

Article

Conceptual View of the Implementation of the Nuclear Energy Program in the Republic of Kazakhstan

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Abstract: This paper presents an analysis of the existing prerequisites and opportunities for the start-up of the Republic of Kazakhstan's own full-fledged Nuclear Energy Program, a conceptual vision of the development of the Kazakhstani nuclear industry. Recommendations have been formulated for the timely and successful implementation of the program for the introduction of nuclear power plants into the country's energy generation structure, the development of the necessary related nuclear infrastructure facilities, national legislation, and other issues directly related to nuclear power development.

Keywords: Nuclear Energy Program; Republic of Kazakhstan; integration of nuclear sources; priority tasks; analysis and recommendations; development scenarios

1. Introduction

The world community connects the meeting of growing energy needs with nuclear power development, along with the development of renewable energy sources (solar, wind, and water) [1]. Achieving the goals of the sustainable development of the Republic of Kazakhstan while improving the well-being of the population requires reliable, guaranteed, and stable provision of sufficient energy. A strategic goal has been formulated for the development of safe, carbon-neutral power resources and the creation of the foundations of nuclear power as a source of reliable basic generation to meet the growing energy needs of the economy of the Republic of Kazakhstan [2].

Kazakhstan joined the Paris Agreement, and the “Concept for the Transition of the Republic of Kazakhstan to a ‘Green Economy’” was approved in Kazakhstan in 2013 [3]. It was oriented toward increasing the innovation and competitiveness of the state. One of its objectives is to increase the share of alternative sources in electricity generation to 50% by 2050. As noted in this concept, alternative sources include solar power plants, wind farms, hydroelectric power plants, and nuclear power plants. The so-called “carbon tax”, which is going to be introduced by the European Union in the near future, on imported goods produced using energy based on carbon sources gives additional relevance to the transition to alternative ones [4–6]. The Kazakhstani economy may lose billions of dollars due to the introduction of a carbon tax in Europe, since approximately 90% of the energy in Kazakhstan is generated from carbon sources [7].

“The Strategy for Achieving Carbon Neutrality of the Republic of Kazakhstan until 2060”, approved by the decree of K.J. Tokayev, the president of the Republic of Kazakhstan, states that the capacity structure will include nuclear power plants as a stable energy source [8].

In 2023, in his State of the Nation Address, the President of the Republic of Kazakhstan proposed to submit the issue of building or abandoning the construction of an NPP in Kazakhstan to a national referendum, calling for continued public discussions and comprehensive broad discussion on this issue [9]. The referendum was held on 6th October 2024 and showed that more than 71% of the population that voted agreed with the construction



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of an NPP [10]. With this in mind, the authors of the article conducted an objective analysis of the potential for nuclear power development in Kazakhstan and proposed a conceptual vision for the implementation of the Nuclear Energy Program in the country.

2. Materials and Methods

2.1. Relevant International Experience

Reviewing international experience in developing and implementing relevant programs is important in creating a program for nuclear industry development in Kazakhstan. The experience of the countries implementing the Nuclear Energy Program for the first time is of greatest interest. Such countries include the United Arab Emirates (UAE) and the Republic of Belarus, which have been among the countries with nuclear power since 2020.

In 2015, having the goal of strengthening the energy security and increasing the energy independence of the Republic of Belarus, the third edition of the “Concept of Energy Security of the Republic of Belarus until 2035” was approved [11]. The first and second versions of the document were adopted in 2007 and 2014, respectively. To ensure energy security, the concept provides for the diversification of energy resources, which should be based on reducing the use of natural gas as a fuel, including through the use of nuclear power. The decision made to develop nuclear power in Belarus required the creation of a sustainable infrastructure, providing legal, regulatory, technological, human, financial, and industrial support for the nuclear program throughout its existence. As a result, the first unit of the Belarusian NPP was put into commercial operation in 2021. The second unit of the Belarusian nuclear power plant was put into commercial operation on 1 November. Together with the first unit, the new nuclear power plant will provide about 40% of the country’s electricity needs. Both units are based on the VVER-1200 (Rosatom, Moscow, Russia) design and are already underway in Bangladesh, Hungary, Egypt, Turkey, and China [12].

The experience of implementing a nuclear power plant construction project in the United Arab Emirates (UAE) is interesting. The UAE started implementing its Nuclear Energy Program almost from scratch when its nuclear infrastructure was not developed and technological and human resources were limited (with an absence of proper legislation, specialists with relevant experience in the nuclear field, and a developed scientific and technical basis). In 2007, after conducting a detailed analysis in the UAE, it was decided to introduce nuclear power. The first of four nuclear power reactors designed by South Korea was connected to the UAE grid just eight years after starting construction in 2012. The export of Korean nuclear technology to the UAE was a breakthrough point for the Korean nuclear industry. Currently, many countries are considering the implementation of Korean nuclear reactors in their power systems. This trend is especially visible in Central Europe, where Poland is considering the construction of APR1400 (KHNP, Gyeongju, Republic of Korea) nuclear reactors, and the Czech Republic is considering constructing the APR1000 (KHNP, Gyeongju, Republic of Korea) [13]. The nuclear power plant Barakah is the first nuclear power plant in the Arab world. The UAE managed to successfully implement its program and build a nuclear power plant in such a short time, observing all safety standards and regulatory rules of the UAE grid just eight years after construction began in 2012 [14].

Turkey can also be singled out from the newcomer countries in the nuclear sector. Turkey plans to meet energy needs with NPPs. The first NPP will come into operation at Akkuyu in Mersin [15]. The result of the Nuclear Energy Program development at that time was the licensing of the site in Akkuyu, and the immediate implementation of the program was started only in 2008, when Turkey announced a tender for the construction of the first nuclear power plant in the country. In 2010, the governments of the Russian Federation and the Republic of Turkey signed a cooperation agreement providing for the construction of the Akkuyu nuclear power plant on the southern coast of Turkey, which included four nuclear units with VVER-1200 reactors with a total capacity of 4800 MW. After signing the agreement, a design company was established—AKKUYU NUCLEAR JSC (Mersin, Turkey). This nuclear power plant was constructed according to the Build-Own-Operate model. AKKUYU NUCLEAR, as the owner of the project, assumed the obligations for

the design, construction, maintenance, operation, and decommissioning of the plant. The majority shareholder of the Akkuyu nuclear power plant is Rosatom (Moscow, Russia), the Russian state corporation, which fully finances the plant's construction project.

The same approach was chosen by Bangladesh, which was facing a severe energy shortage. By the 2010s, with 4.5 GWe of energy produced per year, the country's population and economy needed 6 GWe. Only about 48 percent of the total population had access to electricity. In 2011, to solve this problem, the government of Bangladesh entered into an agreement to build the country's first nuclear power plant, which started in November 2017. The plant is planned to have two units. According to the Power System Master Plan 2016, the first unit (1200 MW) is expected to begin operations in 2024, with the second (1200 MW) in 2025 [16]. The reactor type to be constructed will be VVER-1200/V-523 [17].

Egypt intends to add nuclear power to its energy mix and has signed a preliminary agreement with the Russian state nuclear corporation Rosatom to build a commercial plant at the El Dabaa site. The International Atomic Energy Agency (IAEA) noted that the proposed nuclear power plant at this site would be a four-unit plant where each site generates a gross electric power capacity of 1200 MWe, producing a total of 4800 MWe of electricity. The reactor type to be constructed will be VVER-1200/V-529 [18].

In May 2024, Uzbekistan signed a contract with Rosatom to construct an NPP with 300 MWe of capacity based on six small reactors of 55 MWe each. The reactors mentioned in the agreement are water-cooled, water-moderated RITM-200 reactors. This project is being considered by Uzbekistan as safer, flexible, and economically efficient due to the ability to supply small towns and individual industrial facilities. Construction works are planned to begin in 2024, and the NPP will be commissioned in 2033 [19].

2.2. Prerequisites for the Development of Own Nuclear Industry

There is no doubt about the expediency of an approach when countries starting nuclear power programs fully take into account previous international experience. In this regard, it is rational to use existing international experience when implementing nuclear power in the Republic of Kazakhstan, taking into account such important national factors as

- The Republic of Kazakhstan possessing about 14% of all explored world uranium reserves [20];
- The developed uranium mining and uranium processing industry;
- The production of uranium dioxide, fuel pellets, and fuel assemblies for the nuclear power reactors;
- Scientific organizations working in the field of peaceful atomic energy use;
- Positive experience in the operation of the BN-350 reactor in the past [21];
- An increasing shortage of electricity [22];
- The strategy of achieving carbon neutrality by 2060 [8];
- The developed regulatory and legal framework for the peaceful use of atomic energy.

