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CONSTRUCTION OF NUCLEAR POWER PLANTS IN KAZAKHSTAN: ECONOMIC, ENVIRONMENTAL AND SCIENTIFIC IMPLICATIONS

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ABSTRACT

This article reveals the main goals of international experience in nuclear power plant (NPP) construction, analyses of benefits and risks that NPP operations may have on the economy and the development of a country's scientific potential and examines annual report data.

The article's methodological approach examines the full range of opportunities and prospects not only in energy production but also in the development of new technologies, medicine, environmental protection, and promotion of scientific and technological progress.

The originality and value of the article analyze the economic, environmental, and social aspects of NPP construction, focusing on safety, greenhouse gas emissions, includes NPV analysis to assess the investment attractiveness, as well as institutional risks, potential advantages and comparative analysis of the RK electricity development scenarios.

The article finds out that nuclear energy contributes to increased national energy security, creation of high-tech companies which are involved into the energy research, creation and providing people with working places, as well as the development of start-ups.

Keywords: nuclear, energy, emissions, reactor, benefits

INTRODUCTION

World Nuclear Association says that there are about 400 nuclear reactors in 32 countries in the world. Among with this, about 60 nuclear reactors are under construction and about 100 more are in the process of development. At the same time, over the past 20 years, just over 100 reactors have been decommissioned due to wear and tear and obsolescence of equipment. As it seen, the process of building nuclear reactors is constantly in a dynamic state. International experience shows that the decisions made on the construction of nuclear power plants are very different. The head of state's decision to advance the construction and further development of nuclear energy is influenced by many factors. As practice shows, many states are inclined to hold a national referendum and vote in Parliaments. The results of such votes lead to a decision on the construction, continued use or closure of the nuclear power plant. The consequences of such elections will determine the future development of not only the energy sector, the economic development of the country but also the issues of industrial safety and industrialization of the country in general. Among other things, most countries namely the world's top countries in the development of nuclear energy (the USA, Great Britain, China, France) are still inclined to choose energy security and independence. It is important to note that this issue is accompanied by the maintenance of the peaceful use of the nuclear industry and mainly under the control of the governments and leaders of countries who directly make decisions on the construction of nuclear power plant units.

Modern authors from international and national scientific community actively researching issues related to the role of nuclear energy and renewable energy sources.

Literature review. The authors of Kazakhstan reveal their research regarding the national interests, energy policy, development of nuclear power plants in the country, as well as the legal regulation of this sector. Nuku-

sheva and Umarhalinova et al. propose to improve the regulatory framework and control system in the nuclear sphere [1]; Martok-Tynysy [2] and Lada.kz [3] emphasize that nuclear power plants bring a certain economic effect, increases the number of working places, and contributes to the development of regions. RK Government reveals the issue of reducing dependence on coal and the possibility of developing low-carbon technologies [4]. IEA [5] and KEGOC [6] highlight the electric power system of Kazakhstan. According to the RK Law “On the Use of Atomic Energy as of 2016 the regulatory framework related to nuclear energy connected with the use of nuclear energy, environmental safety for the population, and the biological system.

Research work on the nuclear energy and renewable energy sources is also reviewed in the works of foreign authors. Sabine et al. emphasize the role of oceans as carbon dioxide sinks [7]. Thomas et al. and Rosenzweig et al. examined climate change and its impact on biodiversity and the decline in agricultural activity [8, 9]. The Paris Agreement aims to implement recommendations related to emission reductions [10]; the Convention on Nuclear Safety 1994 [11] and the Vienna Convention 1963 [12] address the need for strict regulation and risk management. Ciais et al. and NOAA study climate change due to greenhouse gases and CO₂ [13,14]. The IPCC report focuses on the factor of greenhouse gas emissions and climate change [15,16]. Meadows et al. (1972) explain economic growth and environmental sustainability [17,18]; U.S. EIA [19], World Bank [20,21], and World Energy Council [22] consider the issues of global energy resources, hydropower fundamentals, and world water and energy indicators. Data from REN21 [23,24] and IRENA [25] show a growing interest in the global status of renewable energy as a stable energy source; Kaunda et al. and Kibler & Tullos base their study on the potential of small hydropower plants and the environmental impacts of hydropower [26,27]. The World Nuclear Association emphasizes the reliability of nuclear power plants [28,29]. At the same time Brook and Bradshaw note the impact of nuclear power plants on reducing pressure on ecosystems and biodiversity [30].

The purpose of the study is to analyze, examine the data of annual reports and identify the economic advantages and prerequisites for the development of the country’s scientific potential in the context of the construction of a nuclear power plant for the future.

The scientific novelty of this research topic lies in the study of various approaches, technologies and international experience in the construction of nuclear reactors to identify the benefits and risks that can lead to confusion in society and cause a negative attitude. Analysis of the economic efficiency of these process and previous social factors help to study in more depth and develop a strategy to improve interaction with the population and thereby strengthen public support. The construction of nuclear power plants covers a range of technical, economic and social aspects is aimed to optimizing the overall vision and developing new opportune in nuclear energy.

Research methods. To achieve the stated goals and objectives, unstructured observation, statistical analogy, and data sampling, a comprehensive analysis of the research object, and a generalization method were used. Unstructured observation is a qualitative method where the researcher does not follow fixed checklists but observes and analyzes phenomena flexibly. In this study, it was used to examine international examples of nuclear power plant construction and operation, enabling the identification of emerging patterns, risks, and benefits. A generalization method was used in order to synthesize the various results into broader conclusions. International experience and data in the field of nuclear energy allow us to identify the risks and benefits of nuclear energy in the Republic of Kazakhstan. Discounted cash flow analysis, specifically the calculation of net present value (NPV), was also used to assess the investment attractiveness of nuclear power construction. Furthermore, the analytical block was supplemented by a consideration of institutional risks and the potential benefits of project implementation.

MAIN BODY

A special report and analysis of the hydropower market conducted by the International Energy Agency (IEA) showed that energy demand growth will raise over the next few decades [31]. Furthermore, population growth, urbanization, and industrial expansion will contribute to this process [32]. It should be noted that the forecast in the “Limits to Growth” report showed a decreasing volume of fossil fuel consumption, while, at the same time, it showed an increasing fuel’s life use [17]. However, the recent data from the International Energy Agency (based on reserve estimates from BP and the International Energy Agency) have shown the raise of fuel use, which leads

to its rapid depletion. This irrational approach clearly highlights the problem of fossil fuels shortages. In addition, the continued importance of hydropower is considered. Beyond that, international assessments of renewable energy (such as REN21 global status report) highlight the role of hydropower as a source of renewable electricity. As well, it should be noted that hydropower can provide a stable, adjustable supplement to fluctuating energy sources [23, 24]. It merits attention that hydropower's purpose is not limited to energy production alone; it also offers benefits in irrigation, large-scale dam construction, and flood control. Hydroelectric power plants also develop river waterways and support logistics between the periphery and the center.

