Nuclear Power in the World Today, 2024).

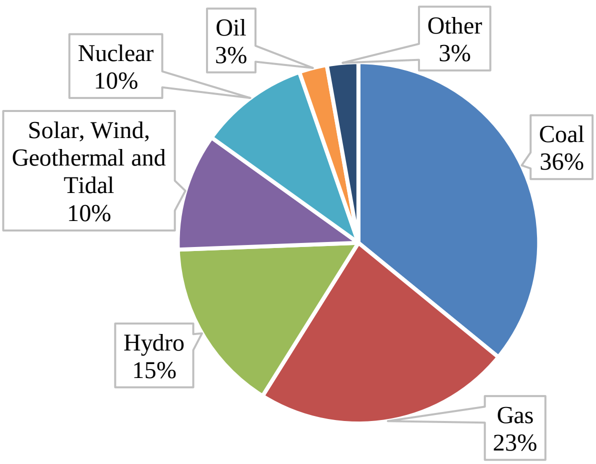

Figure 1. Structure of energy production in the world as of 2023.
Source: built on (Nuclear Power in the World Today, 2024).

According to the World Nuclear Association (Balat, 2007) (Fig. 2), as of 1 January 2024, there are 220 nuclear power plants with 440 power units with a total electric capacity of about 396269 GW in operation in the world, including 99 reactors in the United States, 58 in France, 46 in China, 42 in Japan, 36 in russia, 24 in South Korea, and 15 in Ukraine and the United Kingdom (Nuclear Power in the World Today, 2024).

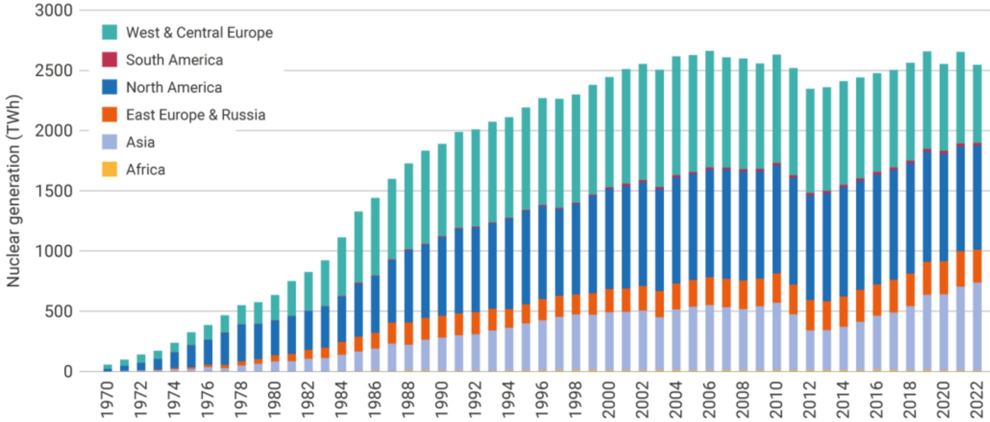

Figure 2. Nuclear power generation in the world by continent
Source: built on (Nuclear Power in the World Today, 2024).

60 power units are under construction, and another 214 are closed (Nuclear Power in the World Today, 2024). Nuclear energy is produced in 50 countries.

5. Global trends in the development of nuclear power

As for Ukraine, according to NPC Ukrenergo, as of the beginning of 2024, the total installed capacity of the IPS of Ukraine was 56.169 GW, of which 49.7% were thermal power plants (TPPs, CHPs, block stations), 24.6% were nuclear power plants (NPPs), 11.2% were hydroelectric power plants and pumped storage power plants, and 14.3% were RES power plants (Small Modular Reactors, UWEA Annual Report "Wind Energy Sector of Ukraine 2021. Market Overview", 2021).

Thus, in the near future, Ukraine, as well as other leading countries in the industry, will face the task of developing and implementing innovations that can meet the criteria of environmental friendliness, efficiency and safety of nuclear energy use.

