International Journal of Environmental Science and Green Technology
https://journals.ayu.edu.kz

Ecological Aspects of the Constructing a Nuclear Power Station in Kazakhstan

Gulzat Abdikarim[1], Davlat Yuldashbek[1*], Nurlan Akhmetov[1]

[1]*Ecology Research Institute, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkistan, Kazakhstan*

*Corresponding Author e-mail: davlat.yuldashbek@ayu.edu.kz

Keywords

nuclear power plants

greenhouse gases

nuclear fuels

radioactive waste

environmental pollution

Abstract

Kazakhstan is rich in natural resources, including coal, oil, natural gas, and uranium, and has significant potential for renewable energy sources, such as wind, solar, hydropower, and biomass. Nuclear energy is often considered an alternative source of energy, capable of reducing the impact on the environment compared to traditional fossil sources such as coal and natural gas. There are currently no operating nuclear power reactors in Kazakhstan. In this context, the potential impact of the planned nuclear power plant in Kazakhstan on the territory and environmental situation of Kazakhstan is considered. However, like any method of energy generation, nuclear energy has its own environmental aspects. NPPs emit almost no other pollutants, such as sulfur (SOx), nitrogen oxides (NOx), and solid particles, which are characteristic of burning fossil fuels. Low carbon emissions: nuclear power plants produce large amounts of electricity with minimal greenhouse gas emissions, which can help combat climate change. High-efficiency nuclear reactors are able to produce a large amount of energy from a relatively small amount of fuel. Uranium-235 and plutonium-239 radioactive elements are often used as reactor fuel. Used in nuclear reactors, they have high energy density. Kazakhstan's uranium production is carried out exclusively by underground well drilling, which is the most environmentally friendly and least expensive method. Given that Kazakhstan accounts for 40% of global uranium production, it is assumed that transporting reactor fuel could be cost-effective. Stable electricity supply: nuclear plants provide reliable and continuous production of electricity, which makes them important for maintaining the stability of the energy system. Reducing dependence on fossil fuels, the development of nuclear energy can reduce the consumption of coal, oil, and gas, which in turn helps to reduce the negative impact on the environment associated with their extraction and combustion. Long-term energy: nuclear reactors can operate for several decades, which makes them convenient for providing long-term energy needs. The development of waste disposal technologies and research and development in the field of nuclear waste disposal create opportunities for safer handling of them and reduction of negative impact on the environment. These aspects make nuclear energy in Kazakhstan an important part of solving problems in the field of energy, ecology, and economy.

Cite

Abdikarim G., Yuldashbek D., Akhmetov N. (2025). Ecological Aspects of the Constructing a Nuclear Power Station in Kazakhstan. International Journal of Environmental Science and Green Technology, 1(1), 1-13. doi: 10.5281/zenodo.15741805

Article Process

Submission Date: 12.01.2025; Revision Date: 03.02.2025; Accepted Date: 10.02.2025; Published Date: 25.03.2025;

1. INTRODUCTION

Kazakhstan is an independent state that emerged after the collapse of the Soviet Union in 1991. It is currently a middle-income country with a population of about 21 million. The total area of the country is 2.7 million km^2. 47% of the population lives in rural areas. Kazakhstan is located in Central Asia and consists of steppe and pasture lands in the north and desert and semi-desert areas in the central and western parts. The southern part of the country is surrounded by water resources of national importance, surrounded by the Caspian and Aral Seas and the high mountains of the Tien Shan and Pamir ranges. Kazakhstan has a good economic situation, benefiting from its natural resources (especially oil, gas, and uranium), heavy industry (ferrous and non-ferrous metals), and agricultural sectors [1]. There are currently no operating nuclear power plants in Kazakhstan. A nuclear power plant is planned to be built on the shores of Lake Balkhash in southeastern Kazakhstan. Nuclear power plants are planned to be built from 2024 to 2035.

Pro-nuclear groups advocate the use of nuclear energy as a solution to the problem of anthropogenic climate change and the reduction of fossil fuel reserves, while some groups of environmentalists and various experts disagree, arguing that the rapid expansion of nuclear energy will increase the risk of accidents and long-term problems with waste disposal [2]. In article [3], a survey of the attitudes of the different countries' populations was analyzed, and the factors contributing to the formation of a positive or negative attitude of citizens toward the nuclear industry were identified and described. As part of the study, four countries were selected: the USA, France, and Russia, which are leaders in the production and use of nuclear energy in their regions, and Japan.

As part of the research, we studied a survey of the population of the USA, France, Russia, and Japan for 2019; the results are presented in the diagram (Figure 1).

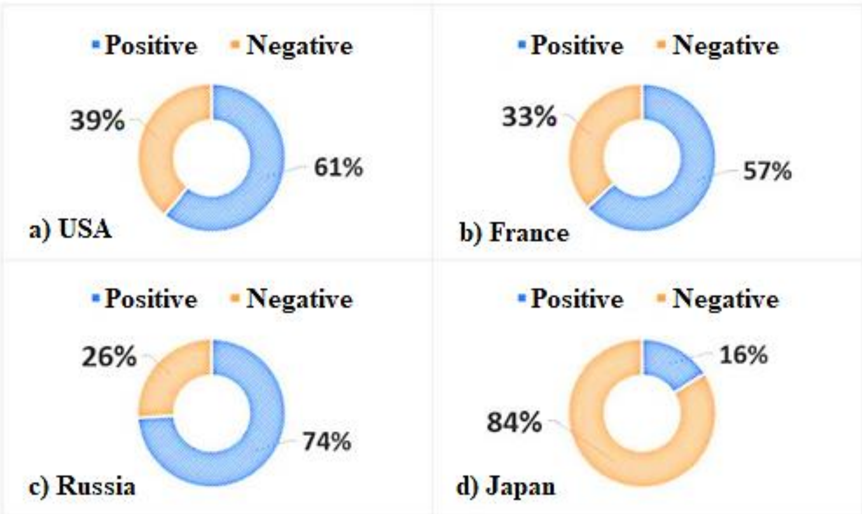

Figure 1. *The public's perception of nuclear energy in several nations in 2019**