2.3. Previous Studies and Missions

In 2007–2009, the National Nuclear Center of the Republic of Kazakhstan conducted “Pre-Feasibility Studies to Justify the Construction of Nuclear Power Plants in the Republic of Kazakhstan” (<https://www.atomic-energy.ru/news/2016/11/29/70576> (accessed on 5 January 2024)). Based on the results of the research, reactor designs were identified for economic analysis of the NPP project in the Republic of Kazakhstan; the assessment of technical and economic indicators of the NPP was carried out; financial analysis of the project and analysis of the economic efficiency of investments were carried out; the areas for NPP construction were proposed by taking into account the projected consumption and production of electricity (on self-balancing terms); preliminary assessments were carried out on the natural, climatic, and geological characteristics of the proposed construction sites in the selected areas; and existing transport infrastructure, power lines, and water resources for cooling the power equipment and the issues of choosing the unit capacity of the NPP units were considered. As a result, almost all the necessary studies, which

should be implemented in accordance with the recommendations of the IAEA, have been completed [23,24]. The calculation methods used for financial and economic analysis in the Republic of Kazakhstan, as well as the methodology of the Organization for Economic Cooperation and Development (OECD) [25], were applied in the course of that work.

In 2023, two IAEA expert missions were organized at the request of the government of Kazakhstan. In March, the second stage of the INIR (Integrated Nuclear Infrastructure Review) mission took place, which assessed the status of the national infrastructure for nuclear power implementation (the first stage of the INIR mission in Kazakhstan was carried out in 2016) [26]. In October of the same year, the SEED (Site and External Events Design) mission was implemented, whose work focused on the quality of the data in the site selection report and the data collection methodology, their applicability to the site selection procedure, and the simulation of hazardous situations in relation to the construction of two power units at the proposed NPP construction site. In the end, the IAEA team did not find any safety problems at the sites under consideration in the northeast and southeast of the country [27].

2.4. Forecasting the Need for New Energy Sources

When considering the structure of Kazakhstan's energy capacities from 2014, it can be seen that by 2022, 68.2% of the energy was generated by coal-fired power plants, 20.1% of the energy was generated by gas, hydroelectric power plants accounted for 8.1%, and wind and solar power plants accounted for 2.1 and 1.6%, respectively (Figure 1) [28].

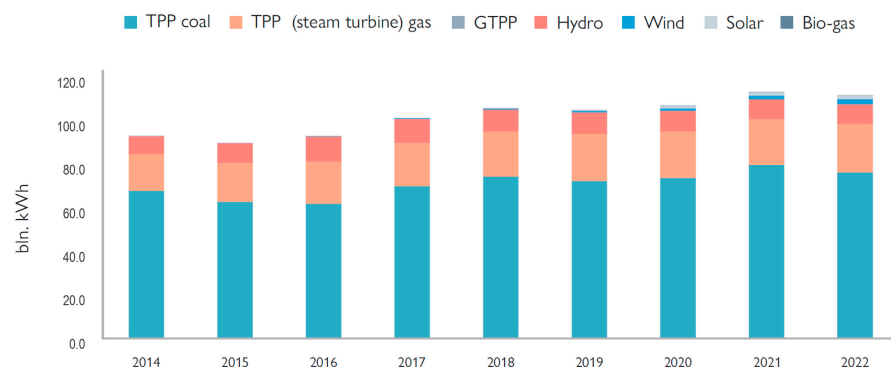


Figure 1. Structure of electricity production in 2014–2022 (Source: The National Energy Report KAZENERGY 2023).

According to the forecasted balance of electric power of the Republic of Kazakhstan [22], there is a permanent shortage of electric power in the country, and a shortage of at least 6.24 GW is expected by 2030 (Figure 2).

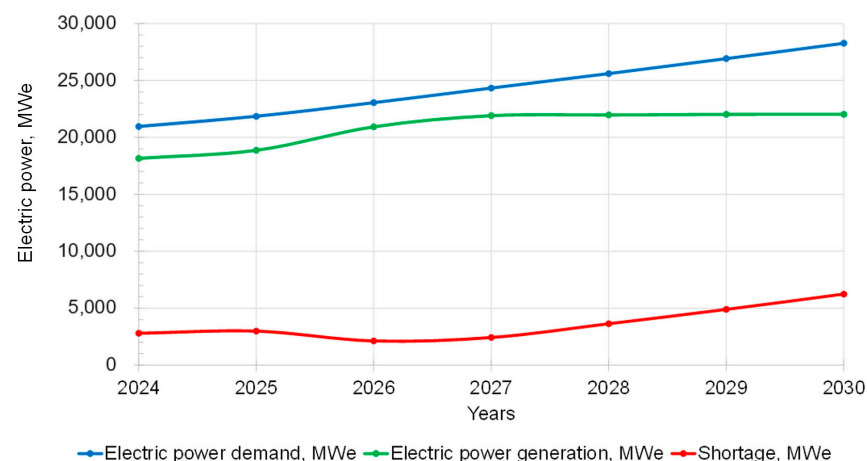


Figure 2. Forecasted electric power balance of the Republic of Kazakhstan until 2030.

Nuclear generation is predicted to account for more than 2 GW of capacity by 2035, with at least 4 GW by 2050 in the structure of new energy capacities required for commissioning (Figure 3) [28].

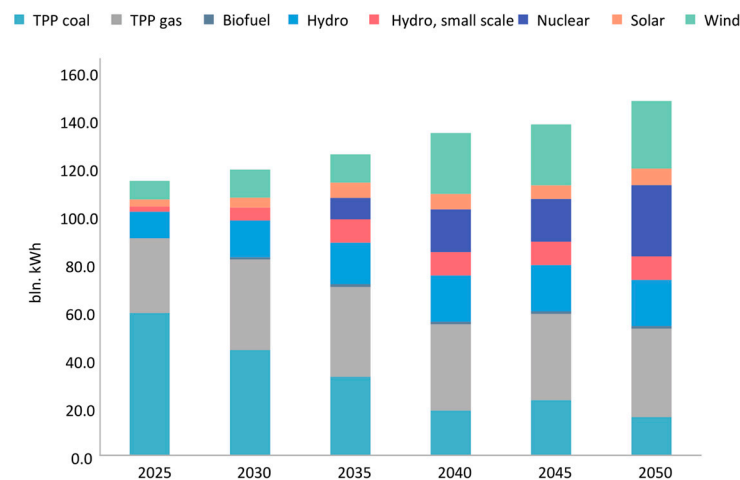


Figure 3. Structure of electricity generation by power plants in Kazakhstan in 2025–2050 (Source: The National Energy Report KAZENERGY 2023).

Along with the increasing electricity shortage, it is also necessary to note the general condition of the main equipment of the operating power plants in Kazakhstan. Today, the share of equipment with a wear of 50–75% is about 39%, while that of equipment with a wear of more than 75% is 52%, and as statistics show, this share is increasing (at the beginning of 2018, the share of equipment with a wear of more than 75% was 36%). There was also an increase in the share of turbine equipment with a wear of more than 75% [29].

The upgrading of existing capacities, as well as the active introduction of renewable energy sources, will not be able to fully solve the problems facing the country in the energy sector and the tasks of fulfilling its obligations. The clear solution is to develop nuclear generation in the Republic of Kazakhstan. Based on an in-depth analysis of the available information, the authors have proposed recommendations for its successful implementation, the development of the necessary related atomic infrastructure facilities, national legislation, and other issues directly related to nuclear power development.

2.5. Energy System Parameters

From a technical point of view, it is important that the unit power does not significantly exceed the capabilities of the Kazakhstan power system (in some projects, the operation of the reactor at a level below the nominal is allowed, but the operation in this mode will negatively affect the economic characteristics of the project).

The energy system of Kazakhstan (Figure 4) has the following specific features that must be taken into account when considering the plan for the implementation of nuclear power plants and the choice of power unit capacity:

- There are three energy zones of the system: South, North, and West;
- Most generating capacities are located in the North of the energy system, which is connected to the Russian energy system;
- The South zone is energy-deficient and is connected to the energy system of Central Asia;
- The South and North zones are connected by three 500 kV power lines, which ensure the transmission of electricity from the energy-rich North zone to the energy-deficient South zone;
- The West zone is actually energy-isolated from the rest of the energy system of Kazakhstan and is connected to the Russian energy system, where the maximum unit power is up to 300 MWe.