Ukrainian nuclear energy should be guided by the global development of this sector (Sinovets, 2022).

One of the main trends is the gradual replacement of traditional high-capacity nuclear reactors with modular low-capacity reactors and improvement of design reactors. Combating the proliferation of nuclear materials and technologies has become a powerful economic and geopolitical tool (Table 1).

It should be noted that, unlike solar/wind energy, surf energy, etc., nuclear energy plants operate continuously (non-stop). Nuclear power plants also require much less land area (compared to solar and wind power) per megawatt generated. As for the other type of hydropower (this type has reached its maximum capacity in most developed countries, including the United States), nuclear power plants will not require the use of environmentally hazardous dams.

Table 1: Global trends in the development of innovative activities in the nuclear power sector

Countries - initiators	Prospects for introduction, implementation of innovations	Innovative solutions	Significance and prospects for application in the nuclear power industry of Ukraine
Argentina, China, USA	Gradual replacement of traditional high-capacity nuclear reactors with small modular reactors	There are about 50 SMR projects and concepts in the world that are at different stages of development	Extremely important in the context of terrorist destruction and destruction of ZNPP and other energy infrastructure by russia
USA (the company Westinghouse Electric Company LLC.)	EnCore's fuel and fuel cladding improvement programme	The EnCore product line is capable of providing severe accident resistance, improved fuel cycle economy, and more	Important in the context of war and rocket attacks on the Ukrainian energy structure
USA (project of the companies ExelonGeneration та ORNL)	Improving modelling of boiling water reactor (BWR) designs	Implementation of the project announced in 2018 will improve the performance of the reactors	Potentially important in view of the experience of leading countries
USA (General Atomics)	Project on fusion research at the DIII-D tokamak for detailed study of fusion plasma properties	It will help in the future operation of the international thermonuclear reactor ITER. In 2018, a reactor modernisation programme was launched to improve ITER management and increase capacity	

Source: compiled by the authors based on (Association "Ukrainian Nuclear Forum", 2021, Bredikhina, 2022).

On the one hand, nuclear power plants emit almost no CO_2 and are fully compliant with the carbon neutrality policy. On the other hand, they produce hazardous nuclear waste, and the risk of accidents still makes people distrust even high-tech reactors.

Most leading economies are interested in the independence energy of all democracies. Nuclear energy plays an important role in the fight against catastrophic climate change, decarbonization of economies, etc. And nuclear power plants will become a highly efficient source for reliable and uninterrupted energy supply. Unlike other fossil resources (coal/natural gas, oil, etc.), nuclear power plants do not produce direct carbon dioxide emissions (polluting the environment) when generating energy. This has also contributed to the reduction of CO_2 emissions by almost sixty gigatons over the past fifty years.

The European Parliament has recognized nuclear energy as a “green” energy. This means that this type of energy is classified as a type that will help the global community prevent climate catastrophe and will shape and continue stable economic development. This action demonstrates a turnaround in energy policy and will contribute to further growth of investments in nuclear energy.

The European Union has yet to make a final decision on the status of nuclear energy.

At the same time, on the other side of the world, India and China are actively investing in quotpeaceful nuclear powerquot. These countries, along with others, have pledged to reduce CO_2 emissions and plan to do so through the development of nuclear power.

China plans to build 150 reactors with a capacity of 147 GW in 15 years and $440 billion. This is more than has been built in the world since 1986 (Popov, etc. 2023).

The country had ambitious nuclear plans many years ago, but the Fukushima Daiichi accident forced a moratorium on new projects. Now, China is ready to build a large number of nuclear power plants and 30 reactors abroad, competing with Russia, France and the United States in this market.

India plans to launch nine reactors in three years. The construction of 12 more was approved in 2020. This is the first time a nuclear power plant is being built on such a scale in the country.

The United States has also decided to return to active development of the industry. The number of operating reactors in the US peaked in the nineties. Since then, more of them have been shut down than new ones have been built. However, the US government now sees the development of nuclear power plants as part of the fight against climate change.