** was put together utilizing information [3]*

Based on these sources of population surveys for 2019, the vast majority of the population of the USA, France, and Russia has a positive attitude towards nuclear energy production and supports the industry's development, while in Japan, only 16% of recipients have a positive attitude towards nuclear energy.

Currently, the nuclear power plant is developing rapidly, and its application is involved in many aspects, including life, the military sphere, industry, and many other important spheres that benefit people's lives. However, the nuclear power plant has a relatively special structure. After a safety-related accident occurs, the consequences will be unimaginable, and the cost of its operation and maintenance will be relatively high. Therefore, how to effectively diagnose the state of health of a nuclear power plant is an urgent problem that needs to be solved. The state of health allows you to make an approximate diagnosis and provides a guideline for the development of a strategy for operation and maintenance [4].

2. STRUCTURE AND PRINCIPLE OF NPP'S OPERATION

The NPP works on nuclear fuel, the most common of which are uranium-233, uranium-235, and plutonium-239. The nuclear reactor is the main difference between NPPs and other power plants. At a nuclear power plant there are three mutual transformations of forms of energy: nuclear energy is transformed into thermal energy, thermal energy is transformed into mechanical energy, and mechanical energy is transformed into electrical energy [5].

A nuclear power plant is a complex of buildings in which technological equipment is located. The main building, which houses the reactor hall, is the main and most important building. It houses a reactor, a storage pool for nuclear fuel, and a transshipment machine. The main element of the reactor is the active zone - this space in which a controlled chain reaction takes place. It is usually placed in a concrete shaft. The most important component of any reactor is the control and protection system. It determines the optimal course of the chain reaction or stops it in the event of an emergency. A separate building is allocated under the turbine hall, where the steam generator and the turbine are located. Next, there are capacitors and high-voltage power lines that go outside the NPP site (Figure 2).

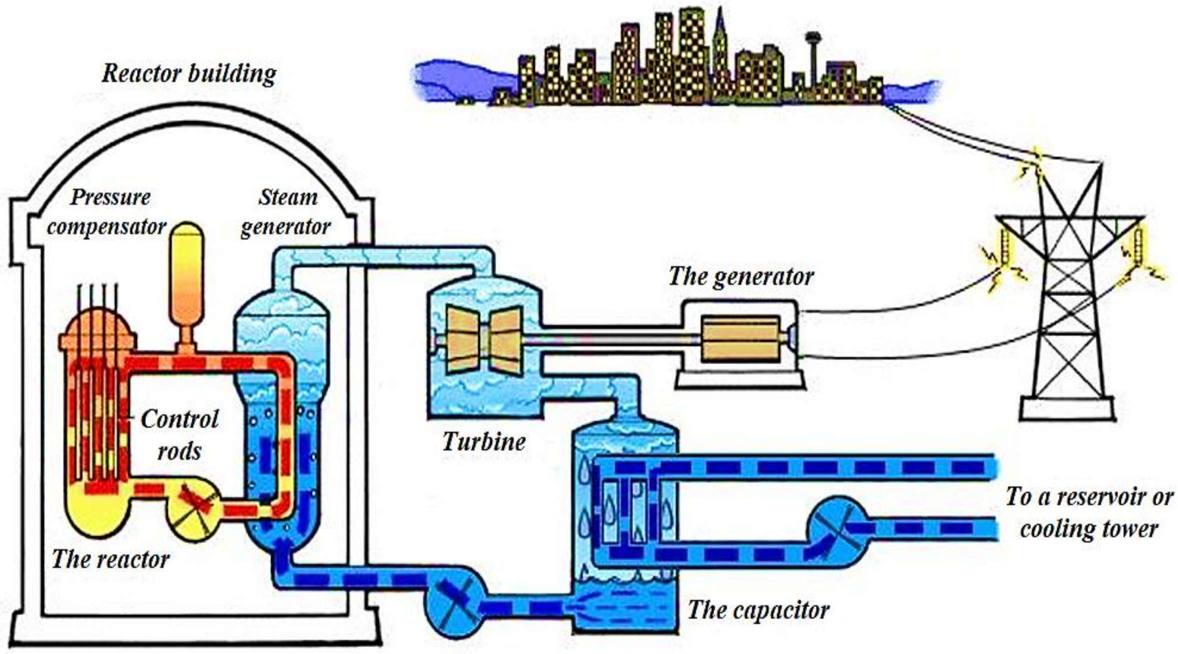

Figure 2. *Scheme of NPP's operation*

3. POSITIVE ASPECTS OF ATOMIC ENERGY: LOW EMISSIONS OF GREENHOUSE GASES

In the process of producing electricity, nuclear power plants (NPPs) emit significantly less carbon dioxide (CO_2) than coal and gas plants. This makes nuclear energy more attractive from the point of view of combating climate change. Atomic energy has several positive aspects that make it an important element of the global energy system [6].

