The Main Scenarios for the Development of Nuclear Power Industry: Opportunities and Risks

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Abstract: The proposed article is aimed at discussing the need to choose the optimal long-term scenario for the development of Russian nuclear power industry, to reveal its content, directions, expected risks and consequences of implementation. The authors take the position of strengthening the state's responsibility for choosing innovation priorities in the country's energy sector. It is impossible to foresee the directions of Russia's socio-economic development without substantiating the ways of transformation of nuclear power industry – the basis for the formation of sustainable development of society under the conditions of sanctions pressure. Russian industry experts identify five basic scenarios for the development of nuclear power industry: from an innovative scenario to a digital model in the format of digitalization of the industry. The scenario of a complete abandonment of nuclear energy is not being considered by Russian specialists. Each of the discussed scenarios has its limitations and carries certain risks, but the growing energy needs of the Russian economy cannot be satisfied by the current model of nuclear power industry development, which requires a significant increase in economic, social and environmental efficiency.

1 INTRODUCTION

The energy crisis that has affected the global economy, combined with the need to control the climate agenda, dictates the need to develop an optimal source of energy: affordable, reliable and environmentally friendly – nuclear power. Despite the slowdown in the development of nuclear power industry in the world over the past ten years, a number of countries have decided to accelerate the development of nuclear power industry by increasing its share in the fuel and energy balance.

The growth of nuclear capacity is increasing several times every year. This trend is especially observed in countries such as China and India. Countries such as Vietnam, Indonesia, Malaysia and others are showing great interest in developing their own nuclear industry. The preference for energy resource leaders is gradually changing. Until 2020, the leadership in electricity production belonged to developed countries of the world, such as the USA and France. But the trend is changing and China is coming out on top in energy production. The possible distribution of nuclear power will be as follows: the United States will take 2nd place, and France will take 3rd place. Russia may also see a decline to 5th place with an increase in nuclear power production by 43% by 2040. Due to the rapid growth of nuclear power production, South Korea will occupy the 4th place. Japan will take 6th place if it goes through the relevant certification procedures to meet the new safety regulations. India is also actively working on these issues, achieving significant success. India's nuclear energy production will increase fivefold and it could take 7th place by 2040.

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2 RELEVANCE AND PROSPECTS

The growth rate of nuclear energy in the world is constantly increasing. If before 2014 there were 5 nuclear reactor launches per year, then in subsequent years there has been a significant increase in the commissioning of new nuclear power plants. Thus, during the period from 2015 to 2018, an average of ten reactors were launched. In 2019, it is planned to launch 14 new reactors. Countries such as Belarus and the UAE are joining the ranks of nuclear nations, as in the next two years, the commissioning of 30 new reactors with a capacity of up to 33 GW is planned. All this was provided for by the Harmony plan proposed by the WNA, which assumed a significant increase in nuclear energy, and its share will reach 25% in the world by 2050.

The hypothesis of the study is based on the assumption that the optimal choice of a long-term scenario for the development of nuclear power industry can form the basis for high rates of economic and social development and sustainable growth of the Russian economy.

The research methodology is based on a systematic approach that includes a synthesis of academic and industry science and methods such as the method of comparisons and groupings, the logical method, as well as cluster analysis. The authors used the information base presented on the official websites of the Federal State Statistics Service and international information platforms.

3 NUCLEAR SAFETY CONCEPTS

Regarding security in the energy industry, a concept that first appeared in the 1970s is inextricably linked to the restriction of oil embargoes. The concept of “energy security” itself has different approaches in different countries. However, in many countries of the world, the safety of nuclear energy is tied to three main goals:

Ensuring high quality and cost-effective energy supply,

Promoting the efficient use of energy

Environmental protection aimed at sustainable ecological development.

All target strategies of the Russian Federation within the framework of nuclear power industry development relate to strengthening cooperation and coordination of stakeholders to ensure reliability and security in the field of electricity supplies.

For example, in Malaysia, electricity generation capacity is provided by gas (10,494.4 MW), coal (8,066 MW), hydro power (2,149.1 MW) - data for 2015 (Demetriu, 2013). The electricity sector is strictly regulated and the national grid is operated by Tenaga Nasional Berhad (TNB) in Peninsular Malaysia, while the other two grids are operated by Sabah Electricity Sdn Bhd (SESB) and Sarawak Energy Berhad (SEB) in Sabah and Sarawak, respectively (Demetriu, 2013).