Avoiding catastrophe: how the world will save the Earth from overheating. According to the Glasgow outcome, the US will allocate $1.85 billion to support the industry in 2022, which is 23% more than in 2021. Another $6 billion will be spent on extending the term (Popov, etc. 2023).

To further develop Ukraine's nuclear power industry, its energy strategy should include the construction of new modular NPP units with evolutionary reactors with increased safety and economic attractiveness.

6. Trends in the Ukrainian nuclear complex

Ukraine, although it possesses key nuclear technologies, materials and a developed nuclear power industry, is a conventionally nuclear-weapon state, as it has no industry for isotope separation, uranium enrichment or fuel production. It has surrendered its nuclear weapons and pledged not to produce them. For these reasons, the development of nuclear energy in Ukraine today is realistic only in close cooperation with the leading nuclear powers (Osadcha, etc. 2024).

Having analysed the dynamics of Ukrainian nuclear energy production in throughout 2007-2022 (thousand tonnes of oil equivalent), we can state a tendency of decreasing consumption since 2014 (Fig. 3).

It is clear that in 2023-2024, the volume of nuclear energy production in Ukraine will decrease significantly due to the destruction of nuclear power plants by Russian invaders. Given the IAEA's complete disregard for Russia's war crimes in the nuclear energy sector and their impunity, in particular at the largest nuclear power plant among European countries (Zaporizhzhya NPP), the likelihood of further terrorist attacks at Ukraine's nuclear power plants is growing significantly. This significantly increases the risk of energy security on the continent.

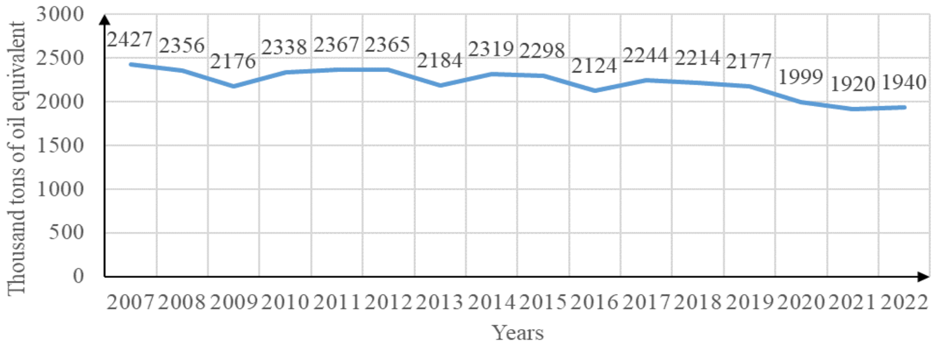

Figure 3. Nuclear energy production in Ukraine in 2007-2022 (thousand tonnes of oil equivalent)
Source: (Official website of the State Statistics Service of Ukraine, 2024)

Considering the prospects for the development of nuclear energy in Ukraine, one should take into account the peculiarities of the country's nuclear status. First, nuclear power and industry are not self-sufficient (there is no closed fuel cycle, no organizations that fully develop, design and build nuclear reactors). Therefore, Ukraine is still using reactor technologies, fuel and spent nuclear fuel reprocessing facilities from other countries.

There are 15 nuclear reactors in operation in Ukraine, which account for about half of electricity generation.

Nuclear generation, which provides basic electricity production in the country, is represented by 4 nuclear power plants with a total capacity of 13,835 GW, consisting of 15 power units. As of the end of 2021, 12 power units have already reached the end of their normal 30-year lifetime, so their operation has already been extended for the next 10-20 years. However, by 2030 (inclusive), the already "extended" operating licences for 10 power units with a total capacity of 9,420 MW will expire.

In addition, one more power unit with a capacity of 1,000 MW will reach the end of its 30-year lifetime in 2026. Thus, SE NNEGC Energoatom will have to re-extend the lifetime of the existing power units after their designated service life is exhausted, which will have relevant man-made threats.