Nuclear energy is a low-carbon energy source that plays an important role in preventing CO_2 emissions. Over the past 50 years, the use of nuclear energy has allowed us to reduce global emissions of CO_2 by approximately 74 Gt, which is equivalent to the total volume of global energy-related emissions in almost two years. Only hydropower has played a more significant role in reducing emissions in the past period [7-8].

4. HIGH ENERGY PER UNIT OF FUEL

Nuclear fuel has a much higher energy density than coal or gas. This means that for the production of the same amount of energy, the nuclear power plant requires a significantly smaller amount of resources. The generation of electricity with the help of nuclear energy is becoming more and more important in the light of growing concern about global climate change [9]. Nuclear energy is one of the most important sources of energy in the modern world, providing electricity to millions of people around the world. However, the construction of nuclear power plants on rivers has become the subject of intense debates due to potential risks. Although nuclear power is an efficient and reliable source of energy, it is extremely important to understand the potential risks and benefits before building power plants on rivers.

As of May 2024, 440 nuclear reactors were operating in 32 countries of the world (Figure 3). At that time, the largest number of nuclear reactors in operation was in the USA-94. Active nuclear reactors are reactors connected to the grid [10].

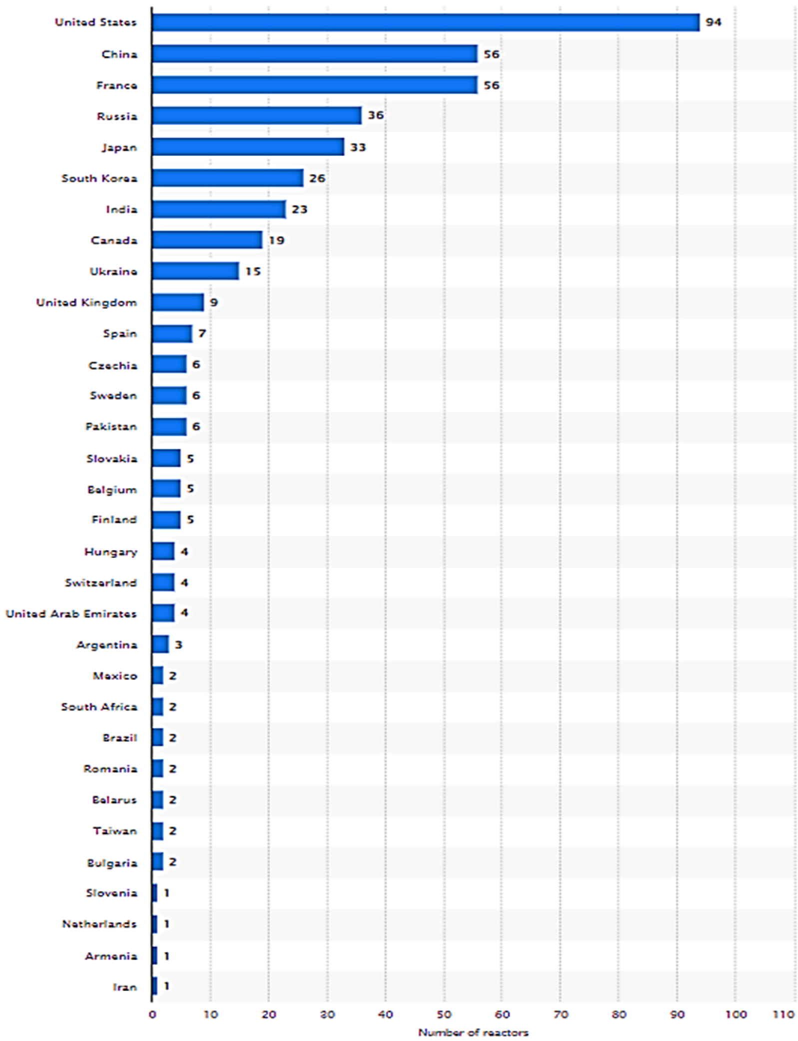

Figure 3. *Operating nuclear power reactors in the world in 2024, by country*

5. INNOVATIONS IN THE FUEL CYCLE

Fast neutron reactors can increase the amount of energy obtained from uranium mines up to 6000%, increasing the ratio of reserves to the level of more than 4000 years. Among the Asian countries, Kazakhstan operates 4 reactors for the production of uranium raw materials used as nuclear fuel [11]. In Russia, there are two operating fast neutron reactors with a sodium coolant, and it is planned to develop a reactor with a sodium coolant with a capacity of 1200 MW (BN-1200) along with a project of a reactor with a lead coolant with a capacity of 300 MW (BREST-300) (Figure 4). The development of fast neutron reactors is being resumed in the USA, where it was recently announced that the state financing of the fast reactor Natrium with sodium heat carrier, which will be developed by the companies TerraPower and GE Hitachi,. Other countries have also built and operated fast neutron reactors in the past [12].