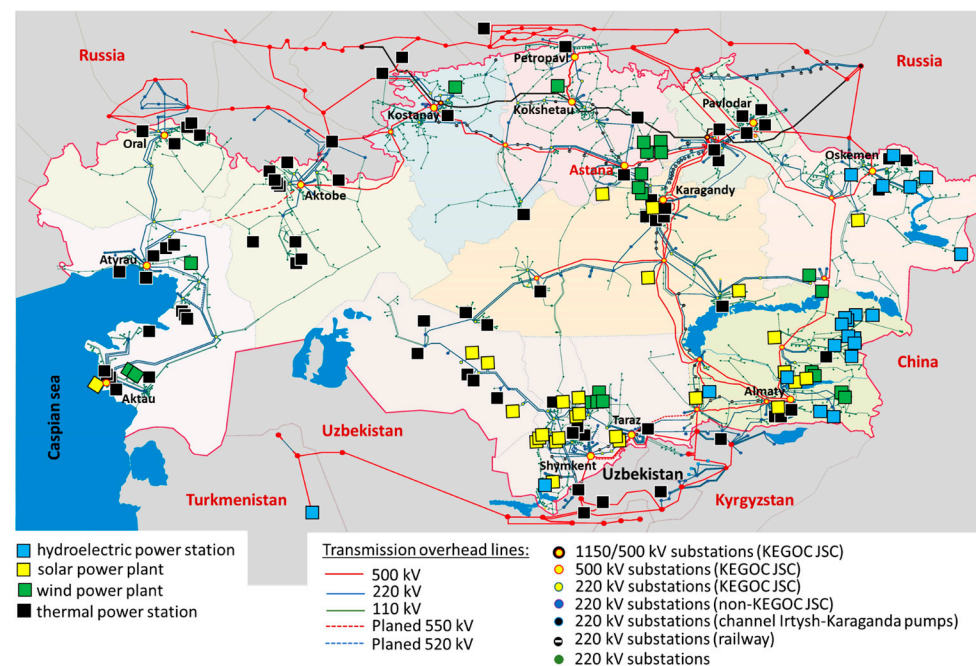


Figure 4. Scheme of Kazakhstan energy system (source: Kazakhstan Electricity Grid Operating Company).

2.6. Cost Analysis of NPP

The detailed cost estimates for building an NPP are covered by investor secrecy, so the component costs of the various stages of construction are not known. Therefore, this analysis includes open-source information: originally planned construction costs (those announced to the public before construction commenced), currently projected costs (those revised over time to reflect the costs originally planned for the plant during construction), and actual costs (those actually incurred to build the plant up to commercial operation). The data were used to estimate the recent NPP construction cost and to compare it with initial proposals made by potential vendors who declared their interest in NPP construction in Kazakhstan, which were KHNP (Gyeongju, Republic of Korea), CNNC (Beijing, China), Rosatom (Moscow, Russia), and EDF (Perleberg, France).

2.6.1. APR-1400 Technology

APR-1400 NPPs have been well commissioned in the Korean domestic market. Information on the construction cost of six country units shows a range of USD 6.46–8.80 billion for doubled units at three NPPs (Shin-Kori 3 and 4, Shin-Kori 5 and 6, and Shin-Hanul 1 and 2). From this, the cost of one unit for the domestic market is USD 3.23–4.40 billion.

Abroad, in an APR-1400 project in the UAE, a Barakah NPP is estimated to cost USD 24.40 billion for four units, or USD 6.1 billion per unit [30].

2.6.2. HPR-1000 Technology

Two Chinese-supplied third-generation Hualong One reactors, constructed in Pakistan and known as K2 and K3, cost roughly USD 10 billion. K2 and K3 are fully functional and supply 2200 MWe of electricity to the Pakistani grid. In 2023, Pakistan and China signed a USD 4.8 billion deal to build one more 1200 MWe unit in Chashma [31].

The cost of building a one-gigawatt (GW) nuclear power plant in Kazakhstan by the China National Nuclear Corporation (CNNC) is estimated at 20 billion yuan (USD 2.8 billion), with a five-year construction timeline. If a Chinese contractor is selected, the cost to build a two-unit nuclear power plant with a total capacity of 2 GW, to be completed by 2035, would be approximately USD 5.6 billion [32].

2.6.3. VVER Technology

The financial cost of the NPP project in Bangladesh with two units at Rooppur, Ishwardi, each with 1200 MW of capacity, is USD 12.65 billion [33]. The construction cost of an NPP in Belarus with the same 2×1200 MWe units is estimated to be USD 11.1 billion [34]. An NPP in Turkey with 4×1200 MWe units is estimated to cost USD 24–25 billion, with an average of USD 6–6.25 billion per unit [35]. According to the agreement between Russia and Egypt on the construction of an NPP with 4×1200 MWe units, the contract price might be around USD 30 billion, or USD 7.5 billion per unit [36]. The project's cost of a VVER-1000 unit for a Tianwan NPP finally reached over USD 3.2 billion [37]. Hungary's government and Russia's Rosatom have reached an agreement to add two VVER-1200 reactors to the Paks nuclear power plant. The cost of the project is estimated at around USD 13.2 billion, with an average cost of USD 6.6 billion per unit [38].

The preliminary cost of an NPP with 2×1200 MWe VVER units in Kazakhstan is estimated at USD 5.4 to 6 billion per unit and correlates with earlier proposals made for other countries.

2.6.4. EPR Technology

The open data concerning the cost of EPR construction in different countries show that there are two projects with the largest ratio of actual cost/initial cost planned. These are Okiluoto-3 in Finland, with an estimated cost of USD 9.4 billion (as of 2021), and Flamanville-3 in France at USD 13.6 billion (as of 2021). At the same time, Chinese experience shows the construction cost of two EPR-1600 units at the Tishan-2 NPP to be USD 9.1 billion, or USD 4.55 billion per unit. Meanwhile, the construction cost of two EPR units in England at Hinkley Point C-1 and 2 is estimated at USD 31.30 billion, or USD 15.65 billion per unit [30].

2.6.5. SMR Technology

The average target capital costs of the FOAK SMRs under development in the world are evaluated as about USD 7333/kWe. NuScale is the nearest reactor to commercialization among these SMRs, and its target cost is estimated at about USD 4386/kWe. The average capital cost of the SMR NOAK plants currently under development in the world is valued at USD 5130/kWe, which is estimated to be 30% less than that of FOAK. The target capital cost of NuScale's NOAK plant is valued at USD 3509/kWe [39].

Detailed evaluations of a 12×77 MWe (924 MWe total) light-water SMR (LW-SMR) plant, a 4×262 (1048 MWe total) gas-cooled SMR (GC-SMR) plant, and a 5×200 MWe (1000 MWe total) molten salt SMR (MS-SMR) plant completed in [40] showed the overnight capital cost of the LW-SMR, GC-SMR, and MS-SMR to be USD 4844, 4355, and 3985/kW, respectively.

Of course, the cost of building SMRs varies significantly depending on the country in which they are built, the timing, the site, and the contractor.

3. Results

3.1. SWOT Analysis

A system's performance, quality, and prospects can be evaluated by SWOT analysis, which considers the system's strengths, weaknesses, opportunities, and threats in order to implement management strategies to capitalize on the system's strengths, make the most of its opportunities, mitigate the system's weaknesses, and protect itself from potential threats [41]. By combining existing data from the sources, SWOT analysis might be able to present a visual picture of the prospects for adopting nuclear energy in Kazakhstan. It not only identifies potential benefits but also highlights potential issues and areas that require careful consideration. A brief review of existing data, let us form the SWOT matrix (Figure 5).



Figure 5. SWOT matrix for nuclear power program in Kazakhstan.

3.2. Objectives of the Nuclear Power Development

A special program that meets the requirements of the state planning system, i.e., the concept of nuclear power development in the country as a separate full-fledged industry, is needed for nuclear industry development in order to ensure accelerated industrial and innovative development of the country [42]. When determining the vision for nuclear industry development, it is necessary to propose the main factors that ensure the optimal use of available resources, nuclear fuel cycle enterprises, and scientific and technical potential while taking into account world experience and the specifics of the existing nuclear industry in Kazakhstan.

The analysis of the available potential allows for the formulation of the main goals of nuclear power development in the Republic of Kazakhstan:

Providing the country with a reliable, safe, cost-effective, and environmentally friendly source of electricity by creating a national nuclear industry with a developed infrastructure;

Ensuring the sustainable development of nuclear science, technology, nuclear non-energy technologies, and infrastructure for the safe use of atomic energy with the training of qualified national personnel.