For instance, China's Three Gorges Dam flood mitigation, shipping and agricultural irrigation in addition to power generation; the Itaipu Dam in Brazil/Paraguay has been key to regional energy security and cross-border cooperation; and the Grand Ethiopian Renaissance Dam (GERD) is intended not only to supply electricity but also to support economic growth and regional integration in East Africa.

Compared to previous periods, for example, in 2020 the hydropower market grew, mainly due to the added capacity of China by 24% [23, 24]. This would have been more dynamic, but the consequences of the COVID-19 pandemic made their own adjustments: construction was suspended, equipment supplies were also stopped, and in general, the demand for energy fell [33]. However, the total hydropower generation worldwide increased by 1.5% and is estimated to be 4,370 TWh, which is about 16.8% of the total world supply [34]. The most significant contribution was made by China with 12.6 GW of hydropower capacity [23]. To increase the capacity of hydropower, modernization of technologies and increase in the productivity of the least resource protentional are included [23]. If we look at the frequency of construction of hydroelectric power plants, we can see the following:

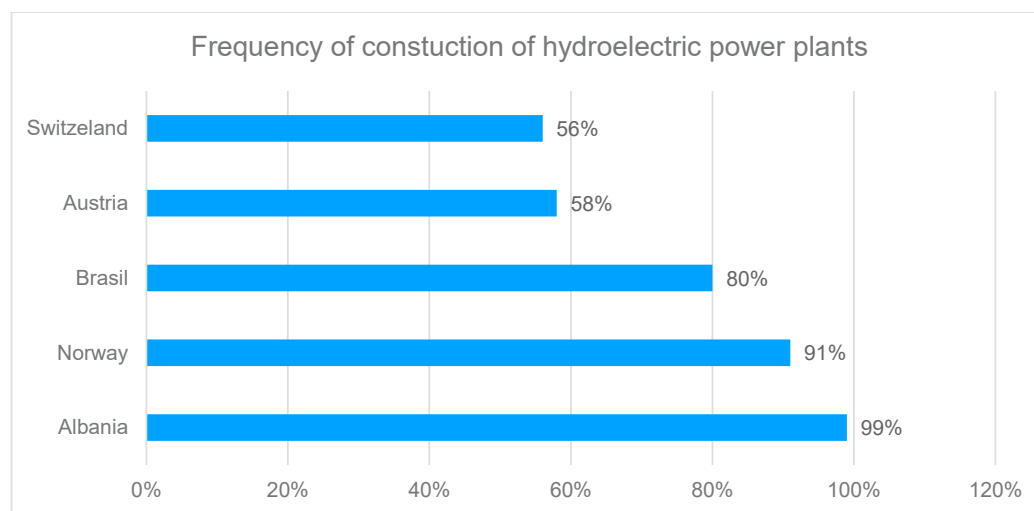


Figure 1– Frequency of construction of hydroelectric power plants

Note – compiled by the authors based on [26].

In general, hydropower is a traditional form of energy along with alternative sources [26]. The term traditional form of energy in this context refers to long-established renewable technologies such as hydropower, which has been exploited for centuries, compared to newer alternatives like wind or solar [31]. One of the key advantages of hydrogen is that it does not lead directly to CO₂ emissions [35]. Hydroelectric power plants are a low-carbon source of energy and accordingly have a minimal harmful impact on the environment and the release of toxicity to humans [15, 31]. In the CIS countries, as well as throughout the world, hydropower is recognized as one of the most common renewable sources of electricity [25]. Water supply by rivers is almost always stable, the current is not fast, and the territory of most countries is flat [20]. Most rivers in the countries of the former Soviet Union are up to 100 km long, but only 25% of this water is involves in the water management balance [36]. Nevertheless, small rivers play a significant role in the life of the country's population, as they

provide up to 95% of the total length of water supply [37]. Water and energy are quite interdependent when it comes to energy production [38]. The process of building a hydroelectric power plant begins with choosing a reservoir location and selecting options and types of hydraulic structures, which is the most voluminous type of work and takes a lot of time [27]. All construction risks are considered before construction. On average, over the last 20 years, the commissioning of hydroelectric power plants (HPPs) in the world has been more than 25 GW annually [39]. The total capacity of HPPs is around 1,330 GW [32]. According to forecasts, by 2030, the total capacity of hydropower facilities will increase to around 1,555 GW, which is approximately a 17% rise [40]. The development of hydropower on a global scale continues because it has the lowest long-term cost of electricity compared to other types of power plants and, accordingly, is one of the lowest-carbon sources of generation [31,15]. The largest hydroelectric power plants in the world belong to China, with the Three Gorges Dam (22.5 GW), Baihetan Dam (16 GW), and Xiluodu Dam (13.9 GW), together totaling around 47.4 GW of installed capacity [41].

In particular, the Itaipu Dam in South America, jointly operated by Brazil and Paraguay, has a capacity of 14 GW [42]. Other South American dams also produce GW of power: the Guri Dam in Venezuela produces 10.2 GW, and the Tucuruí Dam in Brazil produces 8.37 GW [25] (IRENA, 2021). The Grand Coulee Dam in North America, with a capacity of 6.8 GW, is the largest hydroelectric power station in the United States [43] (U.S. Energy Information Administration, 2021). The Eurasian continent is marked by other dams in Russia, such as the Sayano-Shushenskaya and Krasnoyarsk. In implementation, the capacity of large hydroelectric power stations, including dams, contains approximately 12.4 GW [22].

Hydroelectric systems contribute the energy necessary for economic growth. However, it is now noted that some developed world regions have already achieved high levels of renewable hydropower generation. For example, 75% of renewable hydropower is in Europe, and approximately 70% is in the North America [31]. Africa and Asia account for 25% of global hydroelectric power generation. This fact indicates that hydroelectric capacity will expand in the future on the continents of Africa, South America, and Asia [25]. The Republic of Kazakhstan is not the exception in the issue of electricity generation. Kazakhstan has large hydroelectric power plants in the East Kazakhstan region, such as the Shulbinsk, Ust-Kamenogorsk, and Bukhtarma hydroelectric power plants, as well as the Kapchagay hydroelectric power plant in the Almaty region [6]. However, Kazakhstan, which produces over 80% of its electricity, relies on coal for power generation. Natural gas accounts for approximately 7%, and hydropower for only about 8% [32]. Thus, in the coming years Kazakhstan needs to optimize and diversify its energy production and consumption, according to these highlighted percentages.

At the same time, operating hydroelectric power plants is more expensive than constructing them [27]. This proves that hydropower is not entirely harmless. According to IRENA, by 2021, the range of available alternative energy sources has sufficient potential to develop strategies that meet the country's economic, environmental, and political needs.

