

The Russian nuclear industry

during wartime,
2022 and early 2023

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Foreword

Bellona is an ecological non-governmental organization founded in 1986 after the Chernobyl disaster. The founders of Bellona state that this disaster motivated them to create an ecological protest group in prosperous Norway. Bellona's work with nuclear issues in Russia initially concerned nuclear tests on Novaya Zemlya and their consequences, as well as the hazardous state of nuclear sites on the Kola Peninsula. In 1992, to protest nuclear testing, Bellona sent a ship to the Soviet atomic testing ground on Novaya Zemlya. The ecologists' ship with the banner "stop the nuclear threat from Russia" was permitted to enter waters by the Novaya Zemlya nuclear testing ground, and enter the port of Murmansk. This was a gesture of openness, and a sign that Russia intended to put an end to nuclear testing and rectify the consequences of the Cold War in the Arctic region, as well as pursue a policy of glasnost (for more detail about Bellona's atomic project see <https://bellona-atom.tilda.ws/>).

Since 1992, Bellona has prepared analytical reports concerning its work on nuclear issues. From 1994 to the present, Bellona has prepared and published over 30 major reports and documents on this topic. Additionally, the Bellona website has published hundreds of related articles by journalists, experts and activists.

In 2004, Bellona published the report "The Russian Atomic Industry – the need for reforms"¹.

This was the first major survey in which Bellona used its capabilities and resources to examine the state of the Russian nuclear industrial complex, new tendencies of Russia nuclear policy, as well as to analyze work on programs of international cooperation on

¹ https://bellona.ru/publication/red_report_rus/

nuclear and radiation safety that emerged at that time. The main reason for preparing this report was to provide the public with information about the state of the nuclear sphere in Russia and matters relating to it. Many questions lacked clear, well-founded and convincing answers. The leadership of the nation had changed, the country's economy and the nuclear sphere were not in the best condition, and transformations were taking place in governmental and government-related structures. Minatom (the Atomic Ministry), the successor to the gigantic and influential Minsredmash (the Ministry of Medium Machinery) of the USSR, was reduced to the status of a federal agency after restructuring, and held one of the lowest positions in the structure of the Russian government. The restructuring also affected state nuclear supervision, which caused additional alarm and uncertainty among the public over changes restricting the rights and capabilities of an organization which controlled the nuclear safety of nuclear facilities.

These structural transformations which took place from top to bottom at all levels, along with economic difficulties, the insufficient and incomplete legislative base concerning the atomic industry, the complex nuclear legacy of the Cold War and the recent memory of the Chernobyl disaster, caused wide concern among the entire international community. The traditional secrecy of the Russian state, and of its nuclear sector in particular, increased this concern. The international community was prepared to cooperate and finance many programs, expecting that this help to shed light on issues of nuclear and radiation safety in Russia, and provide an understanding of the situation

In preparing its report in 2004, Bellona took the position that it was impossible not to criticize the state of the nuclear sector in Russia. But it was just as important to offer proposals and initiate projects to reduce nuclear and radiation danger, and support public initiatives and discussions of what needed to be done to eliminate a potential nuclear radiation threat. Bellona adhered to this position throughout the period of its activity, until 24 February 2022, when its work in Russia was suspended.

Introduction

In preparing the report “The Russian atomic industry and the need for reforms”, Bellona, noting the “twilight” that Minatom was experiencing at the time, asked a question – did this “twilight” proceed the sunset, as the anti-atomic community predicted, or was there a different fate in store for Minatom²?

The nuclear industry of any country, its conditions, safety and development strongly depend on the political decisions of the leadership, the country’s economy, as well as the state’s place in the international system of coordinates, and on the global situation.

Since late 2005, when Minatom came under new management, the nuclear industry of Russia has undergone an eventful path in its political, economic and functional development. Minatom began to transform into a state holding which now brings together around 360 enterprises and organizations, including scientific institutes, organizations of the nuclear weapons complex and the fleet of nuclear icebreakers.

In this report, we present a survey of Russia’s atomic sector at the present time, i.e. late 2022 and early 2023. The authors try to take into account the challenges that have emerged recently as a consequence of Russia’s full-scale war with Ukraine, the international sanctions placed on Russia, the new global economic and climactic situation, as well as express their opinion on possible future prospects for the Russian nuclear industry.

² https://bellona.ru/publication/red_report_rus/p.27

Chapter 1. ***The place of the “Rosatom” state corporation (hereinafter Rosatom) in the state structure of Russia.***

This chapter gives a brief description of Rosatom and its place in the state structure of the Russian Federation, as well as information about the system of managing the atomic department and its enterprises. The main data on the structure of Rosatom management given in Chapter 1 applies to early 2022. However, it should be remembered that Rosatom develops quite swiftly and transforms itself, and new tasks emerge, along with new management structures to solve these tasks. Here we provide information on the main organizational units of Rosatom, their composition and areas of responsibility. The chapter also provides a survey of the main scientific and educational institutes which are not part of the structure of Rosatom, but with which enterprises of Rosatom constantly work.

Chapter 2. ***The nuclear fuel cycle.*** A survey of the state of Rosatom’s assets in the nuclear fuel cycle – production, conversion, enrichment and fabrication of nuclear fuel, with assessments of existing facilities and production indicators of all elements of supply, technological developments and areas of development of the sector.

Chapter 3. ***“Energy, research and transport reactors”.*** Descriptions and specifications of reactors used at nuclear power plants of various modifications and constructions. An analysis of the condition of power units of nuclear power plants which are in operation, under construction and which are being phased out of operation.

Chapter 4. ***Projects of the Russian nuclear industry abroad.*** Data on Russian projects for building nuclear power plants abroad, the role of Rosatom in international supplies of the nuclear fuel cycle, scientific and educational projects.

Chapter 5. ***Economic, ecological and social components in the activity of Rosatom.*** This chapter provides a survey of current projects of Rosatom for solving ecological and social issues. Data on economic and social indicators in the atomic sector in recent years.

Chapter 6. ***How the nuclear industry functions in a state of war and under international sanctions.*** A brief survey of the restrictions and international sanctions which have affected the activity and realization of domestic and foreign projects of Rosatom, as well as Rosatom’s involvement in international institutions and programs.

Chapter I.

The structure of Russia's nuclear sector

The place of the State corporation Rosatom in the state structure of Russia.

In a nation with nuclear weapons, the atomic department is primarily a political institution with its own specifics, which not only addresses energy and economic issues, but also fundamental issues of state security, as it is responsible for the creation of nuclear weapons.

In late 2005, Sergei Kiriyenko was appointed the head of the federal agency Rosatom, a relatively young but experienced manager and politician, who had worked for almost five years in the administration of the current Russian president, holding the position of authorized representative of the president in the Volga federal district. This was a person of the new administrative and political system created by President Putin, with experience of working in the previous structure under Yeltsin.

In 2007, Rosatom was converted into a state corporation by legal form, i.e. it became a non-commercial organization, with its sole founder being the Russian Federation. At the same time, a law was passed on the Rosatom state corporation, determining that it was created for pursuing state policy in the field of using nuclear energy for peaceful and military purposes. Thus, ultimately Rosatom became a very powerful business company, privatizing the assets of the atomic sector and partially of other sectors with important state functions.

At present, Rosatom has consolidated all assets of the nuclear industry of around 360 enterprises and organizations, employing a total of approximately 289,000 people. Rosatom is formally not part of the structure of any government ministry, and formally under the jurisdiction of one deputy prime minister. The head of Rosatom is appointed (and dismissed) by the Russian president.

Rosatom is practically one of the three state political and economic “bastions” (along with the oil and gas sector and the weapons industry state corporation Rostekh) that form the basis of the country’s security and economy, and its foreign and domestic policy. The weapons manufactured by Rostekh are Russia’s main technological export, with its foreign turnover amounting to US\$15 billion in 2021. The foreign turnover of Rosatom for the same period was \$9 billion, and for the oil and gas sector around \$240 billion.

It should also be noted that the present management system of Rosatom is organized in such a way that it is essentially managed by the presidential administration, as the advisory board that is the highest body of management of Rosatom is headed by one of Putin’s most entrusted representatives at present, the first deputy head of the presidential administration Sergei Kiriyenko – that is to say that today, Rosatom is practically part of the administrative office of the Russian president.

1.1. Management of the nuclear sector

The highest body of management of Rosatom is the supervisory board³.

The supervisory board approves Rosatom strategy, long-term programs, the financial plan, the procedure for investments in Russian and foreign organizations and other important decisions, as well as appoints the board of Rosatom and makes a work agreement with the general director. Members and the chairman of the supervisory board are appointed by the Russian president.

The collegial executive body of Rosatom is the management board⁴.

The board includes the general director of Rosatom, his deputies, the director for state policy and several heads of major divisions of Rosatom. Members of the Rosatom board are appointed and dismissed by decision of the supervisory board on the suggestion of the general director.

The board develops projects, programs, and financial plans of Rosatom for the long term, approves the list of projects financed by special reserve funds of Rosatom, and approves the procedure for directing part of profit, the annual accounting report of Rosatom organizations, along with other responsibilities.

The head of the activity of Rosatom and its executive body is the general director, who has four first deputies and nine other deputies. The general director is appointed by decree of the Russian president. Since October 2016, A.E. Likhachev has held this position⁵.

³ <https://rosatom.ru/about/management/supervisoryboard/>

⁴ <https://rosatom.ru/about/management/board/>

⁵ <https://rosatom.ru/about/management/director/>

The structure of the civil section of Rosatom is based on the principle of a divisional model. The division is the organizational unit, which unites enterprises and organizations of Rosatom by certain types of activity and areas of business, and carries out operational management of organizations. The civil structure of Rosatom has seven main business divisions – Mining, Fuel, Machine Building, Electricity, Engineering, “Ecological Solutions” as well as “Sale and trading”.

The structure of Rosatom also includes a number of incubating businesses and sector functional organizations, which include various enterprises of the atomic sector depending on their types of activity.

Additionally, there are several directorates which manage (coordinate) several important areas – the directorate of the nuclear weapons complex (coordinates and manages enterprises of the nuclear weapons complex) and the directorate of the Northern Sea Route (coordinates and manages the nuclear fleet and other organizations of the Northern Sea Route).

The first deputies and other deputies of the general director are usually heads or coordinates (curators) of the main divisions and sections.

In this structure, the leadership, subordination and coordination of management of separate organizations and enterprises of Rosatom appear quite complex. Often, the functions of management and coordination are duplicated, so many enterprises and organizations are in dual or even triple subordination. This takes place because the same enterprise may carry out various works and projects which concern various areas of activity of Rosatom, for example Mayak is the executor of projects and work for the nuclear weapons complex, Atomenergoprom, the “ecological solutions” division and others.

Additionally, the structure of the central apparatus of Rosatom has a number of separate but important departments and directorates which are usually linked to one deputy of the general director. Primarily, these are structural divisions such as the department of communications, the department for work with regions, the department of nuclear and radiation safety, licensing and permission activity, the department of international cooperation, the department of internal control and auditing, the department of personnel management and a number of others.

Rosatom assets, scientific and educational institutions

As noted above, Rosatom is a multi-faceted holding that owns assets and competences in all links of the production and technological chain of atomic energy: geological surveying and uranium mining, conversion and enrichment of uranium, fabrication of nuclear fuel, planning and construction of nuclear power plants, machine building, generating electricity, decommissioning nuclear facilities, and treatment of used nuclear fuel and radioactive waste.

Additionally, at present Rosatom is also responsible for the manufacture of innovative nuclear and non-nuclear production, carrying out scientific studies, development of the northern sea route and ecological projects, including eco-technoparks and a state system for treating hazardous industrial waste.

Recently, Rosatom has been actively developing new areas of business, such as wind energy, nuclear medicine, prospective materials and technologies, digital products, infrastructural solutions, additive technologies and energy accumulators, automated control systems and electronics, ecological solutions and other fields.

1.2. Mining division

The mining division of Rosatom (managing company Atomredmetzoloto) manages uranium mining assets located in the Zabaikalsky Krai (PPGKhO), the Republic of Buryatia (Khiagda), the Kurgan Oblast (Dalur), as well as owns and manages uranium mines abroad through other divisions.

Additionally, the ARMZ uranium holding includes planning enterprises – the First mining company (Pavlovskoe project), Elkonsky GMR, AO Lunnoe, AO UDK Gornoe.

The enterprises that service the activity of the mining division include organizations for the production of heating and electricity, sulfuric acid, mining equipment (PPGKhO), as well as organizations carrying out drilling and geological surveying (RUSBURMASH), engineering and scientific studies (AO VNIPIpromtekhnologii).

Besides uranium production, the Mining division also develops fields of business not relating to uranium, including the additional mining of scandium (AO Dalur), coal mining (PPGKhO), planning a production complex on the basis of the Pavlovsky lead and zinc mine (Novaya Zemlya archipelago), projects for developing the gold mines of Elkonsky GMK (Republic of Sakha/Yakutia) and several others^{6,7}.

1.3. Fuel division

The fuel division of Rosatom (managing company AO TVEL) is the only supplier of nuclear fuel for reactors of various purpose working in Russia, as well as for several reactors working abroad. According to TVEL data, the company supplies fuel for research reactors to 9 countries worldwide⁸ and provides nuclear fuel for 75 energy reactors⁹, i.e. almost every sixth reactor for NPPs worldwide out of the 422 operating as of late 2022¹⁰.

⁶ https://www.report.rosatom.ru/go/rosatom/go_rosatom_2021/rosatom_2021_ru.pdf

⁷ *Annual report of the mining division of Rosatom for 2021*

⁸ <https://tvel.ru/activity/nuclear-products/nuclear-fuel/fuel-for-research-reactors/>

⁹ *Rosatom annual report for 2021*

¹⁰ <https://pris.iaea.org/pris/>

According to Bellona data, of these 75 reactors, 37 are located at NPPs in Russia, and 38 of them are located in 11 countries (see section 4.3 for more detail) – in Czechia, Slovakia, Hungary, Bulgaria, Finland, Belarus, Armenia, Iran, India, China and Ukraine. However, since 2022 Ukraine has completely ceased deliveries of Russian nuclear fuel¹¹.

The fuel division also provides a wide spectrum of non-nuclear production and services for such areas as metallurgy, chemistry, machine building, additive technologies and energy accumulators. Rosatom believes that the optimal organizational format for developing the non-nuclear business for the fuel division is the creation of sector integrators.

Table 1. Assets of the fuel division

Separation and sublimate complex (uranium enrichment and conversion)	
Angarsk electrolysis chemical combine (AO AEKHK) Angarsk, Irkutsk Oblast	Enterprise for the manufacture of uranium hexafluoride, used for nuclear fuel of atomic energy stations, actively develops perspective fields for new types of production.
Electrochemical factory (AO PO EKHz) Zelenogorsk closed city, Krasnodar Krai	The factory produces low-enriched uranium, stable and radioactive isotopes of various chemical elements, carries out storage and treatment of depleted uranium hexafluoride, also obtaining hydrofluoric acid and anhydrous hydrogen fluoride, as well as a number of other high-technology goods.
Siberian chemical combine (SKhK) ZATO Seversk closed city, Tomsk Oblast	The production core of SKhK is four factories for treatment of nuclear materials: a plant for the separation of isotopes, and sublimate, radiochemical, and chemical metallurgic plants. The SKhK facility realizes a strategic project for Roastom, Proryk ("Breakthrough").
Urals electrochemical combine (UEKhK) Novouralsk closed city, Sverdlovsk Oblast	Major enterprise for uranium enrichment. 48% of the separating facilities of Russia. On the basis of the combine, a center for uranium enrichment was created – a joint enterprise with NAK Kazatomprom
Complex for fabrication of nuclear fuel	
Machine building factory (AO MCZ) Elektrostal, Moscow Oblast	Factory for production of nuclear fuel for nuclear power stations and ship reactor systems. Additionally, the enterprise carries out preparation of special packaging containers for the transport of nuclear fuel, production of non-standard equipment and gear.
Novosibirsk factory of chemical concentrates (PAO NZKhK) Novosibirsk	The factory specializes in the fabrication of fuel cannisters for VVER-1000 reactors, PWR reactors of foreign design, as well as for experimental reactors in Russia and abroad. NZKhK is also a manufacturer of metallic lithium and its salts, as well as zeolite catalysts widely used in the oil and gas industry.
Chepetsky mechanical factory (AO ChMZ) Glazov, Republic of Udmurtia	Manufactures items from zirconium and its alloys. The main field of activity of AO ChMZ is the manufacture of zirconium shells for fuel elements, from which nuclear fuel cannisters are formed. The factory also develops production of titanium alloys, calcium metal and hafnium.
Moscow factory of polymetals (AO MZP, Moscow)	At present the main field of activity for the factory is the development, production and realization of production of special purpose.

¹¹ <https://www.reuters.com/article/ukraine-crisis-nuclear-fuel-idUSR4N2V1019>

Gas centrifugal complex	
Kovrov mechanical factory (PAO KMZ) Kovrov, Vladimir Oblast	The factory carries out serial production of gas centrifuges for the needs of the sublimate-dividing facilities of the TVЕД fuel company. At present, PAO KMZ manufactures gas centrifuges of the ninth generation – high-capacity equipment for the separation of uranium isotopes.
Vladimir PO Tochmash (AO VPO Tochmas) Vladimir	The enterprise manufactures parts for gas centrifuges, products for storage of processed nuclear fuel, as well as items of general industrial purpose.
Scientific industrial association Tsentrotekh (OOO NPO Tsentrotekh) Novouralsk closed city, Sverdlovsk Oblast	NPO Tsentrotekh manufactures a whole spectrum of innovative types of production – from 3D-printers to electricity accumulators
Scientific constructor complex	
High-technology scientific research center of non-organic materials named for Academic A.A. Bochvar (AO VNIINM) Moscow	Leading scientific research institute for problems of material engineering and technologies of the nuclear fuel cycle for all types of reactors. AO VNIINM carries out the functions of the central head organization of the metrological service of Rosatom
Central planning and technological institute (AO TSPTI) Moscow	An integrated company consolidating planning and construction divisions of enterprises of the TVEL fuel company
Sector integrators	
OOO RusAT	Specialized integrator of additive technologies in the atomic sector. The main activity of the company includes: manufacture of 3D-printers, metallic powders for 3D-printing, software development for additive systems, as well as services of 3D-printing and introduction of additive technologies into production.
OOO RENERA	Sector integrator for systems of energy accumulation. Manufactures cathode materials for lithium-ion batteries and energy accumulators. The company produces lithium-ion batteries for telecommunications systems, uninterrupted power supply systems, electronic transport, railways, batteries for use in outer space and other fields.
AO RusVellGrup	Integrator of sector solutions for the fuel and energy complex. Company activity is directed towards creating and developing technologies, products and services required in the sphere of energy and development of natural resources.
OOO Rusatom MetallTekh	Divisional integrator in the metallurgy sphere.

1.4. Machine-building division

The machine-building division (managing company AO Atomenergomash) is part of Rosatom and is the main supplier of key and auxiliary equipment at nuclear power stations of Russian design. The division includes engineering and construction centers, major power machine building and metallurgic complexes, as well as scientific research and material engineering organizations in Russia, the CIS and EU countries.

Table 2. Industrial assets of Atomenergomash

Metallurgical enterprises, reactor equipment	
Branch of AO AEM-technologies Petrozavodsk	Manufacture of long-cycle equipment of atomic power station reactors. Manufacture of various vessels working under pressure, steam and water-heating boilers, steam and hot-water pipes.
AO ZiO-Podolsk Podolsk	Manufacturer of heat exchange equipment for thermal electric stations: atomic and thermal power stations, oil and gas industry, as well as for ship building.
Branch of AO AEM-technologies Atomash Volgodonsk	Main supplier of equipment for enterprises of the atomic industry, the oil and gas complex, and thermal energy
Turbine and pump equipment, armature and pipe	
AAEM Turbine technologies St. Petersburg	Manufacture of steam turbines and generators with a power of 1000-1800 MWt with the slow-speed Arabelle technology, integration and complete delivery of equipment for NPPs with the Russian-type VVER reactor
Atomturboprovmontazh (ATM) Moscow	. Manufacture of parts, assembly units and pipeline blocks of high and low pressure of perlite and austenite steel for nuclear power stations of Russian design.
AO TsKBM St. Petersburg	Russia's only developer and manufacturer of main circulation pumps for VVER reactors, also designs and manufactures practically all types of pumps used at NPPs, as well as remotely controlled equipment for working with radioactive materials.
Scientific research institutes and development design bureaus	
AO OKB GIDROPRESS Podolsk	Carries out complex of construction, theoretical calculation, experimental research and production works of Russian reactor facilities of RU for nuclear power stations of various types.
AO TsKBM St. Petersburg	Developer and constructor of pumps and reloading equipment.
AO NPO TSNIITMASH Moscow	Chief metal-engineering organization of Rosatom
AO OKBM Afrikantov Nizhny Novgorod	Carries out the entire complex of works for creating various types of reactor systems and equipment for atomic power stations, including developing construction documentation, making necessary calculations, R&D, preparing and testing specimens with development of industrial technology of manufacture, preparation and assembly of equipment, its launch and operation, servicing equipment at functioning objects, decommissioning them.
AO AEM-technologies St. Petersburg	Engineering company. Manufacture of nuclear reactors and their component parts, including for transport reactors
AO SverdNIikhimassh Yekaterinburg	R&D in creating new specimens of equipment for the machine building division of Rosatom

1.5. Electricity division

Electricity division of Rosatom (managing company – Rosenergoatom Concern) is the operator of atomic power stations in Russian. The main type of activity of the electricity division is producing electrical and thermal energy with atomic stations and carrying out functions of maintained organization of nuclear systems (atomic stations), radiation sources, facilities for storage of nuclear materials and radioactive substances.

The electricity division includes 10 functioning nuclear power stations (Balakovsky, Beloyarsky, Bilibin, Kalinin, Kola, Kursk, Leningrad, Novovoronezh, Rostov, Smolensk NPPs) as well as the floating nuclear thermal power station “Academic Lomonosov”, the directorate of atomic power stations under construction, the branch for realizing capital projects, the technological branch, the test and demonstration engineering centers for decommissioning stations, the Akkuyu engineering center, as well as 20 affiliated societies and over 20 controlled organizations, including AO Atomenergoremont, AO Atomtekhenergo, AO VNIIAES, OOO Energoatominvest, AO KONSIST-OS, AO Atomdata-Tsentr, AO KONTSERN TITAN-2 and several other organizations.

1.6. “Ecological solutions” division

The “Ecological solutions” divisions includes the following organizations and enterprises:

- Directorate for nuclear and radiation safety
- Test and demonstration center of uranium graphite reactors (ODTS UGR), Seversk
- Mining chemical combine, Zheleznogorsk
- National operator for treating radioactive waste
- Federal ecological operator
- RADON

Additionally, the Division includes 19 branches and departments in various regions of Russia.

The chief task of the division is to realize the federal target program “Nuclear and radiation safety”, the federal projects “Infrastructure for treatment of waste of the 1st-2nd classes of hazard”, “Clean country”, “Protection of Lake Baikal”. Additionally, RADON (an enterprise of the division) has been appointed specialized sector operator for managing the “nuclear legacy”.