It is necessary to ensure the implementation of a number of priority tasks for achieving the main goals.

3.3. Priority Tasks for Nuclear Industry Development

3.3.1. Creation of a Specialized Organization

The implementation of the Nuclear Energy Program with the goal of the successful creation and expansion of nuclear energy requires various activities, such as the establishment of national institutions, the development of a legal and regulatory framework, human resource education, the development of financial strategies, solving radioactive waste management problems, and involving stakeholders. This will require the consolidation of all available industrial and scientific resources, including the raw material resources of the country.

To date, the LLP Kazakhstan Nuclear Power Plants (<https://qsamruk.kz/company/jsc-kazakhstan-nuclear-power-plants>, accessed on 7 July 2024) organization operates in Kazakhstan, which deals with the issue of the substantiation of the construction of a nuclear power plant in Kazakhstan. The current structure and status of this organization are insufficient to fulfill the full scope of the tasks for the Nuclear Energy Program implementation.

In order to effectively implement the Nuclear Energy Program, it is necessary to consider the creation of a specialized organization uniting existing scientific and industrial enterprises of the nuclear industry of Kazakhstan, as well as the academic institutions of the education system engaged in training specialists in this field, with the definition of its functions, authorities, institutional position, etc.

3.3.2. Development of a Comprehensive Plan for the Integration of Nuclear Power Plants into a Unified Energy System

The long-term development of the electric power industry should be based on the unified state plan for the development of electric-generating capacities. The annual plan should reflect the volumes of output capacity, the input capacity after expansion, the upgrading and reconstruction of the equipment at existing power plants in Kazakhstan, the approved volumes of the newly commissioned capacity, and the necessary volumes of additional capacity to cover the projected shortage of electric and thermal energy. In the future, it is necessary to consider the inclusion of nuclear power plants in the plan to replace the output capacities of base coal-power plants on the basis of the analysis carried out and take into account the tasks set to achieve carbon neutrality and the development of alternative energy sources.

The basis for the plans for NPP construction is the approved plans for the commissioning of new energy-generating capacities in Kazakhstan for the long term (with consideration for the forecasts of an increase in electricity demand in the regions, as well as the withdrawal of out-of-date generation sources), in which the location areas, years of commissioning, and capacities of new energy sources should be determined.

Based on the data available today and current conditions (not including the source and financing schemes), a possible (indicative) scenario for NPP construction in the territory of Kazakhstan may be proposed for consideration. The proposed scenario has been developed on the assumption of the projected electricity shortage, which occurs primarily in the southern region, with the need to replace the outgoing coal plants in the northern area (which includes up to 70% of the installed capacity of all power plants), and are based on data from the previous studies, as well as the projected balance of electricity and the planned scheme of the location of generating capacities in Kazakhstan.

Indicative NPP introduction scenario:

1. Construction of the NPP with high-power PWR reactors (up to 2×1.4 GW) in the southeast of Kazakhstan. The start-up of the first unit in 2033 and the second in 2035.
2. Construction of NPPs with high-power PWR reactors (up to 2×1.4 GW) in the northeast of Kazakhstan. The start-up of the first unit in 2034 and the second in 2036.
3. Construction of the NPP with small modular reactors (up to 4×300 MW) in the south of Kazakhstan. The start-up of the units: the first in 2034, the second in 2036, the third in 2038, and the fourth in 2040.
4. Construction of the NPP with small modular reactors (up to 2×300 MW) in the west of Kazakhstan. The start-up of the first unit in 2035 and the second in 2037.
5. Construction of the NPP with small modular reactors (up to 2×300 MW) in the north of Kazakhstan. The start-up of the first unit in 2035 and the second in 2037.

Figure 6 shows an indicative scenario of the introduction of NPP units. The forecasted electric power shortage line until 2030 is drawn by taking into account information from [22]. Due to the lack of data for the long-term electric power balance in Kazakhstan, the forecasted shortage for 2030 to 2040 is presented in the form of an approximation line with the assumption that in 2040, the relationship between energy production in accordance with [28] and the forecasted shortage will remain at the same level.

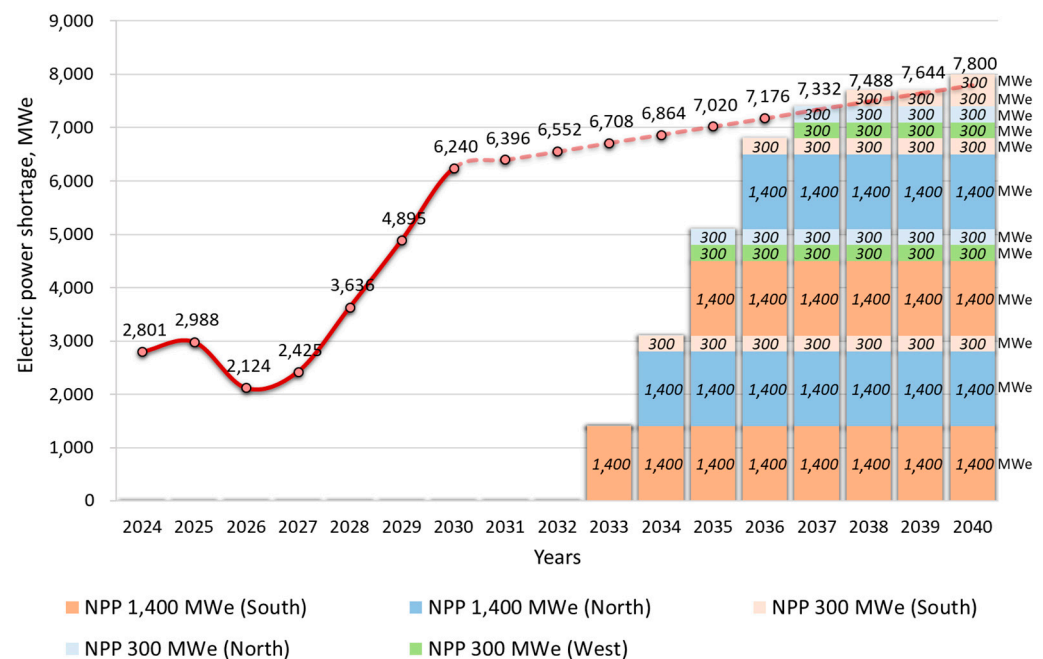


Figure 6. Indicative scenario of the introduction of NPP units with reference to forecasted electric power shortage.

In the short and medium term, when choosing nuclear power plant technologies, it is helpful to adhere to the principles of reliability (safety), unification, and an integrated approach to project implementation. That is, it is desirable to interact with 1–2 suppliers of modern, the most common, and proven nuclear reactor technologies that provide a full range of related services, including the fuel supply, the return and handling of spent nuclear fuel (SNF), personnel training organization, and so on. The unification of nuclear power plant projects will optimize the process of their construction and operation, taking into account the use of the same type of equipment and operational personnel training.

It is necessary, however, to take into account the fact that the implementation of such an ambitious scenario for the commissioning of nuclear energy sources will require significant financial costs, as well as the maximum consolidation of resources.

Detailed economic modeling will be a task for specialists in the field of economics and finance working on the energy development strategy in Kazakhstan. At the same time, it is clear that the contribution to the economic development of the country in the implementation of such a scenario will amount to hundreds of billions of USD, which will inevitably affect its development and have a positive economic effect.

In the long term, Kazakhstan may participate in the development of new-generation reactor projects with the creation of prototypes and technology development in cooperation with leading development companies with respect to existing experience with participating in development to support the safety of new nuclear power plants and advanced testing facilities, as well the availability of a resource and production basis for reactor fuel production.

3.3.3. Development of the Regulatory Body of the Nuclear Industry

According to the IAEA guidelines for the development of a national nuclear infrastructure [43], three phases of the Nuclear Energy Program are distinguished. The first includes the preparatory work carried out with the goal of making a state decision on the start of the Nuclear Energy Program; the second includes the development of the infrastructure issues that need to be resolved to ensure the readiness to start and monitor the NPP construction; the third includes the NPP construction up to commissioning approval and operation. At the same time, the IAEA provides recommendations on planning the workforce, including those related to the personnel of the regulatory body for each phase of the Nuclear Energy Program implementation.

It is necessary to overview the existing organizational structure of the regulatory body and increase the number of its employees to perform their duties of developing rules and guidelines, conducting reviews and assessments, issuing licenses/permits, conducting checks, and applying sanctions for the Nuclear Energy Program implementation in Kazakhstan.