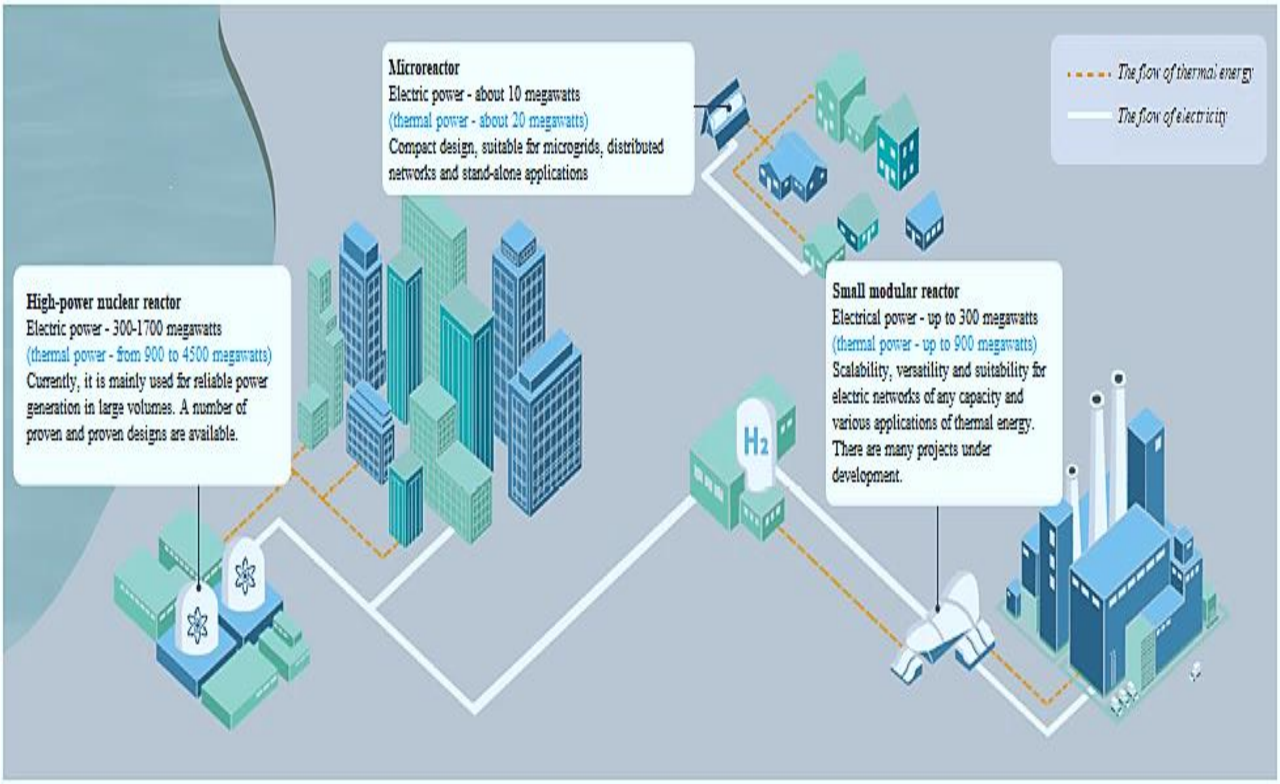

Figure 4. *Production of nuclear energy*

Nuclear power reactors can be used to produce useful radioisotopes for civilian applications. This can be done by processing spent fuel to extract useful materials, for example, americium-241, which is used as a radioisotope energy source for space flights. In addition, useful radioisotopes can be obtained by irradiating materials placed in the active zone of the reactor. Reactors of the PHWR type are especially suitable for this purpose. Thus, the CANDU reactor in Canada is used for the production of cobalt-60 and molybdenum-99 for medical purposes [13-14].

6. NEGATIVE ASPECTS OF ATOMIC ENERGY: WASTE NUCLEAR FUEL

One of the main environmental challenges of nuclear power is the management of radioactive waste. Storage and disposal of spent nuclear fuel require reliable and safe solutions, which have not yet been fully implemented.

It is known that radionuclides are released during normal operation of nuclear power plants. Sources of radioactivity and environmental pollution are analyzed in the article, for example, Khmelnytskyi NPP in Ukraine. According to the content of radionuclides in emissions into the atmosphere, the highest concentrations were found for nitrogen-16, krypton-83m, argon-41, tritium, and xenon-131m [15-16]. Of the non-radioactive chemical substances, only the concentration of nitrogen dioxide in the air is below the permissible limit. The highest concentration of suspended particles in the air near the Khmelnytsky NPP was measured in the range of 3.4-7.7 mg/m^3. Up to 90% of non-radioactive emissions into the atmosphere are generated in the boiler room. The main contribution to the gas-aerosol emissions of the Khmelnytskyi NPP is made by inert radioactive gases that either migrate directly or migrate through the food chain in the ecosystem. The expected contribution of iodine radioisotopes and activated corrosion products to the total emission is very small. Pollution of agricultural crops with aerosol radionuclides from nuclear power plants was analyzed. Contamination of agricultural production with aerosol radionuclides in the case of the maximum predicted accident at the Khmelnytsky NPP (Ukraine) is calculated [17].

Nuclear power plants emit various wastes (Kamboj, 2019) [18], including gaseous and liquid forms of radioactive materials (Delgarm et al., 2020) [19]. Gaseous waste usually consists of noble gases, such as xenon and krypton, as well as tritium, in the form of hydrogen (Kong et al., 2017) [20]. Liquid waste usually contains radioactive isotopes such as tritium (Hirao and Kakiuchi, 2021 [21]), as well as metals such as cobalt and strontium (Kang and Cheong, 2020) [22]. Solid emissions consist of particles such as dust and ash containing radioactive isotopes.