1.7. Engineering division

The engineering division of Rosatom brings together the following companies and enterprises of the nuclear sector:

- Atomstroieksport (AO ASE, Nizhny Novgorod) share-holding society
- Atomenergoproekt share-holding society (United planning institute including Moscow, St. Petersburg and Nizhny Novgorod branches) and affiliated organizations.

Key organizations of the Division are AO ASE and AO Atomenergoproekt.

The main areas of activity of the Engineering division are planning and construction of high capacity NPPs in Russia and on international markets, as well as developing digital technologies for managing complex engineering sites.

1.8. "Sale and trading" division

The managing organization of the "Sale and trading" division is Tekhsnabexport (TENEX).

The division includes AO LTS YATS, AO SPB IZOTOP, OOO Kraun AO, Uranium One Group, as well as foreign affiliated societies of TENEX and Uranium One Group: INTERNEXCO GmbH (Switzerland), TENEX-Korea Co., Ltd. (South Korea), TENEX-JAPAN Co. (Japan), TRADEWILL LIMITED (UK), TENEX-USA, Incorporated (USA).

The sole shareholder in TENEX is the Atomic Energy Industry Complex share-holding society.

The main task of the division is to promote Russian goods and services of the nuclear fuel cycle on foreign markets. The priority areas of the division are delivering NFC products abroad, promoting solutions for green energy (solid biofuel, rare earth metals and others) and transport and logistic services.

1.9. Nuclear Weapons Complex directorate

The nuclear weapons complex directorate of Rosatom advances state policy in the field of developing the nuclear industry, carrying out tasks of the state arms program and the state defense order.

The leading enterprise of the nuclear weapons complex of Russia is PO Mayak, where supplies of weapons-grade uranium and plutonium are processed and stored for the manufacture of nuclear weapons.

Additionally, the nuclear weapons complex directorate includes two nuclear centers:

- The Russian federal nuclear center – the All-Russian scientific research institute of technical physics named for Academic Ye.I. Zababakhin (RFYaTs-VNIITF, Snezhinsk, Chelyabinsk Oblast). As a branch of the institute joined at the All-Russian electrotechnical institute named for Lenin. The main task of the center is solving technical problems connected with ensuring and maintaining the reliability and security of nuclear weapons.
- The Russian federal nuclear center – All-Russian scientific research institute of experimental physics (RFYaTs- VNIIEF, Sarov, Nizhny Novgorod Oblast). This center has five institutes: theoretical and mathematical physics, laser physics studies, experimental gas dynamics and explosion physics, nuclear and radiation physics, digital technologies; scientific production center of physics; four design bureaus and a technological production complex, uniting two factories and a technological center. A branch of the nuclear center Scientific-Research Institute of Measuring Systems named for Yu.Ye. Sedakov is located in Nizhny Novgorod.

Today, RFYaTS-VNIIEF is a major multi-core scientific-technological center, with the primary task of providing the reliability and security of Russia's nuclear arsenal. Additionally, the nuclear center develops civic areas of activity, including laser, supercomputer and information technologies; development in the sphere of medicine and space exploration.

Subdepartmental enterprises of the Nuclear Weapons Complex directorate include:

- Coordinated center for creation of systems of security and control "Atombezopasnost", State corporation for atomic energy Rosatom (Atombezopasnost, Sergiev Posad)
- Scientific-technical and certification center for comprehensive information protection (Atomzashchitaingorm center, Moscow)
- Special scientific production association Eleron (SNPO Eleron, Moscow)
- Departmental security service of Rosatom (Atom-okhrana, Moscow)

1.10. Northern Sea Route directorate

Rosatom has functions as the infrastructural operator of the Northern sea route and is responsible for organizing shipping on the route, building infrastructural facilities, navigational and hydrographical provision and a security system for navigation in harsh Arctic conditions. The corporation is the curator of the federal project "Development of the Northern Sea Route", part of the Comprehensive plan for modernization and expansion of route infrastructure in the period until 2024, and head of the federal project "Northern Sea Route – 2030" of the Russian state program "Development of the atomic energy industrial complex".

The leading enterprise of the directorate is Atomflot, with the status of a federal nuclear organization. The function of navigational-hydrological provision of shipping for the northern sea route is carried out by the "Hydrographical Enterprise", which is part of the Directorate.

At present, Atomflot has 31 vessels (seven with nuclear power units, 5 vessels of nuclear technological provision, 19 other vessels and floating craft) and 10 shore facilities for treating radioactive materials.

1.11. Science and education

In 2021, Rosatom's expenditure on scientific research came to 45.6 billion rubles

In accordance with the decision of the Russian government, Rosatom carries out the program for innovative development and technological modernization in the period until 2030 (hereinafter PID).

PID projects are grouped by thematic sections:

- Strategic areas (scientific and technological development of state significance). Key projects – closed nuclear fuel cycle, managed thermonuclear synthesis, small atomic reactors, increasing ecology of atomic production;
- Priority projects (fields of technological development). Key projects and events – the "Breakthrough" project, developing technologies of pressurized water reactors, small NPPs, processing spent nuclear fuel, laser technologies; thermonuclear and plasma technologies; nuclear medicine; superconductivity; hydrogen energy;
- Priority innovative projects and measures for digital transformation;

Many specialized scientific research institutes are part of the above-listed divisions of Rosatom. Additionally, the scientific division of Rosatom includes 12 scientific production companies, including AO GNTs NIIAR, AO IRM, AO GNTS RF – FEI named for A.I. Leipunsky, AO NIII NPO LUCg, AO NIIgrafit, AO GNTs RF TRINITI, AO NIIP, AO VNIKhT, AO GIREMET, AO Radium institute named for V.G. Khlopin”.

Scientific research and development for Rosatom in various fields are carried out by non-sector scientific organizations (mainly organizations of the Russian Academy of Sciences), The Kurchatov Institute, IBRAE RAS, OIYaI, United institute of high temperatures of RAS, Institute of problems of chemical physics of RAS, Physical-Technical Institute named for A.F. Ioffe of RAS, Institute of Nuclear Physics named for G.I. Budker CO RAS, Federal Research Center “Institute of Applied Physics of RAS”.

The main participants of realizing scientific education projects of Rosatom are the following institutes of the Russian education ministry: NIYaU MIFI, MISiS, NGTU named for R.Ye Alexeev, NNGU named for N.I. Lobachevksy, the St. Petersburg State University of Peter the Great, Tomsk Polytechnic University, Moscow State Technical University named for N.E. Bauman, MEI, Urals Federal University, MGSU, Moscow State University. Additionally, practically all polytechnical institutes and universities of Russia have faculties where specialists for the atomic sector are trained.

In summary, we may note several important facts and tendencies which concern the current position of the atomic sector. Rosatom today is one of Vladimir Putin’s personal projects. In over 20 years of management, the Putin administration not only returned the atomic sector the power and importance that it had under the Soviet Minsredmash, but significantly expanded its tasks, and accordingly its economic and administrative resources. At the same time, by creating a new juridical form of “state corporation”, as well as passing a separate law for it, the state gave the atomic sector the possibility not only to carry out state defense programs, but to turn it into a powerful business structure, which is today present on international markets and owns foreign assets.

Inside Russia, Rosatom, thanks to the defense, technological and economic component, occupies a leading place by its significance for the state, and the proximity of the head of the atomic sector to the Russian president provides additional capabilities and protects the sector from economic and political rivals and enemies.

Rosatom remains practically the only sector in Russia with technologies and resources comparable with the resources of developed countries. So the nuclear industry does not depend very strongly on the problem of “import replacement”, which in the present geopolitical situation is especially critical for many companies and enterprises. At the same time, as the potential of other leading corporations and companies of Russia (Gazprom, Rosneft etc.) rests almost exclusively on the exploitation of natural resources that they produce and sell, the potential reserve of Rosatom is concentrated in technologies, production capacities and science.

Chapter II.

The nuclear fuel cycle

The nuclear fuel cycle is the agglomeration of technological processes for treating nuclear materials, from producing natural uranium, including such processes as the conversion of uranium, its enrichment, fabrication of fuel, extracting nuclear energy in reactors, and ending with treatment of spent nuclear fuel. There are two types of fuel cycle: open and closed.

The open fuel cycle involves the single use of nuclear materials without processing spent nuclear fuel.

In the closed fuel cycle, spent nuclear fuel is processed, nuclear materials, uranium and plutonium are extracted from it, and they are used again as fuel.

At present, Russia has all the technological elements of the open fuel cycle, which it uses both for its own needs, and for providing services for export, with the exception of infrastructure for burying high-level radioactive waste as the final link of any fuel cycle. At the same time, Rosatom works constantly to gradually close the fuel cycle, attaching particular importance to this task, and with the confidence that it can be solved.

The main enterprises of the nuclear fuel cycle, with the exception of producers, are part of the structure of the fuel division of Rosatom.

2.1. Uranium production

Uranium production in Russia is carried out by the mining division of Rosatom (managing company AO Atomredmetzoloto (ARMZ)). Production is carried out at three enterprises – in the Zabaikalsky Krai (PAO PPGKhO), the Republic of Buryatia (AO Khiagda) and in the Kurgan Oblast (AO Dalur).

The summary uranium production for 2021¹² was 2,635 tons, around 7% less than the previous year. Additionally, there is a large and promising field, Elkonskoe, in Yakutia, where development is not yet being carried out.

¹² Rosatom annual report for 2021 – <https://www.report.rosatom.ru/655.html>

Table 3. Data for volumes of production, supplies and production methods at ARMZ enterprises

Enterprise	Share of ARMZ in 2021	Production method	Volume of supplies ¹³ for 1 January 2022, thou. t.
PAO PPGKhO	44 % ¹⁴ (1159 tons)	Shaft mining	95.4
AO Khiagda	35% (395 tons)	Underground leaching	33.5
AO Dalur	21% ¹⁵ (264 tons)	Underground leaching	12.7
AO Elkonsky GMK	-	Production not carried out	357.1
Total	2635 т		499.9

At present, for economic reasons around 50% of uranium is produced by the method of underground leaching. However, according to assessments of IAEA and NEA¹⁶ presented in the Red Book 2020, only 4% of surveyed supplies of uranium in Russia can be classified as easily extractable, with a production cost of less than \$80 per ton of uranium.

It should be noted that annual requirements of atomic energy in Russia for uranium come to around 5000 t – 5500 t¹⁷, and are not covered by production within the country. Additionally, Rosatom delivers at least 5000 tons of uranium annually to the USA and EU countries (see section 4.3). The summary uranium production in Russia and abroad, mainly in Kazakhstan, by the companies ARMZ and Uranium, part of Rosatom, came to just 7100 t in 2021.

For this reason, Rosatom usually secondary fuel sources, such as impoverished uranium in the form of accumulated supplies of depleted uranium hexafluoride (see section 2.2. for more detail), regenerated uranium, which is used for treating spent fuel, as well as works on closing the fuel cycle for expanding the fuel basis in the future (see section 2.4). The precise volumes of annual production of uranium for secondary sources are unknown at present. They are probably variable and depend on the economic expediency of pre-enrichment of uranium, world uranium prices and the load of enrichment facilities in Russia. According to some assessments¹⁸, Russia may receive from secondary sources up to 5800 t of the equivalent of natural uranium per year. It is also possible that Russia purchases additional uranium on the free market.

¹³ https://report.rosatom.ru/go/2020/armz_2020.pdf ARMZ annual report for 2020

¹⁴ https://priargunsky.armz.ru/images/File/priargunsky/newspaper/gornyak_1s.pdf (p. 4)

¹⁵ <https://www.armz.ru/press-tsentr/novosti/2593-gornorudnyj-divizion-podvel-itogi-2021-g>

¹⁶ *Uranium 2020: Resources, Production and Demand. NEA and IAEA RED BOOK*

¹⁷ *Russia's Nuclear Fuel Cycle. World Nuclear Association. 2021*

¹⁸ <https://euratom-supply.ec.europa.eu/system/files/2022-12/Euratom%20Supply%20Agency%20-%20Annual%20report%202021%20-%20Corrected%20edition.pdf> p. 63

2.2. Conversion and enrichment of uranium

Conversion of uranium in the nuclear fuel cycle means the process of converting concentrated uranium oxide obtained in the production of uranium ore into uranium hexafluoride suitable for enrichment.

At present, the conversion of uranium in Russia is carried out by a factory of the Siberian chemical combine (AO SKhK, Seversk). According to assessments of the WNA, in 2020 the facilities for conversion of the factory in Seversk came to 12,500¹⁹ tU per year, and its capacity was over 95%. This factory actively works for export and covers around one third of all world requirements for conversion.

Uranium enrichment (separation of isotopes) is a process for obtaining uranium with a high content of uranium-235 isotope (enriched uranium product – EUP) from the natural level of 0.071% to around 5%, necessary for use as nuclear fuel.

In the enrichment process, a side product is also formed – uranium with depletion of isotope 235. In Russia, it is regarded as a secondary fuel resource. At present, over 1 million tons of hexafluoride of depleted uranium has been accumulated²⁰. This is the legacy of both the military and civic atomic program of the USSR and Russia, including side products for providing services of uranium enrichment and pre-enrichment of depleted uranium to foreign clients, primarily European. For example, around 100,000 tons of hexafluoride from these reserves is the result of contracts for uranium pre-enrichment with the companies Eurodif and Urenco²¹ from 1996 to 2014. Before the end of 2022, a new contract from 2018²² was to be signed with the company Urenco, as a result of which another 10,000 tons of hexafluoride will remain in Russia, primarily from Germany.

Since 1992²³, Russia has rejected the energy-intensive gas diffusional method of enriching uranium, and has moved completely to a more effective method of enrichment, using gas centrifuges.

At present, the country possesses around 40% of world capacities for uranium enrichment. It is difficult to give precise figures, as they are kept secret, and at enrichment plants, modernization is constantly underway, with old generations of centrifuges being replaced with new, more productive ones.

¹⁹ World Nuclear Association Nuclear Fuel Report (2021 edition) (p. 32)

²⁰ <http://www.ueip.ru/ekologicheskaya-politika/Documents/%D0%9F%D1%80%D0%B8%D0%BB%D0%BE%D0%B6%D0%B5%D0%BD%D0%B8%D0%B5%203%20-%20%D0%9F%D1%80%D0%BE%D0%B3%D1%80%D0%B0%D0%BC%D0%BC%D0%B0%20%D0%9E%D0%93%D0%A4%D0%A3.pdf>

²¹ <https://greenpeace.ru/wp-content/uploads/2019/10/Minatom-to-mitrokhin-lettre.pdf>

²² <https://dserver.bundestag.de/btp/19/19117.pdf>

²³ <https://www.ecp.ru/activity/nuclear/uran>

Russia currently uses centrifuges of its own development. Their development and manufacture are carried out by three companies²⁴: PA KMZ (Kovrov), AO VPO Tochmash (Vladimir) and OOO NPO Tsentrrotekh (Novouralsk).

Since 2012, ninth-generation centrifuges have been installed at plants²⁵, and since 2017, generation 9+²⁶. Usually, new generations of centrifuges are distinguished by greater productivity and lower electricity use.

Table 4. At present, there are four uranium enrichment plants operating in Russia

Plant	City of location	Capacity, million SWU*/year (%)
Urals electrochemical combine (UEKhK)	Novouralsk	10
Electrochemical factory (EkhZ)	Zelenogorsk	8.7 (expansion to 12 underway ²⁷)
Siberian chemical combine (SKhK)	Seversk	3
Angarsk Electrochemical Combine (AEKhK)	Angarsk	2.6
Total		23.4 (27.6*)

* SWU – separate work unit, including for uranium enrichment

The Urals electrochemical combine (UEKhK) currently accounts for 40% of separation facilities in Russia and around 20% worldwide. The combine is capable of carrying out enrichment of depleted uranium to natural level, natural uranium to the level of 4-5%, used in most atomic power stations, and up to 30% for fuel for forest reactors. UEKhK is actively involved in works for pre-enrichment of accumulated supplies of hexafluoride and expert contracts. UEKhK carried out enrichment of uranium hexafluoride by contract from 2018 with Urenco Enrichment Company Ltd, which involved enrichment to natural equivalent of around 12 000 tons of hexafluoride²⁸ in 2019-2022.

UEKhK was also the first enrichment combine in Russia with a foreign share of ownership. In 2013, 25²⁹ of its shares were transferred into ownership of the Russian-Kazakhstan Uranium Enrichment Center. But in 2020, the Kazakhstan company Kazatomprom sold its 50% share in the UEC to the Russian AO TVEL, thus putting UEKhK fully under Russian control once more³⁰.

²⁴ <https://www.tvel.ru/about-company/struktura-toplivnoy-kompanii/gazotsentrifuzhnyy-kompleks/>

²⁵ <https://www.tvel.ru/about-company/history/>

²⁶ http://www.chmz.net/press/mass-media/element/element_12_2017.pdf

²⁷ <https://world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-fuel-cycle.aspx>

²⁸ <https://dserver.bundestag.de/btp/19/19117.pdf> (p. 14363)

²⁹ https://jv-uec.ru/o_tsentre/istoriya

³⁰ https://www.kazatomprom.kz/ru/media/view/kazatomprom_zavershil_sdelku_po_prodazhe_doli_vladieniya_v_ao_tsou

The electrochemical plant (EKhZ) in Zelenogorsk has comparable capacities to UEKhK, and has been developing them in recent years. According to previous plans, its capacities will be raised to 12 million separation units per year. From 2019 centrifuges of the latest generation 9+ have been installed³¹, and in 2021 5 new launch sites were put into operation³². Besides uranium enrichment, EKhZ obtains stable isotopes in centrifuges for various fields of industry and medicine.

Since 2009, EKhZ has operated the only W-ECP device in Russia to convert hexafluoride into depleted uranium oxide, obtaining products containing fluoride. The capacity is 10,000 tons a year, and over 100,000 tons have been processed over the entire period. In 2023 it is planned to launch a second device of equivalent capacity, W2-ECP, supplied by the Orano company³³.

The Siberian chemical combine (SKhK) differs from the others in that it specializes in work with regenerated uranium, its purification and enrichment, as well as converts uranium and produces uranium hexafluoride for all enrichment combines of Russia and for foreign clients. At present at least two contracts are operating. One is for the delivery to Russia of 1150 tons³⁴ of regenerated uranium for the needs of Rosatom with the Orano company, with deliveries in 2021 and 2022. The second contract signed in 2018 with the EDF company³⁵, is for delivery to Russia of regenerated uranium from France for processing and enrichment, with consequent return of the enriched product for use as fuel at atomic power stations. The contract is estimated at a cost of \$600 million.

The Angarsk electrochemical combine (AEKhK) has around 11% of the separation facilities of Russia. Since 2014 its separation production has been working in a "shaft" regime, carrying out pre-enrichment of accumulated scrap of depleted uranium hexafluoride (DUH). At the AEC in 2007, with the involvement of Kazakhstan, the International Uranium Enrichment Center (IUEC)³⁶ was created, with a guaranteed supply of low-enriched uranium under control of the IAEA in case of a disruption in international chains of supply of nuclear fuel. By 2010 120 tons of low-enriched uranium were stored at the IUEC with an enrichment of 4.95%. Recently there has been no news about the work of the IUEC.

³¹ <https://www.atomic-energy.ru/news/2020/03/27/102458>

³² <https://newslab.ru/article/1075574>

³³ <https://www.ecp.ru/node/4082>

³⁴ <https://www.orano.group/en/unpacking-nuclear/recycled-uranium-an-energy-source-for-low-carbon-electricity>

³⁵ <https://www.lefigaro.fr/flash-eco/2018/05/25/97002-20180525FILWWW00206-une-filiale-de-rosatom-signe-un-contrat-avec-edf.php>

³⁶ International Uranium Enrichment Centre. IAEA

2.3. Fuel fabrication

facilities for the production and processing of fuel for the open fuel cycle

Fabrication of fuel in Russia is presently underway at the main two plants – the Machine building plant in Elektrostal, Moscow Oblast, and at the Novosibirsk plant of chemical concentrates.

The summary capacity of the two plants is around 2,800³⁷ tons of nuclear fuel annually, and the real production of fuel is within the margin of 1400 t³⁸. According to data from the annual report of Rosatom³⁹, in 2021 the corporation manufactured nuclear fuel in the equivalent of around 1030 tons of heavy metals or around 1,160 tons of fuel in the equivalent of uranium dioxide⁴⁰ (subsequently in the report, unless otherwise specified, nuclear fuel is calculated in the form of uranium dioxide).

From this volume, according to the assessments of Bellona given in this report (see sections 2.4 and 4.3) up to 800 tons may cover the requirements of Russian atomic power stations and 300 tons deliveries abroad. A small amount of fuel may be used for transport and research reactors. As of early 2022, Rosatom delivered fuel to 75 reactors of atomic power stations, 37 in Russia and 38 in 11 other countries: Czechia, Bulgaria, Slovakia, Hungary, Finland, Armenia, Belarus, Iran, India, China and Ukraine.

Besides MCZ and NZKhK, small and experimental batches of MOKS-fuel for reactors with fast neutrons are produced by AO NIIAR, GKHK and PO Mayak. The Chepetsky mechanics plant in Glazov manufactures zircon casings for heat insulation elements. The head organization of Rosatom in developing new types of fuel is AO High technology scientific research institute of non-organic materials named for academic A.A. Bochvar (VNIINM).

The Machine building plant (MCZ) fabricates fuel for Russian and foreign reactors, such as VVER-440, VVER-1000, VVER-1200, RBMK-1000, as well as research reactors, sea reactors for ice-breakers and floating nuclear power plants, including for RITM-2000 reactors. The MCZ also produces fuel from enriched uranium and regenerated uranium. For foreign clients, MCZ manufactures uranium dioxide powder and fuel pellets, including for the Indian PHWR and BWR reactors⁴¹. Since 2004, the MVZ in cooperation with the company Framatome ANP (Areva NP)⁴² has manufactured fuel rods for the foreign reactors PWR and BWR. In 2013, the 3000th fuel rod for Areva was produced.

³⁷ *Russia's Nuclear Fuel Cycle. World Nuclear Association. 2021*

³⁸ <https://atomicexpert.com/page3174296.html>

³⁹ https://report.rosatom.ru/go/rosatom/go_rosatom_2021/rosatom_2021_ru.pdf, p 40-41

⁴⁰ 1 t of UO₂ is equivalent to 0.8815 t U - <https://www.wise-uranium.org/rup.html>

⁴¹ <http://www.elemash.ru/produktsiya/produktsiya-yaderno-toplivnogo-tsikla/toplivo-dlya-reaktorov-pwr-i-bwr/>

⁴² <http://www.elemash.ru/about/history/>

MCZ also manufactures highly enriched fuel. For example, for the BN-600 reactor, which uses uranium fuel with enrichment of 17%, 21% and 26%. In 2021, MCZ began producing fuel for the Chinese fast reactor CFR-600, with similar specifications to the BN-600. The contract stipulates deliveries of fuel for the first load and first seven years of its work⁴³, and the first delivery took place in 2022⁴⁴. The MCZ also manufactures fuel for the Chinese Experimental Fast Reactor CEFR with enrichment of up to 64,4%⁴⁵.