In accordance with the recommendations of the IAEA, the number of employees of the regulatory body should be 40–50 people for the first phase of the Nuclear Energy Program implementation. During the implementation of the second and third phases, the number of specialists in the regulatory body increases significantly to about 80–120 people.

The staff of the regulatory body is required to have an appropriate level of competence, which is the understanding and ability to apply scientific and technical concepts to perform their duties.

As part of the regulatory body reorganization, a resolution should be given to the issue of granting it an independent status, including the financial one, from the government agencies, institutions, and officials whose activities are related to the use of atomic energy, in accordance with the fundamental principles of ensuring nuclear and radiation safety.

3.3.4. Improvement in the Regulatory Framework in the Nuclear Field

The regulatory framework in the field of atomic energy use in the Republic of Kazakhstan is continuously being improved and, taking into account the current state of the nuclear industry, is quite sufficient, but with some need to refine it in certain issues. Meanwhile, NPP construction will require a significant expansion of the regulatory framework handling the issues of the design, assessment, and selection of the NPP construction site, the construction itself, commissioning, quality assurance and environmental impact assessments, and others.

Nevertheless, it is necessary to assess how fully the regulatory framework of the Republic of Kazakhstan in the nuclear field meets the requirements, including the IAEA recommendations, for NPP construction. Which documents should be developed and released for this, and which existing documents need to be finalized?

The development and passage of all procedures for the approval of such a number of documents can take years and require the availability of specialists with appropriate competencies. Therefore, when concluding an agreement, it is useful to consider the possibility of transferring to Kazakhstan the regulatory documents in force in the nuclear technology supplier country, according to which the design, construction, and operation of the nuclear power plants are carried out, for their use in the development of the relevant regulatory legal acts of the Republic of Kazakhstan.

3.3.5. Scientific and Technological Development of the Atomic Industry

The main scientific activity in the field of nuclear science and technology in Kazakhstan is currently concentrated in such organizations as the National Nuclear Center and the Institute of Nuclear Physics, on the basis of which unique scientific, technical, and technological infrastructure operates, including research nuclear reactors, experimental installations, a modern laboratory, and instrument-analysis equipment. A wide range of relevant scientific problems in the field of nuclear science and technology, nuclear power safety, radioecology, geophysics, plasma physics, radiation materials science, nuclear and radiation physics, nuclear physical methods and technologies, nuclear medicine, etc., have been successfully solved on the scientific and experimental basis of these enterprises. A wide range of scientific research for almost three decades has been carried out within the framework of the scientific and technical program “Development of Nuclear Power in the Republic of Kazakhstan”.

Even today, the scientific enterprises of the nuclear industry of Kazakhstan, primarily the National Nuclear Center with its institutes, are able to provide scientific and technical support for the development of the nuclear industry in the broadest sense of the term.

The promises for the development of scientific research in nuclear power should primarily be related to the following factors:

- Improving the safety and efficiency of the nuclear energy;
- Nuclear radiation technologies and materials;
- Development of a system for monitoring and responding to nuclear and radiation accidents;
- Radioactive waste management, etc.

In the long term, it is advisable to ensure the transition to participation in NPP design and, ideally, to create one's own nuclear power plant project on the basis of the acquired experience of the operating NPP, as well as one's own scientific developments.

3.3.6. Scientific and Technical Support

High-quality and complete scientific and technical information, as well as the appropriate advisory support, is a very important element in ensuring the safe operation of nuclear power plants by providing decision makers with the high-quality and objective data necessary to make informed decisions regarding safe and efficient NPP operation with a full understanding of all the necessary aspects. The basic principles and recommendations for providing scientific and technical support for nuclear power plant projects and Nuclear Energy Programs are set out in [44].

The scientific and technical support of such a project as the construction of a nuclear power plant is necessary in all stages—preparation, construction, and operation of the NPP and its decommissioning. It should be carried out in order to ensure quality and reliability, and it is a complex of scientific and methodological, expert-control, information-analytical, and organizational-legal work.

Of course, grounded in the extensive experience of the development of nuclear power in different countries, it seems optimal today to attract leading suppliers with a developed resource base and practical experience in the successful implementation of such projects for the implementation of the first NPP projects in Kazakhstan.

Nevertheless, the NPP design should be accompanied by scientific and technical support from the Kazakhstani scientific organizations with the necessary expertise. In this area, it is necessary to assess the capabilities of the national scientific enterprises to fulfill the main tasks of scientific and technical support for NPP construction and operation.

3.3.7. Localization of Production

NPP construction is a multibillion-dollar investment of funds by the customer, received mainly through the allocation of borrowed and credit funds. In this case, it is advisable to spend part of the allocated financial resources by the national companies, subcontractors, and suppliers of equipment and materials during NPP construction. This process is called localization of production. The main problem in this regard is achieving the maximum degree of localization during NPP construction in Kazakhstan. When concluding a contract with the NPP supplier, it is necessary to consider the issue of localization of the construction in detail, taking into account the production capabilities of the national suppliers of goods, work, and services. To implement this, it is necessary to consider the possibility of creating a special working group for the organizational and technical support of the localization of production and supply of equipment and materials for NPP construction by Kazakhstani organizations.

3.3.8. Training of Personnel

The effective and safe management and maintenance of an NPP requires the availability of a sufficient number of operational personnel. The assessment of the required number of personnel depends on many factors, such as the reactor type, the number of NPP units, and maintenance features. According to various sources [45,46], the number of operational personnel for an NPP with two units is, on average, approximately 2000 people. NPP operation requires a wide range of specialists with higher and secondary vocational education, as well as working specialties in primary and secondary vocational education. Some of the specialists needed for NPP operation are already being prepared and can be trained in Kazakhstan. To do this, it is necessary to work out the issue of organizing the appropriate training programs for the new specialties on the basis of the technical

departments of universities, as well as training the working professions on the basis of educational institutions of secondary special education.

Taking into consideration all available options for the training of specialists, it is necessary to develop a separate training program/plan for training the specialists for the nuclear industry of Kazakhstan, providing for the long-term maintenance and development of the industry.

3.3.9. Increasing Participation in the Nuclear Fuel Cycle

Providing the plant with fuel is one of the main issues when planning NPP construction. There are various options for fuel provision. The main one is the import of ready-made fuel assemblies for a specific reactor type, carried out on the basis of a signed contract, as a rule for the entire service life. The preferred option is local production, under the condition of obtaining a license for the production technology of fuel assemblies, equipment, documentation, etc., from national raw materials, taking into account the economic feasibility and the development of new markets.

Taking into account the resources available in Kazakhstan (uranium reserves), segments of nuclear fuel production, and, since recently, an operating plant for the production of fuel assemblies, the organization of the local production of nuclear fuel (fuel assemblies) for the future Kazakh NPP should become a priority. Today, the first important steps have been taken in this direction. In December 2022, the first batch of nuclear fuel for Chinese NPPs was delivered—the fuel assemblies (FAs) of the AFA 3G TM design, manufactured at the Kazakh–Chinese joint venture LLP ULBA-TVS [47]. In January 2024, JSC NAC Kazatomprom (Astana, Kazakhstan) announced the successful completion of the certification process for the production of AFA 3GTM type A fuel assemblies [48].

In the process of setting up the production of the fuel assemblies, there are specific market restrictions: the need for certification, the customization of fuel assemblies for the type of reactor, the complexity of the offer, etc. Each series of fuel assemblies is made for a specific type of reactor. Therefore, it is necessary to work out the issue of a strategic partnership with a nuclear technology supplier or a company with the technology for a specific type of fuel production, with a view to its further transfer to Kazakhstan. The implementation of this orientation will ensure the stability and independence of the nuclear fuel supplies with the ability to minimize the price fluctuations for uranium and the components within the national economy.

Most of the technological stages of fuel production are currently carried out in Kazakhstan or will be started in the near future (refining). In addition, the country's leadership sets the task of focusing on such factors as the conversion and enrichment of uranium [9]. A certain advantage of Kazakhstan in fuel element claddings is the availability of a developed experimental and methodological base and long-term experience in organizing the tests of the fuel rods and fuel assemblies, which can be used both for the certification of new types of reactor fuel or its elements and for testing the technical solutions used in the design of FAs to reduce the consequences of severe accidents with core meltdown [49–54].