Assessment of macroeconomic effects from the implementation of nuclear energy projects

All nuclear energy projects can be assessed from different perspectives:

Efficiency assessment for the supplying countries

Assessment of benefits for the purchasing (recipient) countries

The supplying country receives an increase in external demand for products and an increase in external demand for related products of industries.

The second assessment gives advantages to the recipient country, which consists in an increase in demand for the products of the fund-forming industries and does not require initial investments, since the financing of projects in the nuclear energy sector is either at the expense of external funds or at the expense of the supplying company.

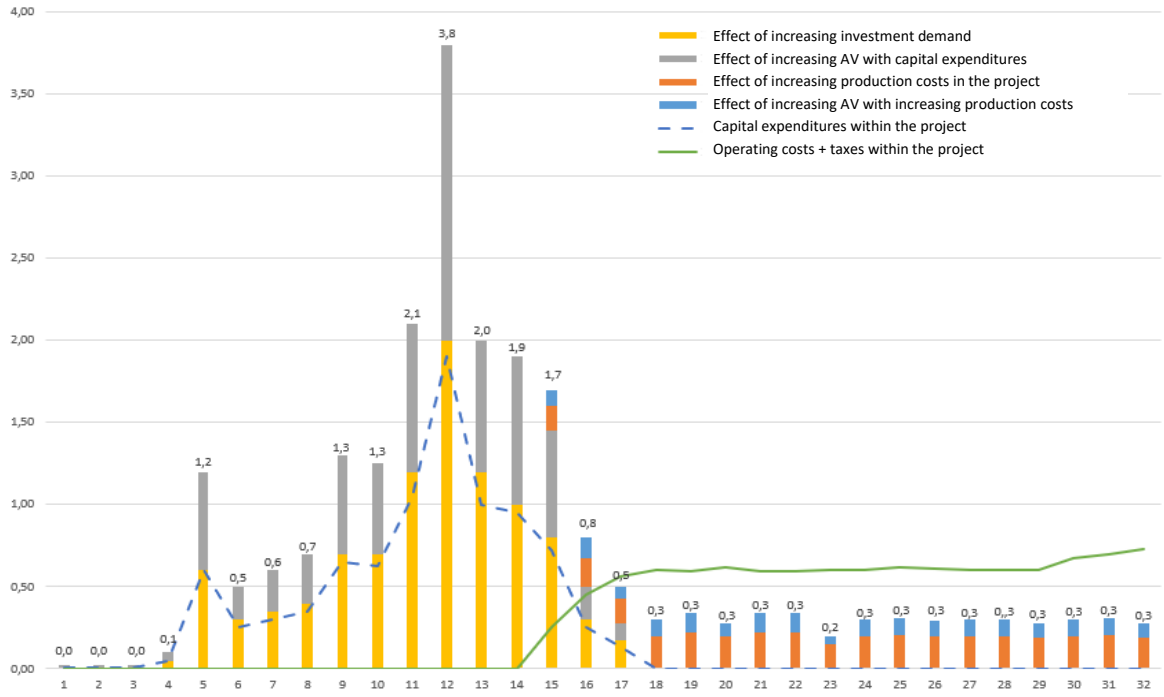

Figure 1: Estimates of the multiplicative effects on production for the supplying country by year (in constant prices in 2013, billion US dollars). Source: calculations by the Institute of Economic Forecasting of the Russian Academy of Sciences.