The Novosibirsk factory of chemical concentrates (PAO NZKhK) specializes in the production of fuel for the VVER-1000 and VVER-1200 reactors both for atomic power stations in Russia and in Ukraine, Bulgaria, India and China. Additionally, since 2012 the factory has produced the fuel TVS-Kvadrat (TVS-K) of the TVEL development for PWR reactors of the western model – the 3 and 4 loop PWR Westinghaus⁴⁶. Experimental and commercial batches of TVS-K were supplied to the Swedish atomic power station Ringhals⁴⁷.

New types of nuclear fuel developed in Russia

New fuel for the VVER-1000 is currently used at the reactors of the Balakovsky NPP, Rostov NPP and the Tianwan NPP in China, as well as offered for new stations in Russia and abroad. All 4 reactors of the Balakovsky station have been moved to TVS-2M fuel with a demonstration of its advantages – increased depth of fuel combustion, transition from a 12 month (fuel company of around 300 effective days) to an 18-month interval of fuel load (fuel company around 510 effective days), and an increase in the power of blocks to 104% from the nominal⁴⁸. Now work is underway to increase the capacities of existing blocks to 107% from the nominal. There is also development of 4th generation fuel, in which regenerated uranium may be used.

Since 2011, TVS-2M has been introduced to reactors of the Chinese NPP in Tianwan⁴⁹. In 2018 an agreement was signed on transferring the first block of the Iranian NPP in Buser to TVS-2M fuel⁵⁰. In the summer of 2022, the first batch of TVS-2M was delivered to two blocks of the Kudankulam NPP in India, and will allow them to move to an 18-month fuel cycle⁵¹.

Accident Tolerant Fuel (ATF) is resilient to accidents with a loss of cooling of the active zone, and its construction prevents a zirconium-steam reaction if the fuel overheats.

⁴³ <https://world-nuclear-news.org/Articles/TVEL-unit-launches-CFR-600-fuel-manufacturing-site>

⁴⁴ <https://www.world-nuclear-news.org/Articles/Fuel-despatched-to-China-for-CFR-600-fast-neutron>

⁴⁵ https://fissilematerials.org/blog/2021/02/chinas_cefr_fast_reactor_.html

⁴⁶ <https://world-nuclear-news.org/Articles/Alliance-brings-Russian-fuel-to-US-market>

⁴⁷ <https://world-nuclear-news.org/Articles/TVEL-starts-PWR-fuel-fabrication-at-Novosibirsk>

⁴⁸ https://www.rosenergoatom.ru/zhurnalistam/news/41660/?sphrase_id=107699

⁴⁹ <http://www.gidropress.podolsk.ru/files/publication/publication2015/documents/003.pdf>

⁵⁰ <https://www.world-nuclear-news.org/UF-Irans-Bushehr-I-changes-to-TVS-2M-fuel-25041801.html>

⁵¹ https://www.tvel.ru/press-center/news/?ELEMENT_ID=9318

At present, tests of accident tolerant fuel are underway at the experimental reactor MIR at GNTS NIIAR⁵². Additionally, since September 2021 in the second power unit of the Rostov NPP with a VVER-1000 reactor, the first 18-month cycle of experimental industrial operation has begun with three TVS-2M, containing 12 fuel rods with ATF, 6 of which have shells of chromium-nickel alloy and 6 of zirconium alloy with a chromium coating⁵³.

Third generation fuel for VVER-440 has high enrichment (up to 4.87% by Uranium 235) and uranium content, allowing to raise the length of the fuel campaign to 5-6 years, and the power of the block by 5-9% from the nominal⁵⁴.

Since 2010, third generation fuel RKZ and RKZ+ has been introduced at the Kola atomic power station. Additionally, the new fuel will be delivered by the Hungarian Paks nuclear power station, and in mid-2021, development of the new fuel will be completed for the Finnish Loviisa nuclear power station⁵⁵.

2.4. Closing the fuel cycle and recycling nuclear materials.

Closing the fuel cycle has been declared an important strategic task for Russian nuclear energy. At present, Rosatom is working on creating dual-component nuclear energy⁵⁶ based on a combination of classic water reactors, and fast neutron reactors, with processing of nuclear fuel of both types and recycling of nuclear materials.

It is proposed that in this configuration, all elements will carry out the following functions:

1) Fast neutron reactors (FNR – sodium-, lead-cooled)

- process electricity in the basic load regime
- work entirely on recycled materials – use accumulated scrap or regenerated uranium, and plutonium separated from SNF of heat reactors, and in the course of work produce plutonium suitable by isotope composition for use in VVER fuel
- burns long-lasting highly active waste – minor actinides emitted in processing all times of SPNF. For these purposes, an additional salt alloy reactor may also be created at GKKh⁵⁷.

⁵² <https://strana-rosatom.ru/2022/05/19/v-rosatome-nachalis-ispytaniya-tole/>

⁵³ <https://www.nucnet.org/news/first-fuel-bundles-containing-atf-loaded-at-rostov-2-nuclear-plant-9-1-2021>

⁵⁴ <http://www.gidropress.podolsk.ru/files/publication/publication2014/documents/53.pdf>

⁵⁵ <https://www.world-nuclear-news.org/Articles/Modified-fuel-assemblies-developed-for-Loviisa-uni>

⁵⁶ Adamov E.O. and others. Dual-component nuclear energy. 2021. pp 450-458 <https://sciencejournals.ru/view-article/?j=vestnik&y=2021&v=91&n=5&a=Vestnik2105002Adamov>

⁵⁷ Adamov E.O. and others. Dual-component nuclear energy. 2021. pp 450-458 <https://sciencejournals.ru/view-article/?j=vestnik&y=2021&v=91&n=5&a=Vestnik2105002Adamov>

2) Thermal neutral reactors (TNR – VVER)

- processes electricity in the basic load regime and meets requirements of the system operator for maneuverability;
- uses MOKS-fuel and REMIX-fuel instead of fuel from UO_2 ;
- delivers abroad with the service of return of SNF to Russia, bringing nuclear materials into a closed fuel cycle;
- plutonium extracted from the VVER SNF is sent for manufacture of MOKS fuel for RBN with the goal of improving its isotope composition and burning of even-numbered plutonium isotopes

3) NFC enterprises

- may be both centralized (GKhK, MAYak), and station-based (BREST-OD-300);
- ensure processing of SNF RTN and RBN, separation of nuclear materials for repeat use;
- scrap or regenerated uranium and plutonium separated from SNF are used for preparation of MOKS and other types of fuel;
- ensure fractioning of radioactive waste for the purpose of subsequent utilization of lesser actinides and reducing risk of distribution of nuclear material, conditioning and burying of radioactive waste.

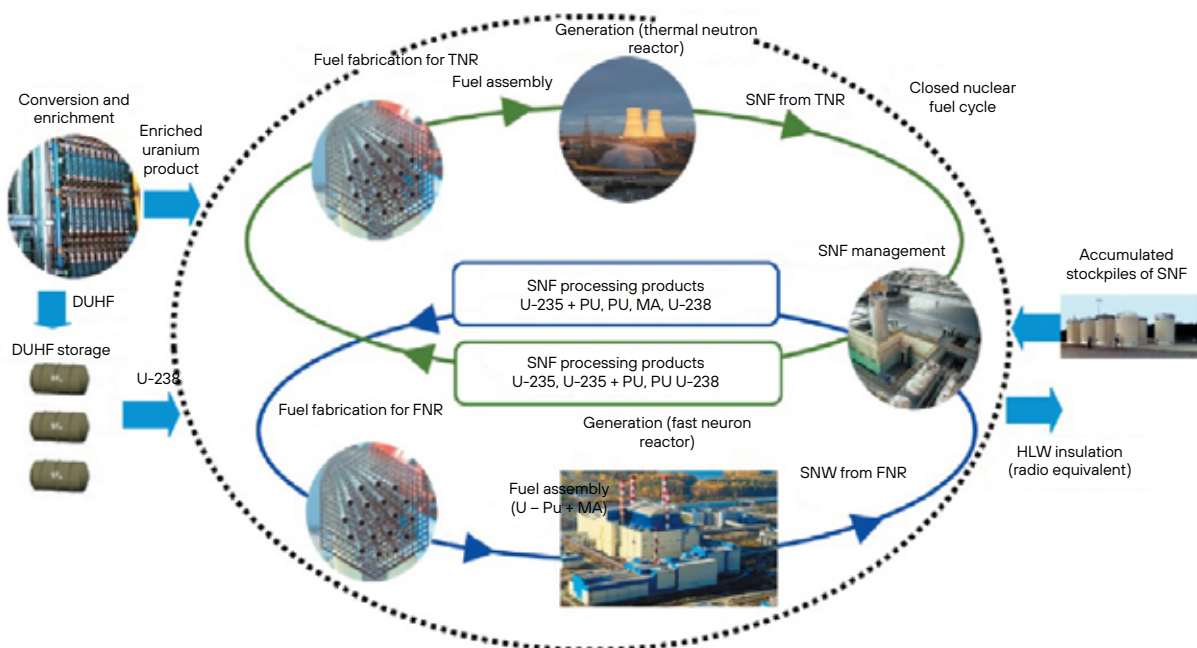


Figure 1. Principle diagram of dual-component nuclear energy with fast neutron reactors (FNR) and thermonuclear reactors. Source⁵⁸

⁵⁸ Adamov E.O. and others. *Dual-component nuclear energy*. 2021, pp 450-458. <https://sciencejournals.ru/view-article/?j=vestnik&y=2021&v=91&n>

According to plan, the closed fuel cycle and dual-component nuclear energy will reduce the need for natural uranium, involve spent uranium in the fuel cycle, solve the problem of accumulated SNF and reduce the volume of waste buried.

However, this is a very difficult task, with many questions that have yet to be answered. A number of important issues must be solved, such as economic efficiency, radiation and nuclear safety, public acceptability and observance of international guarantees of non-proliferation, and the principle of not shifting responsibility for accumulated radioactive waste. Constant clarification and elaboration of this strategy is required in the course of its realization.

At present, there is a large resource of prognoses both on the deadlines of moving to dual-component atomic energy in Russia, and on its quantitative and qualitative composition. This will depend both on the state of the economy and atomic sphere in wartime and post-war, and on the success (or failure) in solving quite specific technical tasks and issues. In particular:

- Operation of BN reacts at full capacity with MOKS fuel (began in summer 2022 with the full capacity with BN-800 MOKS fuel).
- Launch and operation of the fast lead reactor BREST-OD-300 with a station model of processing and manufacturing fuel (construction of the reactor began in 2021, launch is expected in 2027⁵⁹).
- Construction and operation of RT-2 factory at GKKhI for processing accumulated and forming VVER nuclear waste.
- Launch and operation of new types of pressurized water reactors with more effective use of fuel, including from regenerated materials: VVER-TOI (construction is underway at the Kursk APS-2, launch not earlier than 2024) and VVER-600S with spectral regulating (planned for building at the Kola APS-2 with a launch not earlier than 2034⁶⁰).

Processing nuclear fuel of industrial reactors in the USSR/Russia began in the late 1940s for military purposes to obtain weapons-grade plutonium for nuclear weapons. At present, centralized storage and processing of nuclear waste of civil reactors is carried out at two facilities – PO Mayak and GKKh. The RT-1 factory at the PO Mayak began to accept NPP fuel for storage in 1971, and began processing it in 1977.

At present, RT-1 is the only enterprise in Russia for processing nuclear waste of civic use in industrial volumes. At present, mainly fuel of VVER-440 reactors is processed at RT-1, as well as fuel of experimental and sea reactors of both the civic fleet and submarines. This fuel has a higher enrichment than NPP fuel.

=5&a=Vestnik2105002Adamov

⁵⁹ https://rosatom.ru/journalist/smi-about-industry/glava-magate-nazval-stroitelstvo-reaktora-brest-prodvizheniem-mirovoy-atomnoy-industrii/?sphrase_id=3320403

⁶⁰ <https://www.rosatom.ru/journalist/news/kolskaya-aes-nachalo-stroitelstva-kolskoy-aes-2-namecheno-na-2028-god/?fbclid=IwAR0dYbljsqJgbsmRLO0cwTYHeYCROSAFbJdJPbYoQ2M2STeABM2rCYLogI>

At the RT-1 the classic purex-process of treating nuclear waste is used by dissolving it in acids, with the subsequent liquid extraction of the required components. Products of processing nuclear waste of RT-1 are⁶¹:

- Uranium compounds with enrichment of up to 3.1% for subsequent manufacture of RMBK fuel
- Uranium compounds with enrichment from 10% to 76%, used for manufactured of fast reactor fuel and REMIX-fuel.
- Plutonium dioxide, which goes into storage and for creating MOX-fuel.
- Neptunium – for developing uranium-238 for space RITEGs
- Various isotopes from the composition of products of separation for preparation of isotope production.

The forecast annual capacity of the RT-1 factory is 400 tons of SNF. However, the real volumes of processing are much less. For 2009–2020 at RT-1 on average, around 100 t of SNF was processed per year, with a maximum volume of processing of 233 tons of SNF in 2016⁶². By 2020, RT-1 had processed around 6500 tons of SNF (including uranium)⁶³.

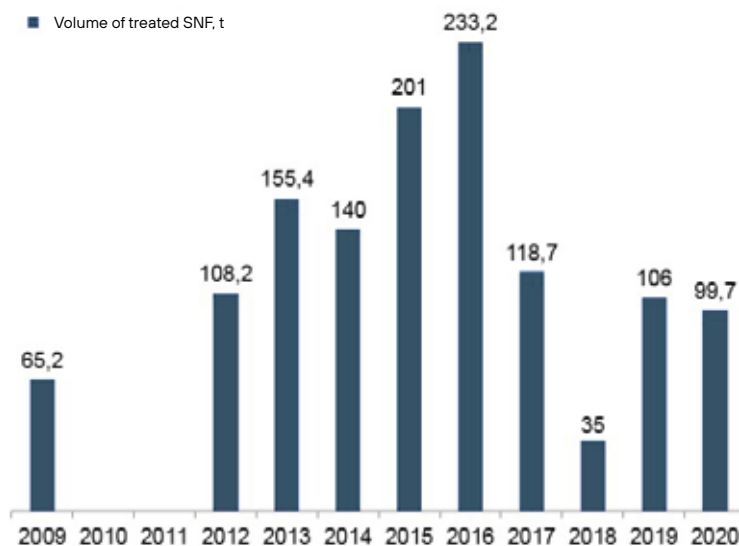


Figure 2. Volume of treated SNF at Mayak in 2009-2020.

⁶¹ Gorn V.F. and others. PA "Mayak": Development perspectives of the technologies at the plant RT-1. 2012. <https://www.atomic-energy.ru/technology/33253>

⁶² <https://xn---2030-bwe0hj7au5h.xn--p1ai/>

⁶³ <https://nucleus.iaea.org/sites/connect/SFMpublic/Rosatom/%D0%9F%D0%B5%D1%80%D1%81%D0%BF%D0%B5%D0%BA%D1%82%D0%B8%D0%B2%D1%8B%20%D0%A0%D0%B0%D0%B7%D0%B2%D0%B8%D1%82%D0%B8%D1%8F%20%D0%A0%D0%B0%D0%B4%D0%B8%D0%BE%D1%85%D0%B8%D0%BC%D0%B8%D1%87%D0%B5%D1%81%D0%BA%D0%BE%D0%B3%D0%BE%20%D0%9F%D1%80%D0%BE%D0%B8%D0%B7%D0%B2%D0%BE%D0%B4%D1%81%D1%82%D0%B2%D0%B0%20%D0%A4%D0%93%D0%A3%D0%9F%20%D0%9F%D0%9E%20%D0%9C%D0%B0%D1%8F%D0%BA%20-Opports%20Develop%20Radiochem%20Production%20MAYAK.pdf>

Summarily from 1971 at the RT-1 for processing over 2400 tons of SNF from foreign NPPs from 7 countries, mainly with VVER-440 reactors, as well as from 2006 around 1,200 tons of highly enriched uranium fuel of experimental reactors from 13 countries. In 2022 at foreign NPPs over 25,000 tons of nuclear waste of Russian origin remained⁶⁴.

Regenerated uranium

Regenerated uranium is actively used as a secondary fuel resource in Russia. It is mainly obtained in processing fuel of VVER-440 reactors at the RT-1 factory of the Mayak combine and is used for manufacturing fresh fuel for RBMK-1000 reactors with an enrichment of around 2.8%⁶⁵. Conversion and enrichment of regenerated uranium is carried out at the Siberian chemical combine, and manufacture of fuel at AO MCZ. According to assessments of the International nuclear association, in Russia around 2,500 tons of regenerated uranium was used repeatedly in Russia for fuel manufacture⁶⁶.

REMIX-fuel

Considering the gradual phasing out of RBMK reactors and the move to a dual-component atomic energy combining fast and water pressure reactors, a more promising method of using regenerated nuclear materials in thermal reactors in Russia is considered to be REMIX-fuel. This fuel, in which an unseparated mixture of uranium and plutonium is used, with a plutonium content of up to 2-3%, separated from processed nuclear fuel, with an addition of enriched uranium – up to 17-20% by mass with enrichment of 19.75% by uranium-23⁶⁷. The repeat processing of spent REMIX-fuel according to theoretical assessments⁶⁸ is possible at least 5 times.

REMIX-fuel has already been tested on existing energy blocks. In 2021, a five-year program of experimental industrial tests was ended (lead test rods stage), when at unit №3 of the Balakovsky NPP with reactor VVER-1000 three experimental TVS were used, which had six experimental REMIX fuel rods. These fuel rods processed three cycles of radiation of 18 months each in total⁶⁹.

After this, at the end of 2021, the stage of lead test assemblies testing began. At energy block №1 at the Balakovsky APS six fuel rod arrays, fully equipped with fuel rod elements with uranium-plutonium fuel composition of REMIX-fuel. They are also supposed to process three cycles of 18 months each⁷⁰.

⁶⁴ <https://nucleus.iaea.org/sites/connect/SFMpublic/Rosatom/%D0%9F%D0%B5%D1%80%D1%81%D0%BF%D0%B5%D0%BA%D1%82%D0%B8%D0%B2%D1%8B%20%D0%A0%D0%B0%D0%B7%D0%B2%D0%B8%D1%82%D0%B8%D1%8F%20%D0%A0%D0%B0%D0%B4%D0%B8%D0%BE%D1%85%D0%B8%D0%BC%D0%B8%D1%87%D0%B5%D1%81%D0%BA%D0%BE%D0%B3%D0%BE%20%D0%9F%D1%80%D0%BE%D0%B8%D0%B7%D0%B2%D0%BE%D0%B4%D1%81%D1%82%D0%B2%D0%B0%20%D0%A4%D0%93%D0%A3%D0%9F%20%D0%9F%D0%9E%20%D0%9C%D0%B0%D1%8F%D0%BA%20-Opports%20Devolopt%20Radiochem%20Production%20MAYAK.pdf>

⁶⁵ <https://vant.ippe.ru/images/pdf/2020/issue2020-3-63-67.pdf>

⁶⁶ https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.aspx?fbclid=IwAR3yM3Z26OqAL5zjCFbi7OX3PQC33jg1B_P_P0k51kXybdyUctMYDkqM2oE

⁶⁷ <https://www.fips.ru/cdfi/fips.dll/ru?ty=29&docid=2702234>

⁶⁸ <https://static.nuclear-power-engineering.ru/articles/2016/01/11.pdf>

⁶⁹ <https://rusatom-energy.ru/media/rosatom-news/na-balakovskoy-aes-zavershilis-ekspluatatsionnye-ispytaniya-tvelov-s-remiks-toplivom/>

⁷⁰ <https://www.rosatom.ru/journalist/news/v-reaktor-energobloka-1-balakovskoy-aes-zagruzhen-pervaya-partiya-remiks-topliva/>

MOX-fuel

MOX-fuel is nuclear fuel of a mixture of uranium and plutonium oxides. In 2022 in Russia MOX-fuel is used in one reactor – in the BN-800 fast reactor at unit № 4 of the Beloyarsky NPP. Initially the BN-800 was designed for working with MOX-fuel, but delays with serial manufacture of the fuel did not make this possible.

BN-800 was first attached to the network at the end of 2015 in a hybrid active zone, partially equipped with uranium fuel produced by AO MCZ, partially by experimental MOKS-assemblies, manufactured at the Scientific research institute of atomic reactors (Dmitrovgrad). The industrial manufacture of MOKS fuel began in early 2018 at the Mining chemical combine. From 2020 the BN-800 began to load serial assemblies, and in September 2022, after the latest load of fuel, the reactor was launched entirely in the active zone with MOKS fuel⁷¹.

MOKS fuel for BN-800 is manufactured from completely secondary resources – plutonium extracted from reprocessed nuclear fuel VVER-440, and supplies of depleted uranium, accumulated from the enrichment production. The complete load of fuel at BN-800 is around 16 tons. The plutonium content in fuel is around 20% by mass⁷². According to assessments of Rosatom, the work of BN-800 on MOKS-fuel economizes 300 tons of natural uranium per year⁷³.

Spent fuel processing waste. Since 1987 a complex of glassing of VAO has been put into operation. In special electrical ovens, highly radioactive waste (HRW) is immobilized and placed in a special aluminophosphate glass. By the end of 2020 all five electrical stoves used at the plant were stopped. Liquid HRW in the period of an absence of functioning electric stoves is gathered in vessels for temporary storage. Over the entire work of the complex, by the end of 2020 over 34,000 m³ of HRW were processed, with around 7,721.5 tons of vitrified HRW, with an activity of 787.2 Ci.

The existing volumes of processing spent nuclear fuel in Russia are currently significantly behind the speed of its formation. According to various estimates, the annual volume of formation of SNF at Russian atomic power stations is from 650–700 t⁷⁴ to 770 t per year⁷⁵, which also coincides with our own assessments (see table 5) – up to 800 t/year.

The summary volume of SNF accumulated in Russia for 2022 is close to 27,000 tons⁷⁶.

⁷¹ https://www.tvel.ru/press-center/news/?ELEMENT_ID=9378

⁷² https://www.gen-4.org/gif/upload/docs/application/pdf/2019-01/gifiv_webinar_pakhomov_19_dec_2018_final.pdf

⁷³ <http://www.atominfo.ru/newsz05/a0788.htm>

⁷⁴ https://www.youtube.com/watch?v=UDJ_N41dQmE

⁷⁵ <http://atominfo.ru/newsz05/a0500.htm>

⁷⁶ <http://atominfo.ru/newsz05/a0500.htm>

Table 5. Assessment of volumes of SNF formed at NPPs in Russia

Reactor type	Number of reactors in Russia	Average consumption in fuel per reactor, t/year	Summary consumption in fuel for given type of reactor, t/year	Features
VVER-440	5	7,5	38	
VVER-1000	13	23	300	
VVER-1200	4	25	100	
RBMK-1000	8	42	334	Use of regenerated uranium + afterburning of fuel assembly from remaining reactors
BN-600	1	6	6	Enrichment of 17/21/26%
BN-800	1	8	8	MOX-fuel
EGP-6	3	1	3	
KLT-40S	2	0,5	1	Enrichment to 20%
TOTAL	37		794	

Over recent decades and at present, at GKKh a single complex for treatment of SNF is being created, including wet and dry centralized SNF storage facilities, new facilities for processing spent fuel, complexes for fabrication of MOX fuel for the BN-800 reactor, as well as a system of treating radioactive waste, including a liquid salt reactor for afterburning minor actinides and an underground laboratory for the future deep burial of radioactive waste.