3.3.10. Issues of RW and SNF Handling

Radioactive waste is generated during NPP operation. Low-, medium-, and high-level RWs are formed depending on the specific activity at the NPP. The main share of the total amount of solid radioactive waste (98%) generated during NPP operation in the operational modes is low-level waste. The total amount of low- and medium-active solid RW generated per year at one power unit (1–1.2 GW) under normal operation conditions is 50–100 m³, and that for high-active ones is 0.5 m³, or about 10 tons of the RW of modern reactor plant projects (generations III and III+) [55]. In addition, up to 30 tons of spent nuclear fuel is produced at the NPP with a capacity of 1 GW per year. Over 60 years of operation (the design life of a modern power unit), a 1 GW NPP will produce 600 tons of RW, 98% of which is low-active, with 1800 tons of SNF.

According to the legislation of the Republic of Kazakhstan [56], all generated radioactive waste should be disposed of in compliance with environmental requirements to ensure that the population and environment are protected from radiation for a period of time during which it poses a potential danger.

The primary handling of RW and SNF takes place on the plant industrial site. The radioactive waste is conditioned, i.e., transferred to a stable form for storage, and then it is placed in on-site storage facilities for temporary storage. In this case, these storages can be designed for a different service life, on average for 10–15 years, depending on the project. Further, these wastes should be removed from the NPP storage to the final isolation point. The high-level waste is usually stored in on-site storage facilities for the entire operation period of the NPP due to their significantly smaller amount.

The construction of the disposal site includes measures to create a complex for processing and preparing RW for disposal; the handling of RW, including the sorting of RW by category, processing and amount reduction, and conditioning; and the selection of potential disposal areas and sites for RW in accordance with the requirements of the regulatory documents.

The handling of RW at the NPP includes its exposure to water in the pools located in the building of the power unit to reduce its activity and release the residual energy to acceptable values. The cubic capacity of the exposure pool ensures SNF storage, as a rule, for ten years, taking into account the unloading of the entire core at any time of power unit operation. Further SNF handling depends on the national strategy for SNF handling. If the SNF is considered as RW, it is eventually subject to disposal. Otherwise, the SNF can be used as a valuable raw material to produce the components of a new fuel and a number of radioactive isotopes used in medicine, agriculture, and industry. With the current development of technologies for closing the nuclear fuel cycle, the second approach is more rational. Along with that, the strictest requirements are imposed on SNF disposal, requiring the implementation of complex engineering solutions (disposal in deep geological formations) as well as financial investments, which may ultimately affect the price of electricity supplied by the NPP. In this context, it is necessary to take into account that, today, Kazakhstan does not have the technologies and capacities for SNF processing. On a global scale, the capacity for SNF processing is also limited; only a few countries have such technologies. However, even if an agreement is reached on SNF processing by the Kazakhstani NPP with the supplier, the products of its processing, the high-level waste, will be returned. Considering the above, it is necessary to provide the conditions for SNF long-term storage in Kazakhstan.

In the long term, the SNF operating time will increase, and, at some point, the processing of the accumulated amount of SNF may become economically profitable, which will allow the closing of the country's nuclear fuel cycle with the phased commissioning of new nuclear power units. It is necessary to consider the issue of obtaining or developing our own technologies for SNF processing by performing scientific and engineering research in this regard.

It is necessary to carry out an engineering study of the options for long-term SNF dry storage after its unloading from the exposure pool before it is sent for processing and before the subsequent handling of the high-level waste as the first approach, in the initial stage. One of the most important issues in developing a strategy for RW and SNF handling is considering the possibility of appointing a specialized organization. This decision will require the development of the mechanisms for interaction between a specialized organization and enterprises in need of providing the services for the disposal of the produced RW, the financing procedure and schemes, and the improvement in the relevant legislative framework.

3.4. On the Issue of Choosing the NPP Supplier

The choice of NPP supplier should take into account a wide range of factors: economic, technical, political, and so on. Even today, it is clear that in order to solve the problem of electric energy shortage in the future, in light of the planned retirement of fossil fuel

capacities and the need to implement a low-carbon policy, Kazakhstan will need to build not one but several NPPs. Therefore, the choice of supplier for the first Kazakhstani NPP should be considered through the prism of further plans for nuclear power development. In this regard, it is preferable to choose the option of serial construction of the same type of units (one technology supplier, reactor type). In this case, the effect of reducing the amount of capital expenditure (by increasing the work efficiency) and the effect of reducing the electricity production cost at each subsequent unit are achieved.

The experience gained in the operation at the first NPPs will allow the highest possible capacity factor of the NPP to be maintained in the future, i.e., ensuring the maximum possible operating time of the NPP at the nominal power level. This will be achieved through a better understanding of the operational issues, the application of experience, and the minimization of the time required for planned shutdowns of the units for fuel overloads and maintenance of the equipment.

In addition to economic advantages, such an approach will allow for optimizing the process of nuclear power development from the point of view of creating a regulatory framework and staffing for NPP operation and providing an opportunity for the rapid exchange of operational experience, operational personnel, spare parts, equipment, and technologies for NPP construction and operation. All of these aspects will be unified.

Another important factor that can significantly affect the project cost includes the conditions for financing the NPP construction, i.e., the loan offer that can be defined by the state supplier of the NPP technology.

The most important factors affecting the cost and payback time of the NPP project are the interest rate on the loan and the NPP construction period—that is, the time when the NPP still does not generate income in the sold electricity form (the shorter the construction period and the delay from the schedule, the better it is from an economic point of view).

It is known that the NPP is characterized by very high capital expenditures. These expenditures are usually covered to a greater extent by the borrowed funds. At the same time, a very important criterion affecting the project's total cost and the price of electricity on the basis of a future NPP is the interest rate. In the case of Kazakhstan, it will certainly be the funds raised from foreign sources.

In international practice, there are examples when the state-owner of the NPP technology provides a loan on favorable terms for the implementation of the NPP construction project using its technology. This approach will be preferable both from the point of view of minimizing the one-time cost loading and from the position of greater interest, and therefore, there is a greater responsibility of the supplier of the NPP technology for the successful and, most importantly, timely implementation of the project.

Another important factor is the set of services that are important from the point of view of the issues related to NPP construction, which can be offered by a potential NPP supplier: training of the personnel, creation of the simulators, issues of handling the spent nuclear fuel and radioactive waste generated at the NPP, support of related nuclear knowledge and technologies, provision of the equipment for transportation and assembly of the oversized and heavy equipment for the construction period, advisory support, etc.

It is important from a technical point of view that the proposed NPP power unit has referentiality for construction and operation—this will allow previous experience to be taken into account to avoid possible mistakes in the NPP project implementation. It is also essential that the output of the power unit does not significantly exceed the capacity of the power grid of Kazakhstan, which will ensure the maximum capacity factor of the plant. This, in turn, will allow the project's economic indicators to be improved.

It is practical to use a similar approach in the case of small modular reactors. At the same time, under the conditions of very low referentiality in this market, as an option, it is possible to consider the alternative of creating a first-of-its-type SMR unit in Kazakhstan based on one of the most advanced projects available in the world and requiring appropriate approval, taking into account the current situation of the development of SMR projects. SMRs will be in demand both in closed regional power systems and in small cities, for power

supplies to industrial complexes, government research centers, mining enterprises, and in electrical grids with low capacity. The key issue for SMRs is economic competitiveness. Today, SMRs are among the most expensive proposals in the nuclear power-generation construction market per unit of power.

The economic principle states that an increase in volume leads to a reduction in unit cost. A reactor that produces twice as much electricity does not require twice as much concrete or twice as many operators to operate the power plant. For this reason, SMRs are expected to have higher capital and operating costs per MW of power than large reactors.

There is, however, another economic principle that can help SMRs become more competitive; production becomes more profitable from “acquired knowledge”. When releasing new reactors of a certain type, manufacturers improve production processes and thereby reduce costs. To produce a certain amount of electricity, it is necessary to build more SMRs than large-power reactors. Proponents of SMRs argue that the benefits of mass production can offset the costs of size. However, the number of reactors that would need to be built for this benefit to be realized ranges from simply large to astronomical.

4. Conclusions

This publication contains a number of recommendations for the timely and successful implementation of the program for the introduction of nuclear power sources into Kazakhstan’s generation structure (including almost all stages of the operation cycle of the atomic energy facilities), the necessary developments related to nuclear infrastructure facilities, national legislation, and other issues directly related to atomic energy issues.