In addition, it is necessary to note the close connection between alternative energy sources (RES), which include wind, solar and hydropower in Kazakhstan [44].

Along with nuclear energy, there is a close interconnection of it with RES. Moreover, they can complement each other in generating energy sources. However, nuclear power plants (NPPs) in the Republic of Kazakhstan will provide the state with a stable energy system and low electricity tariffs. All these factors allow the country to decide economic, technical, and environmental issues. Furthermore, the presence of NPPs in the state will provide the national economy with the balanced energy supply to all regions of Kazakhstan. It is interesting to mention the fact that activity of NPP is not dependent on natural conditions, unlike renewable energy sources.

The nuclear power plant is considered a complex and expensive project. Its construction requires large costs such as human, technological and natural resources. OECD-NEA, 2016 says: "This process, which, having started, must be completed, because the costs of decommissioning the power plant exceed the costs of putting it into operation".

Nuclear electricity generation leads to emission of greenhouse gases. Observation shows that nuclear reactors produce a smaller percentage of greenhouse gas emissions compared to emissions produced by coal or gas-fired thermal power plants [45]. According to this fact, it is necessary to reduce CO₂ emissions, i.e. to carbon neutrality, which relates to the possibility of being absorbed naturally by vegetation, forests and other

natural absorbers. Taking this matter into consideration Kazakhstan adopted the “Strategy of achieving carbon neutrality by 2060” [66]. Due to the set strategy, Kazakhstan will solve a few important goals aimed at improving the country’s economic growth.

Upholding and sustaining world temperature increase to well below 2°C was discussed by the 2015 Paris Agreement under the United Nations Framework Convention on Climate Change [10].

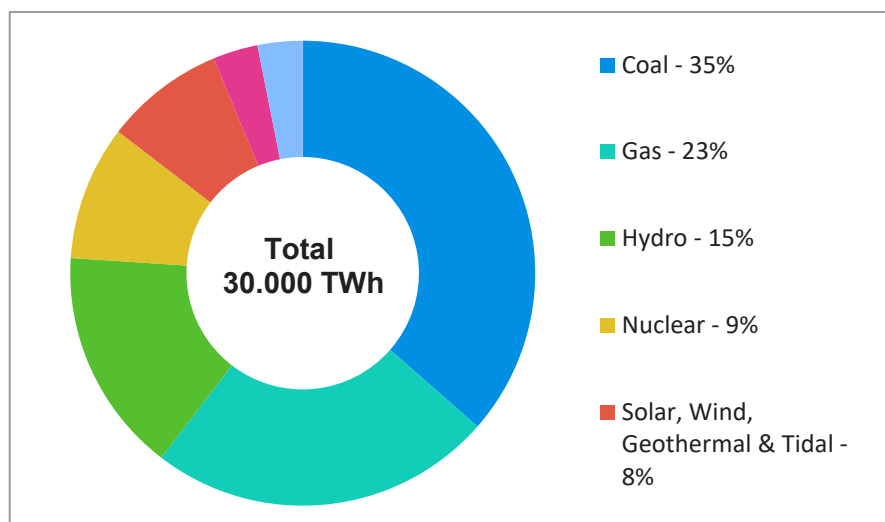


Figure – 2 World electricity Production by Source 2023

Note – compiled by the authors based on [46].

As it is seen, the world’s energy production still predominates from fossil resources. In this regard, the active use of nuclear technology will help to control the spreading of diseases, promote the advancement of human health research and the identification of risks and diagnosis of patients, and of course, achieve higher goals such as space exploration.

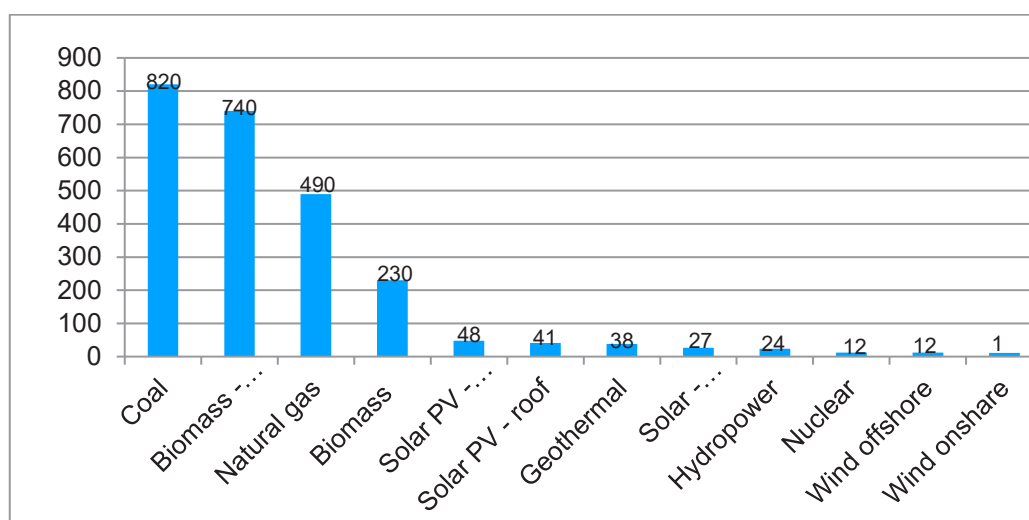


Figure – 3 Average life cycle CO₂ equivalent emissions

Note – compiled by the authors based on [15].

Furthermore, it is noted that coal-fired power generation accounts for the largest volume of CO₂ emissions, while nuclear power emits a small amount of CO₂ [15, 65]. This statement requires understanding of the

retention time and dispersion of greenhouse gases in the atmospheric air. Accumulation of greenhouse gases in the atmosphere leads to the greenhouse effect, warming, melting of glaciers, and increasing number of natural disasters such as hurricanes, droughts, and floods [16]. Moreover, analysis has shown that the world's oceans absorb approximately 25% of emitted CO₂, while carbon dioxide is absorbed by plants through photosynthesis [47]. Greenhouse gases have several negative consequences:

- limited use of water resources in the agro-industrial complex.
- intensification of migration.
- changes in ecosystem variety and shortening number of species.

Regarding this issue, climate imbalance depends on greenhouse gas emissions. Atmospheric greenhouse gas release affects the surrounding air, oceans, terrestrial ecosystems, and the planet's socioeconomic system [48]. Nuclear power is considered as a low-carbon energy source after hydroelectric power [31, 15]. Furthermore, the need for nuclear energy is strategically important for many countries. The UK and European countries are committed to reducing greenhouse gas emissions from energy production [28].

The COVID-19 represents a pivotal stage, separating the world into periods before and after outbreak. Nuclear reactor use in countries with nuclear power was stable before 2019, but the situation changed after COVID-19. The decline in interest and negative public attitudes toward the construction of nuclear power plants emerged just after COVID-19. Interest in renewable energy sources and their rapid development played a significant role here.