The composition of the enterprises that make up the nuclear industrial complex of Ukraine can be presented as follows (Table 2).

The structural elements of the Ukrainian nuclear energy sector are the National Energy Generating Company Energoatom, including separate subdivisions, the nuclear industrial complex (Table 2), which includes the Eastern Mining, Processing Plant, the State Enterprise Smoly, and research-design institutes.

Ukraine's nuclear industrial complex includes uranium mining, which creates the basis for meeting the uranium needs of nuclear power plants in the long term; zirconium mining to establish its industrial production (the main structural material in the manufacture of fuel assemblies for nuclear power plants), given its unique physical properties and rather insignificant interaction with neutron fluxes in reactor cores; production of ion exchange materials and their supply.

Table 2: Main enterprises of the nuclear industry of Ukraine and their activity profiles

Companies names	Profiles
State Concern Nuclear Fuel	Specializes in the production of zirconium, uranium
SE Vostochny Ore Mining, Processing Plant	Mining of uranium, production of its oxide concentrate
SE Smoly	Production, sale of ionised materials and full supply of uranium production in Ukraine
SE Ukrainian Research and Development Institute of Industrial Technology	Design, scientific support of the nuclear fuel cycle and production
Organizations and enterprises that support the activities of the key nuclear power units, provide their maintenance, including all components of the energy and industrial complex, including nuclear power	

Source: built on (Bredikhina, 2022)

However, seven of these reactors were disconnected from the grid as a result of the conflict to keep them cool (as a result of the military conflict). Therefore, the key is the end of the war and Ukraine's victory. Only then can we talk about the prospects for investing in the country's nuclear energy sector.

Existing nuclear power units should be decommissioned as they reach the end of their service life. However, there are difficulties with "young" nuclear power plants, as Ukraine remains heavily dependent on nuclear fuel supplies from the Russian Federation, which still meets more than 50% of the needs of Ukrainian nuclear power plants. Electricity imports from the Republic of Belarus and the Russian Federation, which have periodically exceeded 1 GW of capacity since the beginning of 2021, pose a threat to the country's energy security, leading to a decrease in electricity production by domestic enterprises. In general, the fuel and energy sector does not use innovations and new technologies. Today, this sector of the economy (as well as many others) is also experiencing a significant shortage of personnel. First of all, we are talking about highly qualified personnel. The situation is deteriorating due to the increase in labor migration caused by the war. The ability of Ukrainian companies to provide design, commissioning, and maintenance services for fuel and energy companies of all forms of ownership is declining. Some enterprises of the fuel and energy sector, including coal mines and some thermal, nuclear and renewable power plants, are located in the occupied (russian-occupied) territories. Continued operation of such enterprises or violation of their closure regulations increases the risk of man-made disasters. The growth in electricity production from renewable energy sources, as stated in the Energy Security Strategy, was accompanied by compensating measures to increase the flexibility of the Integrated Power System of Ukraine. Ukraine does not have sufficient energy storage capacities to cover possible peak loads. As for the generation of electricity from renewable energy sources, in recent years there has been a rapid development of solar energy production. Due to the war, this process has, of course, stopped. However, despite all its advantages, solar power generation is characterized by a significant level of instability.