Since 1985, a wet storage facility has functioned at GKKh for SNF of VVER-1000 reactors, where fuel is stored both of Russian NPPs, and NPPs of Ukraine and Bulgaria. The total capacity of the storage facility is up to 8500 tons of SNF. By 2015 dry storage facilities had been built at GKKh and put into operation for SNF of VVER-1000 and RBMK-1000⁷⁷.

In 2015⁷⁸ the first launch of the first stage of the experimental demonstration center for processing SNF of a capacity of up to 5 tons per year took place at GKKh. The construction of the second stage of the center with a capacity of around 250 t is currently underway, and is planned to be put into operation by 2025⁷⁹. The feature of the new plant will be a new technology for processing SNF, with formation of a much lower quantity of secondary radioactive waste, which is buried (at least 5 times less), the complete exclusion of formation of liquid radioactive waste and a lack of emissions of tritium and iodine waste into the air⁸⁰.

⁷⁷ <https://sibghk.ru/company.html>

⁷⁸ <https://sibghk.ru/activity/technological-complex-creating.html>

⁷⁹ <https://xn----btb4bfrm9d.xn--p1ai/about/events-program/direction1event1/>

⁸⁰ https://www.youtube.com/watch?v=UDJ_N41dQmE

To summarize the survey of the state and functioning of the nuclear fuel cycle,

it should be noted that the current structural, resource and technological basis of enterprises and organizations of Rosatom, which carry out the nuclear fuel cycle, cover the requirements of the Russian atomic sector and foreign contracts for the entire chain of the nuclear fuel cycle -from uranium production to treatment of SNF.

The limitation of the resource base and focus on future market niches have determined Rosatom's interest in closing the nuclear fuel cycle: use of regenerated uranium in various types of fuels, introducing REMIX fuel (from an unseparated mixture of uranium and plutonium) for VVER reactors, transfer of the world's largest sodium reactor BN-800 entirely to MOKS fuel. In a number of areas, such as fast reactors, Rosatom holds the leading position in the world.

An important distinguishing and unique feature of Rosatom's offers to foreign clients is comprehensive services on the entire chain of the NFC, including providing fresh fuel and utilization of radioactive waste for the entire life cycle of reactors and APS of Russian design.

Rosatom holds a significant percentage in world supplies of the NFC – 15% of supplies of uranium, 30% of services for conversion, 40% for uranium enrichment, 17% of nuclear fuel supplies. Up to half of these services are for Rosatom's own needs, but in a number of areas (for example enrichment and conversion), Rosatom is the largest supplier in the world.

After the invasion of Ukraine in February 2022, the introduction of sanctions against Russia and the reduction in western economies' dependence on Russia, gradual changes have also been observed in the nuclear fuel cycle. Russia has finally lost one of its largest foreign markets in the NFC – Ukraine. Furthermore, even without sanctions, almost all EU countries critically dependent on Russian nuclear fuel (Czechia, Bulgaria, Finland) acted independently and made the necessary agreements on a gradual transition to alternative supplies in the next 2-7 years.

We may assume that gradually the share of Rosatom on world markets in the NFC will drop, and access to the world market with new services and products will be complicated. Especially if sanctions are introduced on the Russian atomic sector, which as of early 2023 had not yet been declared.

Chapter III.

Energy, research and transport reactors

3.1. NPPs of Russia (operating, suspended, constructed and planned)

The owner and operator of all APS of Russia is the open joint-stock company Rosenergoatom Concern.

As of September 2022, at 11 NPPs of Russia 37 reactors were functioning, with a capacity of 29,577 MWt.

10 NPP reactors have been suspended, but none of them have completed the process of final decommissioning and utilization.

Four reactors (Baltic APS-1, Brest-OD-300, Kursk 2-1 and Kursk 2-2) are in the stage of construction. Construction of the Baltic NPP has been suspended, although the board for construction of this station is active and one of the branches in the structure of Rosenergoatom. The atomic block "Brest – OD – 300", construction of which began in June 2021, is being built as part of the "Proryv" project.

No plans have been announced to commence construction of new blocks of APS of major capacity in Russia for 2022-2023. At the Leningrad NPP-2 since 2022, preparatory works to construct the 7th and 8th blocks have been proceeding. Concrete pouring at the first of them is planned for 2024, and at the second for 2025.

The engineering division of Rosatom is at present working on the further improvement of design of NPPs on the basis of reactors of generation III+, as well as fast neutron reactors of generation IV (BN-1200 sodium cooled reactor, BR-1200 lead-cooled reactor). Rosatom work on improving the design of modern NPPs of large capacity is also directed towards increasing their life cycle to 100 years: – NPP construction – 5-7 years, – NPP functioning – 60 years; – decommissioning NPPs – 20-45 years.

Functioning and suspended NPP reactors

Russia currently holds fourth place in the world by the number of APS energy blocks in operation. The share of APS in the energy balance of Russia in 2022 came to 19.9% (223.371⁸¹ billion kWth of a total 1,121.5⁸² billion kWth). According to optimistic plans, the share of atomic energy is to be increased to 25% by 2045⁸³.

Of 37 NPP reactors currently operating, 22 work with VVER type reactors (13 VVER-1000 reactors, 4 VVER-1200 reactors, 5 VVER-440 reactors of various modifications), 11 energy blocks work with channel reactors (8 reactors of type RMBK-1000 and 3 reactors of type EGP-6), 2 sodium-cooled fast neutron reactors (BN-600 and BN-800). Additionally, 2 reactor turbogenerators of the “Academician Lomonosov” floating nuclear thermoelectricity station are in operation, reactor type KLT-40S.

Table 6. Overview of the Russian functioning and suspended NPP reactors

Name of NPP	Year of construction Year of decommissioning (extension)	Established capacity (MWt) as of 01.01.2022
Balakovsky NPP (VVER 1000) PU 1 PU 2 PU 3 PU 4	1985/(2045) 1987/(2043) 1988/(2048) 1993/(2053)	4000
Beloyarsky NPP PU1,2 PU 3 (BN-600) PU 4 (BN- 800)	Stopped 1980/(2040) 2015/2075 (plan)	1485
Bilibin NPP (EGP 6) PU 1 PU 2 PU 3 PU 4	Stopped 1975/(2025) 1976/(2025) 1977/(2025)	36
Kalinin NPP (VVER -1000) PU 1 PU 2 PU 3 PU 4	1984/ (2025) 1986/ (2038) 2004/-2064(unconfirmed plan) 2011/-2071(unconfirmed plan)	4000
Kola NNP (VVER 440) PU 1 PU 2 PU 3 PU 4	1973/ (2033) 1974/ (2034) 1981/ (2036) 1984/ (2039)	1760

⁸¹ <https://www.rosatom.ru/journalist/news/-rosenergoatom-aes-rossii-postavili-v-2022-godu-rekord-po-vyrabotke-223-371-mlrd-kvt-ch/>

⁸² https://www.so-ups.ru/fileadmin/files/company/reports/disclosure/2023/ups_rep2022.pdf

⁸³ <https://rosatom.ru/journalist/interview/a-likhachev-atomnaya-otrasl-mozhet-stat-osnovoy-perekhoda-k-nizkouglerodnoy-energetike/>

Kursk NPP (RBMK 1000) PU 1 PU 2 PU 3 PU 4	Suspended 1979/ (2024) 1983/ (2028) 1985/ (2030)	3000
Leningrad NPP (1,2,3,4 – RBMK 1000; 5,6 – VVER 1200) PU 1,2 PU 3 PU 4 PU 5 PU 6	Suspended 1979/ (2025) ? 1981/ (2026) ? 2018/- 2078 (unconfirmed plan) 2020/-2081 (unconfirmed plan)	4375,8
Obninsk NPP (AM-1)	Suspended	
Novovoronezh NPP PU 1,2,3 (VVER-210,-365,-440) PU 4 (VVER 440) PU 5 (VVER 1000) PU 6 (VVER 1200) PU 7 (VVER 1200)	Suspended 1972/ (2032) 1980/ (2036) 2016/ -2076 (unconfirmed plan) 2019/ -2080 (unconfirmed plan)	3778,3
Rostov NPP (VVER -1000) PU 1 PU 2 PU 3 PU 4	2001/2031 (unconfirmed plan) 2010/2040 (unconfirmed plan) 2014/2045 (unconfirmed plan) 2018/2048 (unconfirmed plan)	4071,9
Smolensk NPP (RBMK1000) PU 1 PU 2 PU 3	1975/ (2027) 1976/ (2030) 1984/ (2035)	3000
Floating NPP (KLT 40) PU 1 PU 2	2020/ ? 2020/ ?	70

Note: According to accepted procedure in Russia, at present the service period of VVER-440 and VVER-1000 is extended to 60 years, and RBMK-1000 to 45 years.

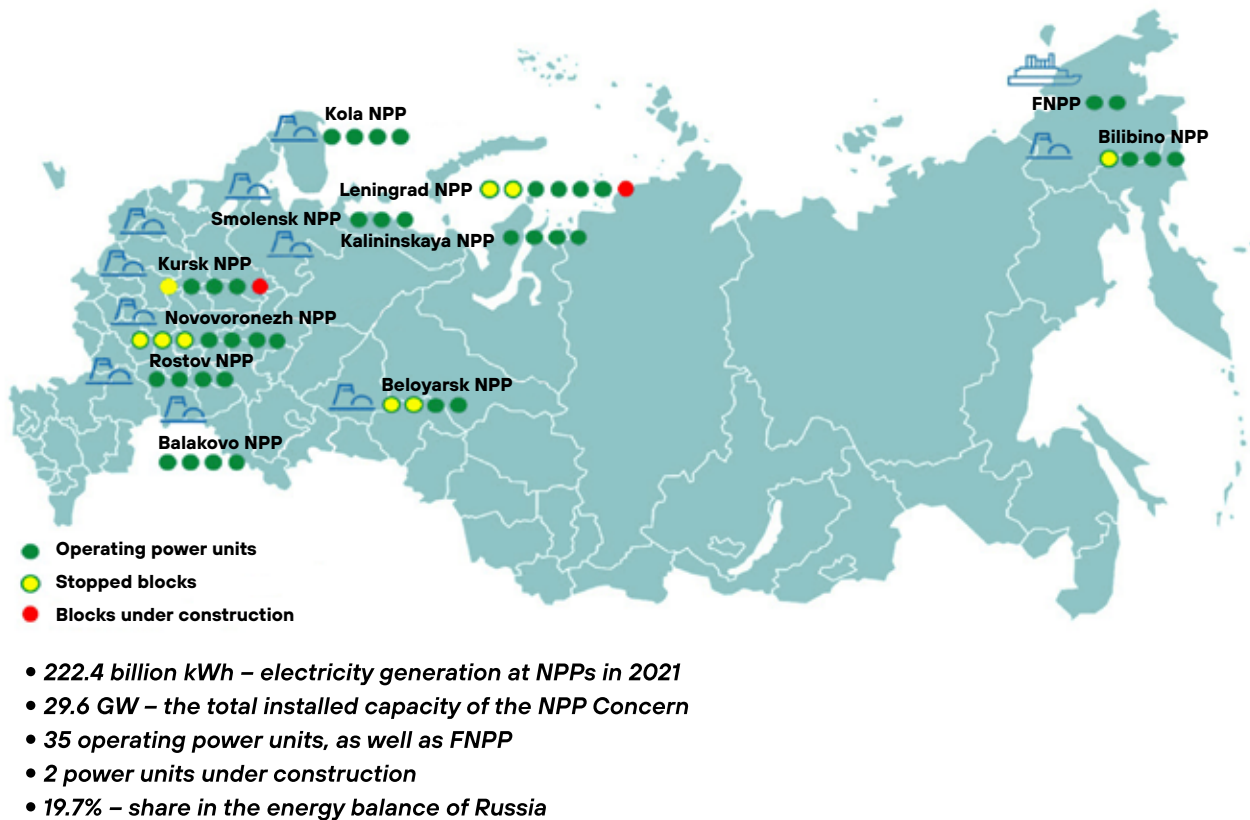


Figure 3. A map of the Russian NPPs

Special features of operating and suspended Russian reactors include the fact that of the 37 reactors operating at NPPs in Russia, 23 (almost 62%) are operated with an extended resource and operation period, which were established in the design and construction of these reactors.

All VVER-440, RMBK-1000 and EGP-6 work with an extended period. Of the 13 VVER-1000 six blocks have extended operation, but neither of the two BN. Only the VVER-1200 and KLT-40S work without extension. Of the 37 currently operating blocks in Russia, their average age is 29 (average work figure according to IAEA data 31 years⁸⁴).

Despite the extension of service periods of RMBK reactors to 45 years, by 2035 all remaining blocks of this type in Russia will be suspended. Like the three oldest VVERp-440 reactors, which by that time will have reached a service period of 60 years.

According to Bellona’s assessments, by 2035-2040 13 blocks of a total capacity of around 9.3 GWt will be suspended, and in the period from 2040 to 2045 around 4.5 GWt will be

⁸⁴ <https://pris.iaea.org/PRIS/WorldStatistics/OperationalByAge.aspx>

taken out of operation. From 2022 to 2045, for reasons of exhausted resources, almost 14 GWt will be taken out of operation. This means that unless new blocks are built to replace the suspended ones, by 2035 the total power of the atomic depot of Russia will drop by a third, and by 2045 almost by half from the current level of 29.5 GWt.

The graph below shows the plan for decommissioning NPP of Russia, taking into account the extension of operation periods of RMBK-1000 to 45 years, and VVER-440 and VVER-1000 to 60 years. Source – Bellona’s own calculations.

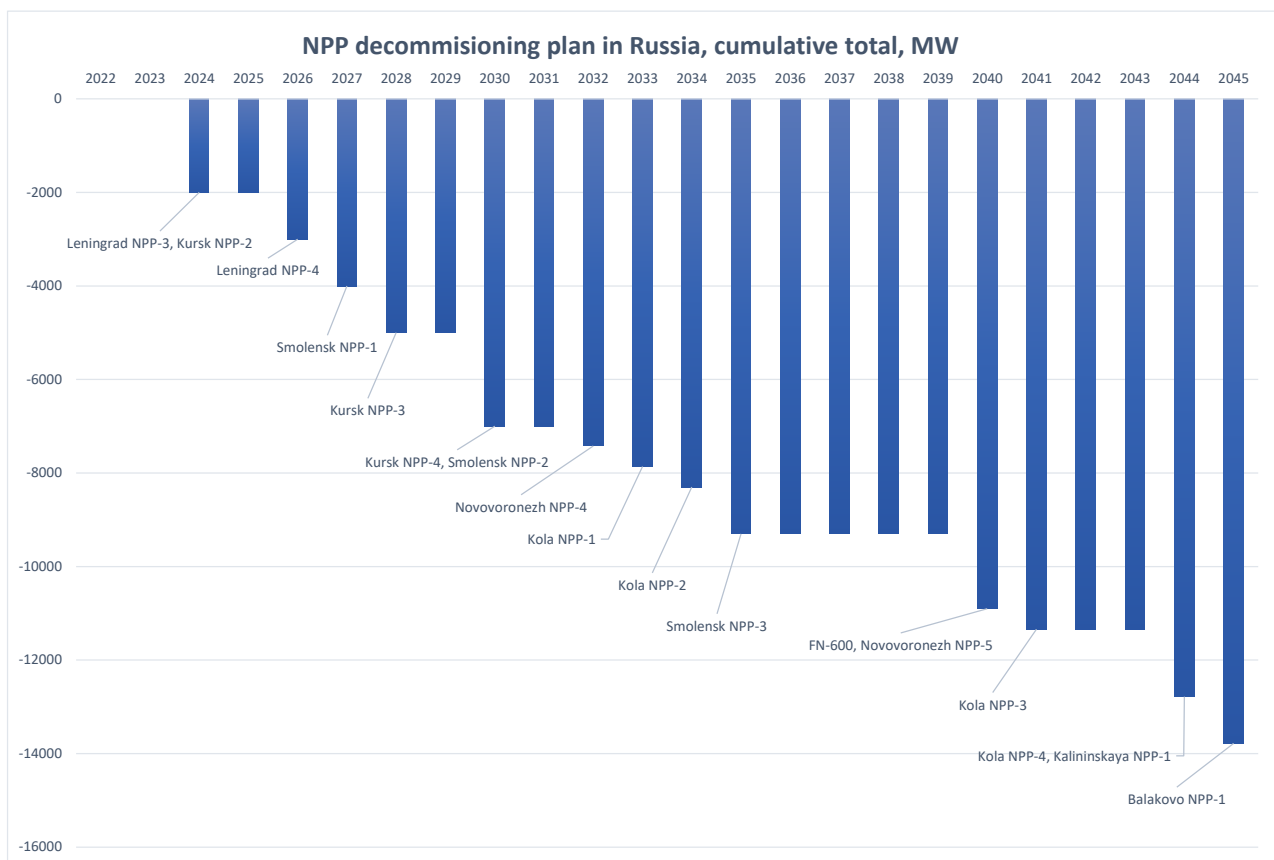


Figure 4. NPP decommissioning plan in Russia

Extending the service term of nuclear energy facilities is an international practice which is also followed in Russia. This is why there are so many energy blocks that are operated with an extended service period. The main issue which always concerns the interested public (including Bellona) in extending service periods of atomic power stations is safety. It is thought that old equipment, metal fatigue in the main equipment, and outdated technology may all create additional conditions for accidents to occur.

For example, in extending operation of reactors, it is impossible to change the philosophy of safety that was used in the project several decades ago and realized in these reactors. It is impossible to create a properly echeloned protection which blocks danger from human error and the combination of equipment malfunction and operators' mistakes. In other words, the on the old reactors it is impossible to install and tune many safety processes which "smart networks" of modern power units have, as 40-50 years ago the logic, technical and technological possibilities, and philosophy of how safety systems should work was different.

The bitter practice of incidents and accidents at atomic facilities (not only atomic power stations) has influenced changes and improvements. On the old power units with extended service periods (VVER-440 or RBMK-1000), it is impossible to install hermetic shells (containments), to place vessels above the reactor with a large amount of borium solution, which is poured into the reactor in accidents and neutralizes radioactivity if it arises, to install melt traps underneath etc. At the same time, some units of the second generation (VVER – 1000) have protective shells and borium reserves.

It should be noted that the extension process is strictly regulated and controlled by bodies of nuclear and radiation supervision. Extension is carried out with the involvement of constructors and manufacturers of equipment, who bear serious responsibility for decisions made. In extending the service period, practically all equipment that influences the nuclear safety of the power unit is subject to replacement, with the exception of the reactor vessel. Over the last decades, world scientific metallurgical institutes have made great advances, and today many methods of spectral and other analyses are used effectively in order to determine the state of the reactor vessel.

At present, a considerable number of technologies for firing and other methods have been developed and applied for restoring the metal quality of the reactor vessel. It should be noted that in assessing safety, it is important above all to watch and calculated the results of a probability analysis of safety, which is a generalized criterion of safety for all nuclear reactors.

The IAEA believes that in most cases, the extension of the service period of nuclear facilities is justified and corresponds to safety norms. Additionally, the IAEA believes that extending the NPP reactors raises the competitiveness of these electricity sources, and if the cost of extension work is lower than USD40/MWt/h, NPPs may compete with inexpensive solar photoelectric and wind electricity stations⁸⁵. In any case, expenses on extending the service period will always be lower than expenses for building new nuclear reactors, if of course profound modernization of the power units is not carried out, with replacement of all the main equipment, and not only what is important to ensure nuclear safety. But there are no examples of this kind in the world practice of extending service periods of power units. For many governments, the economic component is decisive in

⁸⁵ <https://www.iaea.org/reports/nuclear-power-and-secure-energy-transitions/executive-summary>

making decisions on using atomic energy in their countries. For ecological organizations, including Bellona, the level of safety is usually determinative, but this is always a question of compromise, as absolute safety does not exist.

Tem power units on 6 Russian NPPs have been fully suspended, but on none of them the process of final decommissioning and utilization has been completed, if one does not count the world's first NPP in Obninsk, which was finally decommissioned in 2002 and converted into a museum complex.

In the structure of Rosenergoatom, two branches were created on the basis of the Novovoronezh and Leningrad nuclear power plants, which develop technology for decommissioning, accordingly EB VVER – 400 and RMBNK (ODITs VVEER and ODITs RBMK). Furthermore, on the basis of SKhK (Seversk) in 2010, the “Experimental demonstration center of uranium-graphite reactors” was created, which developed technology and realized the first project to decommission small industrial uranium-graphite reactors.

For many reasons, the issue of decommissioning suspended power units of large capacity is rather slow. Firstly, this is because historically, Rosatom did not prepare for this important and rather complex process. Funds for decommissioning were never created in the USSR (or subsequently in Russia), and accordingly today there is no targeted money for this or elaborated technologies. Only in 2010 was the first scientific practical group created (ODTs UGR), which began to develop technologies for decommissioning small industrial (not large energy) reactors).

The concept of decommissioning large power units was developed and approved only in 2015, i.e. at present measures for decommissioning specific units is only in conceptual development. The only practical step which is made at all suspended power units is the unloading of nuclear fuel from reactors and placing it in storage facilities. Such issues as where radioactive waste will be moved and buried, along with contaminated radioactive equipment accumulated in the process of disassembly, and what the final goal of decommissioning specific energy blocks will be – the formation of a “green” or “brown” meadow”, or a “postponed decision” and a number of other issues, remains unclear at present.

Here it should be noted that suspending reactors is only the start of the process of decommissioning power units, and the end of the process is when the power units is excluded from the balance of Rosenergoatom and the territory on which the power units is located is transferred to the balance of the appropriate territorial formation or appointed organization. Furthermore, it is possible to use these sites for building new units.

Power units under construction and planned for construction. A decree of the Russian government of 2016 stated that by 2030, Russia would build 11 new nuclear reactors for the production of electricity.

At present (late 2022) four projects are being realized in Russia for the construction of large energy blocks – Kursk 2-1 and 2-2 with VVER-TOI reactors, the reactor Brest – OD – 300. The Baltic NPP (<https://www.baltaes.ru/>) is “frozen”, and while the board for building the NPP has not been dissolved, in all likelihood, there are no prospects for building this NPP in the current geopolitical situation.

The power units Kursk 2-1 and 2-2 of the TOI type with fast turbines are promising, according to Rosatom assessments. Their readiness as of 1 January 2022 was around 37.5%.

Construction of a fast reactor with lead cooling and an on-site fuel cycle BREST-OD-300 as part of the “Proryv” project began in June 2021, and construction is planned to be completed by 2026–2027. “Proryv” (or “breakthrough” in English) is a separate project of the engineering division of Rosatom, directed towards developing technologies for closing the nuclear fuel cycle, which raises many issues and even doubts among experts at present. The declared main goal of the Proryv project is to raise the efficiency of using natural uranium and liquidate the nuclear legacy, i.e. to “burn” spent nuclear fuel in the Brest reactor, which was accumulated in the work of heat reactors.