We focus on the need to intensify the development of the nuclear industry in the Republic of Kazakhstan, taking into consideration the worldwide importance of the problems of achieving the UN Sustainable Development Goals, global environmental and energy problems that humanity is already facing today, and the global trend toward an increased share of nuclear energy in the generation structure oriented toward resolving the above problems as soon as possible. It is necessary to note the importance of societal solidarity and consolidation in an effort to implement the decarbonization strategy and ensure national energy security as a whole. In these processes, the role of nuclear power, according to the authors, is extremely significant, if not decisive, and the country today has everything necessary to join the club of states with nuclear power.

For Kazakhstan, nuclear energy has the potential to make a sustainable and long-term contribution to the country’s development. The implementation of a Nuclear Energy Program will contribute to the emergence of specific important results:

- In the energy sector, the construction and commissioning of nuclear power plants with the achievement of established electricity production indicators will be obtained;
- In the field of subsoil use, the optimal volume of uranium production in the country will be ensured, and geological exploration work will be carried out with the growth of available uranium resources;
- In the field of ecology, a safe system for radioactive waste and spent nuclear fuel management will be created, and measures to address issues of environmental protection will be taken;
- In the industrial sector, the production of nuclear fuel and its components will be expanded with access to new export markets;
- In the field of science, structures for scientific and technical nuclear expertise will be improved, and scientific and technical support for the operation of nuclear power plants will be provided in all stages of the life cycle.

The indicative scenario proposed by the authors for the commissioning of nuclear energy sources to cover the forecasted electricity shortage and achieve energy independence will require significant financial costs, as well as maximum consolidation of resources. When forming a strategy for the development of nuclear energy in Kazakhstan, detailed economic calculations should be carried out to justify possible costs, taking into account specific projects, their cost and financing schemes, and the economic effect for the state.

However, it is already obvious that the contribution to the economic development of the country when creating even one nuclear power plant amounts to billions of dollars. In addition, this will inevitably affect its development and will not only solve the problem of providing the economy with the necessary volumes of electricity but also give a new impetus to the development of the economy as a whole.

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References

1. The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2023–2040. World Nuclear Association. 2023. Available online: <https://world-nuclear.org/our-association/publications/global-trends-reports/nuclear-fuel-report.aspx> (accessed on 12 June 2024).
2. State of the Nation Address by President of the Republic of Kazakhstan Kassym-Jomart Tokayev “Unity of the People and Systemic Reforms Are a Solid Foundation for the Nation’s Prosperity”. Available online: <https://akorda.kz/en/state-of-the-nation-addressby-president-of-the-republic-of-kazakhstan-kassym-jomart-tokayev-38126> (accessed on 1 September 2021).
3. On the Concept of the Transition of the Republic of Kazakhstan to a “Green Economy”. Decree of the President of the Republic of Kazakhstan. No. 577. Available online: <https://adilet.zan.kz/rus/docs/U1300000577> (accessed on 30 May 2013).
4. Vaughan, A. EU’s carbon tax will apply globally. *New Sci.* **2021**, *251*, 18. [CrossRef]
5. Yin, H.T.; Wen, J.; Ma, J.; Chang, C.P. Carbon tax: Catalyst or hindrance for renewable energy use in climate change mitigation? *Energy Strategy Rev.* **2024**, *51*, 101273. [CrossRef]
6. Mehboob, M.Y.; Ma, B.; Sadiq, M.; Zhang, Y. Does nuclear energy reduce consumption-based carbon emissions: The role of environmental taxes and trade globalization in highest carbon emitting countries. *Nucl. Eng. Technol.* **2024**, *56*, 180–188. [CrossRef]
7. Carbon Tax Could Affect Competitiveness of Kazakh Products—Tokayev. Kazakh Telegraph Agency. Available online: <https://kaztag.kz/en/news/carbon-tax-could-affect-competitiveness-of-kazakh-products-tokayev> (accessed on 10 June 2022).
8. Decree of the President of the Republic of Kazakhstan. No. 121. On Approval of the Strategy for Achieving Carbon Neutrality of the Republic of Kazakhstan Until 2060. Available online: <https://adilet.zan.kz/rus/docs/U2300000121> (accessed on 2 February 2023).
9. State of the Nation Address by President of the Republic of Kazakhstan Kassym-Jomart Tokayev “Economic Course of a Just Kazakhstan”. Available online: <https://akorda.kz/en/president-kassym-jomart-tokayevs-state-of-the-nation-address-economic-course-of-a-just-kazakhstan-283243> (accessed on 1 September 2023).
10. Central Election Commission of the Republic of Kazakhstan. About the Results of Voting in the Republican Referendum. Available online: <https://www.election.gov.kz/rus/news/acts/index.php?ID=9570> (accessed on 8 October 2024).
11. Resolution of the Council of Ministers of the Republic of Belarus No. 1084. Available online: <https://pravo.by/document/?guid=3961&p0=C21501084> (accessed on 23 December 2015).
12. World Nuclear News. 2023. Available online: <https://www.world-nuclear-news.org/articles/second-belarus-unit-enters-commercial-operation> (accessed on 4 November 2024).
13. Oettingen, M.; Kim, J. Monte Carlo Modeling of Isotopic Changes of Actinides in Nuclear Fuel of APR1400 Pressurized Water Reactor. *Energies* **2024**, *17*, 4864. [CrossRef]
14. AlKaabi, H. Nuclear Newcomer Countries—The Path of the United Arab Emirates. In *Nuclear Law*; T.M.C. Asser Press: The Hague, The Netherlands, 2022. [CrossRef]
15. Yüksel, S.; Dinçer, H. *Handbook of Research on Strategic Management for Current Energy Investments*; IGI Global: New York, NY, USA, 2021; pp. 1–422.
16. People’s Republic of Bangladesh Power & Energy Sector Master Plan P. 2016. Available online: <https://openjicareport.jica.go.jp/pdf/12269742.pdf> (accessed on 8 October 2024).
17. World Nuclear Association. Nuclear Power in Bangladesh. 2024. Available online: <https://world-nuclear.org/information-library/country-profiles/countries-a-f/bangladesh> (accessed on 8 October 2024).
18. World Nuclear Association. Nuclear Power in Egypt. 2024. Available online: <https://world-nuclear.org/information-library/country-profiles/countries-a-f/egypt.aspx> (accessed on 4 November 2024).