7. RISK OF ACCIDENTS

Although major accidents at nuclear power plants are rare, the consequences can be catastrophic for the environment and human health (e.g., Chernobyl and Fukushima). The possibility of such events, even at low probability, requires stringent safety measures. Every nuclear power plant in Canada has several robust safety systems designed to prevent accidents and reduce the consequences if they occur. All of these systems are regularly maintained, inspected, and upgraded as necessary to ensure that the plants meet or exceed the strict safety standards set by the Canadian Nuclear Safety Commission. The systems perform three primary safety functions: reactor control, fuel cooling, and radiation containment [23].

8. IMPACT ON HUMAN HEALTH AND THE ENVIRONMENT

Today, there are no 100% reliable energy facilities and systems. The impact of NPPs on the environment begins from the beginning of construction, continues during operation, and even continues after its completion. Significant factors of NPP impact on the environment include:

- Change in the landscape of both the construction site itself and the adjacent territories;

- Change in vegetation and animal habitats;

- Change in the flow of surface and ground waters that contain chemical and radioactive components;

- Release of radionuclides into the environment;

- Climate change in adjacent areas.

Nuclear power is associated with its own inherent risks, such as radiological accidents and radioactive waste management, but comprehensive life cycle assessments show that when assessed across a wide range of environmental indicators, the impact of nuclear power is one of the least in terms of impact among all energy sources.

Air quality is one of the most important issues facing the global community in the field of health and environmental protection. The World Health Organization reports that outdoor air pollution kills 4.2 million people worldwide each year, with much of this pollution related to energy production and use. Household pollution from exposure to smoke during cooking causes 3.8 million deaths each year. Nuclear power plants do not contribute to air pollution, and the use of this technology over the years is believed to have saved more than a million lives. [24] The two most serious nuclear accidents were the Chernobyl accident in 1986 and the Fukushima Daiichi accident in 2011. [25] They caused significant public concern, led to long-term evacuations, and were the basis for political decisions to close the facilities, as noted above. Lessons learned from these accidents and other incidents at nuclear facilities are shared with countries around the world and are taken into account in the design of new reactors and in operational practices.

Radioactive materials are generated during the production of electricity at nuclear power plants. They require sustainable management methods that protect personnel and the environment, as well as subsequent disposal at specially designed facilities. Radioactive waste is classified according to its levels of radioactivity and the length of time it remains radioactive, the latter being determined by the half-life of the radioisotopes it contains. Very low-level waste (VLLW) and low-level waste (LLW) are wastes that are suitable for disposal in near-surface disposal facilities. Intermediate-level waste (ILW) and high-level waste (HLW), including spent nuclear fuel, require disposal in deep geological repositories. ILW and HLW contain long-lived radionuclides that require disposal depths of 10 to 100 meters. About 97% of radioactive waste generated in the nuclear industry is classified as LLW or VLLW based on its radiochemical characteristics. HLW constitutes the smallest share by volume (less than 0.1%) but accounts for about 95% of the total radioactivity. HLW mainly consists of spent nuclear fuel or SNF reprocessing materials. There are currently no final disposal facilities for HLW from nuclear power plants in the world; construction of such a facility is currently underway in Finland. When commissioned in 2023, it will become the world’s first final geological repository for HLW [26].

9. IMPACT ON WATER RESOURCES

Nuclear power plants require significant amounts of water for cooling, which can cause problems with water shortages and disturbances in water body ecosystems. This paper presents an assessment of the radiological hazard to humans from a nuclear power plant wastewater discharge into a river under normal operation scenarios (NOS). A hypothetical study was conducted to estimate the annual effective dose (AED) received by the population due to the nuclear power plant wastewater discharge. The results indicate that the radiological hazard to humans from a nuclear power plant wastewater discharge under NOS is minimal. The estimated AED received by the population was found to be below 0.1 mSv/year, which is well below the annual dose limit of 1 mSv/year set by the International Commission on Radiological Protection (ICRP). The detected excess lifetime cancer risk (ELCR) remained within acceptable limits. These results indicated that nuclear power can be a safe and reliable energy source when operated in accordance with established safety protocols. The study found that the concentration of 137Cs in the sediments was higher than that of other radionuclides studied, leading to an increase in the potential hazard over time. Overall, this study provides valuable information on the radiological hazard associated with nuclear power plant wastewater discharge into the river (NOS), which can be useful in developing radiation protection strategies for nuclear power plants and in informing the public about the risks associated with nuclear energy [27].

Since each plant requires a huge amount of water, most nuclear facilities are built on coastlines or, as in the case of Chernobyl, are surrounded by huge lakes. Water is a critical component of nuclear power plants as it is needed to cool the reactor core, which produces heat (Panov et al., 2023) [28]. After the coolant absorbs the thermal energy released by the fission of nuclear fuel, this heat is then transferred through the steam generator to the secondary circuit, promoting steam generation (Qi et al., 2023) [29].

During accidents, water is contaminated with radionuclides; in order to remove as many radionuclides as possible, it is necessary to filter and treat contaminated water after storage. For example, according to R. Bejenar et al. [30], as a result of the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident, 1.27 million m3 of contaminated water was stored in tanks. The filtered water is then stored in huge steel tanks or discharged into nearby water bodies. The filtered wastewater can then be discharged into the ocean or lake after authorities have assessed its safety and confirmed it. Building nuclear power plants on rivers can provide a reliable source of energy for millions of people around the world. However, it is critical to understand the potential risks and benefits of such an approach before building these power plants. Since the volumes of radioactive materials that can be released as a result of NPP operations are great, there is great concern about the potential risks associated with the normal operation of NPPs. In addition, it is important to consider the potential pathways of external and internal exposure and possible long-term effects when assessing the radiation hazard.