In future years, Rosatom plans to begin the construction of four major power units in Russia. In early 2023, preparatory work is underway in the place of construction of the 3rd and 4th units of the Leningrad NPP-2 with VVER-1200 reactors. The first concrete pouring is scheduled for 2024 and 2025, and physical launch for 2030 and 2032⁸⁶, respectively.

In 2022, development was carried out for planning documentation and engineering surveys on the site of future construction of the Smolensk NPP-2 with the two power units VVER-TOI with a summary capacity of 2510 MWt. According to the “roadmap” approved in 2020, in 2024 it is planned to receive a license for construction, and from 2027 to start building the power units⁸⁷.

Furthermore, according to an announcement in 2021, in 2028 it is planned to start construction of the dual-unit Kola NPP-2 with VVER-600S reactors with spectral regulation⁸⁸.

⁸⁶ <https://tass.ru/ekonomika/15516381>

⁸⁷ <https://www.rosatom.ru/production/design/stroyashchiesya-aes/>

⁸⁸ <https://www.rosatom.ru/journalist/news/kolskaya-aes-nachalo-stroitelstva-kolskoy-aes-2-namecheno-na-2028-god/?fbclid=IwAR0dYbljsqQJgbSmRL00cwTYHeYCR0SAFbJdJPbYoQ2M2STeABM2rCYLogI>

These projects are included in the General plan for power facilities until 2035⁸⁹, approved by the Russian government in 2017. In the basic scenario of the plan, besides the units mentioned above, another 7 major units of VVER-TOI and one BN-1200 are included, both at current and new sites, but they are planned to be into operation in 2030-2035. According to the basic scenario of the plan, taking into account the added plans to build an additional unit at the Kola NPP (plans to construction two units have been announced, although one is indicated under the general plan), and a series of SMR. By 2035 it is planned to put into operation around 17 GWt of new atomic facilities.

There are grounds to believe that the basic scenario of the General plan will not be realized according to schedule, or to the full extent. The first 4 VVER-1200 units, two at the Leningrad NPP-2 and at the Novovoronezh NPP-2, were built within the period indicated in the General plan, with connection to the electricity network in the period from 2016 to 2020. However, the units currently being built at the Kursk NPP-2 and the units that are being prepared for construction at the Smolensk NPP-2 and the Leningrad NPP-2 are already lagging behind the schedule by a period from 1 to 5 years.

However, besides the major units contained in the general plan, in recent years plans have emerged to build a series of small floating NPPs. This allows the management of Rosatom to publish plans for new construction. In September 2021, at a general conference of the international agency for nuclear energy, the head of Rosatom Alexei Likhachev announced to journalists that by 2035 around 15 new reactors would be put into operation in Russia. "We will gradually decommission Soviet reactors built in the 1970s," he said. "By 2035 they will be replaced by around 15 new reactors".

Despite these statements, Russia's plans for developing nuclear energy should be regarded with some doubt, especially considering the changes in geopolitics and economy which began to take place in the world and in Russia after 24 February 2022. Taking into account the delays in construction and economic slump, and accordingly the decreasing demand for electricity expected in Russia since the invasion of Ukraine, plans for developing Russian energy, including nuclear energy, may be reduced.

At a meeting on energy by the Russian government in January 2023, the initial figures were announced on the adjusted general plan, which proposes the construction of around 12 GWt of new nuclear facilities, which corresponds to the minimum scenario of the General plan for 2017. Thus, plans for new construction are already been downscaled.

⁸⁹ <http://static.government.ru/media/files/zzvuuhfq2f3OJIK8AzKVsXrGlbW8ENGp.pdf>

3.2. Reactors of low and medium capacity

Reactors of low and medium power, as well as microreactors are planned and built for use at land and water based civil atomic power stations of low capacity, vessels of civilian and military purpose, special sites (space RITEGs), land transport, underwater etc.) as well as in scientific research and educational institutions.

Low-capacity nuclear plants. According to the classification of the International Agency of Atomic Energy (IAEA), LCNP and SMR (small modular reactors) are stations with an electricity capacity of up to 300 MWt. Although this division is rather arbitrary, and they often include medium capacity NPP – up to 700 MWt. Additionally, there is a separate classification of micro-NPPs up to 10 MWt.

We may assume that Russia's nuclear energy sector in Russia may make the construction of LCNP a priority. Perhaps this would be a logical decision, given the enormous Siberian and Far Eastern territory of Russia, which must be developed without creating large and powerful electricity lines or large settlements given the difficult climatic conditions and poor land transportation routes. But here other tasks must be solved, for example logistics, creating developed hubs of air or water transport for ensuring the construction, operation and safe functioning of LCNP.

In June 2021, the Russian government approved the federal program "New nuclear energy, including small atomic reactors for remote territories" (hereinafter the Program). On 11 February 2022, the Russian government passed a decision on additional financing, after which the total cost of this program came to 96 billion rubles⁹⁰.

A key area of the program is building LCPS. Under this program, it is planned to bring the capacity of LCNP to 350 MWt by 2030. This will mean that Russia will occupy 20% of the world market of small capacity atomic power stations and 24% of the market of nuclear fuel.

The first project for a land-based LCNP base with the RITM-200 reactor will be realized in the Far East of Russia, in Yakutia. According to this plan, the LCNP will be put into operation in 2028. It will serve as a source of energy for development and operation of the Seligdar gold field Kyuchus in the northeast of Russia in the Republic of Sakha (Yakutia). The cost of the project has not yet been announced, but if the cost is estimated based on the floating NPP with a RITM-200 reactor, then a single-block NPP with this reactor will cost at least 24 billion rubles (USD 320 million).

⁹⁰ <http://static.government.ru/media/files/ENAjmvZYARitZ1xlr9GDdXycklAX18XB.pdf>

The nature of the KLT-40 and RITM-200 reactors is the ability to work in a maneuverable regime, with a fast rise and drop of capacity, and greater fuel enrichment than ordinary VVER – up to 20% instead of 5%. High enrichment means fuel can be loaded less frequently. For example, the KLT-40 reactor on “Academic Lomonosov” will have to be recharged once every 3-4 years depending on the type. Reloading of fuel at the RITM-200 reactor will take place once every 10 years. In reloading this reactor, fuel from the entire active zone will be replaced.

This interval between loads for RITM-200 will make it possible to combine this procedure with repairs and hauling NPP to the factory base. This eliminates the need for temporary storage of SNF at the station, and simplifies procedure for treating waste by the operating organization.

Future floating NPPs will have new reactors. Construction is currently underway of four more floating power units with RITM-200 reactors with a capacity of 55 MWt and a service period of up to 60 years. Unlike KLT-40, which had a block design (elements of the first contour side by side, but not in one vessel), RITM-200 has an integral design, so it is almost twice as light and compact, but more powerful.

The price of the contract for 4 floating NPPs with RITM-200 is 190 billion rubles in total, i.e. capital expenses for the floating NPP are around USD 6000/kWt of capacity (based on an exchange rate of around 75 rubles to the dollar). This is slightly higher than for an ordinary Russian NPP with VVER-1200 – up to USD 4500/kWt, but lower than for European projects of the EPR-1600 type – from USD 7500/kWt (see table 7).

Table 7. Capital expenses of several NPPs

Type of reactor	NPP and price	Cost \$/kWt
VVER-TOI (1255 MWt)	Akkuyu, Turkey. 4 reactors for USD 22 billion ⁹¹ .	4400
VVER-1200 (1200 MWt)	Belarussian NPP. Two reactors for USD 10 billion ⁹² .	4200
EPR-1600 (1600 MWt)	Olkiluoto-3, Finland, 1 reactor for USD 12 billion ⁹³ .	7500
	Flamanville03, 1 reactor for USD 14.4 billion ⁹⁴	9000
	Hinkley Point C, UK, 2 reactors for USD 30 billion ⁹⁵ .	9400

⁹¹ <https://interfax.com/newsroom/top-stories/73638/>

⁹² https://www.ng.ru/ng_energiya/2016-01-12/14_belorussia.html

⁹³ <https://yle.fi/a/3-12356596>

⁹⁴ <https://www.reuters.com/business/energy/edf-announces-new-delay-higher-costs-flamanville-3-reactor-2022-01-12/>

⁹⁵ <https://www.bbc.com/news/uk-england-somerset-61519609>

In 2011, Rosatom announced the cost of building the floating NPP “Academic Lomonosov” at 16.2 billion rubles⁹⁶. According to data published in 2016, the cost increased to 21.5 billion rubles⁹⁷. Final data on the cost have yet to be published.

It should be noted that all these plans were drawn up and approved before Russia invaded Ukraine. For example, plans for the Baimsky field, for which it was planned to build 4 floating NPPs, and for Kyuchus, focused on export production of gold. But because of sanctions this export dropped drastically, and so today these projects are in question.

Transport – mainly sea-based reactors which are used in atomic energy facilities of surface and underwater vessels of civic and military purpose.

For civic purposes, low-capacity reactors began to be used widely in the USSR on atomic icebreakers and submarines from the late 1950s. Over this time four generations of atomic reactors were used on icebreakers: OK-150 (“Lenin”, 1957), OK-900A (“Arktika”, pr. 10520), KLT-40 (“Taimyr”, pr. 10580), RITM-200 (UALy pr. 22220 from 2019). Submarines and atomic surface vessels of the navy, there are even more different types of small reactors used for energy in these vessels. Some of them are quite unique. They are mainly high water pressure reactors, and there have also been some projects with liquid metal coolers.

Experimental reactors – these are nuclear reactors used in spheres of scientific research, developments, education and personnel training. At present, according to IAEA, there are 124 experimental reactors of various types and purposes in Russia, of a capacity from 0.1 to 200,000 kWt. Some of these low-capacity reactors are in the category of so-called subcritical and critical assemblies, i.e. devices for experimental study of characteristics and parameters of a multiplying neutron environment.

All of these reactors are in different states. Fifty are operating, while the others are in “temporary shutdown”, “extended shutdown”, “decommissioned” or “decommissioning”. Around 90 of the 124 reactors are located in Moscow, the Moscow region and Obninsk, and the others are in other regions of Russia, mainly in Dmitrovgrad and in closed cities of Rosatom. According to IAEA data, several dozen experimental reactors are in shutdown and have been scheduled for final utilization for a long time.

Russia is working on replacing its experimental fast reactor BOR-60 at the Scientific Research Institute of Atomic Reactors in Dmitrovgrad near Ulyanovsk, where the reactor was launched in 1969. It will be replaced by an MBIR reactor of a capacity of 150 MWt with sodium cooling, a fast neutron reactor with a calculated service period of 50 years. Rosatom claims that the reactor will be ready for operation in 2027⁹⁸.

⁹⁶ http://www.bellona.org/filearchive/fil_fnpp-en.pdf

⁹⁷ <http://bellona.org/news/nuclear-issues/nuclear-russia/2016-01-russian-floating-nuclear-power-plants-port-to-cost-58-million>

⁹⁸ <https://www.world-nuclear-news.org/Articles/Completion-of-MBIR-reactor-brought-forward>

The multipurpose fast neutron reactor (MFNR) can use lead, lead-bismuth and gas coolants, working on MOX-fuel (a mixture of uranium oxide and plutonium). The NIIAR intends to create a closed nuclear cycle facility at the MFNR using pyrochemical developments elaborated on an experimental industrial scale. The company responsible for building the experimental reactor is AEM-Technology. It was planned to launch the MFNR project for foreign cooperation together with the International Atomic Energy Agency's international project for nuclear energy for innovative nuclear reactors and fuel cycles)⁹⁹. However, it is unlikely that these plans will be realized in the near future owing to geopolitical and economic problems.

To summarize, it should be noted that in Russia there are around 250 nuclear reactors (counting nuclear reactors of military function) of various capacity, function and at different stages of the life cycle. The reactors of large NPPs are rather old, 62% of power units operate with an extended resource, and 10 power units are in the process of decommissioning.

At present, the accepted practice is to extend the operation period of VVER-440 reactors (at the Kola NPP) to 60 years, RBMK-1000 reactors to 45 years. VVER-1000s have a planned service period of 30 years, but like the VVER-440 they will probably be extended to 60 years. At present, the oldest VVER-440 unit (unit №5 of the Novovoronezh NPP) is just over 40 years old. The BN-600 reactor will also be extended to 60 years, according to the plan. Nevertheless, even if these extension periods are kept and replacement units are not built, by 2035 the total number of nuclear reactors in Russia will drop by a third, and by 2045 by almost half of the level of 2022.

The system for decommissioning NPP and other atomic facilities may be assessed as rather incomplete for several reasons, including organizational, structural, economic, technological etc. Therefore, in the medium-term perspective, decommissioned units will be a heavy burden on the entire nuclear industry. The rates of replacing old units with new ones is rather slow and evidently assumes that nuclear energy should have a real percentage of 18-20% in Russia's energy balance.

In 2022 active construction of just two major VVER-TOI reactors with a capacity of 1250 MWt at the Kursk NPP-2 was underway. For another four reactors at the sites of the Leningrad NPP-2 and the Smolensk NPP-2, preparation is underway for receiving permissions and starting construction work over the next 5 years. However, these projects are being realized with a delay in previously scheduled plans. These plans, described in government documents, envisaged construction up to 2035 of up to 17 GWt of new atomic capacities. However, the present geopolitical situation will probably put restrictions on these plans. According to preliminary figures announced by the Russian government in early 2023, these plans have already been downscaled to just over 12 GWt.

⁹⁹ <http://www.world-nuclear-news.org/NN-Russia-starts-to-build-MBIR-vessel-27031702.html>

According to IAEA data, in Russia 17 projects of small-capacity energy reactors are being developed. At present in Russia, of actually working SMR there are only two KLT-40S units on the floating NPP "Academic Lomonosov" in the Far East of Russia in the Chukotka autonomous district, in Pevek, which should replace the Bilibin NPP, which is scheduled for decommissioning from 2025.

A rival for LCNP may be renewable energy resources, which have a low cost and ease of construction that may be a determining factor in decision making.

The issue of building and using floating NPPs still looks rather dubious, although Russia has wide experience and good results in creating sea-based transportable nuclear reactors on icebreakers and nuclear-powered vessels. The experience of creating the first floating NPP cannot be assessed positively, mainly because of the length of construction and its cost. But even this is not the most important thing. The main questions are why and for what regions these energy units need to be built, where a system of technical support can be created (reloading reactors, current, dock and capital repairs etc.) as well as how to replace a floating NPP that is removed for repairs or docked.

The idea of building floating NPPs for export is problematic and raises concerns for ensuring nuclear, radiation and physical safety, and the unacceptability of uncoordinated and uncontrolled spread of nuclear technologies and materials in politically and economically unfavorable and unstable regions of the world.

However, despite all the doubts and uncertainties, in January 2021 the general director of Rosatom Alexei Likhachev confirmed Rosatom's intention to continue building a floating NPPs, announcing that "we are developing with the government a flotilla of floating atomic stations, and I hope that this plan will be passed in 2021"¹⁰⁰.

But no such plan exists to this day. The situation for Russia, primarily economically and geopolitically, is drastically changing for the worse, so Rosatom's prospects for building floating NPPs over the coming decades are unclear.

¹⁰⁰ <https://www.atomic-energy.ru/news/2021/01/11/110347>

Chapter IV.

Foreign projects of the Russian nuclear industry

Generally, Russia remains an important player in the international nuclear business. Rosatom in late 2021/2022 held first place in the world by the number of blocks under construction abroad and by uranium enrichment (40% of the market), second place in uranium production (if one includes the joint production of the ARMZ and Uranium One companies among uranium producing companies^{101,102}), and third place for deliveries of uranium fuel.

Before the start of the war with Ukraine, two countries dominated in the international system of agreements on cooperation in the nuclear sphere, Russia and the USA. After the war began, several western countries began to reject Russian energy resources and projects, including projects of nuclear energy. The first was a Finnish consortium, which on 2 May 2022 announced the annulment of a contract for construction of a reactor of Russian design with a capacity of 1200 megawatts in Finland.

However, despite this situation Russia continues to dominate in international construction of NPPs, with around 40% of the total number of agreements for construction. At present, Rosatom is working in Europe, in the Middle East, in North Africa, as well as in the Asia and Pacific region. As of early 2022, Rosatom had 152 companies of various fields in 41 countries around the world. Among these enterprises, a special role was played by the 14 offices of Rosatom managed by the private institution Rusatom – International Network, realizing various sector functions abroad, including the construction of several NPPs. Additionally, the company Atomstroieksport continues to function.

¹⁰¹ https://www.report.rosatom.ru/go/rosatom/go_rosatom_2021/rosatom_2021_ru.pdf

¹⁰² <https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx>

In October 2014, Rosatom opened a western European operations center, founding the French affiliated company ROSATOM Western Europe SARL. The geographical zone covered by this company includes Belgium, Austria, the UK, Germany, Greece, Spain, Italy, the Netherlands, Norway, Portugal, Finland, France, Sweden and Switzerland.

In early 2022, the portfolio of western orders of Rosatom for a ten-decade period was USD 139.9 billion, including 84 billion for building NPPs in various countries. Building NPPs in developing countries such as Bangladesh and Egypt is accompanied by creation of social infrastructure (roads, bridges and other objects). In 2022, Rosatom planned to invest around 6 billion rubles in these countries for creating and developing publicly significant objects.

Bellona believes that as a consequence of the war with Ukraine, the international activity of Rosatom will decrease. In countries where Rosatom has major and long-term effective contracts for building NPPs, which it is difficult to annul or change, the situation is unlikely to change quickly, but at the same time everything will depend on the geopolitical situation. Small projects that have been noted in several Asian, African, South American countries and former Soviet republics that involve the creation of joint centers of nuclear science and technologies (Vietnam, Kyrgyzstan, Kazakhstan, Armenia, Ethiopia, Zimbabwe, Burundi, Nicaragua, Costa Rica etc.) may slow down, especially if Rosatom reduces its representative offices abroad.

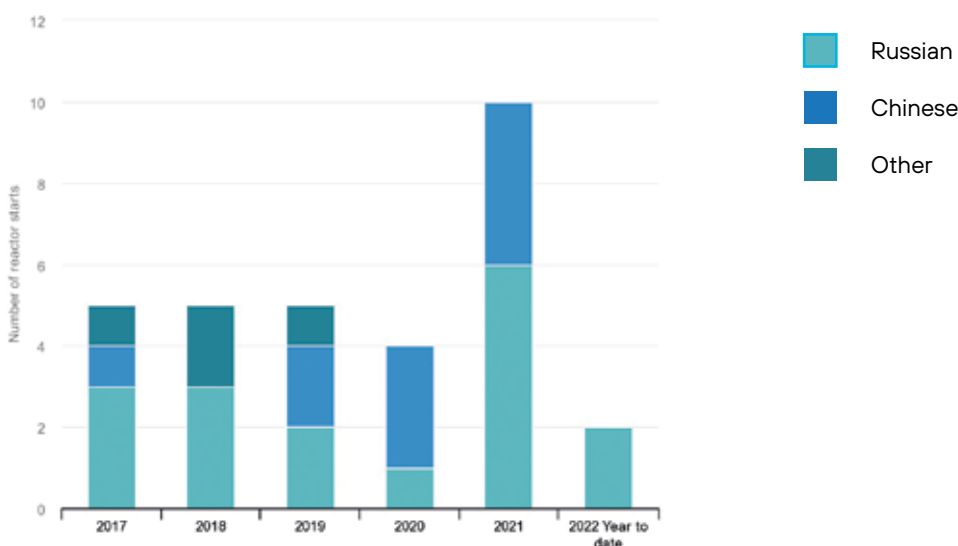


Figure 5. Of the 31 reactors which commenced construction from early 2017, all but 4 have Russian or Chinese design. Source¹⁰³.

At present, the main real and potential competitors on the international market for NPP

¹⁰³ <https://www.iea.org/reports/nuclear-power-and-secure-energy-transitions/executive-summary>

planning, engineering and construction are companies from South Korea (Korea Electric Power Corp), China (China National Nuclear Corp, China General Nuclear Power Corp, State Power Investment Corporation), France (EDF Group⁷), the USA (Westinghouse Electric Company LLC) and Japanese-American companies (General Electric Co. and Hitachi Ltd).

4.1. Construction of NPPs abroad

Foreign projects for construction of new NPPs have always been a priority for Rosatom compared with other projects. This may be explained by the fact that for the political leadership of Russia, Rosatom is a department which is actively used for achieving geopolitical as well as economic goals. The construction of nuclear power stations, acquiring foreign uranium-producing and other companies, opening its own scientific, educational and commercial branches abroad – all of this is directed towards increasing its influence on the economy, energy sphere and as a result the political situation of the countries where Rosatom has a presence.

There would not seem to be anything unusual about this in a normal situation, as many companies from developed countries strive to occupy foreign markets, and move their technologies and production facilities abroad, and thus influence the economy and even politics of these countries. However, since the invasion of Ukraine and the aggressive Russian energy blackmail, which many countries have faced, it has become clear that it is now very risky to fall into any economic or energy dependence on Russia, and undesirable in the long term. Russia has shown the entire world that it has become a dangerous, aggressive country with unpredictable domestic and foreign policy.

In 2009, Rosatom proposed a new concept for construction of atomic station abroad, according to the formula "BOO" (Build – Own – Operate). The first realization of this model began in 2010 in Turkey at the Akkuyu NPP. The second NPP which was to be built according to this model was the NPP in Finland, Hanhikivi-1. But because of a long delay in construction, and then the war in Ukraine, the project was suspended. Thus, Rosatom, which planned to invest 34% of the cost in the construction of the Finnish NPP, as well as ensure the fuel cycle of this station, is making a loss because of the political risks.

In a normal situation, for many countries the BOO concept, from the economic and technological standpoint, could be quite attractive, also because Russia provides many foreign countries with state export long-term loans on favorable conditions of up to 90%¹⁰⁴ of the cost of NPP construction. Furthermore, Russia offers a model of treating spent nuclear fuel which provides the possibility for returning the SNF to Russia, without

¹⁰⁴ https://atom.belta.by/ru/belaes_ru/view/belarus-i-rossija-obsuzhdajut-prodlenie-sroka-kredita-na-stroitelstvo-belaes-na-10-let-karankevich-10251/

returning the radioactive waste to the country that used this fuel. At present it is hard to name the countries for which these “privileges” are provided, as intergovernmental agreements are usually kept secret. However, it must be said that no other country or company in the world offers conditions of non-return of radioactive waste into the country that has used the spent nuclear fuel. In 2021, the foreign turnover of Rosatom from the construction of NPP came to around USD 5 billion. Rosatom states that as of early 2022 the portfolio of projects of NPP construction abroad included 35 energy blocks which are at different stages of realization. (Table 8).

Besides the constructed and planned energy blocks indicated in Table 8, Rosatom currently has intentions and certain agreements to realize its projects for construction of NPP in former Soviet republics.