Greenhouse gas output could be reduced by 80% with the widespread use of solar batteries and wind turbines, while 20% could be given to the use of nuclear energy [76].

Economically developed countries are interested in nuclear power plants. It is generally accepted that 5-10 years are given to the plant and reactors construction. For example, France spent 5-8 years on this process, while the United States spent 5-7 years, and China 5-6 years. The entire construction process consists of several stages, including engineering, obtaining operating permits, and reactor construction, as well as the availability of resources and service of an experienced engineering company.

Development of a nuclear power station in Kazakhstan is attainable if the following factors are considered: an experienced engineering company for nuclear reactor construction, ensuring public and environmental safety, as well as a profitable operation for Kazakhstan.

Hence, Kazakhstan explores the adoption of services of an experienced engineering company in the construction of nuclear reactors, and it is holding a tender. The Republic of Kazakhstan defines the fact that there are several companies specializing in this field worldwide.

However, there are other problems besides finding the right company which can construct a nuclear power plant in Kazakhstan.

An analytical synthesis of the advantages of constructing a nuclear power plant in Kazakhstan can be presented as follows:

The foundations of the energy sector and its sustainable development in Kazakhstan directly depend on the construction of nuclear power plants. Importantly, this sector offers a number of strategic, economic, and environmental advantages. First, its primary objective is to ensure energy security and reduce dependence on hydrocarbon resources [31]. Second, it should be noted that, in line with Kazakhstan's climate agenda and international commitments, nuclear energy in the country can provide a stable energy supply with low greenhouse gas emissions [15].

Furthermore, from an economic perspective, the construction of a nuclear power plant provides a boost to various related industries, such as construction, science, engineering, and education, and creates new highly qualified personnel with advanced knowledge of nuclear energy technologies [29]. Thus, nuclear energy, supported by the state and appropriate tariff regulation, will help attract investment in the energy sector and can guarantee the stability of long-term energy costs [31].

Moreover, nuclear energy will strengthen the country and help Kazakhstan to gain a stronger position on the global stage, expand cooperation with other countries, develop science, and transition to environmentally friendly energy sources. This approach will expand opportunities for the integration of scientific and technological progress and, consequently, the transition to a low-carbon economy. Therefore, the construction

of nuclear power plants in Kazakhstan brings economic benefits, guaranteeing the stability of the country's energy system.

In order to evaluate the benefits further, we will conduct a scenario analysis that will examine alternative paths for the development of the energy industry in Kazakhstan and conduct a comparative analysis of these scenarios.

Let us consider three basic scenarios for the development of Kazakhstan's energy infrastructure in the medium-long term [31, 4].

1st baseline scenario “without NPP”: this development scenario assumes predominantly coal-fired power generation. Among the risks is that increased electricity demand will lead to capacity strain, much of which is significantly depreciated [31]. This will most likely lead to an electricity crisis, a return to import dependence, and an increase in CO₂ concentrations, which is at odds with sustainable development goals and decarbonization policies [31].

2 nuclear-inclusive scenarios “with NPP”: input exploitation nuclear power plants generally provide reliable energy generation and minimize dependence on external supplies from neighboring countries. In terms of environmental development, they contribute positively to the advancement of sustainable development goals [49]. Despite long-term development and high investment costs, this scenario offers more predictable energy security, price stability, and a reduction in carbon emissions [31].

3 renewable energy - dominated scenario: This trajectory shifts the emphasis toward renewable energy sources, specifically wind and solar power. This approach is fully consistent with current decarbonization trends, but has several unique characteristics: generation fluctuations, the need for sustainable capital investment, and climate sensitivity [34]. Without baseload generation, there is a risk of grid failure, which could lead to outages, power outages, and power supply instability [87].

Next, we will compare the proposed scenarios for energy development in Kazakhstan and conduct a comparative analysis.

Table 1 – Comparative analysis of electricity development scenarios in Kazakhstan

Criteria	Scenario “without nuclear power plants”	Scenario “with nuclear power plants”	Green Transition Scenario
Energy stability	↓ threat of import shortages	↑ constant base generation	→ climate dependence
Generation order	prevalence of coal	Diversity (NPP + coal + renewable energy)	predominantly renewable energy sources
CO₂ emissions	↑ high	↓ low	↓ very low
Infrastructure development costs	Without extra costs	Very high	High costs
Energy saving safety	Deteriorates due to equipment wear and tear	Tall and stable	Unstable without the use of energy storage systems
Implementation period	Short-term	Long-term	Medium-term
Investment efficiency	Moderate	Not high, but with potential to increase in the long term	Sensitivity to the volume of subsidies
Price stability in the energy sector	↓ low (linked to coal power)	↑ high (stable power generation)	→ average (price volatility)
Environmental impact	unfavorable	positive	favorable
Innovative development	Restrained	High	High
Systemic risks	Deteriorating infrastructure, carbon pressure	Regulatory and investment risks	Inadequacy of technological and infrastructure base
Note – compiled by the authors based on [31].			

Brief conclusion:

According to a comparative analysis, the baseline scenario is not designed for the long term, including achieving sustainable development and energy security goals. The renewable energy trajectory is the most environmentally friendly but also requires high capital investment and a balancing grid system. At the same time, the development model with the launch of nuclear power offers the most balanced structure of operational

reliability, environmental sustainability, and strategic stability. This forecast plan is a priority for Kazakhstan within the combined model of energy infrastructure and industry development.

Thus, despite the availability of alternatives in Kazakhstan's energy industry, the nuclear power scenario offers several advantages, including stable electricity generation, decarbonization, enhanced energy security, and technological process improvement. Based on this, an analytical synthesis of the advantages of constructing a nuclear power plant in Kazakhstan substantiates the advisability of considering nuclear energy as a key component of a long-term strategy.

To more thoroughly analyze the need and feasibility of constructing a nuclear power plant in Kazakhstan, we applied the net present value (NPV) method, which is widely used to evaluate capital-intensive infrastructure projects with long operating periods. This calculation method allows us to calculate not only the initial investment but also the distribution of cash flows over time, considering the present value of future payments.

The baseline scenario is based on a typical unit capacity of 1200 MW, which corresponds to modern Generation III+ reactor technology. According to international estimates from the International Energy Agency and the World Nuclear Association, capital costs for such projects range from USD 4,500 to USD 6,500 per kW of installed capacity, making the adopted investment level realistic for a large-scale project.