In recent years, many steps have been taken to develop and build nuclear power plants and replace nuclear fuel from Russia. For example, Westinghouse Electric Company and NNEGC Energoatom signed a contract under which Westinghouse will provide the necessary technical information to update NNEGC Energoatom's feasibility study for the construction of two AP1000 reactors at the Khmelnytsky Nuclear Power Plant (NPP) in Ukraine. This effort advances the previously signed agreement between the companies to build AP1000 units at KhNPP Units 5 and 6, start the licensing process and further develop Ukraine's clean energy initiatives.
An important point on the way to transforming the nuclear energy industry is the creation of a closed nuclear fuel cycle in Ukraine, which will ensure guaranteed independence of nuclear power plants from imported nuclear fuel and reduce the state's need to purchase it. The closed cycle involves reprocessing and reuse of spent nuclear fuel. Ukraine does not reprocess spent nuclear fuel, but sends it to Russia for reprocessing. Due to the positive dynamics of changes in the innovative development of nuclear energy, the state can get rid of the status of "the only country in the world with developed nuclear energy that does not have its own spent fuel storage facility".
At a meeting on 29 December 2021, the Cabinet of Ministers of Ukraine approved the Concept of the State Targeted Economic Programme for the Development of the Nuclear Industry for the period up to 2026 (Order of the Cabinet of Ministers of Ukraine, 2021). The main goal of this concept is to create conditions for increasing uranium production to fully meet the needs of the domestic nuclear power industry, as well as to increase Ukraine's energy independence (Order of the Cabinet of Ministers of Ukraine, 2021).
The concept envisages, in particular (Order of the Cabinet of Ministers of Ukraine, 2021):
- increase in uranium production and reduction of production costs through the development of Novokonstantinovskoye and Aprelskoye deposits with the construction of new uranium facilities in 2023-2025 and their commissioning in 2026;
- ensuring the operation of the Smolinsky mine until 2023 and the Ingulsky mine until 2028;
- reconstruction of the hydrometallurgical plant and sulphuric acid shop of the Eastern Mining and Processing Plant;
- technical re-equipment and creation of 320 tonnes of zirconium dioxide production capacity per year;
- providing design and information support for uranium and zirconium production [16].
In addition, it is planned to organise cooperation on the integration of zirconium dioxide produced in Ukraine into the production of zirconium alloys and rolled zirconium products at foreign producers of nuclear fuel for Ukrainian nuclear power plants [16].
The concept was developed pursuant to the NSDC decision of 29 January 2021 "On Measures to Neutralise the Threat in the Field of Nuclear Energy and Industry" [16].
It is clear that all strategic areas of development have been significantly affected by military events. Diversification of fuel, increasing its own base is the third of these areas. Ukraine needs to continue its fuel diversification course, reducing the risks of using fuel supplied from Russia. Ukraine's mineral resources, technological base make it possible to increase its own uranium production. The qualitative development of the nuclear industry is impossible without similar development of the system of radioactive waste and spent nuclear fuel management.It should be noted that the source of uranium is exhaustible and

will not exist for some time. Let us see the calculations based on the provided methodology of resource exhaustion.

According to the 2022 data, U0 = 62,00 ktU was mined, which is slightly below the NPP demand of 63,40 ktU per year (Nuclear Power in the World Today, 2024). Since 1990, uranium production has been lagging behind the demand of nuclear power plants..

The uranium deficit was compensated for by using existing reserves and secondary (other) sources, which have been significantly reduced. In 2022, the known recoverable natural uranium resources at a cost price of less than $260/kg U were about 7.6 Mt (million tonnes), which together with the remaining stockpiles (about 0.2 - 0.54 Mt (Nuclear Power in the World Today, 2024) give an the maximum estimate of M ≈ 8.10 Mt. Moreover, 61.00% of traditional uranium resources in nature are concentrated in only 4 nations: Australia, Kazakhstan, Russia, Canada. Ukraine owns 2.30% of the world's reserves.

To forecast energy production at conventional NPPs, it is advisable to use the third expression. Under the condition that q is 424 GW/kg. The dependence of the demand for natural uranium on the period is determined by formula (3).

As follows from Table 3 for the accepted initial data, the peak of nuclear energy production (42 EJ per year) innovative thermal reactors are expected to 2052.

It should be noted that there is a general tendency in the world to increase the use of energy resources (Fig. 4).

For comparison, the structure of energy consumption in the world (Wróbel, etc., 2020) is shown (Fig. 4).