The Armenian government and Rosatom have signed an agreement with the government of Armenia which remains in force today, on the possible construction of new energy blocks which will be built in the location of the present atomic power station is Metsamor. Additionally, Rosatom has contributed to extending the term of operation to 2026 of the second energy block of the Metsamor NPP¹⁰⁵. At present possible extension of the work of the NPP for another 10 years is under discussion¹⁰⁶, as well as the construction of a new NPP in Armenia¹⁰⁷.

Uzbekistan and Russia in December 2017 signed an intergovernmental agreement on cooperation in the sphere of using nuclear energy for peaceful purposes. In September 2018 the two countries signed an intergovernmental agreement on the construction of two VVER-1200 blocks in the Navoi province of Uzbekistan. The goal of the agreement was to select a site and issue a license for the site by September 2020. The launch of the first power unit was initially planned for late 2028. However, talks dragged out over technical issues, and so far a contract for the construction of two VVER-1200 blocks has yet to be signed.

In Kyrgyzstan, Rosatom proposes to build an NPP based on low-capacity reactors.

Besides foreign projects indicated in the table and listed above, there are no other projects for the construction of NPP currently being realized by Rosatom at present.

¹⁰⁵ https://www.report.rosatom.ru/go/rosatom/go_rosatom_2021/rosatom_2021_ru.pdf

¹⁰⁶ <https://www.rosatom.ru/journalist/news/pri-uchastii-rosatoma-zavershen-proekt-po-modernizatsii-i-prodleniyu-sroka-ekspluatatsii-armyanskoy/>

¹⁰⁷ <https://rusatom-energy.ru/media/rosatom-news/rosatom-i-zao-aykakan-atomayin-elektrokayan-armeniya-podpisali-soglashenie-o-sotrudnichestve-po-soor/>

Table 8. Portfolio of the Rosatom's projects outside Russia

№	Name of site and number of power units from the Rosatom portfolio	Power unit type	Main events on foreign sites of Rosatom in 2021-2022
1	Belarussian NPP (two PU)	VVER-1200	In 2021 – PU № 1 put into operation. Physical launch started at PU № 2.
2	Akkuyu NPP Turkey (four PU)	VVER-1200	March 2021 – construction of 3rd PU begins. Reactor of PU № 1 installed. May 2022 – in the reactor section of PU №1 the fifth tier of the inner protective shell installed July 2022 first concrete poured at reactor № 4 September 2022 installation of reactor shell completed at reactor № 2.
3	Paks 1 NPP (two reactors) Paks 2 NPP Hungary (two reactors)	VVER- 440 VVER-1200	In summer 2022 , announcement to extend service period of VVER-440 reactors at Paks-1 NPP in August 2022 national regulator issued license to build two PU with VVER-100 reactors. in autumn 2023 it is planned to start construction of two VVER-1200 reactors (№ 5 and № 6) at Paks-2 NPP
4	El-Dabaa NPP Egypt (four reactors)	VVER-1200	June 2021 – licensing documents submitted to Egypt regulator for № 1 and 2 reactors December 2021 – licensing documents submitted for № 3 and 4 reactors December 2021 – technical project for reactors № 1 and 2 June 2022 Rosatom issued license for NPP construction July 2022 first concrete poured for reactor № 1 By 2028 all four reactors planned for construction
5	Kudankulam NPP India (six reactors)	VVER-1000	June 2021 construction of reactors № 5, 6, starts, first concrete poured Construction of reactors 5 and 6 scheduled for 2027 Construction of another 6 new reactors is discussed April 2022 – period of additional construction extended until 2026 for storage facilities of SNF for reactors 1 and 2
6	Busher 2 NPP Iran (two reactors)	VVER-1000	Construction of reactors 2 and 3 underway, scheduled for completion in 2024 and 2026 respectively
7	Rooppur NPP Bangladesh (two reactors)	VVER-1200	August 2021 – shell of reactor № 2 delivered to building site September 2021 – installation completed of reactor № 1 shell in planned position 2022 – installation of reactor № 2 in planned position; 2023 and 2024 – electricity production planned to begin at two reactors
8	Tianwan NPP China (eight reactors)	VVER-1000 VVER-1200	May 2021 – license received for building reactors № 7 and 8 May 2021 – first concrete poured for reactor № 7. February 2022 – first concrete returned for nuclear island reactor № 8.
9	Xiudapu NPP China (two reactors)	VVER-1200	July 2021 – license received for building reactors № 3 and 4. July 2021 – first concrete poured for reactor № 3. May 2022 – first concrete poured for reactor № 4.
10	Hanhikivi NPP Finland (one reactor)	VVER-1200	May 2022 Finnish company Fennovioma annuls contract for NPP construction, after Russia's invasion of Ukraine.

4.2. Experimental and scientific enterprises

The main experimental and scientific projects that Rosatom currently realizes abroad concern the creation of core sites and scientific and education infrastructure for holding events on their basis targeted at advancing Russian nuclear technologies.

In 2021-2022 in Bangladesh, Bolivia, Serbia, Hungary, Ruanda, Vietnam and Uzbekistan and other countries projects were coordinated, and center of nuclear science and technology were created, and their informational sites. These centers are usually equipped with an experimental reactor, a complex of laboratories, optionally a multi-target radiation center, as well as a center of nuclear medicine.

Russia continues cooperation under the ITER project (International Thermonuclear Experimental Reactor), and international project of seven nations directed towards constructing the largest experimental thermonuclear TOKOMAK reactor in the world.

4.3. Uranium and fuel projects

Uranium production of Rosatom in fields outside Russia in 2021 came to 4,500¹⁰⁸ tons of uranium, which is 1.8 times higher than inside Russia – 2635 tons. Rosatom has important foreign assets for uranium production and at present has purchased in its entirety¹⁰⁹ the former Canadian company Uranium One Inc, and has mainly concentrated its foreign assets in Kazakhstan. Together with Kazatomprom, Uranium One owns various shares, from 30% to 70% in six fields in Kazakhstan¹¹⁰. Besides fields in Kazakhstan, Uranium One owns fields in Namibia and Tanzania¹¹¹, but development of these fields has yet to begin.

Total uranium production of the companies ARMZ and Uranium One, part of Rosatom, in 2021 came to 7,100 tons, or around 15% of world production.

¹⁰⁸ 7100 (summary production in 2021)-2635 (ARMZ production in 2021) = 4465 t.

¹⁰⁹ <https://financialpost.com/commodities/mining/uranium-one-bought-by-top-russian-shareholder-armz-for-1-3-billion>

¹¹⁰ <https://uranium1.com/ru/our-operations/#operations>

¹¹¹ <https://strana-rosatom.ru/2022/09/23/vzjali-pod-krylya-kak-prodvigaetsya-p/>

Table 9. Uranium production of the largest uranium-producing companies in 2021.
Source – WNA¹¹²

Company	tonnes	% of world total
Kazatomprom	11,858	25
Orano	4541	9
Uranium One	4514	9
Cameco	4397	9
CGN	4112	9
Navoi Mining	3500	7
CNNC	3562	7
ARMZ	2635	5
General Atomics/Quasar	2241	5
BHP	1922	4
Energy Asia	900	2
Sopamin	809	2
VostGok	455	4
Other	2886	6
Total	48,332	100

In 2021, 14% of uranium in the USA was delivered by Russian companies. In 2020 this share was higher – 20%. In absolute terms, in 2020 Russia exported around 3,100 tons of uranium to the USA, and around 2,500 tons to the EU¹¹³. On average for 2017-2021 the USA purchased 2,400 tons of uranium per year from Russia, and the EU on average for 2016-2020 purchased 2,800 tons of uranium. According to data from Investigate Europe, in 2021 the EU purchased 20% of required uranium in Russia, or 2,358 tons, paying Russia 210 million Euros¹¹⁴.

Conversion and enrichment of uranium are projects which put the international nuclear sector, particularly the European sector, in considerable dependence on Rosatom. Rosatom has around 20% of world capacities for uranium conversion (12,500 tons) and occupies around 30%¹¹⁵ of the world market of uranium conversion. Its share in services for uranium conversion for EU countries has been around 25%¹¹⁶ in recent years, or slightly more than 3000 tons of uranium in absolute figures.

¹¹² <https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx>

¹¹³ <https://thebulletin.org/2022/08/us-and-eu-imports-of-russian-uranium-and-enrichment-services-could-stop/>

¹¹⁴ <https://www.investigate-europe.eu/en/2022/russias-multi-million-euro-nuclear-exports-untouched-by-eu-sanctions/>

¹¹⁵ <https://world-nuclear.org/getmedia/9a2f9405-1135-407a-85c8-480e2365bee7/nuclear-fuel-report-2021-expanded-summary.pdf.aspx>

¹¹⁶ https://euratom-supply.ec.europa.eu/system/files/2021-10/MJAA21001ENN_002.pdf

Table 10. Estimated world primary conversion capacity in 2020¹¹⁷.

Company	Country	Location	Nameplate capacity (tU)	Capacity utilization (%)	Capacity utilization (tU)
Orano	France	Pierrelatte & Malvesi	15,000	17%	2600
CNNC	China	Lanzhou & Hengyang	15,000	53%	8000
Cameco	Canada	Port Hope	12,500	72%	9000
Rosatom	Russia	Seversk	12,500	96%	12,000
ConverDyn USA	Metropolis	7000	0%	0	
Total			62,000	51%	31,600

World Nuclear Association Nuclear Fuel Report (2021 edition)

Russia possesses around 45%¹¹⁸ of world capacities for uranium enrichment (27.7 million ERR) and occupies around 36%¹¹⁹ of the world market of services for uranium enrichment.

In 2021 in the USA, 28%¹²⁰ of services for uranium enrichment were ordered in Russia. In the EU in 2021 this figure came to 31%, or 8% more than in the previous year¹²¹. According to assessments from The Bulletin of the Atomic Scientists, the total annual export of uranium and enrichment services in the USA and the EU bring Russia around USD 1 billion per year¹²². According to other assessments from The Washington Post, the export of uranium products and services in the USA alone in 2021 may have reached USD 1 billion¹²³.

In absolute figures in 2017-2021, nuclear companies of the USA purchased an average of 3,300 million ERR per year in Russia. Companies from the EU in 2016-2020 purchased an average of 3.4 million tons of ERR per year in Russia¹²⁴.

In 2021 the world observed an excess of facilities for uranium enrichment. For over 57 million ERR of facilities of supply, only 52 million of ERR of demand¹²⁵. Another 9 million ERR were accounted for by providing secondary deliveries. Taking into account the foreign isolation of Russia and attempts to reduce dependence of the EU and the USA on Russian services in the nuclear sphere, various methods are being examined for increasing their own facilities for conversion and enrichment.

¹¹⁷ <https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/conversion-and-deconversion.aspx>

¹¹⁸ <https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx>

¹¹⁹ <https://www.bloomberg.com/news/articles/2022-10-07/france-mulls-new-uranium-plant-to-cut-west-s-reliance-on-russia>

¹²⁰ <https://www.eia.gov/uranium/marketing/>

¹²¹ *ESA Annual Report 2021*, p. 22

¹²² <https://thebulletin.org/2022/08/us-and-eu-imports-of-russian-uranium-and-enrichment-services-could-stop/>

¹²³ <https://www.washingtonpost.com/politics/2022/04/20/does-russia-sell-nearly-1-billion-uranium-us-year/>

¹²⁴ <https://thebulletin.org/2022/08/us-and-eu-imports-of-russian-uranium-and-enrichment-services-could-stop/>

¹²⁵ *ESA Annual Report 2021*, p. 68

For example, the French company Orano may increase facilities for enrichment at the Georges Besse II factory from 7.5 to 11 million ERR for 1.3 billion Euros by 2028, if the board of directors approves this in 2023. The company Urenco Ltd also reported that it was examining options for placement of new facilities and increasing production¹²⁶. According to WNA data¹²⁷, current western facilities for uranium conversion work at 40% capacity, but it is expected that from 2026 their capacity will grow to 90%.

Additionally, Russia is the world's only supply of HALEU (uranium with enrichment from 5% to 20%), required for developing advanced reactors and SMR¹²⁸. The French company Orano announces that it may start production of HALEU in five to eight years, but will submit an application to receive a license for production only after it gains clients with long-term contracts. The US government is already supporting a number of American projects of SMR using HALEU, which are supposed to start working by the end of the decade. Therefore, the DOE plans to allocate USD 700 million to developing HALEU deliveries in a consortium with the company Centrus. However, even after the expected launch of the factory in 2023, five years will pass before Centrus can start producing 13 tons of HALEU a year, and even after this it will only cover a third of the demand in the USA. So the USA is considering an alternative option of using part of the supplies of weapons-grade uranium¹²⁹.

Deliveries of fuel for export

According to Rosatom data, as of early 2022 its fuel company TVEL delivered fuel to 75¹³⁰ energy reactors of NPPs in the world. Rosatom delivered fuel entirely or partially, but since the war began Ukraine ceased purchase and deliveries of Russian fuel. This means that without considering deliveries to new or prepared units (Belorussian NPP-2, Akkuyu-1, Ruppur-1) as of early 2023 the number of NPP reactors to which fuel from the TVEL company is delivered dropped from 75 to 62.

¹²⁶ <https://www.bloomberg.com/news/articles/2022-10-07/france-mulls-new-uranium-plant-to-cut-west-s-reliance-on-russia>

¹²⁷ <https://world-nuclear.org/getmedia/9a2f9405-1135-407a-85c8-480e2365bee7/nuclear-fuel-report-2021-expanded-summary.pdf.aspx> p 32

¹²⁸ <https://www.reuters.com/business/energy/americas-new-nuclear-power-industry-has-russian-problem-2022-10-20/>

¹²⁹ <https://www.reuters.com/business/energy/americas-new-nuclear-power-industry-has-russian-problem-2022-10-20/>

¹³⁰ <https://www.tvel.ru/activity/>

Table 11. Effective contracts for foreign deliveries of fuel by Rosatom

Country	NPP (№ of blocks)	Type of reactor	Alternative deliveries
Ukraine*	Zaporizhzhya (2,6)*	2 of 6 VVER-1000*	Cessation of deliveries of Russian fuel from 2022. Contract for Westinghouse fuel for VVER-1000 and fuel testing for VVER-440 from 2024.
	Khmelnysky (1,2)	2 VVER-1000	
	South Ukraine (1)*	1 of 3 VVER-1000*	
	Rivne (1,2,4)*	1 of 2 VVER-1000*, 2 VVER-440	
Czechia	Temelin (1,2)	2 VVER-1000	Contract on transition to Westinghouse and Framatome fuel for Temelin NPP with two VVER-1000 from 2024 ¹³¹ .
	Dukovany (1-4)	4 VVER-440	
Hungary	Paks (1-4)	4 VVER-440	
Finland	Loviisa (1,2)	2 VVER-440	Contract with Westinghouse for fuel deliveries from 2027-2030.
Slovakia	Bogunice (3,4)	2 VVER-440	
	Mohovce (1,2)	2 VVER-440	
Bulgaria	Kozlodui (5,6)	2 VVER-1000	Contract with Westinghouse for 10 years on delivery of nuclear fuel for the fifth NPP ¹³² from 2024
Armenia	Armenian (2)	1 VVER-440	
India	Kudankulam (1,2)	2 VVER-1000	
China	Xiapu (1,2)	2 CFR-600	
Iran	Bushar (1)	1 VVER-1000	
Belarus	Belarussian (1)	1 VVER-1200	

* Ukraine actively uses Westinghouse, an alternative to Russian fuel, for VVER-1000 reactors. It is loaded fully in at least 2 reactors and partially in another 5. During the war Ukraine decided to cease deliveries of Russian fuel entirely.

The volume of fuel delivered abroad (with the complete exception of Ukraine) may be assessed at around 300 t/year¹³³. With prices up to USD 1 million for the average VVER-1000 fuel rod with 0.5 tons of fuel, the cost of fuel delivered by Rosatom abroad does not exceed USD 500-600 million per year.

¹³¹ <https://www.world-nuclear-news.org/Articles/Framatome-and-Westinghouse-to-supply-fuel-to-Temel>

¹³² <https://info.westinghousenuclear.com/news/westinghouse-vver-1000-nuclear-fuel-fabrication-agreement-helps-cement-bulgarias-energy>

¹³³ $300=7*23$ (annual fuel need for 7 VVER-1000 reactors)+ $15*7,5$ (annual fuel need for 15 VVER-440 reactors)+ 26 (annual fuel need for one VVER-1200 reactor)+ $2*12$ (annual fuel need for 2 CFR-600 reactors) - Bellona's assessment.

Additionally, Rosatom builds new NPPs, including comprehensive contracts for fuel delivery, as well as intergovernmental agreements (secret) on the return of spent nuclear fuel to Russia for processing.

An exception is China, which independently¹³⁴ manufactures fuel using Russian technology for four VVER-100s at the Tianwan NPP built by Rosatom in China in 2006-2018. For four VVER-1200s which Rosatom is currently building in China¹³⁵, as well as for other projects of foreign construction, Rosatom offers fuel deliveries for at least initial loading and work for the first few years.

Table 12. NPPs being constructed abroad by Rosatom requiring fuel deliveries

Country	NPP (№ of reactors)	Reactor type
Turkey	Akkuyu (1-4)	4 VVER-1200
China	Xiudapu (3,4) and Tianwan (7,8)	4 VVER-1200
India	Kudankulam (3-6)	4 VVER-1000
Egypt	El-Dabaa (1-4)	4 VVER-1200
Bangladesh	Rooppur (1,2)	2 VVER-1200
Iran	Busher-2 (1)	1 VVER-1200
Belarus	Belarussian NPP (2)	1 VVER-1200

The volume of additional fuel supplies for NPPs which Rosatom is building abroad may be valued at 500 t/year by 2030 after they are put into operation¹³⁶.

Survey of the situation with deliveries of fuel in individual countries:

In 2022, after the start of the war in Ukraine and sanctions on flights of Russian planes in the EU airspace, Russia received permission and delivered fuel by air for European countries: in March to Slovakia, and in April to Hungary. Since April Czechia received three batches of fuel¹³⁷.

Ukraine

Development of the first project of Westinghouse fuel of VVER-1000 for delivery to Ukraine began in 2001 as a result of a government agreement between Ukraine and the USA

¹³⁴ <https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx>

¹³⁵ <https://rusatom-energy.ru/media/rosatom-news/toplivnaya-kompaniya-rosatoma-tvel-postavit-toplivo-dlya-novykh-energoblokov-aes-syudaypu-kitay/>

¹³⁶ =4*23m (annual fuel need for 4 VVER-1000 reactors)+16*25 (annual fuel need for 16 VVER-1200 reactors)

¹³⁷ <https://ria.ru/20220401/toplivo-1781400738.html>

on energy cooperation and safety¹³⁸. In 2008 the first contract was signed for delivery of fuel between Energoatom and Westinghouse. In 2018 the contract was prolonged until 2025¹³⁹. In June 2022 the contract was expanded and now stipulates the complete rejection of Russian fuel and a transition to Westinghouse fuel¹⁴⁰.

In 2022, deliveries of American fuel were made at 7 VVER-1000 units in Ukraine: four at the Zaporizhzhya NPP, two at the South Ukraine NPP and from 2022 one unit at the Rivne NPP. The conversion of active zones to new fuel takes place gradually, and the process takes several years. Since 2018 unit №3 of the South Ukraine NPP has worked entirely on American fuel, in 2019 unit №5 at the Zaporizhzhia NPP was completely converted, in 2020 №2 at South Ukraine UNPP and №1 at Zaporizhzhia NPP, and in 2021 units 3 and 4 at Zaporizhzhia NPP. Thus, by mid-2020 six units worked entirely on American fuel and the unit of the Rivne NPP partially. Its complete conversion to American fuel is expected in 2025¹⁴¹.

Accordingly, six VVER-1000 units continue to work on Russian fuel (2 at Khmelnytsky, 1 at Rivne, 2 at Zaporizhzhya and 1 at South Ukraine) and two VVER-440 units at the Rivne NPP.

Agreement on licensing Westinghouse fuel for Ukrainian VVER-440 was signed in 2020. In 2024, loading of the first experimental batch in a quality of up to 12 fuel rods is expected, and the current contract stipulates in the total sum a delivery of 1056¹⁴² fuel assemblies, which is sufficient for full loading of two Ukrainian VVER-440 reactors.

The present contract for deliveries of nuclear fuel to Ukrainian NPP between Energoatom and the fuel company of Rosatom TVEL expires in 2025. In 2018 an additional agreement was signed which stipulates reducing volumes of deliveries of Russian fuel¹⁴³.

Czechia

In spring 2022, the operator of the Czech CEZ NPP signed a 15-year contract with Westinghouse and Framatome for fuel deliveries for Temelin NPP with two VVER-1000 from 2024¹⁴⁴. According to representatives of CEZ, the Temelin NPP has a supply for more than two years, Dukovany NPP for three years¹⁴⁵. Fuel for four VVER-440 is still delivered from Russia.

¹³⁸ <https://www.neimagazine.com/features/featurediversification-of-the-vver-fuel-market-4682502/>

¹³⁹ <https://www.energoatom.com.ua/app-eng/parts/pdf-file/nonfinpeport2020.pdf>

¹⁴⁰ <https://info.westinghousenuclear.com/news/energoatom-and-westinghouse-reaffirm-clean-energy-partnership>

¹⁴¹ <https://www.neimagazine.com/news/newswestinghouse-fuel-assemblies-delivered-to-rivne-npp-8919297>

¹⁴² <https://world-nuclear-news.org/Articles/Energoatom-contracts-Westinghouse-for-VVER-440-fue>

¹⁴³ <https://www.vedomosti.ru/politics/news/2022/03/11/913033-ukraina-yadernoe-toplivo>

¹⁴⁴ <https://www.world-nuclear-news.org/Articles/Framatome-and-Westinghouse-to-supply-fuel-to-Temel>

¹⁴⁵ <https://ria.ru/20220401/toplivo-1781400738.html>

Slovakia

In 2019, a contract was signed with TVEL on fuel deliveries until 2026, with possible extension until 2030¹⁴⁶. The 4 already functioning VVER-440 in Slovakia have had a 5th unit added, at Mohovca-3, where in October 2022 physical launch was carried out. In March 2022, the last delivery of fuel was made, and its current supplies are sufficient for two years.

Bulgaria

Bulgaria plans to convert two functioning units with VVER-1000 reactors of its Kozlodui NPP to deliveries from the company Framatome and Westinghouse as an alternative to Russian fuel. The last has already been undergoing licensing procedures since 2019, which should be completed by 2024¹⁴⁷.

On 22 December, the management of Kozlodui NPP signed a contract with Westinghouse for 10 years on delivery of nuclear fuel for the fifth NPP reactor¹⁴⁸. By the end of 2022 it was planned to sign a similar contract with Framatome on deliveries of fuel for the 6th reactor¹⁴⁹.

Hungary

In 2017, a contract for development and delivery of modified fuel for 4 VVER reactors of Paks NPP was signed. In 2020, the first delivery of new fuel was made¹⁵⁰. In March–April 2022, despite transport restrictions between Russia and the EU, Hungary replenished the fuel supplies for its NPP. However, the fuel had to be delivered by air through Belarus and Poland. Both countries are uncertain about whether to cease delivery Russian nuclear fuel, as the fuel from the potential American supplier Westinghouse is 20% more expensive.