Initial calculation parameters:

installed capacity: 1,200 MW

capital expenditures (CAPEX): USD 6 billion

construction period: 40 years (generally accepted calculation period)

capacity utilization rate: 85%

electricity price: USD 0.07/kWh

operating expenses: USD 120 million/year

discount rate: 8% (average)

Annual electricity generation calculation:

$$E = 1,200 \times 0.85 \times 8,760$$

Thus, the annual generation is:

≈ 8.93 billion kWh

Annual revenue calculation:

Annual revenue is determined based on the average selling price of electricity:

$$R = 8.93 \times 109 \times 0.07$$

≈ USD 625 million per year

Operating expenses and cash flow

Operating expenses for nuclear power generation costs are relatively stable and include operation, maintenance, personnel, and fuel turnover:

$$OPEX = 120 \text{ million USD/year}$$

Net operating cash flow:

$$CF = 625 - 120$$

CF ≈ 505 million USD annually

Discounted and present value of revenues

$$\frac{1 - (1 + 0.08)^{-40}}{0.08}$$

At an 8% discount rate, this is approximately:

A ≈ 11.92

Present value of future cash flows:

$$PV = 505 \times 11.92$$

PV ≈ 6.02 billion USD

Net present value of the project

$$NPV = 6.02 - 6.00$$

NPV ≈ 0.02 billion USD

Analysis of results:

According to the results, the nuclear power plant construction project is formally investment-acceptable, but it is costly. Consider that its economic viability remains low. Capital cost calculations are the most vulnerable. On the other hand, according to research by the IEA, economic deviations or budget overruns of 20-30% are common risks for such nuclear initiatives, which in turn pushes the NPV into unfavorable territory [31]. However, nuclear generation has significant characteristics, such as low marginal costs of electricity production and constant productivity, which creates a stable cash flow structure in the long term. This reality affects these projects, making them more resilient to changes in fuel prices compared to coal and gas generation.

Thus, the results of the study allow us to conclude that, given the initial data obtained, the nuclear power plant construction project in Kazakhstan remains within the limits of economic feasibility, but at the same time does not generate a high level of profitability.

In this context, within the framework of the long-term and prospective development of the energy sector in Kazakhstan, it is proposed to consider the construction of nuclear power plants not as an investment initiative, but rather as an aspect of strategic policy aimed at diversifying energy generation sources, improving the level of energy security and promoting the sustainability of national energy complexes.

The obtained net present value (NPV) calculation results provide a starting point for assessing the project's economic feasibility. However, given the high capital intensity of initial investments in nuclear energy, we propose an additional analysis of the project's resilience to risk factors.

Risks.

Kazakhstan will be in touch with the following risks which are divided into units:

The first unit contains:

- safety ensuring.
- crash of the reactor during its activity.

Examples of such problems are the explosion of the reactor of the Chernobyl Nuclear Power Plant in 1986 and the catastrophe of the Fukushima Daiichi Nuclear Power Plant in 2011 [50, 51]. Crash of nuclear reactors illustrates the clear threat that humanity could be in touch with. Moreover, crash will be the reason to radiation emissions into the atmosphere, which in turn could cause environmental imbalances in the surrounding area and even lead to transboundary radiation contamination.

- issues of technical safety. There are several levels of special protection methods to ensure the safe operation of a nuclear reactor and avoidance of operational problems, [52].

- insignificant uranium reserves worldwide.

Statistics of the World Nuclear Association show that only a few countries have enough uranium reserves. For example, Kazakhstan had the first position in 2020 with 45.1% of the world's uranium production [22].

Further, 28% of the world's natural uranium reserves are mined in Australia, 15% in Kazakhstan, 9% in Canada, while Uzbekistan has 2% of the world uranium reserves and is on the 11th position [91] (OECD-NEA and IAEA, 2020).

Table 2 – Kazakh Uranium Production

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Tonnes U	21,317	22,451	23,127	23,607	24,586	23,321	21,705	22,808	19,477	21,819	21,227	21,112	21,27	25,800

Note – compiled by the authors based on [53].

Geographical location. One should be observed that geographic location of a nuclear power station holds substantial importance. This location is crucial relevance, as the reactors must be constructed in a manner that meets seismic safety standards, must have access to water sources, and does not affect harmfully on the climate of the region.

The second unit contains the matters of radioactive waste utilization:

- Radioactive waste can be active for centuries, so it is essential to run its long-term, environmentally safe storage. Long-term storage of nuclear waste requires specific design processes and nuclear industry technologies [52].

- Careless delivery of nuclear materials to reactors can lead to accidents and cause damage to the environment and human health [54].

- Coming generation will bear financial expenses and liabilities. All risks must also be considered by means of the long-term planning [55] (Schneider and Froggatt, 2019).

- Further, the issues of economic development and country efficiency are revealed.

- The costing of a nuclear power plant project considers not only financial investments but also equipment repairs and service costs. Nuclear power plant construction requires significant financial investments, much greater than those for renewable energy sources [56].

- Governments prioritize in building nuclear power plants, so they inject funding into this sector of the economy. It follows that, countries of Asia, Africa, and South America build nuclear power plants with the help of state investment [22].

- Cessation of a nuclear power plant is more expensive than starting it up. Closing and dismantling of nuclear power plants is a costly long-term process [52].

Political and social resistance.

The Republic of Kazakhstan is under considerable strain.

- Political uncertainty:

According to Nukusheva, the construction of a nuclear power plant cannot proceed effectively if there are a state instability and crisis. [1].

- Public distrust: Major accidents at nuclear power plants around the world have led to public distrust and protests. This phenomenon may become an obstacle for the construction of nuclear power plants and can break trust to the project implementation [57].

- The international situation in regions with tense situations, i.e. issues of non-proliferation of nuclear potential [58].

Economically active population. Nuclear power plant construction requires highly qualified specialists with internationally recognized qualifications in nuclear energy [58].

Reliance on nuclear energy inputs. As applied, countries with nuclear power complexes are often dependent on countries that possess nuclear raw materials. Thus, resource constraints are not an obstacle to the development of nuclear energy. However, they can also lead to political crises and financial vulnerability [28].

Digital dependency. Integration of technologies and devices from abroad can make a country dependent on supply sources. This, in turn, leads to additional costs and accounts payable, creating strain on the economy [55].

These circumstances suggest that the development of nuclear energy is a multifaceted process and requires consideration of potential risks and limitations for future power plant construction.

Economic benefits for Kazakhstan. Regarding long-term investments in large-scale public projects, which can encompass not only economic but also technological and social determinants, the implementation of a nuclear power plant may become a key moment.

One of the notable benefits of the nuclear industry is its low carbon emissions, which makes it possible to achieve the global decarbonization goal. One of the most important strength and economic attractiveness of nuclear power units is their relatively low maintenance costs, stable tariffs, and long service life. This ensures a guaranteed and timely return on investment and a balanced price [60]. While clean energy production is dependent on natural factors and chaotic, nuclear power plants generate energy reliably, ensuring the stability of the energy system and the manufacturing sector [28].

