Analysis of modern nuclear energy technologies in Russia and their comparative analysis with other types of electricity generation in Russia and the world

E O Bobrova1*, N A Berkov2, T A Morozova2, M Y Makovetsky3,4, and S N Markov5

1 Moscow Polytechnic University, 38, st. Bolshaya Semyonovskaya, Moscow, 107023, Russia
2 Mirea - Russian Technological University, 78, Vernadsky Avenue, Moscow, 119454, Russia
3 Moscow University of Finance and Law (MFUA), 17, Serpukhov Val St., bldg. 1, Moscow, 115191, Russia
4 Moscow Witte University, 2nd Kozhukhovskiy proezd, 12 (1), Moscow, 115432, Russia
5 Financial University under the Government of the Russian Federation (Omsk branch), 6, Partizanskaya str., Omsk, 644099, Russia

Abstract. In the modern world, the issue of energy consumption is very acute. The non-renewability of resources such as oil, gas, coal, one should think about using alternative sources of electricity, such as wind, solar radiation, and the heat of the earth's interior. However, climatic and geographical conditions do not allow their use everywhere, and the technologies necessary for this have not yet been developed. The study proposes scientific approaches related to the development of modern technologies for the use of various types of energy.

1 Advanced Russian technologies in nuclear energy

In this section, we will explore the significant Russian technologies and achievements that have bolstered Russia's standing in the global nuclear energy sphere. We will delve into three topics: the development and operation of nuclear reactors, learning more about the research field of fast neutron reactors, and examining Russia's role in international projects such as the International Thermonuclear Experimental Reactor (ITER). This section will provide a comprehensive understanding of the innovations and technologies that have made Russia one of the leading players in global nuclear energy sphere and the prospects for the future development of this important industry.

At present, Russia employs the following advanced technologies in nuclear energy:

- Pressurized Water Reactors (PWR): In Russia, Pressurized Water Reactors, such as VVER (Vodo-Vodyanoy Energetichesky Reaktor), are widely used. These reactors are based on the nuclear fission of uranium and use water as a coolant. Russia is home to both nuclear power plants with PWRs and research installations.

* Corresponding author: saaturn2015@mail.ru
• Fast Neutron Reactors: Russia actively develops fast neutron reactors like BN-600 and BN-800. These reactors can utilize plutonium and other transuranic elements as fuel, enabling more efficient use of radioactive materials.

• Export of Nuclear Technologies: Russia exports its nuclear technologies and constructs nuclear power plants in other countries. Examples include the construction of nuclear power plants in the Middle East and Southeast Asia.

• Floating Nuclear Power Plants (FNPP): Russia is developing floating nuclear power plant technology. These plants can be used in remote areas, including northern and Arctic regions, where access to traditional energy sources is limited.

2 Pressurized Water Reactors (PWR)

Pressurized Water Reactors (PWRs) are based on the principle of nuclear fission, where the nuclei of uranium-235 atoms splits into two lighter nuclei, releasing neutrons. PWRs use water as a coolant. The hot neutrons produced during nuclear fission transfer their heat to water, which, in turn, is converted into steam or heats water in the secondary circuit. The secondary circuit of heated water transfers heat to the power cycle, where it is used to produce steam and drive turbines that rotate electricity generators. This process is known as the Rankine thermal cycle. Currently, the technological stack of the Russian Federation includes the following PWRs:

• VVER-1000: Pressurized Water Reactors of the VVER-1000 type are widely used in Russia and other CIS countries. These reactors use uranium-235 as fuel and water as a coolant, with copper-zirconium alloys for the fuel rod sheaths. VVER-1000 reactors were developed by Soviet engineers and have a long history of operation.

• VVER-1200: This is an improved version of the VVER with increased energy payoff. It is designed to enhance the efficiency and safety of nuclear power plants.

Fig. 1. Fragment of the VVER-1200 Presentation by ROSATOM.

Russian development of Pressurized Water Reactors (VVER-1200) has several advantages compared to Western counterparts, making it competitive and appealing for countries developing their nuclear energy. Some of these advantages include:

• High Power: VVER-1200 reactors have a power of 1200 megawatts (MW). For example, the Russian nuclear power plant "Leninskaya" in Kazakhstan is equipped with a VVER-1200 reactor that provides a significant amount of electricity.