Table 3^ Parameters of traditional resources dynamics in the XXI century according to the proposed model

Production parameters	Uranium	Oil	Coal	Gas
Resources thousand EJ	3.40	10.40	23.40	7.30
Initial rate in 2017 % year	2.50	1.10	2.50	2.40
Production in 2021 EJ/year	26.90	206.00	153.00	138.00
Period depletion, years	128	51	153	53
Maximum annual production volumes Gm, EJ	42	214	259	159
Years of maximum production	2052	2024	2059	2029

Source: (World Energy. Issues Monitor, 2021, Hubbert, 1956)

At present, the share of nuclear energy in the global fuel balance is still insignificant. However, according to forecasts, the contribution of nuclear energy in primary sources will be constantly growing until 2100. The reason is that other traditional fossil energy resources will be depleted faster than uranium.

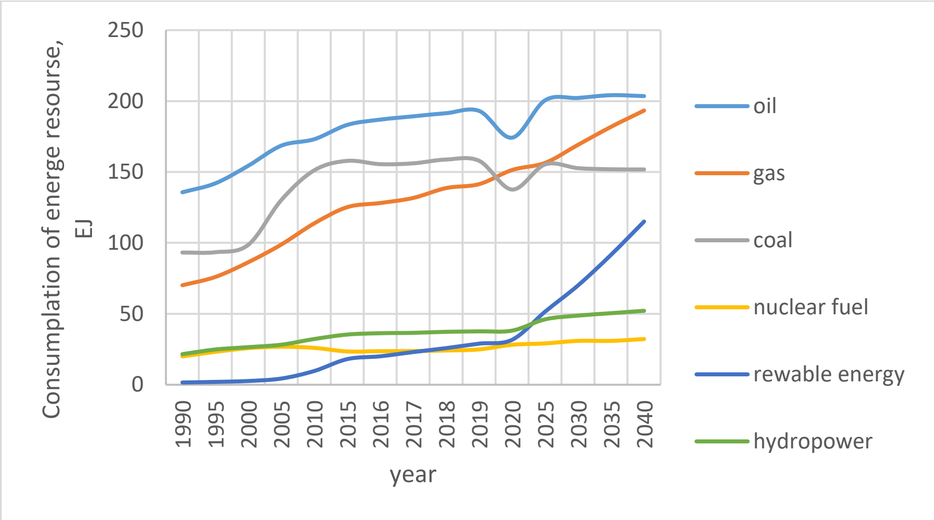

Fig 4. Dynamics of Ukraine's resource supply structure
Source: (Osadcha, etc. 2024).

Uranium is a virgin resource. That is why it is logical for Ukraine to switch to green energy sources after the war. But the first step is to invest in nuclear energy. To move from the trend of uranium use to renewable energy sources. It will take some time.

The topical issue of the state (level) of nuclear energy safety in Ukraine in extreme conditions concerns the situation at the largest nuclear power plant (NPP) in Europe, Zaporizhzhia NPP, due to the location of the plant in the combat zone and difficulties in operating and managing the plant, as well as regulating its safety in the occupied territory. The NPP is located directly in the combat zone. The location of ZNPP in the temporarily occupied territory causes objective difficulties in its operation, management and safety regulation. Therefore, a reasonable assessment of the ZNPP safety status in terms of the probability of nuclear and radiation accidents is an extremely important issue. However, its solution, unfortunately, lies not in the economic plane, but in the military plane and can be solved through the use of all possible levers of international relations.

During 2022-2024, russia grossly violated all 7 principles of nuclear and radiation safety and continues its nuclear terrorism by shelling energy infrastructure facilities that are connected to nuclear power plants in a single energy system.

With regard to risk management and contingency plans for Ukraine's nuclear power industry, especially in the context of current and future geopolitical tensions, the government adopted the Procedure for Managing the Risks of Technological Emergencies and Fires in 2023.

In 2023, more than 20 countries supported the COP28 Declaration on tripling nuclear power capacity by 2050, recognizing the key role of nuclear power in achieving global zero greenhouse gas emissions. The document was adopted at the UN Climate Change Conference (COP28).