In conjunction with providing a stable energy supply, nuclear power plants expand the labor force by creating new jobs, optimizing the economic and engineering sectors, and developing a pool of qualified personnel, thereby strengthening human capital. This also optimizes regional infrastructure and increases tax revenues [56].

Taken together, Kazakhstan possesses significant scientific potential to position itself as an active player in international nuclear cooperation in the future, provided investment activity and the systematic development of legal institutions are maintained [61].

In the group of environmental and economic values, low levels of carbon dioxide emissions into the atmosphere are primarily emphasized. Nuclear power plants generate small amounts of greenhouse gases, and this is becoming a key factor determining priorities in strengthening climate initiatives and the introduction of a carbon tax [15, 31]. In this sense, nuclear energy is a driver of technological progress, strengthening the industrial sector, and developing information technology, which in turn opens new strong point and key contributing factor for the state [54].

Access to affordable energy sources increases the competitiveness of the economy, both domestically and globally. Stable energy generation from nuclear reactors ensures profits for industrial enterprises [32].

Evidence provided by the World Nuclear Association demonstrate that entire nuclear generation potential increased by 1 GW to 392 GW [29]. The assessments also note that the average reactor utilization index increased by 1% over the previous period to 81.5. These metrics and characteristics demonstrate the strength and stability of the nuclear sector. These trends indicate that reactor efficiency remains stable and even optimizes over time as they age.

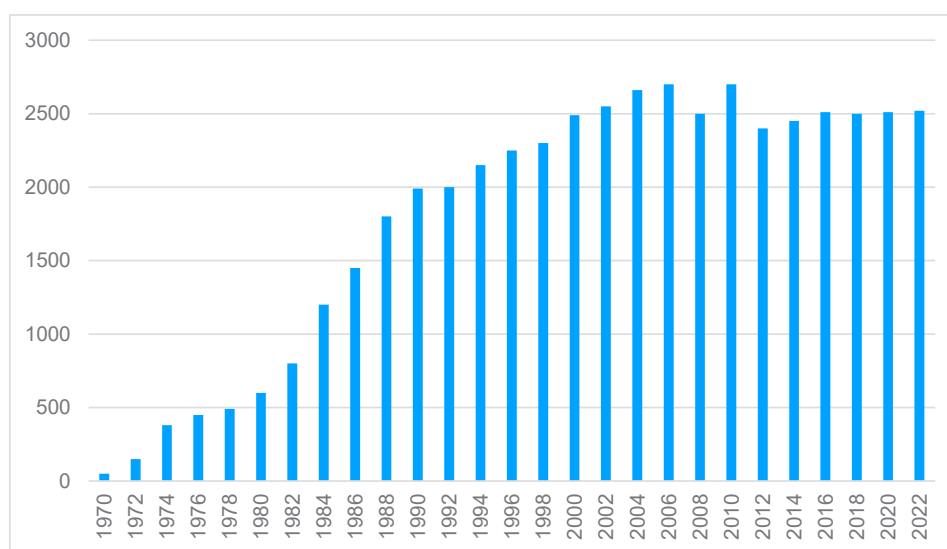


Figure – 4 Total Nuclear Electricity Production by Reactor Age

Note – compiled by the authors based on [29].

Confronted with global transformations, humanity has always strived to find less resource-intensive solutions to global problems. In this regard, the construction of a nuclear power plant (NPP) in Kazakhstan could improve economic development. First, it will ensure energy independence and security through a well-functioning symbiosis of international and national laws. Second, it will create optimal mechanisms for protecting the environment from environmental disasters that have been accumulating in everyday life for years, harming human health, destroying ecosystems, and disrupting agriculture. Third, it will reduce dependence on and instability from fluctuations in oil and gas prices on global markets [2].

Scenarios and concepts of this magnitude, indeed, attract significant and robust investment, which in turn expands development opportunities for the provinces [3]. Overall, the nuclear industry has a beneficial impact on virtually all sectors of the economy. For example, the EU, through the implementation of legal instruments,

places emphasis on compliance with environmental standards, and as a result, this inspires public confidence in the nuclear sector as the main energy supplier [62].

With the guidance of International Atomic Energy Agency (IAEA), which oversees nuclear safety worldwide, numerous international treaties have been drafted and adopted.

The establishing document is the Treaty on the Non-Proliferation of nuclear weapons (NPT). The treaty's core concept is the peaceful use of nuclear energy. Thus, Article IV of the Treaty stipulates that member states may conduct research and utilize nuclear energy to improve their national economies and advance technology, subject to the assurance of maintaining safety. Furthermore, cooperation with the IAEA accelerates the implementation of modern approaches and practices and ensures protection in accordance with global safety standards. Over and above that, compliance with international requirements obliges national legislation not only to formally comply with established norms but also requires the systematic development of national legislation, incorporating IAEA international practices. Additionally, within the framework of international law, the relevance and significance of international cooperation and the risk-free use of the nuclear industry's potential are emphasized [63].

Beyond any doubt, the Convention on Nuclear Safety occupies a leading position, overseeing legal instruments for ensuring safety during the design, construction, and commissioning of nuclear reactors. Environmental and social risks must not be ignored [64]. The 1997 Vienna Convention defines the norms and rules for compensation for damage and replenishment of losses, as well as ensuring safety in the field of nuclear energy supply.

The implementation of nuclear power plant in Kazakhstan will be carried out in accordance with international standards and national legislation, including the Law "On the Use of Atomic Energy", which establishes the legal basis for the use of radioactive materials, substances, and oversight of licensing and regulation in the field of nuclear energy and technology. The impact on the ecosystem and compliance with international radiation safety requirements are also assessed. It should be noted that the construction of nuclear power units depends largely on the transparency of processes and the availability of information, the degree of environmental impact, and compliance with legislation on the processing of radioactive waste [1].

A tangible illustration of evidence-based implementation is Russia's experience, particularly the Russian Federation Law "On the Use of Atomic Energy" (1995). This law regulates strict licensing and oversight procedures for the construction and operation of nuclear power plants [1]. France also offers another successful example, where approximately 70% of energy needs are met by nuclear power plants, while China continues to expand its nuclear power capacity to supply the country with energy and reduce carbon dioxide emissions.

The establishment of nuclear power stations requires strict adherence to international safety standards within the framework of national legislation. Effective legal regulation is the foundation for the safe and sustainable use of nuclear energy. Thus, Kazakhstan will be able to increase its energy independence and strengthen its position internationally, provided that the regulatory framework and international agreements are implemented.

Scientific potential.