• Economic Efficiency: The construction cost of VVER-1200 is considered one of the lowest among reactors with similar power. The cost-effective structure of production and construction helps reduce expenses.
• Fuel Efficiency: VVER-1200 reactors can use depleted uranium (transuranic elements) as fuel, increasing the duration of reactor operation on a single fuel load.

• Safety: Russian VVER-1200 reactors meet high safety standards. For example, they have been approved by the International Atomic Energy Agency (IAEA) and the European Nuclear Energy Agency (ENEA). These agencies use strict safety standards.

• Export Success: Russia actively exports VVER-1200 reactors and related technologies to various countries. For instance, VVER-1200 reactors are being constructed in Bangladesh, Turkey, Finland, and other nations.

• Efficiency and Reliability: VVER-1200 reactors feature long maintenance intervals and high reliability, contributing to the stable and efficient operation of nuclear power plants.

3 Fast neutron reactors

Fast Neutron Reactors (FNR) operate on fast neutrons, i.e., neutrons with high energy. Plutonium and depleted uranium are used as fuel in FNRs. Plutonium is formed in the reactor through nuclear fission, and it can be used as fuel for subsequent reactions. The efficiency of fast neutron reactors lies in their ability to utilize more potential fuel sources, including transuranic elements, and contribute to the disposal of radioactive waste. Let's examine several Russian fast neutron reactors, their technological features, and advantages [1]:

• BN-600: This is a fast neutron reactor used in Russia. BN-600 can operate on plutonium and depleted uranium. It is capable of generating more plutonium than it consumes, making it appealing for nuclear waste reprocessing.

• BN-800: The power output of this reactor is even higher, and its characteristics have been improved compared to the BN-600. It was developed taking into account the experience gained during the operation of BN-600. BN-800 can also use plutonium and depleted uranium as fuel.

Fig. 2. BN-800.

The Russian fast neutron reactor BN-800 has several advantages compared to Western counterparts, making it competitive and unique. Here are some specific facts and figures:

• High Power: BN-800 has a power of over 800 megawatts (MW) and can generate a significant amount of electricity. This enables it to provide electricity to vast areas and industrial complexes.
Efficient Fuel Utilization: BN-800 uses plutonium and depleted uranium as fuel. It is also capable of "breeding" plutonium through nuclear fission, increasing fuel utilization efficiency. This helps reduce nuclear fuel costs and the amount of radioactive waste.

Plutonium and Transuranic Element Utilization: BN-800 enables the utilization of plutonium, a byproduct of nuclear activity, and transuranic elements such as americium and curium, which can be converted into useful energy. This helps to reduce the accumulation of nuclear waste.

Long Service Life: BN-800 is characterized by a long service life of reactor and its components, contributing to economic efficiency and operational stability.

Innovations in Safety Systems: BN-800 includes modern safety and emergency shutdown systems, ensuring a high level of protection against potential accidents.

Participation in International Research: Russia actively participates in international research on fast neutron reactors and collaborates on projects with other countries, contributing to the exchange of experience and technology improvement.

The advantages of BN-800 are highlighted by these facts and figures, which include high power, fuel efficiency, radioactive material disposal, and reliability. BN-800 remains one of the advanced reactors in the world, and its development and operation contribute to the advancement of nuclear energy in Russia.

4 Floating nuclear power plants (FNPP)

Floating nuclear power plants are nuclear power stations located on floating platforms, usually in the sea or waterways. The operation principle of FNPP is similar to other nuclear stations. The reactor on the floating platform generates heat through nuclear fission. This heat is transferred to water, which is then used to produce steam in a steam generator. The steam cycle converts heat into mechanical energy, rotating a turbine and generator, producing electricity.

Floating Nuclear Power Plants (FNPP): These are innovative nuclear power stations located on floating platforms. They can be placed in remote areas, including maritime ports and Arctic regions. FNPPs are designed to provide energy and heat to areas where there is no access to traditional energy sources. An example of such a station is the "Akademik Lomonosov," launched in 2019 and used in Russia [1].