19. Rosatom Newsletter. First SMRs for Export. 2024. Available online: <https://rosatomnewsletter.com/2024/06/28/first-smrs-for-export/> (accessed on 4 November 2024).
20. Ministry of Energy of the Republic of Kazakhstan. The Uranium Industry. Official Website of the Ministry of Energy. Available online: <https://www.gov.kz/memleket/entities/energo/activities/4908?lang=ru> (accessed on 8 October 2024).
21. Dumchev, I. Operational experience of BN-350 (IAEA-TM--25332). International Atomic Energy Agency. 2002, pp. 194–213. Available online: https://inis.iaea.org/search/search.aspx?orig_q=RN:34029224 (accessed on 18 June 2024).
22. Order of the Minister of Energy of the Republic of Kazakhstan “On Approval of Forecast Balances of Electric Energy and Capacity for 2024–2030”. No. 11. Available online: <https://www.gov.kz/memleket/entities/energo/documents/details/584465?lang=ru> (accessed on 11 January 2024).
23. International Atomic Energy Agency, Site Survey for Nuclear Power Plants, IAEA Safety Series No. 50-SG-S9, IAEA, Vienna. 1984. Available online: https://gnssn.iaea.org/Superseded%20Safety%20Standards/Safety_Series_050-SG-S9_1984.pdf (accessed on 8 October 2024).
24. International Atomic Energy Agency, Guidebook on the Introduction of Nuclear Power, Technical reports series No. 217, IAEA, Vienna. 1982. Available online: <https://www.iaea.org/publications/1318/guidebook-on-the-introduction-of-nuclear-power> (accessed on 8 October 2024).
25. OECD/NEA/IEA. *Projected Costs of Generating Electricity 2005*; OECD Publishing: Paris, France, 2005. [CrossRef]
26. IAEA Reviews Progress of Kazakhstan’s Nuclear Infrastructure Development, IAEA Official Website. Available online: <https://www.iaea.org/newscenter/pressreleases/iaea-reviews-progress-of-kazakhstans-nuclear-infrastructure-development> (accessed on 18 June 2024).
27. IAEA Team Concludes Site and External Events Design (SEED) Review in Kazakhstan, IAEA Official Website. Available online: <https://www.iaea.org/newscenter/pressreleases/iaea-team-concludes-site-and-external-events-design-seed-review-in-kazakhstan> (accessed on 18 June 2024).
28. The National Energy Report KAZENERGY 2023. Kazakhstan Association of Oil, Gas and Energy Sector Organizations “KAZENERGY”. Available online: https://www.kazenergy.com/upload/document/energy-report/NationalReport23_en.pdf (accessed on 8 October 2024).
29. Scenarios for Development of the Electric Power Industry (LCGP) and the Balance of Electricity and Capacities of Kazakhstan until 2035, LLP “ESR”. Available online: https://esr.kz/wordpress/wp-content/uploads/2022/06/QG_1_2022-RU_28-35.pdf (accessed on 8 October 2024).
30. Oettingen, M. Costs and Timeframes of Construction of Nuclear Power Plants Carried out by Potential Nuclear Technology Suppliers for Poland, Pulaski Policy Papers, Warsaw. 2021, pp. 1–11. Available online: https://pulaski.pl/wp-content/uploads/2021/06/Pulaski_Policy_Paper_No_6_2021_EN-1.pdf (accessed on 8 October 2024).
31. Voanews. Pakistan Signs \$4.8 Billion Nuclear Power Plant Deal with China. Available online: <https://www.voanews.com/a/pakistan-signs-4-8-billion-nuclear-power-plant-deal-with-china/7144967.html> (accessed on 5 November 2024).
32. Kursiv Media. Chinese Bidder Reveals Estimated Cost of Nuclear Power Plant in Kazakhstan. Available online: <https://kz.kursiv.media/en/2024-08-28/chinese-bidder-reveals-estimated-cost-of-nuclear-power-plant-in-kazakhstan/> (accessed on 5 November 2024).
33. Goswami, G.G.; Rahman, U.; Chowdhury, M. Estimating the economic cost of setting up a nuclear power plant at Rooppur in Bangladesh. *Environ. Sci. Pollut. Res.* **2022**, *29*, 35073–35095. [CrossRef]
34. Nuclear Engineering International. Belarus NPP Unit 2 Formally Commissioned. Available online: <https://www.neimagazine.com/news/belarus-npp-unit-2-formally-commissioned-11265680/?cf-view> (accessed on 5 November 2024).
35. Trend News Agency. Cost of Consturction of Akkuyu NPP in Turkye Announced. Available online: <https://en.trend.az/world/turkey/3912184.html> (accessed on 5 November 2024).
36. Power Technolgy. El Dabaa Nuclear Power Plant. Available online: <https://www.power-technology.com/projects/el-dabaa-nuclear-power-plant/> (accessed on 5 November 2024).
37. Vladislav Sozoniuk. Case Study of the VVER Project at Tianwan, China. OECD Nuclear Energy Agency Nuclear Development Division. 2014. Available online: https://www.oecd-neo.org/upload/docs/application/pdf/2020-07/wpne_workshop_3_4_case_study_of_the_vver_project_at_tianwan_china.pdf (accessed on 5 November 2024).
38. Power Technology. Hungary Agrees Deal for Two More Russian Reactors. Available online: <https://www.power-technology.com/news/hungary-and-russia-agree-on-new-nuclear-reactors/> (accessed on 5 November 2024).
39. Moon, K.H.; Kim, S.S. An Exploratory Study on a Target Capital Cost and Cost Reduction Methodologies of Innovative SMR in Korea. In Proceedings of the Transactions of the Korean Nuclear Society Virtual Spring Meeting, Online, 9–10 July 2020. Available online: https://www.kns.org/files/pre_paper/43/20S-659-%EA%B9%80%EC%8A%B9%EC%88%98.pdf (accessed on 8 October 2024).
40. Asuega, A.; Limb, B.J.; Quinn, J.C. Techno-economic analysis of advanced small modular nuclear reactors. *Appl. Energy* **2023**, *334*, 120669. [CrossRef]
41. Phadermrod, B.; Crowder, R.M.; Wills, G.B. Importance-Performance Analysis based SWOT analysis. *Int. J. Inf. Manag.* **2019**, *44*, 194–203. [CrossRef]
42. Resolution of the Government of the Republic of Kazakhstan. No. 790 “Approval of the State Planning System in the Republic of Kazakhstan”. Available online: <https://adilet.zan.kz/rus/docs/P1700000790> (accessed on 29 November 2017).
43. Milestones in the Development of a National Infrastructure for Nuclear Power, IAEA Nuclear Energy Series No. NG-G-3.1 (Rev. 1), Vienna. 2015. Available online: https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1704_web.pdf (accessed on 8 October 2024).

44. International Atomic Energy Agency. Technical Support to Nuclear Power Plants and Programmes, IAEA Nuclear Energy Series No. NP-T-3.28, IAEA, Vienna. 2018. Available online: https://www-pub.iaea.org/MTCD/Publications/PDF/P1824_web.pdf (accessed on 8 October 2024).
45. The Operating Organization for Nuclear Power Plants, IAEA Safety Standards Series, No. NG-G-2.4. 2004. Available online: https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1115_scr.pdf (accessed on 8 October 2024).
46. Recruitment, Qualification and Training of Personnel for Nuclear Power Plants, IAEA Safety Standards Series, No. NS-G-2.8. 2005. Available online: https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1140_scr.pdf (accessed on 8 October 2024).
47. First Delivery of Nuclear Fuel from Kazakhstan to NPP of the PRC. Official Website of Kazatomprom. Available online: https://www.kazatomprom.kz/en/media/view/first_delivery_nfc/ (accessed on 8 October 2024).
48. Kazatomprom Was Successfully Qualified for the Production of AFA 3G TM Type A Fuel Assemblies. Official Website of Kazatomprom. Available online: https://www.kazatomprom.kz/en/media/view/kazatomprom_certification_afa_3g (accessed on 8 October 2024).
49. Batyrbekov, E.; Vityuk, V.; Vurim, A.; Vityuk, G. Experimental opportunities and main results of the impulse graphite reactor use for research in safety area. *Ann. Nucl. Energy* **2023**, *182*, 109582. [CrossRef]
50. Vityuk, V.; Vityuk, G.; Vurim, A.; Irkimbekov, R.; Kukushkin, I.; Surayev, A.; Mukhamedov, N. Testing of a heterogeneous fuel rod in the research Impulse Graphite Reactor. *Prog. Nucl. Energy* **2023**, *164*, 104889. [CrossRef]
51. Vityuk, G.A.; Vityuk, V.A.; Vurim, A.D.; Skakov, M.K.; Gradoboyev, A.V. Feasibility study mixed oxide fuel tests in the impulse graphite reactor. *Eurasian J. Phys. Funct. Mater.* **2022**, *6*, 98–212. [CrossRef]
52. Serre, F.; Payot, F.; Suteau, C.; Trotignon, L.; Batyrbekov, E.; Vurim, A.; Pakhnits, A.; Vityuk, V.; Kubo, S.; Katoh, A.; et al. R&D and experimental programs to support the ASTRID core assessment in severe accidents conditions. In Proceedings of the ICAPP 2016–2016 International Congress on Advances in Nuclear Power Plants, San Francisco, CA, USA, 17–20 April 2016; Volume 3, pp. 2173–2182.
53. Kamiyama, K.; Konishi, K.; Sato, I.; Toyooka, J.I.; Matsuba, K.I.; Zuyev, V.A.; Pakhnits, A.V.; Vityuk, V.A.; Vurim, A.D.; Gaidaichuk, V.A.; et al. Experimental studies on the upward fuel-discharge for elimination of severe recriticality during core-disruptive accidents in sodium-cooled fast reactors. *J. Nucl. Sci. Technol.* **2014**, *51*, 1114–1124. [CrossRef]
54. Konishi, K.; Toyooka, J.I.; Kamiyama, K.; Sato, I.; Kubo, S.; Kotake, S.; Koyama, K.; Vurim, A.D.; Gaidaichuk, V.A.; Pakhnits, A.V.; et al. The Result of a Wall Failure In-Pile Experiment Under the EAGLE Project. *Nucl. Eng. Des.* **2007**, *237*, 2165–2174. [CrossRef]
55. Information Bulletin No. 10-11, 2010. The National Academy of Sciences of Belarus. State Scientific Institution “United Institute of Energy and Nuclear Research—Sosny”. Available online: http://sosny.bas-net.by/wp-content/uploads/2012/09/bul_2010_10_11.pdf (accessed on 8 October 2024).
56. Ecological Code of the Republic of Kazakhstan. The Code of the Republic of Kazakhstan. No.400-VI LRK. Available online: <https://adilet.zan.kz/eng/docs/K2100000400> (accessed on 2 January 2021).

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