Continuous measurement of atmospheric tritium is important to assess the environmental impacts of nuclear and fusion facilities and to understand the fate of tritium in the environment. A passive sampler is a powerful tool for long-term monitoring because it does not require any power source. This paper demonstrates the performance of a passive sampler for continuous measurement and characterizes the time history of atmospheric water vapor concentrations around the Fukushima Daiichi Nuclear Power Plant. The atmospheric concentrations were successfully obtained at two sampling locations and were within the variation of historical observations, although the concentration at one of the two locations was slightly higher than the background level in Japan. In addition, we measured tritium concentrations in soil pore water and free water in pine needles. These values indicate the reliability of the measured atmospheric tritium concentrations [31].

10. NUCLEAR VS. COAL AND GAS POWER PLANTS: CO_2 EMISSIONS

While coal plants emit large amounts of CO_2 and other pollutants, gas plants burn less coal, making them less harmful than coal, but they still contribute to greenhouse gas emissions [32-33]. Nuclear plants emit minimal amounts of CO_2, making them the greener option in this comparison. Emission Toxicity: Coal plants emit more toxic substances such as mercury and sulfur dioxide, which have adverse effects on human health and ecosystems. Gas plants also emit some pollutants, but in smaller amounts compared to coal. Long-term Effects: Nuclear waste remains radioactive for thousands of years, and its safe storage is an open question. In contrast, emissions from burning fossil fuels have more immediate impacts on the environment and health over a shorter period of time [34].

11. THE SITUATION WITH NUCLEAR POWER PLANTS IN KAZAKHSTAN

Nuclear technology was first developed in the 1940s. During World War II, research focused on bomb production. In the 1950s, attention shifted to the peaceful use of nuclear fission, namely to generate electricity.

A landmark event for the world was the construction of the first nuclear power plant. It was launched on June 27, 1954, in the city of Obninsk in the Kaluga region (USSR). Its capacity was 5 megawatts. Currently, the Obninsk NPP is decommissioned, and a museum of nuclear energy has been created on its basis.

The world's first fast-neutron nuclear reactor was built in Kazakhstan - in the city of Shevchenko, which is now called Aktau. On July 6, 1973, it was put into operation (Figure 5).

Figure 5. *Mangistau Nuclear Power Plant (MNPP)*

In July 1993, its design life ended. After that, the reactor's operation was extended annually based on an analysis of the actual condition of the main equipment and systems. And in 1999, a government decree was adopted to decommission BN-350. This is a difficult process and should take 50 years, half of which has already passed.

According to the World Nuclear Association, the growth of the world's population and economy, combined with rapid urbanization, will lead to a significant increase in energy demand in the coming years. The United Nations (UN) estimates that the world's population will grow from about 8 billion in 2024 to about 9.8 billion by 2050.

The process of urbanization will lead to the fact that by 2050 about two-thirds of the world's population will live in urban areas. Therefore, the task of meeting the rapidly growing demand for energy while reducing harmful greenhouse gas emissions is significant.

From 1969 to 1971, physicists studied the "zero" radioactive background of the area adjacent to the BN-350 reactor and the entire Mangyshlak Peninsula.

In 1971, the plant's management ordered the organization of a physical and technological laboratory (PTL) for BN-350 and the implementation of a set of works to prepare for the physical and energy launches of the BN-350 reactor.

The installation of the reactor was completed in 1972. The loading of fuel assemblies (fuel assembly - a machine-building product containing fissile materials and designed to generate thermal energy in a nuclear reactor – editor's note) into the reactor began on October 28, 1972, and was completed on November 28, 1972.

On November 28, 1972, at 15:00, a chain reaction was registered. The official physical launch of the reactor was carried out the next day.

“In 1973, the world's first nuclear power unit with a pilot industrial reactor on fast neutrons with a liquid-metal coolant (sodium), BN-350, was put into operation at MNPP. This unique reactor on fast neutrons was built in Kazakhstan, as was the world's first cosmodrome,” recalls Nikolai Skorikov. “The BN-350 reactor was designed to generate electric power, desalinate seawater, and accumulate plutonium-239”.

12. CONCLUSION

Nuclear power has its pros and cons in an environmental context. It offers the opportunity to reduce greenhouse gas emissions and reduce air pollution compared to coal and gas power plants. However, waste management, accident risks, and impacts on water resources require careful consideration. It is important to consider not only current risks and benefits but also future resource reserves, technological innovation, and public opinion when making decisions about energy sector development.

In conclusion, countries that support nuclear power plants should not only focus on producing alternative energy sources but also pay attention to their economic and environmental aspects. There are both positive and negative aspects to nuclear energy production. Kazakhstan is not among the most environmentally friendly countries. Since it ranks 64th in the world in terms of air pollution, it is known that the amount of waste from old industrial plants and thermal power plants (TPPs) and greenhouse gases emitted into the atmosphere, as well as harmful oxides that pollute the ozone layer, exceeds the threshold. The planned NPP complex in 2024 is planned to have a positive impact on solving a number of such problems. However, given the negative aspects of NPPs, it is known that there are environmental problems such as the risk of explosions of stations due to technical reasons, the release of radioactive waste from nuclear fuels into the environment, water, air, and soil resources, and various genetic diseases of living organisms. In general, since the fall of 2021, Kazakhstan has been experiencing a shortage of electricity. According to the seven-year forecast balance of electricity and capacity of the Ministry of Energy of the Republic of Kazakhstan, the electricity deficit is expected to exceed 3 GW by 2029. Therefore, it is expected that this deficit will be prevented by building nuclear power plants with high electricity generation capacity.