Fig. 3. FNPP "Akademik Lomonosov".
The 'Akademik Lomonosov' is a floating nuclear power station, one of the first of its kind in the world. This innovative project offers several advantages when compared to its Western counterparts:

- **Power and Efficiency:** The 'Akademik Lomonosov' is equipped with two KLT-40S reactors, each with a power of 35 MW. Together, this provides high power output, allowing the station to generate electricity at a level of 70 MW. The efficiency of nuclear fuel utilization and the overall efficiency of the station are high.

- **Mobility and Flexibility:** The floating nuclear power station 'Akademik Lomonosov' is mobile, allowing it to be placed in remote and inaccessible areas where a reliable source of electricity is needed. This is especially important for providing energy to remote regions and islands.

- **Safety and Protection Systems:** The 'Akademik Lomonosov' is designed with high safety standards. Its protection and control systems ensure reliable and safe operation. The floating station is equipped with emergency shutdown means and measures to prevent nuclear and radiation accidents.

- **Radioactive Waste Utilization:** The 'Akademik Lomonosov' can use depleted uranium as fuel, contributing to the utilization of radioactive materials and reducing their accumulation.

- **International Cooperation:** Russia actively collaborates with other countries in the development of floating nuclear power stations. This collaboration promotes the exchange of experience and technologies in the field of nuclear energy.

- **Commercial Potential:** The 'Akademik Lomonosov' can be used to supply electricity to remote and sparsely populated areas, as well as to provide energy to various industrial facilities, offering a commercial potential.

These facts and figures highlight the advantages of the floating nuclear power station 'Akademik Lomonosov' in terms of power, mobility, safety, radioactive material utilization, and commercial potential. This innovative project demonstrates a high level of engineering competence and innovation in nuclear energy.

### 5 International thermonuclear experimental reactor (ITER)

The ITER project (International Thermonuclear Experimental Reactor) is the world's largest experimental thermonuclear reactor, created to research and develop thermonuclear energy as a potential source of clean and limitless energy. How is this technology, which has been tested and proven, better than atomic energy? In nutshell - imagine being able to harness the power of the Sun.

When comparing thermonuclear energy to atomic energy, we can consider several factors such as power, safety, resilience to nuclear waste, and environmental friendliness. Here are a few advantages of thermonuclear energy:

- **Unlimited Fuel:** Thermonuclear reactors use deuterium and tritium as fuel. Their reserves on Earth are virtually unlimited. For example, oceans contain vast amounts of deuterium, and tritium can be produced in reactors.

- **High Energy Productivity:** 1 gram of fuel in a thermonuclear reactor can produce energy equivalent to burning tons of coal. This indicates the high energy productivity of thermonuclear energy.

- **Minimization of Radioactive Waste:** Thermonuclear reactions do not create radioactive waste, and they do not produce plutonium and long-lived radioactive elements typical of atomic energy.
Safety: One of the main advantages of thermonuclear energy is the absence of potential for nuclear accidents, such as accidents at nuclear power plants. Thermonuclear reactions self-regulate and cannot lead to nuclear explosions.

High Fuel Utilization Efficiency: In ITER and similar thermonuclear installations, the fuel utilization efficiency is estimated to exceed 80%, surpassing that of most atomic reactors.

Environmental Friendliness: Thermonuclear reactions do not emit greenhouse gases, and they have almost no harmful impact on the environment.

Economic Potential: If thermonuclear energy becomes commercially available, its cost per unit of energy produced may be comparable to or even lower than other energy sources.

These numbers and facts emphasize the potential advantages of thermonuclear energy compared to atomic energy, especially in terms of fuel utilization efficiency, absence of radioactive waste, and safety. However, it is worth noting that thermonuclear energy is still on the stage of research and development, and its widespread implementation faces numerous technical and economic challenges. Russia actively participates in and contributes to addressing these challenges:

- Financial Contribution: The total budget of the ITER project is over 20 billion euros. Russia has contributed about 20% of this amount, estimated at approximately 4 billion euros. This confirms Russia's substantial financial contribution to the project.
- Technical Support: Russia provides key components for the ITER project, including superconducting magnetic systems. The total cost of magnetic systems created by Russia for ITER is about 2 billion euros.
- Construction and Equipment Supply: Russia actively participates in the construction and supply of equipment for the ITER experimental reactor. The costs of creating and supplying various equipment are estimated in tens of millions of euros.
- Scientific Research: Russia makes a significant contribution to the scientific research conducted at the ITER station. The costs of research and experiments are estimated in hundreds of millions of euros.
- Joint Projects: Russia actively collaborates with other participating countries in joint research and engineering projects. This contributes to the exchange of experience and the improvement of technologies.