Finland

Rosatom has a contract for deliveries of fuel for two VVER-440 reactors at the Loviisa NPP for the entire period of their operation¹⁵¹, until 2027 and 2030, when they will reach an age of 50 years. In 2021, Rosatom, under additional agreement to the contract from 2018, completed development of a new modification of fuel for these reactors¹⁵². In the spring of 2022, the operator company of the NPP Fortum submitted an application to receive a license for operation both Loviisa power units until 2050, and announced that a new tender would be held for delivery of fuel for this period. In November 2022, Fortum signed an agreement with Westinghouse Electric Company for planning, licensing and delivery of

¹⁴⁶ <https://www.world-nuclear-news.org/Articles/Slovenske-elektrarne-signs-Russian-fuel-supply-dea>

¹⁴⁷ <https://www.mediapool.bg/framatom-vliza-v-bitkata-za-dostavka-na-svezho-yadreno-gorivo-u-nas-news341055.html>

¹⁴⁸ <https://info.westinghousenuclear.com/news/westinghouse-vver-1000-nuclear-fuel-fabrication-agreement-helps-cement-bulgarias-energy>

¹⁴⁹ <https://www.atomic-energy.ru/news/2022/12/22/131466>

¹⁵⁰ <https://www.world-nuclear-news.org/Articles/TVEL-completes-development-of-modified-fuel-for-Pa>

¹⁵¹ <https://rusatom-energy.com/media/rosatom-news/tvel-fuel-company-of-rosatom-to-develop-new-modification-of-nuclear-fuel-for-loviisa-npp-in-finland/>

¹⁵² <https://www.neimagazine.com/news/newsrosatom-modifies-nuclear-fuel-for-loviisa-npp-8766574>

a new type of fuel for VVER-440 units¹⁵³. The basis for this fuel is the fuel of the company British Nuclear Fuel Limited, which was delivered to the Loviisa NPP in 2001-2007 parallel to the fuel delivered by Russian TVEL in the early 2000s.

India

In June 2022, the Rosatom fuel company TVEL delivered the first batches of TVC-2M nuclear fuel to India for the two operating units 1 and 2 of Kudankulam NPP VVER-1000 reactors. After additional fueling in July 2022, power unit 1 began its work in an 18-month fuel cycle of UTVS fuel used at present with 12-month work cycles. After this, TVEL will fulfill the agreement with the Department of Atomic Energy (DAE) / Nuclear Power Corporation of Limited (NPCIL) on the use of nuclear fuel TVS-2M with 18-month operational cycles for the Kudankulam NPP.

Armenia

AO TVEL and ZAO Aikakan Atomayin Elektrakayan (Armenian NPP) signed contract documents on delivery of Russia nuclear fuel. Delivery will be carried out in the fourth quarter of 2022, which will fully meet the present requirements of the Armenian NPP for fresh nuclear fuel. At the only operating atomic power unit in Armenia with a capacity of 448.25 MWt, a vibro-resistant fuel for the VVER-440 reactor is delivered, manufactured by the Machine building factory (AO MCZ, enterpriser of the Rosatom fuel company TVEL in Elektrostal).

4.4. International services for treating spent nuclear fuel

A number of contracts for construction of Russian NPP abroad involve comprehensive services not only for supplies of fresh fuel, but also the return of SNF to Russia. Taking into account the introduced elements of the closed NFC, at Rosatom a proposal is being developed for foreign clients entitled "Balanced NFC"¹⁵⁴. The SNF supplier is asked after its treatment to return short-lived radioactive waste, which does not require burial in deep geological formations, with determination of the quantity and activity of this waste, using the principle of the radiation equivalent. The extraction and use of nuclear materials, uranium and plutonium, as well as the utilization of long-living radio nuclides in this approach rely on Russian infrastructure. The proposal is primarily oriented towards foreign consumers, where NPP are being operated and/or built according to Russian projects (Belarus, Hungary, Turkey etc.). For example, the concept developed for treating SNF at the

¹⁵³ <https://www.fortum.com/media/2022/11/fortum-and-westinghouse-electric-company-sign-agreement-design-and-supply-new-fuel-type-loviisa-power-plant>

¹⁵⁴ <http://atominfo.ru/news05/a0501.htm>

Belarussian NPP involves transporting to Russia around 5300 spent fuel rods or around 2500 tons of SNF for the 60 years of work by the two VVER-1200 units, with subsequent return of vitrified radioactive waste without long-lived isotopes¹⁵⁵.

To summarize, it should be expected that in the short-term perspective Rosatom, despite the unfavorable political and economic situation for it, will strive to maintain its position in the nuclear business, primarily by promoting its projects in third-world countries, offering projects for building NPPs on their territories, creating companies for production of uranium and other minerals, as well as preserving its position in such eastern and African nations as Turkey, Iran, India, Egypt, Bangladesh and partially in China.

As for western countries, Rosatom will maintain its presence for some time primarily in countries that use Russian fuel (Czechia, Slovakia, Bulgaria), as well as in countries which take a patient and favorable attitude to Putin's regime and have agreed to the construction of new NPPs of Russian design in their countries (Hungary, Belarus, Armenia). It must be admitted that Rosatom's number one client in Western Europe is France. Such French companies as EDF, Orano, Framatome, Fortum currently have strategic agreements with Rosatom. Additionally, Rosatom maintains close ties with the French Commission for Atomic Energy (CEA), which is possibly one of the reasons that direct sanctions have not yet been placed on Rosatom.

It is likely that in the short-term perspective, Rosatom's partnership ties will be reduced or even lost, but this will not happen quickly, and by no means with all partners, as there are quite a lot of long-term contracts which will cause losses for all parties if they are annulled. Rosatom is quite sensitive about contracts being annulled on a unilateral basis, and in these cases it will probably try to compensate for its losses through courts, as it has since the annulment of the contract for Rosatom to build the Hanhikivi NPP in Finland¹⁵⁶.

¹⁵⁵ http://www.gidropress.podolsk.ru/files/proceedings/mntk2019/documents/mntk2019-055_rus.pdf

¹⁵⁶ <https://defuel-russias-war.org/rosatom-nuclear-boogeyman/>

Chapter V.

The economic, ecological and social components in Rosatom's activity

5.1. The business and economic activity of the nuclear sector

It is generally difficult to assess the economic and financial activity of the nuclear sector. Usually, Rosatom and the Russian government disclose and publish information very selectively that concerns the economics and finances of Rosatom, as well as its organizations and enterprises.

As stated above, the legal status of state corporation allows the atomic sector to use the state budget and actively conduct business, including internationally.

In 2020-2022 the economic indicators of Rosatom were significantly impacted by the pandemic restrictions and the war in Ukraine. Nevertheless, as official reports of the main divisions of Rosatom show, the turnover (netto) from sales of main production grew from year to year.

Table 13. Turnover from sales in Rosatom's divisions in 2020-2021

Turnover (net) from sales of production, mln. rub.	2020	2021
Mining division	20 400	23 200
Fuel division	208 737	235 734
Electricity division	592 702	735 129
Machine-building division	83 000	106 000
Engineering division	261 200	292 500

The business model of Rosatom consists of a chain of capitals (resources) which the corporation owns (or partially owns) and uses in its activity. This chain includes six types of capitals used: financial, production, human, intellectual, socio-reputational and natural.

As of early 2022, the management system of the business model of Rosatom included three business cores, which create and form the company cost. The first business core included the division of the nuclear weapons complex, as well as two directorates – the Northern Sea route and ecological solutions. The second business core is the primary one, formed by the mining, fuel, machine-building, electricity and engineering divisions. The third business core is formed by the new business of Rosatom and radiation technologies.

The main results (business indicators) of the state corporation in 2021 were the following: IFRS turnover – 1,447.6 billion rubles (share of non-material assets – 199 billion rubles); production of electricity at NPPs of Russia – 222.4 billion kWt/h; production of nuclear fuel – 1,030 tons of heavy metals; uranium production – 7,100 tons; power units put into operation – 2; cargo flow by the northern sea route – 34.9 million tons¹⁵⁷.

Rosatom's presence on global markets is an important political task. In 2021-2022, Rosatom was present on 12 traditional and new Russian and global markets – natural, uranium, services for conversion and enrichment of uranium, nuclear fuel, energy machine building, electricity, construction and service of atomic sites, decommissioning nuclear and radiation-hazardous sites, treating radioactive waste and SNF, wind energy, composites, treatment of hazardous waste and nuclear medicine.

5.2. Ecological and social policy of Rosatom

Before the start of the war in Ukraine, Rosatom, striving to comply with international practices, activated work in the field of achieving goals of stable development. In 2020, Rosatom joined the UN Global Compact, and announced that it was focusing its ecological and social policy on achieving 17 goals of stable development. In 2020, the Rosatom structure created a department for stable development. From 2021 Rosatom began presenting a public report on progress in achieving its main ESG indicators¹⁵⁸.

Additionally, Rosatom developed a single sector policy in the stable development field (hereinafter the Policy), setting out requirements for its organizations and enterprises in environmental protection, production safety, in the social sphere and in the sphere of corporate management.

Rosatom states that in the ecological aspect it strives to organize its activity in accordance with the principle "Do no significant harm", which means minimizing environmental pollution and negative impact on ecosystems, as well as minimizing risks for human health.

¹⁵⁷ https://www.report.rosatom.ru/go/rosatom/go_rosatom_2021/rosatom_2021_ru.pdf

¹⁵⁸ <https://rosatom.ru/upload/iblock/c3c/c3c498e523d60d11abca89ab19eed623.pdf>

The primary document valid at present concerning environmental protection and ecological safety in the nuclear sector is the single sector ecological policy of Rosatom and its organizations (hereinafter Ecological policy). The main form of safety which Rosatom has traditionally given attention is radiation safety. According to official calculations, in 2021 at Rosatom enterprises, 34 deviations from the zero level on the international INES scale were recorded¹⁵⁹.

Table 14. Dynamics of deviations in NPP operation according to the INES scale in 2017-2021

Dynamics of deviations in NPP operation according to the INES scale	2017	2018	2019	2020	2021
Total, including:	33	42	38	24	34
Level "0" and below scale	33	40	38	24	34
Level "1"	0	2	0	0	0

According to data from the Federal service for ecological, technological and atomic surveillance¹⁶⁰, in 2021 no emergency incidents were recorded at Russian NPPs by their classification or events with radiation consequences for the population, personnel and environment. However, 34 violations were detected in work that are subject to investigation and recording under current legislation. This was four more than in 2020. Investigations were carried out on all violations.

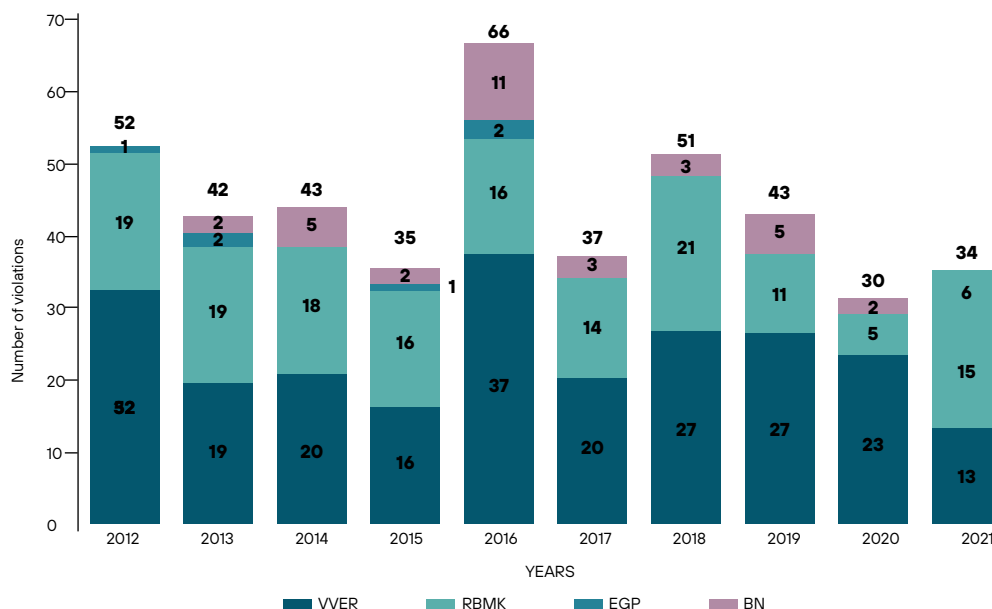


Figure 6. Distribution of violations in the work of nuclear power stations in 2012-2021 (source – annual report of Russian technical surveillance board, p. 38¹⁶¹)

¹⁵⁹ <https://rosatom.ru/upload/iblock/c3c/c3c498e523d60d11abca89ab19eed623.pdf> cmp 23

¹⁶⁰ Годовой отчет Ростехнадзора за 2021 год

¹⁶¹ https://www.gosnadzor.ru/public/annual_reports/%D0%93%D0%BE%D0%B4%D0%BE%D0%B2%D0%BE%D0%B9%20%D0%BE%D1%82%D1%87%D0%B5%D1%82%20%D0%B7%D0%B0%202021%20%D0%B3..pdf

The most significant violations in the work of NPPs in 2021 (by their impact on safety and possible consequences):

- On 23 March 2021 and 4 May 2021 at power unit № 4 of the Beloyarsky NPP emergency protection turned on from pressure in the main steam collector, and the emergency cooling system was turned on (assessment on INES scale – “0”);
- On 20 May 2021 at power unit no 4 of the Kalinin NPP the safety system was triggered after the activation of the projection of unit transformer T-4-750, caused by a short circuit of the transformer cable. The importance of this incident lies in the fact that short circuits in the cables have become a regular occurrence for many years. These violations in work took place in recent years at power units of the Kalinin NPP (four times), the Balakovsky NPP and the Novovoronezh NPP (assessment on INES scale – “0”);
- On 10 June 2021, power unit № 2 of the Kursk NSP was shut down by personnel after a rise in gas temperature of the system for controlling technological channels in cells of 3 technological channels, and the detection of the current channel from the formation of microdefects of the primary metal (assessment on INES scale – “0”);

Besides reports on radiation safety, in recent years Rosatom has begun to present reports on emissions of harmful pollutive substances into the atmosphere and greenhouse gas emissions, as well as on emissions of waste water and formation of waste, including radioactive.

According to official reports, in 2021 at enterprises and organizations of the nuclear sector 33.8 million tons of waste of production and consumption formed, which is 2.9 million tons (9.4%) more than in 2020. These reports stressed that only 8,000 tons of hazardous waste of the 1st, 2nd and 3rd classes (not radioactive) formed, which seems doubtful. Additionally, at enterprises and organizations of Rosatom annually around 2.5 million cubic meters of liquid radioactive waste forms, of which 0.1 million is converted into solid state, and around 1.5 million cubic meters of solid radioactive waste, of which less than 30% is treated.

The amount of emissions of pollutive substances into the atmosphere in 2020 and 2021 is indicated in table 1513. Here one should bear in mind that in presenting this official data, it is stressed that the percentage of pollutive substances trapped is 91.4%, i.e. at Rosatom enterprises practically 385,400 tons of pollutive substances are formed, and the only hope is that these emissions are indeed trapped.

Table 15. Emissions of pollutive substances into the atmosphere, thou. t.

	2020	2021
Total, including:	38.0	37.0
Emissions of solid substances	14.2	13.5
NOx emissions	6.1	7.4
SO ₂ emissions	11.6	9.8
CO emissions	3.3	3.8
emissions of hydrocarbons, including:	2.2	2.1
methane emissions	0.8	0.7
volatile organic compounds	1.2	1.3
other gaseous and liquid	0.6	0.4

Climactic goals of Rosatom Russia only ratified the Parisian agreement in 2019 and has been a party to it since then. The parties to the frame convention of the UN on climate change agreed to develop long-term strategies of development with a low level of emissions. In 2021, without waiting for decisions from the European Union, the Russian government included nuclear energy in the national taxonomy of “green” projects. In February 2022 the EU published additional criteria for qualifying nuclear energy as a transitional source of generation, which is stated in the Complementary delegated act, CDA to the taxonomy of stable financing of the EU.

Russian officials are optimistic that nuclear energy should play a role in the battle with climate change. The problem of the climate has become a kind of assistant or to some extent the salvation of nuclear energy from the complete rejection of the long-term prospects of this type of energy by green activists and even governments of some countries. The battle with climate change has forced opponents of nuclear energy to “put on the brakes” and tone down the discussion about the main ecological and economic shortcomings of NPPs, such as the accumulation of radioactive waste and the lack of a highly safe and publicly acceptable system of treating it, as well as nuclear risks and the relatively high cost of NPPs. At the same time, the climate agenda and the war in Ukraine, which has led to an energy crisis, has added arguments for expert and political opinions that in the near future the process of rejecting nuclear energy in Europe, which started in Germany, will from all appearances be severely slowed down.

At the climate conference in Glasgow, the head of Rosatom, Alexei Likhachev, confidently stated that “without nuclear energy it is impossible to achieve climate goals”. At the same time, he said that “nuclear energy is not the only source of green energy. Climate goals may only be achieved by uniting wind, solar, nuclear and hydro energy. We call these four energy sources the green rectangle, where nuclear and hydro power stations provide

the basic load, and wind and solar energy cope with peak loads¹⁶². The idea of the “green rectangle” has been discussed and promoted at Rosatom for almost ten years now.

At present, Rosatom has indeed had some success in the field of wind energy. In 2021 in the Rostov Oblast and Stavropol Krai, five new wind power stations were built and put into operations, with a total capacity of 570 MWt: the Kochubeev station (210 MWt), the Marchenkov station (120 MWt), the Karmalinov station (60 MWt), the Bondarev station (120 MWt) and the Medvezhensk station (60 MWt). There are currently six wind stations in operation with a total capacity of 720 MWt. In 2022, there were plans to put another three wind stations into operation: Kuzminsk (160 MWt), Trunov (60 MWt) and Berestov (60 MWt). The summary portfolio of wind power sites which Rosatom plans to build by 2027 comes to 1.7 GWt. Today, the wind stations of Rosatom produce 30% (720 MWt) of Russian wind power, but in comparison with Germany, China or other countries, for example, that are leaders in this field, the quantity of this energy is miniscule.

At present, Rosatom is working on hydrogen technologies, but as these require many energy resources, this once again returns us to the topic of developing nuclear power. In April 2021, the Agreement was signed on intentions of cooperation on the project “Creating and developing the hydrogen cluster” between the Ministry of Eastern Development of Russia, the Sakhalin Oblast government and Rosatom, which envisages cooperation in a number of fields, including the construction of a hydrogen production complex; organizing a delivery chain of hydrogen to external markets and local consumers, as well as creating a hydrogen park with enterprises realizing projects in this field.

Parallel to this, at the Kola NPP it is planned to create an experimental site for the electrolysis production of hydrogen. In 2023, it is planned to put into operation a complex with electrolysis units with a capacity of 1 MWt, and then gradually to bring the capacities of the experimental complex to 10 MWt¹⁶³.

In 2021, Rosseti Center and Rosseti Center and Volga region, together with Atomenergopromsbyt, put into operation 18 energy accumulators at sites of electricity distribution networks. This was the first system of commercial dispatch in Russia on lithium ion batteries for industrial consumers.

In October 2022, Rosatom, through its affiliated company Ranera, began construction in the Kaliningrad Oblast of Russia’s largest factory for the production of lithium-ion batteries, with a capacity of 4Gwt/h¹⁶⁴. The first production is expected to be ready in 2025. Development is taking place in cooperation with the South Korean manufacturer of lithium-ion batteries and cells, Enertech International Inc, in which Ranera bought a 49% share in 2021¹⁶⁵.

¹⁶² <https://strana-rosatom.ru/2021/11/04/aleksej-lihachev-vystupil-na-klimatich/>

¹⁶³ <https://www.rosatom.ru/journalist/smi-about-industry/rosenergoatom-planiruet-v-2023-godu-nachat-proizvodstvo-vodoroda-na-kolskoy-aes/>

¹⁶⁴ <https://renera.ru/news/rosatom-has-started/>

¹⁶⁵ <https://renera.ru/news/OOENERAapriobrela49aktsiykoreyskogoproizvoditelyalitiyonnykhatarey/>

In November 2022, Ranera, which is one of the divisions of Rosatom and works on systems of energy accumulation within the corporation, launched a new production of lithium-ion batteries in Moscow. It is expected that around 2,000 automotive batteries will be produced annually, equivalent to 150 MWh/h.

Rosatom is moving towards building small modular reactors, which in future may become an alternative to power stations working on fossil fuel.

The war in Ukraine stopped the many-year practice of Gazprom and oil companies of Russia in the colossal export of natural gas and oil to Europe and other countries. On the one hand, this may mean that the production of fossil fuel may drop, and on the other its use may expand within Russia. For nuclear power, this is an increase in competition from fossil fuel, which because of limitations and sanctions can no longer be easily sold on foreign markets. In future, everything will depend on the cost of energy resources and other parameters (for example, terms of building energy sites), in which nuclear power today evidently loses the competition within Russia.

The social policy of Rosatom, at least before the war in Ukraine, may be characterized as active. Joining the UN global agreement in 2020, Rosatom tried to show that it confirmed its resolve to realize the 10 principles of the global agreement, including human rights, labor relations, combatting corruption, confirming gender equality etc.

In 2013 Rosatom passed a document entitled "Common sector social policy", stating the rules of personnel policy, providing social support to its employees and their family members. In early 2022, at enterprises and organizations of Rosatom, including its foreign branches, around 290,000 people worked, 68% of them men and 32% of them women. 29.7% of employees are aged 35 and under. The total sum of expenses on personnel (including salary and various cash benefits) in late 2021 came to 443.78 billion rubles, and the average monthly salary at Rosatom was around 96,200 rubles in 2021¹⁶⁶. Rosatom enterprises, which are located in 27 cities of Russia, are usually the main enterprises of these cities, which have the status of "atomic cities".

Ten of the 27 "atomic cities" have the status of closed administrative territorial formations. Unlike other cities of Russia, atomic cities look more prosperous in the level and standard of people's living, but on the other hand, the residents realize that they are living next to potential hazardous cities, so they take a keen interest in safety issues. In the Soviet period, "atomic cities" were popularly known as "communist cities", because they were supplied with groceries and other daily items that were of a much higher quality than in the rest of the country.

Practically all atomic cities have leisure facilities and sanatoriums for employees of Rosatom and their families. The population of atomic cities are usually politically loyal

¹⁶⁶ https://report.rosatom.ru/go/rosatom/go_rosatom_2021/rosatom_2021_ru.pdf

to the government and the leadership of Rosatom, so they give local administrations no problems by holding various political events, such as sociological surveys, elections etc.

In concluding this brief survey of the economic, ecological and social block of Rosatom's present activity, we should note:

Details of Rosatom's finances are traditionally classified information. General figures and economic indicators are usually published in annual reports, but they also require clarification and critical analysis. For example, it is practically impossible to see economic figures in the annual reports that state the real cost of building an NPP, for example, or producing fuel, or the revenue and expenditure on Russian-French projects, or processing OGFU and other things.