AUTHOR CONTRIBUTIONS

Writing-review & editing, methodology: Gulzat Abdikarim; conceptualization, writing-review & editing, supervision: Davlat Yuldashbek; conceptualization, data curation: Nurlan Akhmetov.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Marat Karatayev, Michèle L. Clarke, Current Energy Resources in Kazakhstan and the Future Potential of Renewables: A Review, Energy Procedia, Volume 59, 2014, Pages 97-104, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2014.10.354.

2. American Nuclear society, Nuclear Energy’s Role in Climate Change Policy, 2018. [Электронный ресурс]. URL: https://cdn.ans.org/policy/statements/docs/ps44.pdf

3. Koptyaev I.M. Analysis of the attitude of the population of different countries to nuclear energy / I. M. Koptyaev, E.R. Magaril. – Text: electronic // Environmental Safety Management system: Proceedings of the XV International Scientific and Practical Conference includes articles on various theoretical and practical aspects of environmental safety. Yekaterinburg: UrFU, 2021. pp. 311-317. URL: https://elar.urfu.ru/bitstream/10995/97914/1/sueb_2021_056.pdf

4. Xue W, Li X, Huang B. Health diagnosis of nuclear power plant. International Journal of Advanced Robotic Systems. 2019;16(5). doi:10.1177/1729881419880654

5. Gelezha, T. A. Environmental consequences of using nuclear power plants / T. A. Gelezha, V. A. Vysotskaya; scientific supervisor A.A. Pavlovskaya // Actual problems of energy / Materials of the 76th Scientific and Technical Conference of Students and postgraduates : section "Thermal Power Engineering" / comp. T. E. Zhukovskaya. Minsk : BNTU Publ., 2020, pp. 173-177.

6. Chen, B., Li, J.S., Wu, X.F., Han, M.Y., Zeng, L., Li, Z., Chen, G.Q., 2018. Global energy flows embodied in international trade: A combination of environmentally extended input–output analysis and complex network analysis. Appl. Energ. 210, 98-107. 614 https://10.1016/j.apenergy.2017.10.113

7. Eurostat. Greenhouse Gas Emission Statistics-Emission Inventories. 2021. Available online: URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Greenhouse_gas_emission_statistics_-_emission_inventories (accessed on 12 June 2023).

8. Rhodium Group. Global Greenhouse Gas Emissions: 1990–2021 and Preliminary 2022 Estimates. Available online: https://rhg.com/research/global-greenhouse-gas-emissions-2022/ (accessed on 20 September 2023).

9. Grossi, R.M. Climate Change and Nuclear Power (2020). Publishing Section International Atomic Energy Agency. Vienna International Centre ISBN: 978–92–0–115120–9

10. Xiangeng Zhao, Qizhen Ye, Sébastien Candel, Dominique Vignon, Robert Guillaumont. A Chinese-French Study on Nuclear Energy and the Environment. Engineering, 2023, 26(7): 159–172. DOI: https://doi.org/10.1016/j.eng.2023.04.011

11. The growth of nuclear energy in Asia, 2024. [electronic resource]. URL: https://world-nuclear.org/information-library/country-profiles/others/asias-nuclear-energy-growth#:~:text=In%20Asia%20there%20are%20about,build%20an%20additional%2050-60

12. IRENA. Renewable Capacity Statistics 2023; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2023.

13. E. Nichita, J. Haroon. Molybdenum-99-producing 37-element fuel bundle neutronically and thermal-hydraulically equivalent to a standard CANDU fuel bundle / Nuclear Engineering and Design, 2016. – Vol. 307. – P. 86-95. DOI: https://doi.org/10.1016/j.nucengdes.2016.06.036

14. J. Haroon and E. Nichita. Refueling Considerations for 99Mo Production ina CANDU Reactor / Nuclear Technology, 2024. – 9 p. DOI: https://doi.org/10.1080/00295450.2024.23579171

15. Roman, Glushenkov. Research of WWER-1000 Power Change Modes for Operation in the Load-Following Mode / Nuclear and Radiation Safety, 2020. – Vol.3-87. – P. 38 – 45. DOI: https://doi.org/10.32918/nrs.2020.3(87).05

16. Krzysztof Przystupa, Igor Vasylkivskyi, Vitalii Ishchenko, Volodymyr Pohrebennyk, Orest Kochan, Jun Su. Assessing Air Pollution from Nuclear Power Plants / MEASUREMENT 2019, Proceedings of the 12th International Conference, Smolenice, Slovakia. – P. 232-235.