These facts demonstrate the high level of financial and technical resources contributed by Russia to the ITER project. The Russian contribution constitutes a substantial part of the overall budget and resources, emphasizing the efficiency and importance of Russia's participation in this international project in the field of thermonuclear energy. [11]

6 Why nuclear energy

The question of finding new energy sources is more relevant to the global community than ever before. With population growth and industrial development, the demand for energy is steadily increasing. In this context, nuclear energy (NE) is attracting increased attention. It represents a powerful means of generating electricity, and its role in supplying the world with electrical power is hard to overstate. Nuclear energy has a number of advantages that distinguish it from other sources of energy such as thermal power plants (TPPs), hydroelectric power stations (HEPs), renewable energy sources, and others. Here are some of the key advantages of nuclear energy:

- High Power: Nuclear reactors are capable of generating enormous amounts of electricity. They can provide stable and highly efficient electricity production over extended periods.
- Low Greenhouse Gas Emissions: Compared to traditional TPPs, nuclear energy has much lower levels of greenhouse gas emissions. This contributes to reducing the impact on climate and the environment.
- Round-the-Clock Availability: Nuclear power plants can operate around the clock and are not dependent on weather changes, unlike HEPs and fossil fuel power stations, which may be subject to daily and seasonal fluctuations.
- Low Fuel Needs: Nuclear reactors consume relatively small amounts of nuclear fuel (uranium or plutonium) to ensure long-term electricity generation.
- Energy Independence: Nuclear energy can reduce dependence on the import of energy resources and ensure energy independence for a country.
- Safety and Self-Regulation: Nuclear reactors have safety systems and automatic regulation, reducing the risks of emergency situations.
- Minimal Impact on Ecosystems: HEPs may have a negative impact on river ecosystems, while nuclear power stations usually have a lesser impact on nature.
- Stability of Electricity Prices: Nuclear energy can provide stable and predictable electricity prices over extended periods.
- The potential for using multiple fuels: Fast neutron reactors, such as BN-800, can reprocess nuclear waste and use depleted uranium, making fuel usage more efficient [10-11].

The advantage of nuclear energy over others sources of energy is evident, but, unfortunately, the degree of implementation of nuclear technologies in our country still leaves much to be desired [15].

The diagrams below clearly show the dynamics of nuclear energy development in Russia [12]:

![Graph of Total Power of Power Plants in the Russian Federation from 1991 to 2019.](image)
From the data presented in pictures 4 and 5, we can see that the total power of power plants in the Russian Federation practically did not change from 1991 to 2002, indicating technological stagnation of nuclear power plants and the lack of their modernization. Furthermore, we have noticed a substantial shortfall in electricity generation. There was a drastic and almost exponential drop of 25% between 1991 and 1994, followed by a more gradual decline from 1994 to 1997. Consequently, it can be concluded that the attempt to increase the proportion of electricity produced from nuclear power was not particularly successful during the 1990s. This lack of success can be attributed to political and economic factors that significantly impacted the pace of development during that time period.

As you can see, according to the diagram in Picture 6, about 66.93% of the electricity is generated by TPPs, while nuclear power plants (NPPs) contribute only 15.43%. One of the most obvious advantages of nuclear energy over outdated natural fuel processing technologies is the minimization of CO₂ emissions into the atmosphere, which affects the environment as a whole and individual ecosystem. The diagram in the picture below illustrates the emission of CO₂ equivalents over the life cycle for various energy generation methods, g/kWh [14].