The ecological and social policy of Rosatom in recent decades has become more open compared with the Soviet and early post-Soviet periods. Perhaps this assessment by Bellona is subjective to a certain extent, and based on the fact that in the last 10 years Bellona has been able to observe and even influence certain ecological and social decisions of Rosatom and its enterprises, leading a commission on ecology of the public board of Rosatom. However, several ecological and social issues of Rosatom that are important for civil society are no longer kept behind closed doors, and may be published and discussed by ecologists and human rights advocates in Russia.

After Rosatom was entrusted with a section of the projects for treating hazardous (not radioactive) waste, and responsibility for certain highly important projects from the state program "Ecology", as well as many issues concerning the Northern Sea Route, it has gained many ecological and social issues to deal with. Today it cannot be said that Rosatom is easily coping with these new and old ecological tasks.

The "nuclear legacy" of the Soviet atomic project requires considerably more time and enormous funds for liquidation, but this is a separate topic which Bellona will return to in subsequent reports. The volume of financing problems of the nuclear legacy will exceed 2 trillion rubles, according to the most optimistic forecasts¹⁶⁷.

Rosatom's atomic cities, where over 2 million people live, have traditionally more privileges and advantages than other cities of Russia with comparable populations and locations. The personnel of atomic enterprises are higher paid than the employees of state, municipal and even commercial organizations. Rosatom is one of the few companies in Russia which has begun to introduce programs at its enterprises on ecological and social responsibility from the stable development field.

¹⁶⁷ <https://bellona.ru/2021/12/01/prognoz-na-dva-trilliona/>

Chapter VI.

The influence of the war and sanctions and restrictions introduced against Russia

As of late January 2023, the EU, USA and other countries had introduced nine sets of sanctions against Russia, which affected many companies, the political and financial system of the nation, as well as individuals who were in some way involved in starting and waging the war. Rosatom and its management (apart from Sergei Kiriyenko and his family) were practically not affected directly by these sanctions. At the same time, the sanctions and restrictions introduced against Russia could not help but indirectly affect Rosatom and its employees.

The ban on deliveries of a large assortment of semi-conductors, computers and other hi-tech equipment became one of the most serious sanctions introduced against Russia since the war began. According to experts' assessments, these restrictions will hit various sectors, and generally complicate the country's technological development. In the global economy, of which Rosatom is a part, there is no point in creating a nation micro-electronic industry, as this production will be unprofitable. A great deal of time is needed to start a production line with modern technological standards. For comparison, the green factory Mikron, which called itself chip-maker no. 1 in Russia has only mastered the 65 nm technological process – worldwide, this stage was reached in the early 2000s, i.e. modern Russian computers and information products lag about 20 years behind innovative technologies, and in the near future, according to the predictions of the industry portal Tom's Hardware, the remnants of batches of outdated micro-schemes will enter Russia, which foreign retailers will be glad to get rid of¹⁶⁸.

¹⁶⁸ <https://profile.ru/economy/mikroshemy-pod-sankciyami-chem-grozyat-rossii-ogranicheniya-v-sfere-importa-vysokih-tehnologij-1033436/#Kak-sanktsii-povliyayut-na-promishlennost-1646557038005>

Undoubtedly, the war started by Russia and the sanctions will cut off financing to Rosatom's projects, and above all, projects dealing with the liquidation of the nuclear legacy of the Cold War will suffer. Rosatom does not live and work in a vacuum, so the established ties broken by sanctions directly affect the corporation. Countries of the EU, the USA and Canada and others introduced sanctions affecting financial operations of companies and enterprises such as Rostekh, Russian Railways, Sevmash and the united ship-building company, closely linked with Rosatom projects, including with the construction of atomic icebreakers and transport of equipment and materials, including nuclear. Russian energy exchanges began to be excluded from European and international exchanges.

The Russian banking system was affected by the sanctions, negatively influencing Rosatom's activity abroad. The international banking system closed the door to Russian companies. The European Bank of Reconstruction and Development closed its offices in Moscow, depriving many Rosatom projects in northwest Russia of financing. Rosatom announced that it could manage without this money, but it is already evident today that work in some important projects has been postponed to later dates, and it is uncertain whether they will be completed.

Restrictions prohibiting planes of Russian airlines from entering foreign airspace, the refusal of a number of ports and major world insurance companies to work with Russian ships and shipping companies, has complicated Rosatom's work in foreign projects. Especially major projects involving construction of NPPs. It is unlikely these logistical difficulties will critically affect implementation of these projects, but they may cause delays in delivery of equipment, material and specialists, as well as increase expenses in realizing these projects and cause the dissatisfaction of the end consumers.

International organizations, including intergovernmental ones, have suspended work with Rosatom or its projects. Rosatom reacted sensitively to the suspension of activity by the Russian-Norwegian commission on nuclear and radiation safety, as well as the suspension of cooperation between the northern provinces of Norway and Russian regions. At present, practically everything connected with the Arctic and the northern sea route, has been transferred to the zone of responsibility of Rosatom by decree of the Russian President, and the solution of all problems in this field is a very important state task for Rosatom. So, the diplomatic boycott by the Arctic countries, part of the Arctic council headed by Russia in 2022, has caused alarm not only in the Russian Foreign Ministry, but also in Rosatom. Following the boycott of the Arctic Council, there was a refusal to take part in joint activity by the Council of ministers of Nordic Countries.

On 22 March 2022, the Finnish minister for economic development Mika Lintila announced that issuing a license for the Hanhikivi-1 NPP the largest shareholder in which is Rosatom, was "completely impossible". On 2 May, the Finnish Ministry of Employment and the Economy called the decision by the company Fennovoima to annul the contract for

construction of the Hanhikivi-1 with Rosatom “justified and consistent”. However, Rosatom has a valid contract with the Finnish company Fortum until 2030, so the company still relies upon the import of nuclear fuel from Russia for the Loviisa NPP, though it recently announced a prohibition on the import of Russian uranium.

In May 2022, the USA toughened issuing licenses for export to Russia of special nuclear materials and deuterium.

In March 2022, the British-Dutch-German company Urenco announced plans to annul existing contracts for delivery to Russia of OFGU for enrichment “in both directions” until further notice. The present contract of 2018 stipulated deliveries of up to 6000 OFGU from Germany to Russia for pre-enrichment with return of enriched uranium product to Germany, and it was completed in 2020. However, the second part of the contract stipulated deliveries of another 6000 tons from Urenco factories in Germany, the Netherlands and the UK and they were supposed to end before the end of 2022. Evidently, this part of the contract was suspended and not fully implemented.

After the war in Ukraine began, the Swedish company Vattenfall announced suspending current deliveries and new purchases of nuclear fuel in Russia. Previously the company had purchased experimental batches of TVS-square fuel for reactors of the western model. The company owns and operates two NPPs in Sweden, at which 5 power units work (Ringhals 3,4 and Forsmark 1,2,3).

A number of EU countries seriously depend on deliveries of Russian nuclear fuel, which is impossible to replace with alternative fuel quickly. However, Bulgaria and Czechia activated efforts in 2023 to find alternative suppliers and intend to reject Russian fuel from 2024 for four of their VVER-1000 power units. Finland plans to find a replacement for Russian fuel for two of its VVER-440 units after 2027-2030.

Following governments and business companies, a number of nations and organizations have ended or suspended cooperation in the scientific field.

Poland has ended cooperation with the Russian united institute of nuclear research. The European Organization for Nuclear Research (CERN) has suspended Russia’s status as an observer country. CERN also announced that it will not cooperate with the Russian Federation and its institutions, and the organization stopped scientific contacts with United Institute of Nuclear Research, and its management will observe all appropriate international sanctions.

The association for issues of applying demands of European operating organizations for NPPs with light hydrogen reactors has suspended the membership of Rosenergoatom. The European network of technical support organizations has suspended cooperation with the Russian Center for nuclear and radiation safety. On 11 April, the agency for nuclear energy at the OESR suspended Russia’s membership.

The restrictions placed on the freedom of movement of Russian citizens in European and other countries have considerable significance for Rosatom, as do the personal sanctions against individual managers. Undoubtedly, these people, who are no longer able to take holidays and solve their own personal issues, are unhappy with the present situation, when they and their families are unable to make use of their property abroad, to enjoy holidays at resorts around their world, or have their children study abroad. This all affects the moods of people who are often directly responsible for the level of safety of nuclear facilities.

However, it should be noted that despite Rosatom's involvement in aggressive operations against Ukrainian nuclear sites, and Rosatom structures' role in escalating the military nuclear threat, which Russian politicians are constantly making, full and tangible sanctions against Rosatom have not been made by countries of the international community (with the exception of Ukraine). In all likelihood, these sanctions are opposed primarily by Russia's ally in the EU Hungary, as well as countries where Rosatom is building NPPs (Turkey, India, China etc.), as sanctions will make it impossible to pay for the construction and operation of the NPPs. There are also countries where companies have long-term contracts with Rosatom, for example France and Germany. For example, in early April 2022, Siemens announced that it did not plan to annul contracts with Rosatom. The German government has also expressed no concerns about the nuclear deal between Siemens, Framatome and Rosatom, closing its eyes to the obvious risks.

6.1. Restrictions and sanctions of Ukraine

Ukraine is fighting Russia which attacked it, occupied its territory and captured its energy facilities, including the largest NPP in Europe, the Zaporizhzhia NPP. Rosatom is an active and direct participant in the capture of the territories and nuclear sites of Ukraine. Ukrainian president Volodymyr Zelensky is unhappy that sanctions have not yet been introduced against Rosatom, and calls on western partners to do this as soon as possible. An international group of experts from the Working group for sanctions against Russia¹⁶⁹, working with the Ukrainian government, in November 2022 presented a working document with recommendations for sanction pressure on Rosatom¹⁷⁰.

Before the war, nuclear energy provided over 50% of Ukraine's electricity. Ukraine heavily depends on Russia for nuclear technology and supplies for its four NPP with 15 VVER power units. Previously, Ukraine had been the largest foreign client of Russian nuclear fuel. But the program for gradually reducing Ukraine's dependence on Russian in the nuclear sphere began before the war and has been continuing for many years.

¹⁶⁹ <https://fsi.stanford.edu/working-group-sanctions>

¹⁷⁰ <https://drive.google.com/file/d/13gO2tQuOaHYFCBTzCMXcaEmNulkeO8fD/view>

In 2001, spent nuclear fuel of the Zaporizhzhia NPP was sent for dry storage at the industrial site of the station built according to American technology¹⁷¹. For SNF of the remaining three Ukrainian NPPs from 2017 to 2020 in the exclusion zone of the Chernobyl NPP, a centralized dry storage facility was built according to technology of Holtec International. A separate dry storage facility for SNF of Chernobyl, with a cost of over \$500 million¹⁷² was built with funds from the EBRD and put into operation in 2021¹⁷³. These facilities allowed Ukraine to create its own infrastructure for treating spent fuel, and even before the war, to reject completely Russia's services in this field, which cost around USD 200 million annually.

In 2008, the first contract was signed for deliveries of Westinghouse fuel for Ukrainian VVER-1000 reactors. By the start of the war, American fuel was used at 7 of the 13 VVER-1000 reactors, and at two VVER 440 reactors it was planned to start experimental use of the new fuel in 2024. During the war, on 3 June, Ukraine signed an agreement with Westinghouse on converting all of its NPPs to American fuel, and completely rejecting Russian nuclear fuel. At the same time, it remains an open question as to whether supplies of Russian fuel will be sufficient for the work of Ukrainian NPPs during the completion of all licensing and testing procedures for using American fuel at all the power units, a process that may take several years at least.

In April 2022, Ukraine also rejected purchases of Russian enriched uranium for its fuel, and held negotiations on alternative enrichment services with the European company Urenco¹⁷⁴.

Shortly after the war began, the metallurgic plant Energomashspetsstal in Kramatorsk, Rosatom's largest asset in Ukraine, ceased working. In spring of 2022, warfare took place literally several dozens of kilometers away. In April 2022, the factory ceased work because of shooting by the Russian army and damage to equipment¹⁷⁵. But previously, including in March, when the war was already in full swing, it continued sending production to Russia. The factory manufactured parts of special steel for reactor shells and equipment of the first contour, including for export projects of Rosatom, such as the NPPS Kundankulam (India), Akkuyu (Turkey), Xiudapu (China), Tianwan (China), and parts for reactors of Russian atomic icebreakers. It was also planned to use this factory if the Hakikivi project in Finland was realized. In 2022, Energomashspetsstal was supposed to start manufacturing parts for the El-Dabaa NPP, which Rosatom began building in Egypt in the autumn of 2022¹⁷⁶. There is a similar factory in Russia that works closely with Rosatom, the Izhora factory OMZ-Spetsstal. But the loss of the largest asset in Ukraine for any reason, from destruction or

¹⁷¹ <https://www.uatom.org/ru/ekspluatatsyya-shoyat-na-Zaporizhzhyskoj-aes>

¹⁷² <https://chnpp.gov.ua/ru/activity/snyatie-chaes-s-ekspluatatsii/ongoing-projects>

¹⁷³ <https://chnpp.gov.ua/ru/183-proekty/realizuemye-proekty/435-2-ru435>

¹⁷⁴ <https://www.unian.net/economics/energetics/ukraina-otkazalas-ot-obogashchennogo-urana-iz-rossii-novosti-segodnya-11791977.html>

¹⁷⁵ <https://ru.espreso.tv/porazheny-rosatomom-kakie-ukrainskie-kompanii-svyazany-s-rossijskim-yadernym-kontsernom>

¹⁷⁶ <https://emss.ua/ru/na-e-mss-podveli-itogi-raboty-predpriyatiya-za-2021-god/>

nationalization by Ukraine, may cause disruptions in deliveries and delays in manufacturing equipment for Rosatom's major foreign projects.

On March 2022, the managing board of the International Association of Organizations operating nuclear power plants passed the decision to transfer Energoatom and all four Ukrainian NPPs from the Moscow to the Parisian center of the association¹⁷⁷. Preparation for this transfer began before the war, and in 2019 Energoatom signed a memorandum on cooperation with the Parisian center of the association, and holding joint checks with the Moscow center before the complete transfer in 2022¹⁷⁸. As a result, Energoatom became the first operating company of the association that operated reactors of Soviet design and left the Moscow center of the association¹⁷⁹.

On 27 June, Ukraine annulled the Agreement on cooperation between the Minister of environmental conservation and nuclear safety of Ukraine and the Russian Federal inspectorate for nuclear and radiation safety, along with the agreement between the Ukrainian state committee of nuclear regulation and the Russian Federal inspectorate for nuclear and radiation safety on exchange of information and cooperation in the sphere of safety regulation in using nuclear energy for peaceful goals.

On 27 August, Ukraine annulled the agreement with Russian on scientific and economic cooperation in the field of nuclear power.

On 24 May Ukraine introduced personal sanctions against the CEO of Rosatom Alexei Likachev for a period of 3 years.

To conclude the brief survey of the influence of the war and its consequences for Rosatom, we should once more note that unlike other leading Russian companies, Rosatom and its management have not been subject to international sanctions and restrictions since Russia's attack on Ukraine. This angers the leadership of Ukraine and many other politicians, as Rosatom is a direct participant of seizing nuclear sites of Ukraine – the Chernobyl and Zaporizhzhia NPPs. However, sanctions against Russian have begun to have an indirect influence on Rosatom, as shown above. It is predicted that direct sanctions will be applied, but perhaps gradually, as it is impossible to put an end to cooperation and mutual dependence in nuclear projects immediately, as for example is the case in oil and gas projects.

¹⁷⁷ <https://www.epravda.com.ua/rus/news/2022/03/31/685026/>

¹⁷⁸ <https://world-nuclear-news.org/Articles/Energoatom-to-join-WANOs-Paris-Centre-from-2022>

¹⁷⁹ <https://www.wano.info/members/who-are-our-members>

Conclusions

Rosatom is one of the most important global state structures of the Russian Federation, which carries out defense, energy, economic, social and political state functions.

Rosatom today is a powerful, competitive business structure present on international markets and owning foreign assets. The management of Rosatom is close to the Russian president and government, which provides it with additional opportunities and protects the sector from economic and political rivals and opponents.

Rosatom remains practically the only structure in Russia with technologies and resources comparable with those of developed countries. So the nuclear industry does not greatly depend on problems of "import replacement", unlike other large Russian companies.

Enterprises of the nuclear fuel cycle carry out deliveries of fuel and enriched uranium, and provide conversion services for both domestic and foreign consumers. The structural, resource and technological base of enterprises and organizations of Rosatom, which carry out the nuclear fuel cycle, is one of the main resources of the corporation. According to CEO Likhachev, it is expected that in 2023 deliveries of production and services of Rosatom abroad will exceed \$10 billion¹⁸⁰. Rosatom occupies a significant share in world deliveries of SNF – 15% of uranium deliveries, 30% of conversion services, 40% of uranium enrichment, 17% of nuclear fuel deliveries. For example, in 2021 Rosatom delivered 14% of uranium necessary for active zones of commercial nuclear reactors of the USA.

However, since the war in Ukraine western economies, in particular the USA, Czechia, Bulgaria, Finland and others, have announced targeted work on ceasing import of Russian uranium and fuel. Additionally, Rosatom has for once and for all lost one of its largest foreign markets in the SNF sphere – Ukraine. All of this is cause to suspect that the share of Rosatom on world markets in the nuclear fuel cycle will gradually decrease, and it will be increasingly difficult to reach the world market with new services and products.

The share of nuclear power in the energy balance of Russia in 2022 came to 19.9% (223.37179 billion kWt/h of a total of 1,121.580 billion kWt/h). Rosatom's strategy in producing electricity involves keeping its share in the energy balance of Russia at around 20%, and in a favorable situation to increase it to 25%. But in the next few years, favorable

¹⁸⁰ <https://www.nucnet.org/news/despite-geopolitical-situation-rosatom-expects-exports-to-increase-15-12-3-2022>

trends are not predicted because of the general economic slump caused by the war, as well as because the reactors of large NPPs are quite old. 62% of reactors are operated with an extended resource, and 10 reactors are in the process of decommissioning. According to Bellona assessment, by 2035-2040 13 reactors with a total capacity of around 9.3 GWt will have ceased operating in Russia, and in the period from 2040 to 2045 about 4.5 GWt more will be decommissioned. In 2022-2045, around 14 GWt in total will be put out of operation when the resource is exhausted. This means that if new reactors are not built to replace the decommissioned ones, by 2035 the total capacity of the atomic park of Russia will drop by a third, and by 2045 almost by half compared to the current level of 29.5 GWt. At present (early 2023), only two reactors are in the process of construction in Russia, Kursk 2-1 and 2-2, and construction is significantly behind schedule, as established by the general scheme for power facilities until 2035. The same delay can be seen in the reactors of the Smolensk NPP-2 and the Leningrad NPP-2 that are being prepared for construction.

The prospects for the construction and use of floating NPPs in Russia still look rather uncertain. The experience of building the first floating NPP cannot be called successful, as major technical and organizational problems led to construction taking almost 17 years, and as a result the NPP was put into operation with rather outdated equipment, including old generation reactors and servicing systems. In January 2021, Rosatom CEO Alexei Likhachev announced that the plan for building a floating NPP fleet would be passed in 2021, but this plan has yet to materialize.

At present, prospects are being discussed of small land-based NPPs with the RITM-200 reactor, the first of which is to be built in the Far East of Russia, in Yakutia. According to IAEA data, in Russia 17 projects of small power reactors are being developed, but given the geopolitical situation it is difficult to say what the prospects for their mass construction are.

At present, Russia continues to dominate in building nuclear facilities abroad, with around 40% of the total international agreements on construction of NPPs. In early 2022, the portfolio of foreign orders from Rosatom for a 10-year period was equal to USD 139.9 billion, including 84 billion for building NPPs in various countries. However, Bellona suspects that as a result of the war in Ukraine, the international activity of Rosatom for building these facilities will probably decrease. In countries where Rosatom has major long-term contracts for building NPPs, which it is difficult to annul or change, the situation will probably not change soon, but this will all depend on the geopolitical situation.

At present, Rosatom owns important foreign assets for uranium production. The total uranium production of ARMZ and Uranium One, companies that are part of Rosatom, came to 7,100 tons in 2021, or around 15% of world production.

Conversion and enrichment of uranium are the products which make the atomic sphere worldwide, and particularly in Europe, considerably dependent on Rosatom. Rosatom has around 20% of world facilities for uranium conversion (12,500 tons), and occupies around 30% of the world market of uranium conversion.

Rosatom's partner ties may be reduced or even lost as a result of the military political crisis, but this will not fundamentally and swiftly influence the dominant place that Rosatom currently holds in international business, as firstly there are many long-term contracts which it will be detrimental for all parties to annul, and secondly Rosatom's current partners will have to establish the entire chain of production of nuclear fuel for their reactors and reactors of Russian design. This will take time and strategic investments.

At present, Rosatom's financial situation looks stable. But this may change because of the consequences of the war in Ukraine. Economic sanctions against Russia are increasingly beginning to affect Rosatom. It is losing the support of international financial institutions in its projects for liquidating the nuclear legacy, which has a negative effect on ecological safety. The state budget no longer looks guaranteed for Rosatom, and this, for example, may have a negative influence on fulfilling its obligations on contracts for building NPPs abroad. Atomic cities and enterprises of Rosatom, where over 2 million people live and work, constantly require financial and other resources.

In 2017, Rosatom was made responsible for carrying out projects for treating hazardous (not radioactive) waste, along with several important projects from the state program «Ecology», as well as many issues concerning the Northern Sea Route. These are expensive projects which must be financed primarily from the state budget. Today it is hard to say whether the state budget will cover the expenses for these projects, for which Rosatom is ultimately responsible.

Enormous funds are required to liquidate the nuclear legacy of the Soviet atomic project. The volume of financing problems of the nuclear legacy according to the most optimistic predictions will exceed 2 trillion rubles¹⁸¹.

Rosatom took part in capturing and holding Ukrainian atomic facilities – the non-functioning Chernobyl NPP, as well as Europe's largest NPP, the Zaporizhzhya NPP.

The attack on the Chernobyl NPP left the entire facilities without electricity, threatening the sarcophagus of the damaged reactor, as well as the cooling system of spent fuel rods, thus creating the menace of a nuclear and radioactive accident.

The armed seizure of the Zaporizhzhya NPP is an unprecedented case in world practice, and clearly all participants and those responsible for this act of nuclear terrorism must be held accountable. It is hard to say how this will influence the further functioning of Rosatom, but it is clear that this will not be a favorable situation for the state corporation.

¹⁸¹ <https://bellona.ru/2021/12/01/prognoz-na-dva-trilliona/>

Rosatom, being before the war a powerful and respected member of the international nuclear community and its institutions risks not only losing its past economic and political influence, but its authority as a result of its participation in the unprecedented seizure of a nuclear station from another country.

The system of global nuclear safety for nuclear facilities and existing institutions, in whose creation and functioning Rosatom took and still takes an active part, must learn from these current circumstances and reform to prevent such threats in the future.

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