17. Igor Vasylkivskyi, Vitalii Ishchenko, Orest Kochan. Chapter.Environmental Pollution from Nuclear Power Plants: Modelling for the Khmelnytskyi Nuclear Power Plant (Ukraine). Advances in Computer Science for Engineering and Education,VI, 2023, Volume 181 ISBN : 978-3-031-36117-3 (Springer Nature)

18. Sunita Kamboj, Nonhuman biota dose rate estimation from liquid effluent releases during normal operations of light water reactors using the LADTAP II computer code, Journal of Environmental Radioactivity, Vol. 196, 2019, P. 141-149, ISSN 0265-931X, https://doi.org/10.1016/j.jenvrad.2018.10.018

19. Navid Delgarm, Kamran Sepanloo, Ali Haghighi Shad, Darioush Masti, Design and development of a comprehensive program for the assessment and analysis of environmental effects due to the release of radioactive materials from the stack of nuclear installations: A case study in Bushehr nuclear power plant, Applied Radiation and Isotopes, Volume 166, 2020, 109383, ISSN 0969-8043, https://doi.org/10.1016/j.apradiso.2020.109383

20. Tae Young Kong, Siyoung Kim, Youngju Lee, Jung Kwon Son, Sung Jun Maeng, Radioactive effluents released from Korean nuclear power plants and the resulting radiation doses to members of the public, Nuclear Engineering and Technology, Volume 49, Issue 8, 2017, Pages 1772-1777, ISSN 1738-5733, https://doi.org/10.1016/j.net.2017.07.021

21. Shigekazu Hirao, Hideki Kakiuchi, Investigation of atmospheric tritiated water vapor level around the Fukushima Daiichi nuclear power plant, Fusion Engineering and Design, Volume 171, 2021, 112556, ISSN 0920-3796, https://doi.org/10.1016/j.fusengdes.2021.112556.

22. Lan Zhang, Jiying Wei, Xuan Zhao, Fuzhi Li, Feng Jiang, Meng Zhang, Xuzhou Cheng, Competitive adsorption of strontium and cobalt onto tin antimonate, Chemical Engineering Journal, Volume 285, 2016, Pages 679-689, ISSN 1385-8947, https://doi.org/10.1016/j.cej.2015.10.013

23. Khan Bulbul, Sk Ali, Sanjay Kumar Srivastava. 2024/09/13.Nuclear Power Plant Safety System DOI: 10.13140/RG.2.2.35425.72800

24. Paulillo, A.; Striolo, A.; Lettieri, P. The environmental impacts and the carbon intensity of geothermal energy: A case study on the Hellisheiði plant. Environ. Int. 2019, 133, 105226.

25. System analysis of the causes and consequences of the accident at the Fukushima-1 nuclear power plant / R. V. Arutyunyan, L. A. Bolshov, A. A. Borovoy, E. P. Velikhov ; Institute of Problems of Safe Development of Nuclear Energy of the Russian Academy of Sciences. Moscow : 2018. 408 p.

26. Storage and Disposal of Radioactive Waste. World Nuclear Association, updated tuesday, 30 APRIL 2024. URL: https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-waste/storage-and-disposal-of-radioactive-waste

27. Anuor A.T. Ayoub, Yushou Song, Mamoun I.A. Sagiroun, Radiological hazard assessment for human from nuclear power plant effluent released under normal operation scenario (hypothetical case study), Radiation Physics and Chemistry, Volume 216, 2024, 111380, ISSN 0969-806X, https://doi.org/10.1016/j.radphyschem.2023.111380.

28. Aleksei Panov, Alexander Trapeznikov, Vera Trapeznikova, Alexander Korzhavin, Influence of operation of thermal and fast reactors of the Beloyarsk NPP on the radioecological situation in the cooling pond: Part II, Macrophytes and fish, Nuclear Engineering and Technology, Volume 55, Issue 2, 2023, Pages 707-716, ISSN 1738-5733, https://doi.org/10.1016/j.net.2022.10.025

29. M.A. Al-Aqeel, Ibrahim A. Alrammah, Radiological Impact Assessment for hypothetical accident scenarios of a proposed pressurized water reactor using HotSpot code, Radiation Physics and Chemistry, Volume 204, 2023, 110717, ISSN 0969-806X, https://doi.org/10.1016/j.radphyschem.2022.110717

30. R. Bezhenar, H. Takata, G. de With, V. Maderich, Planned release of contaminated water from the Fukushima storage tanks into the ocean: Simulation scenarios of radiological impact for aquatic biota and human from seafood consumption, Marine Pollution Bulletin, Volume 173, Part B, 2021, 112969, ISSN 0025-326X, https://doi.org/10.1016/j.marpolbul.2021.112969

31. Hirao Shigekazu, Kakiuchi Hideki . Investigation of atmospheric tritiated water vapor level around the Fukushima Diichi nuclear power plant. Fusion engineering and design, том 171 october 2021,112556 ISSN 09203796 https://doi10.1016/j.fusengdes.2021.112556

32. Agrawal, K.K.; Jain, S.; Jain, A.K.; Dahiya, S. Assessment of greenhouse gas emissions from coal and natural gas thermal power plants using life cycle approach. Int. J. Environ. Sci. Technol. 2014, 11, 1157-1164.

33. Li, H.; Jiang, H.-D.; Dong, K.-Y.; Wei, Y.-M.; Liao, H. A comparative analysis of the life cycle environmental emissions from wind and coal power: Evidence from China. J. Clean. Prod. 2020, 248, 119192.

34. Vidar T. Skjervold, Giorgia Mondino, Luca Riboldi, Lars O. Nord, Investigation of control strategies for adsorption-based CO_2 capture from a thermal power plant under variable load operation, Energy, Volume 268, 2023, 126728, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2023.126728