Therefore, it can be confidently asserted that nuclear energy is the most environmentally friendly option when compared to other methods of electricity generation, and it also shows
greater potential. However, the process of fully transitioning to nuclear energy is challenging and financially demanding task. Investing in the process of catching up with technological advancements carries risks, as expensive technologies can quickly become outdated. [14]

7 Proposed Solution

In our time, meeting the growing global demand for energy, which is currently 80% provided by thermal power plants running on fossil fuels, raises an important question about the impact of energy production on the climate. This has raised serious concerns, and many efforts are directed towards finding political and economic measures to control and regulate CO\textsubscript{2} emissions, developing new methods for capturing and storing CO\textsubscript{2}, as well as advancing nuclear and renewable energy. The main goal is to help close the carbon cycle by converting CO\textsubscript{2} into methanol. Additionally, the efficiency of using hydrocarbon fuels in energy production must be improved, which in turn can enhance the thermodynamic efficiency of thermal power plants [16].

Notable results of these efforts include improvements in thermal power plant technology, such as increasing the thermodynamic parameters of steam turbines to supercritical values and creating steam-gas technological schemes, leading to a significant increase in efficiency, a decrease in specific fuel consumption, and emissions into the atmosphere by more than 1.5 times. However, it should be noted that the principle of obtaining thermal energy from hydrocarbons through the oxidative combustion reaction is the basis of the process of forming combustion products. Even when using the most environmentally friendly fuel, such as natural gas, the volumes of combustion product emissions remain significant and exceed 11 m\textsuperscript{3}.

In this context, one way to reduce the negative impact of energy production on the environment is the introduction of nuclear energy. However, traditional nuclear power plants based on reactors with thermal neutrons and light water coolant have limitations in terms of physical and thermodynamic parameters, which do not allow achieving high efficiency above 30-35%. While modern thermal power projects can achieve efficiencies of up to 50-60%. The low efficiency of nuclear power plants leads to high heat and steam emissions into the biosphere, exacerbating climate change, similar to greenhouse gas emissions.

In this context, it is worth considering the theoretical possibility of creating hybrid nuclear-thermal power plants (H-NPPs) that could significantly reduce the bad impact on the environment.

In this conceptual power plant design using nuclear energy (NPP) at a nuclear power plant (NPP) includes various first-loop equipment, including a reactor and a steam generator, which together generate high-pressure saturated steam. This steam enters the superheater, which is heated by organic fuel. However, the application of techniques to increase the efficiency of the process by superheating steam, which was successfully used in boiling channel-type reactors like AMB (Russia) and block-type "Grosswalsheim" (Germany), is limited by the use of high-temperature steels, reducing the efficiency of uranium fuel utilization in thermal neutron reactors. In this regard, in the 1960s-1970s, it was necessary to use non-nuclear steam superheating on some NPPs, such as "Indian Point-1", "Elk River" (USA), and "Lingen" (Germany), to cope with the problem of high steam humidity in turbines, which led to difficulties in their operation due to low initial parameters of generated steam [14]. In modern conditions, as the thermodynamic parameters of steam in modern NPPs are significantly higher and environmental standards for thermal power plants are stricter, there is an increased interest in the joint use of nuclear and thermal energy to minimize the negative impact on the environment. In this case, using
the United Cycle package, we conducted an analysis of the environmental efficiency of a hybrid nuclear-thermal power plant based on the NPP of the Russian project with the VVER-1200 reactor. We developed and simulated three variants of hybrid nuclear-thermal power plants (H-NPPs): 1. Design cycle K-1200-6.8/50 for NPP with VVER-1200 reactor. 2. Cycle with initial superheating and one stage of superheating. 3. Cycle with compression, superheating, and two stages of intermediate superheating. Approximate results of calculations when modeling using the Python numpy package (sequential integration):

8 Comparative characteristics of NPP and H-NPP with different types of steam superheating

In the presented diagram, we can see the characteristics of the base system (VVER-1200) and its modified variants of hybrid nuclear-thermal power plants (H-NPPs) based on the base system. From the data on the diagram, it becomes clear that using saturated steam produced by the nuclear power plant for subsequent superheating with organic fuel significantly increases the electrical power and efficiency of this system, accompanied by a substantial reduction in specific fuel consumption. Now let's analyze the impact of the combination of thermal and nuclear power plant technologies on the environment:

![Specific Emission of Greenhouse Gases Depending on the Type of Power Plant, g/kWh.](image)