Nuclear power plants have a significant impact on the development and promotion of research in the field of the country's scientific potential, namely the educational system, international relations and strengthening diplomacy between countries. Even during the age of renewable energy, nuclear energy can be quite competitive, especially nuclear hybrid power [65]. Nuclear energy contributes to the development of nuclear physics, even though now this definition is often tried to be bypassed in many countries with an acute political situation, this opportunity should be considered more broadly, as a benefit and prospects for strategic research of future generations. Training of highly qualified specialists in various fields - ecologists, engineers, chemists. In any country in the world, education is the engine of national progress, therefore, the integration of scientific research in the field of nuclear energy is becoming part of the educational programs of universities, which provide a platform for training and advanced training of students and young scientists.

It is evident that scientific and technological development extends beyond the establishment of experimental facilities in nuclear physics. Moreover, it creates the preconditions and opportunities for the younger generation to participate in international exchange programs and project groups and fosters an academic community for dialogue and mutual learning. We believe that the technological evolution of scientific approaches in the nuclear sector also contributes to the development of medicine, particularly through improved diagnostics

for various diseases, as well as the production of medical equipment to improve and maintain public health. Reactors for research purposes and associated laboratories at nuclear power plants offer an exclusive platform with a rich infrastructure and advanced facilities for conducting various applied and fundamental experiments in physics and space exploration.

In this regard, Kazakhstan, positioned as a country with considerable resource endowment, has a nuclear industry with every prospect and opportunity to develop environmental solutions related to climate change. Therefore, advances in nuclear energy contribute significantly to strengthening economic development while guaranteeing the safety of energy production.

The manifestation of a nuclear infrastructure in a country with growth potential is empirical confirmation that the energy generated by nuclear reactors is used for peaceful purposes. In this case, security risks will be balanced against favorable prospects for economic, social, political, and technological development. Therefore, it is assumed that a key aspect of scientific and technological development is building international cooperation with states that have developed nuclear industries, while also having feasibility and public demand.

This aspect deserves attention that a significant portion of countries continue to focus on developing the nuclear industry. For example, Brook and Bradshaw highlight its positive impact on biodiversity conservation among its significant advantages [30]. While this impact is not direct, it does indirectly influence:

- reduction in greenhouse gas emissions
- cut of fossil fuel utilization
- intensive energy consumption, while using a smaller area, compared to vast agricultural energy zones
- reduction in water consumption, while preserving ecosystems for future generations. Consequently, nuclear power indirectly lowers carbon emissions, mitigates the impact of anthropogenic factors on the environment, and stabilizes the climate, which ultimately shapes socio-economic patterns.

Kazakhstan is progressively integrating into global arena of creating and developing the nuclear energy sector, as a country consolidating its resource potential through participation in international innovative cooperation. As it is shown in the table below, Kazakhstan, along with Argentina, Armenia, Slovakia, and Slovenia, is aiming to build one nuclear reactor.

Table 3 – Involvement of countries in the development of nuclear energy

Country	Nuclear electricity generation 2023		Reactors operable		Reactors under construction		Reactors planned		Reactors proposed		Uranium required 2024
	TWh	% e	No.	MWe net	No.	MWe gross	No.	MWe gross	No.	MWe gross	Tonnes U
Argentina	9.0	6.3	3	1641	1	29	1	1150	1	750	219
Armenia	2.5	31.1	1	416	0	0	0	0	1	1060	55
Bongladesh	0	0	0	0	2	2400	0	0	2	2400	371
Belarus	11.0	28.6	2	2220	0	0	0	0	0	0	357
Belgium	31.3	41.2	5	3908	0	0	0	0	0	0	516
Brazil	13.7	2.2	2	1884	1	1405	0	0	8	8000	339
Bulgaria	15.5	40.4	2	2006	0	0	2	2300	0	0	334
Canada	83.5	13.7	19	13.699	0	0	2	400	9	5700	1455
China	406.5	4.9	56	54.362	30	34.661	37	39.860	158	186.450	13.132
Czech Republic	28.7	40.0	6	4241	0	0	1	1200	3	3600	715
Egypt	0	0	0	0	4	4800	0	0	0	0	0
Finland	32.8	42.0	5	4394	0	0	0	0	0	0	616
Iran	6.1	1.7	1	915	1	1057	2	1417	6	5200	153
Japan	77.5	5.6	33	31.679	2	2756	1	1385	8	11.562	2180
Kazakhstan	0	0	0	0	0	0	0	0	1	1200	0
Korea RO (South)	171.6	31.5	26	25.825	2	2680	2	2800	0	0	4309
Mexico	12.0	4.9	2	1552	0	0	0	0	2	2000	237
Netherlands	3.8	3.4	1	482	0	0	0	0	2	2000	69
Pakistan	22.4	17.4	6	3262	0	0	1	1170	0	0	555

Country	Nuclear electricity generation 2023		Reactors operable		Reactors under construction		Reactors planned		Reactors proposed		Uranium required 2024
Poland	0	0	0	0	0	0	3	3750	26	10.000	0
Romania	10.3	18.9	2	1300	0	0	2	1440	6	462	185
Russia	204.0	18.4	36	26.802	4	3988	14	8930	36	37.716	5436
Saudi Arabia	0	0	0	0	0	0	0	0	2	2900	0
Slovakia	17.0	61.3	5	2308	1	471	0	0	1	1200	527
Slovenia	5.3	36.8	1	688	0	0	0	0	1	1200	127
South Africa	8.2	4.4	2	1854	0	0	0	0	2	2400	277
Spain	54.4	20.3	7	7123	0	0	0	0	0	0	1218

Note – compiled by the authors based on [66].

CONCLUSION

Throughout the period of its modern development, Kazakhstan has placed special emphasis on developing the humanities and applied sciences and continues to cultivate a pool of specialists in law and economics. Marketing specialties are actively sought after, and medicine and engineering have recently seen particularly strong growth. Alongside the development of the national economy, the state is also emphasizing the development of nuclear physics and digital technologies, as the construction of nuclear power plants is a multifaceted process designed for the long term. At the same time, it is worth noting that the dividends from this construction will be high-quality and significant for the entire country. The expansion of nuclear reactors requires the meticulous training of qualified specialists and a very high level of safety. Kazakhstan must approach this process responsibly. If work begins as expected, nuclear energy will provide impetus for our country's path to energy security, climate protection, and sustainable development. The implementation of a nuclear power plant as a long-term economic project not only provides an advantage for the development of alternative energy, but also significantly advances scientific and technological progress, increases the national economy, strengthens the country's position on the global stage, enhances energy independence and the use of its own uranium reserves, and strengthens international cooperation. New jobs are created in the domestic market, and employment levels rise, primarily in technical fields.

In the context of this study, a Net Present Value (NPV) analysis was also conducted, it revealed that the nuclear power plant construction project is economically feasible but requires a stable tariff policy and diversification of energy sources. In long-term planning, the project demonstrates the potential for sustainable development and may be justified in terms of strategic and environmental initiatives. Therefore, we believe that its implementation should follow a comprehensive, balanced, and well-structured strategy that considers not only financial but also systemic aspects.