With regard to risk management, the parties to the declaration pledged to take internal measures to ensure responsible operation of nuclear power plants and compliance with the highest standards of safety, sustainability and non-proliferation, as well as responsible management of spent nuclear fuel over the long term.

According to the State Statistics Committee and the Ministry of Economy, electricity from nuclear generation is not the cheapest. The weighted average cost on the day-ahead market in 2021 is UAH 1,869.7 per MWh.

At the same time, electricity from hydroelectric power plants (Dnipro Cascade and Dniester) is the cheapest, with a market price of UAH 1437.5 per MWh. It should not be forgotten that this price includes the cost of transmission and dispatching services of the transmission system operator (NPC Ukrenergo).

In addition, the state (SE 'Guaranteed Buyer') buys up to 50% of the generated electricity from NPPs and HPPs at a price of 1-15 kopecks per kWh to cover the costs of the population and 'hold off' on tariff increases.

The most expensive of the classical power generation is TPPs and CHPs. At some CHPPs, the cost of 1 MWh is UAH 2417.2 (Odesa CHPP). At coal-fired TPPs, the cost of electricity is somewhat lower, but with a shortage of coal, the use of natural gas as an energy source doubles the cost of electricity produced. That is why in February 2021, we saw an 'emergency' repair of 9 power units of the country's largest TPPs, which were pushed beyond the profitability limit due to a lack of coal. And the end consumer (i.e., each of us) could not pay for the pleasure of switching from coal to gas at a critical time for the power system.

Of course, when using renewable energy technologies (primarily solar energy), the state stimulates the green transition in the form of a high feed-in tariff, which for SPPs commissioned by the end of 2020 is UAH 4372.9/MWh (excluding VAT). However, for new SPPs with a capacity of more than 1 MW, the 'holiday' ends on 1 April 2021 with a 60% reduction in the tariff to UAH 1749.16, which is lower than the market value of nuclear generation. If a new nuclear power plant is being built, the average cost of electricity it supplies to the market is USD 0.063 per kWh, or UAH 1795.5 per MWh.

As you can see, this is higher than the new tariff for green energy produced by solar power plants.

An alternative to nuclear power is green energy, the development of which is encouraged by most countries.

Ukraine has no other chance to build its own energy independence, as the capacities of NPPs and TPPs/CHPs are already outdated and worn out, and public and private energy companies will not be able to invest their own funds (due to lack of resources). Green energy accounts for 9 per cent of Ukraine's energy balance. The transition to green energy will take a long period of time, but it is advisable to make this transition.

7. Conclusions

In the process of development of nuclear energy, the primary task is to ensure safety in the use of nuclear energy and to develop measures to extend the lifetime of NPP units, and therefore it is necessary to determine further actions for the development of the nuclear industry.

Public attitudes toward nuclear power varied at different stages of development. Initially (during the Russian occupation in 1918-1991), it met with virtually no opposition from the

Ukrainian population: it was believed that nuclear power plants would open the way to “clean” electricity, as the negative environmental impact of fossil fuel combustion products was obvious. Indeed, by the mid-1980s, nuclear power had made a confident start in rapidly replacing expensive mineral fuels, primarily coal and oil (Lir, 2017).

However, evidence was gradually accumulating that showed deteriorating radiation conditions around nuclear power plants, shortcomings in their operation, and accidents that were initially concealed (Lir, 2017).

In the minds of many people, nuclear energy is associated with nuclear weapons, and this fact reinforced negative attitudes toward it.The Chernobyl nuclear power plant disaster in 1986 triggered a strong negative reaction to nuclear power around the world (Lir, 2017).

The scientific community responded to the negative reaction of public opinion by developing the concept of nuclear reactors with inherent safety.In fact, the groundwork was prepared for the implementation of the so-called “nuclear renaissance” concept.

However, its implementation will take decades, so the resumption of rapid growth of nuclear energy can be expected after 2030, and it is hoped that this will happen, among other things, using other physical principles.