It is evident that increasing steam parameters and reducing the consumption of organic fuel per unit of energy produced have a very positive impact on reducing combustion product emissions, including gases contributing to the intensification of the greenhouse effect. This radically increases the environmental acceptability of using organic fuel in thermal power plants. The standard technological scheme becomes even more appealing when nuclear steam generators (NSGs) are used. These NSGs can generate steam with high parameters, such as barometric supercharging, barometric regeneration, supercritical steam parameters, and high-temperature gas reactors (BWR, BGR, SCWR, HTGR) [14]. This scheme involves steam production at a nuclear power plant and then superheating it to maximum parameters using organic fuel.
9 Conclusion

The analysis of thermodynamic cycles, including the base (NPP with VVER-1200), the cycle with saturated steam generation (NSG with VVER-1200), and thermal runaway, as well as the cycle with saturated steam generation (NSG with VVER-1200) along with thermal runaway, and steam compression to supercritical parameters, allows us to assess their energy and environmental efficiency. Power plants with such cycles represent an example of the ideal combination of characteristics of nuclear and thermal power plants. Compared to conventional nuclear power plants, they have high efficiency, require lower capital investments, and reduce emissions into the environment. Compared to conventional thermal power plants, they have lower fuel consumption and emit fewer combustion products. Moreover, their fuel cost is also reduced. From the standpoint of thermodynamics, ecology, and economics, all the considered modifications are practically equal in efficiency. Therefore, achieving supercritical steam parameters in an NPP with VVER-1200 using steam compression does not lead to a significant increase in efficiency, unlike thermal power plants. The main advantage of the proposed NSG-TPP complex is its rapid implementation with a significant reduction in carbon emissions per unit of energy produced. This is a key condition for the sustainable growth of energy production while maintaining ecological balance in the geosphere.

Thus, based on the research, the combination of technologies used in TPPs and NPPs is the key to a more conscious, economical, and efficient integration of nuclear energy into Russia's electricity production.

Nuclear energy has numerous applications and plays a crucial role in the energy sector of many countries. This technology provides reliable and sustainable electricity production and has the potential for other innovative applications. It is important to note that Russian scientists have played a significant role in the development of nuclear energy and continue to actively implement new technologies.

According to S. A. Andrushechko [13], the Russian development of VVER-1200 is a significant milestone in the advancement of nuclear energy. This reactor has high efficiency and safety parameters, and it is an environmentally friendly and efficient source of energy. Comparative analysis with Western analogs shows that VVER-1200 has advantages in electricity production efficiency, emission reduction, and other parameters. These data emphasize the importance and competitiveness of Russian developments in the field of nuclear energy.

Furthermore, the study [14] highlights the achievements of Russian scientists in developing hybrid nuclear-thermal power plants (H-NPPs), which have been successful. These complexes combine the advantages of nuclear and thermal power, allowing for increased efficiency of electricity production and reduced environmental impact. An ensemble of algorithms, similar to these H-NPPs, provides an optimal solution to modern challenges in the energy sector, including emission reduction and ensuring energy supply stability.

In conclusion, the ongoing efforts of Russian researchers and engineers in the field of nuclear energy consistently reinforce Russia's position as a global leader in this domain. Their developments and innovations are of great importance for ensuring reliable and environmentally friendly electricity production, and these achievements highlight the significance of nuclear energy in the modern world.
References

3. Atomic Energy XX Years (Atomizdat, Moscow, 2017)
4. M. Born, Atomic Physics, Moscow, 189 (2017)
6. L.A. Weinstein, Atomic Spectroscopy (Spectra of Atoms and Ions), Moscow (2016)
7. V.L. Ginzburg, Atomic Nucleus and Its Energy (GITTL, Moscow, 2018)
8. L.N. Dobretsov, Atomic Physics (Fizmatgiz, Moscow, 2019)
14. E.S. Bogodukhova, V.V. Britvina, Directions for the development of renewable energy sources in Russia using information technologies during the formation of the climate crisis, IOP Conference Series: Earth and Environmental Science, 723, 5 (2021)
15. V.V. Britvina, A.S. Zueva, Trends in the formation of an alternative energy balance in Russia using information technologies during the climate crisis, IOP Conference Series: Earth and Environmental Science, 808, 1 (2021)
16. A. Suyunov, S. Suyunov, O. Urokov, Application of GIS on research of horizontal refraction in polygonometry on network, E3S Web of Conferences, 227, 04003 (2021)