Furthermore, the investigation reveals the other matter that included a comprehensive analysis of the integrated assessment of nuclear power plant construction. Analytical meanings of benefits and comparative analysis of the RK electricity development scenarios show that constructing of a nuclear power plant in Kazakhstan provide the country both with the stable energy supply and low greenhouse gas emissions and can give minimization of dependency on external supplies from neighboring countries.

Thus, its implementation requires a balanced approach considering not only financial factors but also institutional and sustainability-related dimensions.

We must acknowledge the setbacks encountered in unfavorable experiences and tragedies of humanity associated with the disasters at the Fukushima and Chernobyl nuclear reactors, as well as nuclear explosions in the Semipalatinsk region. These examples once again emphasize the importance of adhering to all international safety norms and standards throughout the entire construction period, from commissioning to decommissioning.

The anticipated trajectory of nuclear energy expansion for the implementation of nuclear energy facilities in Kazakhstan inspire great hope for the country's positioning as a leader in clean and alternative technologies. This enhances the overall competitiveness of the economy, creates reliable energy security, promotes the development of related industries such as innovative energy, and enhances environmental stability, and generally

contributes to sustainable development. Under these circumstances, Kazakhstan can position itself as a country of clean energy technologies, particularly in the field of renewable energy sources.

Simultaneously, coal remains responsible for 80% of energy production, making the country one of the world's largest greenhouse gas emitters. Since 1994, Kazakhstan has been the 121st member of the International Atomic Energy Agency (IAEA). To protect the public and the environment, IAEA safety standards establish principles and measures to control human radiation exposure and releases of radioactive materials. These principles pursue the overall goal of protecting the life and health of the population and preventing environmental disasters. Kazakhstan formally joined the Paris Agreement in 2016, agreeing to reduce greenhouse gas emissions by 15% by 2030.

Accordingly, the establishment of a nuclear power station is one step toward achieving the ambitious goal set for the Kazakh government by the head of state. The President has repeatedly emphasized the need for nuclear energy, which is a part of national security, and the nuclear industry provides a powerful boost to the economy and facilitates the search for effective solutions to address the energy crisis [67]. The Minister of Energy of the Republic of Kazakhstan noted that the construction of a nuclear power plant can ensure the country's energy self-sufficiency [68].

Ultimately, we should highlight that the conceptual focus on constructing a nuclear power station in Kazakhstan is more than just strategic. The key idea of the project is to strengthen the country's energy security, ensure technological sovereignty, and further advance and maintain economic growth.

Predictably, the project encounters opposition which resists the development of a nuclear power plant, but we are convinced that with careful consideration to nuclear safety, transparency in decision-making, and mandatory public awareness of social and environmental risks, doubts will be reduced. We do not rule out the possibility that significant international investment, consensus-based political will, and public trust will be required.

Under these circumstances, the construction of nuclear power plant encompasses more than just infrastructure facilities but is also seen as the quintessence of the government's program for modernizing the energy sector and technological development, focused on sustainable economic growth, reducing the carbon footprint, and increasing conscious responsibility among the population in the use of strategic technologies.

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ҚАЗАҚСТАНДАҒЫ АТОМ ЭЛЕКТР СТАНЦИЯЛАРЫН САЛУ: ЭКОНОМИКАЛЫҚ, ЭКОЛОГИЯЛЫҚ ЖӘНЕ ҒЫЛЫМИ АСПЕКТІЛЕР

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АННОТАЦИЯ

Бұл мақалада атом электр станцияларын (АЭС) салудың халықаралық тәжірибесінің негізгі мақсаттары ашып көрсетіліп, АЭС-ті пайдаланудың ел экономикасы мен ғылыми әлеуетін дамытуға тигізетін артықшылықтары мен тәуекелдері талданады, сондай-ақ жылдық есептердің деректері қарастырылады.

Зерттеудің әдіснамалық маңыздылығы энергия өндіру саласындағы мүмкіндіктер мен перспективалардығана емес, сонымен қатар жаңа технологияларды дамыту, медицина, қоршаған ортаны қорғау және ғылыми-техникалық прогреске жәрдемдесу бағыттарындағы мүмкіндіктер мен келешекті жан-жақты қамтуымен сипатталады.

Мақаланың ғылыми жаңалығы мен құндылығы атом электр станцияларын салудың экономикалық, экологиялық және әлеуметтік аспектілерін талдауда көрінеді. Сонымен қатар қауіпсіздік мәселелеріне, парниктік газдар шығарындыларына ерекше назар аударылып, инвестициялық тартымдылықты бағалау үшін таза келтірілген құнға (NPV) талдау жүргізіледі. Сондай-ақ институционалдық тәуекелдер, ықтимал артықшылықтар және Қазақстан Республикасының электр энергетикасын дамыту сценарийлеріне салыстырмалы талдау ұсынылады.

Мақалада атом энергетикасы ұлттық энергетикалық қауіпсіздікті нығайтуға, энергетика саласындағы зерттеулермен айналысатын жоғары технологиялық компанияларды қалыптастыруға, халықты жұмыспен қамтуға, жаңа жұмыс орындарын ашуға, сондай-ақ стартаптарды дамытуға ықпал етеді деген қорытынды жасалады.

Түйінді сөздер: ядролық энергетика, шығарындылар, реактор, артықшылықтар, энергетикалық қауіпсіздік.

СТРОИТЕЛЬСТВО АТОМНЫХ ЭЛЕКТРОСТАНЦИЙ В КАЗАХСТАНЕ: ЭКОНОМИЧЕСКИЕ, ЭКОЛОГИЧЕСКИЕ И НАУЧНЫЕ АСПЕКТЫ

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АННОТАЦИЯ

В данной статье раскрываются основные цели международного опыта строительства атомных электростанций (АЭС), анализируются преимущества и риски эксплуатации АЭС для экономики и развития научного потенциала страны, а также рассматриваются данные годовых отчетов.

Методологическая значимость исследования рассматривает весь спектр возможностей и перспектив не только в области производства энергии, но и в развитии новых технологий, медицины, охраны окружающей среды и содействия научно-техническому прогрессу.

Оригинальность и ценность статьи заключаются в анализе экономических, экологических и социальных аспектов строительства АЭС, акцентируется внимание на безопасность, выбросы парниковых газов, рассматривается анализ чистой приведенной стоимости (NPV) для оценки инвестиционной привлекательности, а также институциональные риски, потенциальные преимущества и сравнительный анализ сценариев развития электроэнергетики в Республике Казахстан.

В статье делается вывод, что атомная энергетика способствует повышению национальной энергетической безопасности, созданию высокотехнологичных компаний, занимающихся исследованиями в области энергетики, созданию и обеспечению населения рабочими местами, а также развитию стартапов.

Ключевые слова: ядерный, энергетика, выбросы, реактор, преимущества.

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