There are many factors that hinder the development of nuclear energy in Ukraine, but the most important is the public's unwillingness to accept nuclear energy.

In Ukraine, due to the prolonged concealment of the truth about the Chornobyl disaster, the population overestimated the real danger of nuclear power plants, which caused a natural negative attitude of a significant part of the public to nuclear energy (Lir, 2017).

The political motives of some parties and movements that tried to gain popularity among the population in this way played a major role here.

But since the early 2000s, and especially since 2022, the situation has changed. And public opinion has become not only more tolerant of nuclear energy, but society has begun to understand that nuclear energy is a condition, strange as it may seem, for the security and future development of their own regions. This applies primarily to Ukraine, which, having been dependent for centuries on the racist energy yoke, will finally be able to gain true energy independence, including through the active development of nuclear energy.

For Ukraine, the construction of new high-capacity nuclear power plants in the coming decades will be limited by financial capabilities, as there is uncertainty about the country's economic development. A more optimistic forecast of investment capital participation is available for small nuclear power. There is a growing global interest in small and medium-sized reactors (up to 300 MW), which are called small modular reactors (SMR).

Analysis of the development of nuclear energy in recent decades has shown the following key issues: safety of operation of operating nuclear power plants; predominance of second-generation reactors at NPPs in most countries developing nuclear energy; approaching end of planned lifetime of most reactors in use and the need for their extension; spent nuclear fuel disposal; priority development of renewable energy, which may lead to a decrease in the capacity utilisation rate of NPPs and earlier.

Uranium is an exhaustible resource and will eventually disappear. It is necessary to diversify risks and invest in green energy

In view of the above, the primary need for the countries representing the industry is to ensure energy security; develop innovative nuclear reactors and fuel cycles; comply with global norms and standards; reduce CO_2 emissions into the environment; comply with environmental harmonisation; improve energy efficiency, etc.

For comparison, electricity from nuclear generation is not the cheapest. The weighted average cost on the day-ahead market in 2022 was UAH 1869.7 per MWh, while the cost of hydropower was UAH 1437.5 per MWh, and from April 1, 2021, the renewable energy tariff was reduced to UAH 1749.16, which is lower than the market cost of nuclear generation. However, 90% of Ukraine's wind power capacity and more than 35% of solar power capacity were destroyed due to the Russian invasion. Therefore, it is difficult to unequivocally point to the advantage of using renewable energy. First of all, it is necessary to restore its capacity.

The key advantage of using nuclear technologies is that they do not require large areas for deployment and, together with renewable energy sources, contribute to the decarbonization of not only the energy sector but also other carbon-intensive sectors of the economy.

It is also important to note that the refusal of one country to produce nuclear energy will not mean that the market, the nearest neighbors, etc. will refuse energy. Therefore, this step does not reduce the danger, which is global in the case of a nuclear power plant accident. We have seen such examples in the Chornobyl accident, the Fukushima nuclear power plant (and now the potential danger at the Zaporizhzhia nuclear power plant, with the IAEA's weak response to war crimes). And among the global trends today is the increase in safety of existing reactors, as well as the development of new technologies, such as Small Modular Reactors (SMR), which are even safer.

The events that occurred in Ukraine in early 2014, especially in early 2022, have dramatically changed the situation in the energy supply system. An important element in the formation of Ukraine's energy strategy is a comparative analysis of the costs, benefits, and feasibility of using renewable energy compared to nuclear energy in the context of Ukraine's recovery. But today it is difficult to do so because a significant share of renewable energy generating capacity was destroyed by the treacherous Russians. The same problem applies to nuclear power because of the occupation of the largest nuclear power plant in Europe (Zaporizhzhya).

The only way out of this situation is to liberate the treacherously seized territories and actively restore all types of energy capacities. The energy situation in Ukraine today is extremely difficult. Power outages last up to 14 hours a day.

Ukraine's energy system is experiencing the largest-scale attacks by the enemy in 2024. Therefore, the number one issue today is to strengthen the energy security and independence of our country.

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