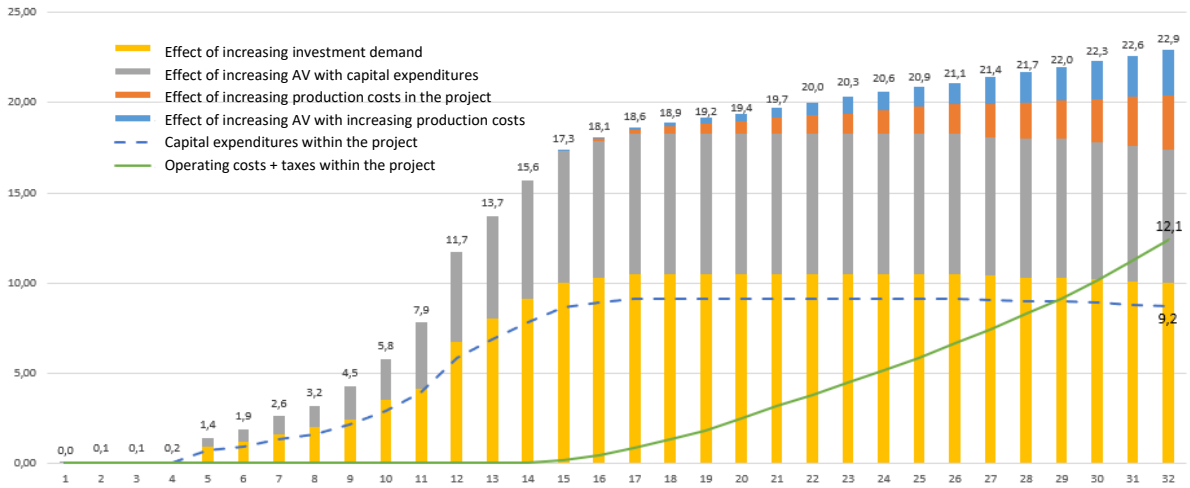

Figure 2: Estimates of the effects on production for the supplying country as a cumulative total (in constant prices in 2013, billion US dollars) Source: calculations by the Institute of Economic Forecasting of the Russian Academy of Sciences.

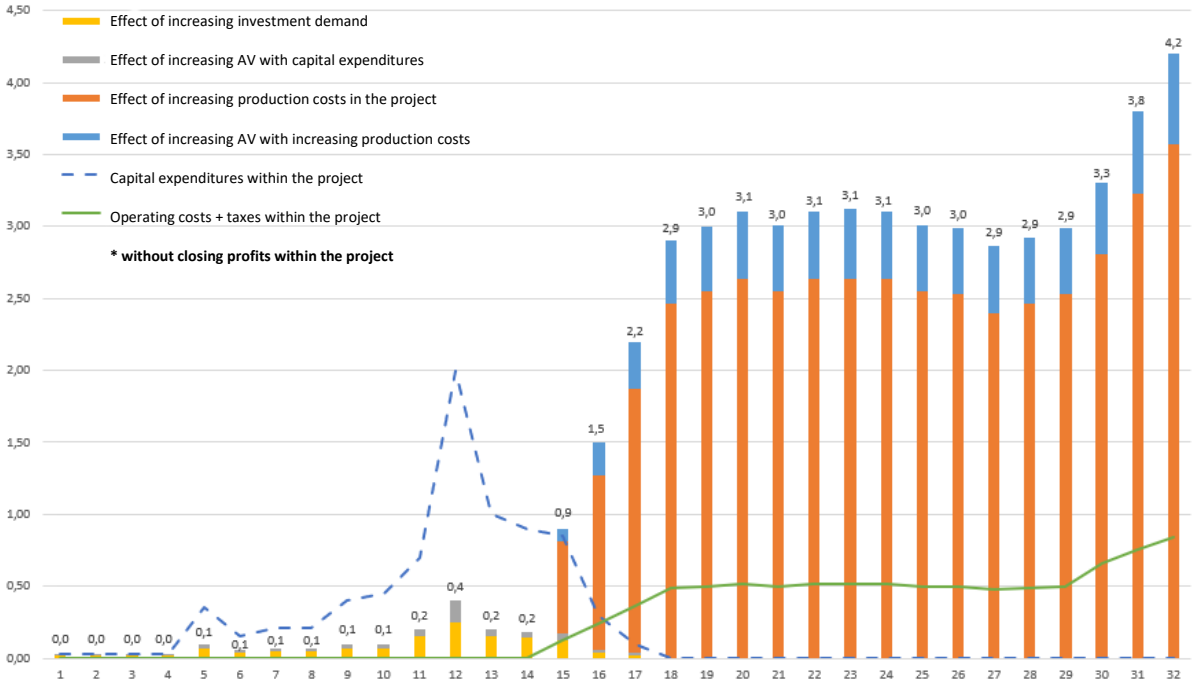

Figure 3: Estimates of the multiplicative effects on production for the recipient country by year (in constant prices in 2013, billion US dollars).

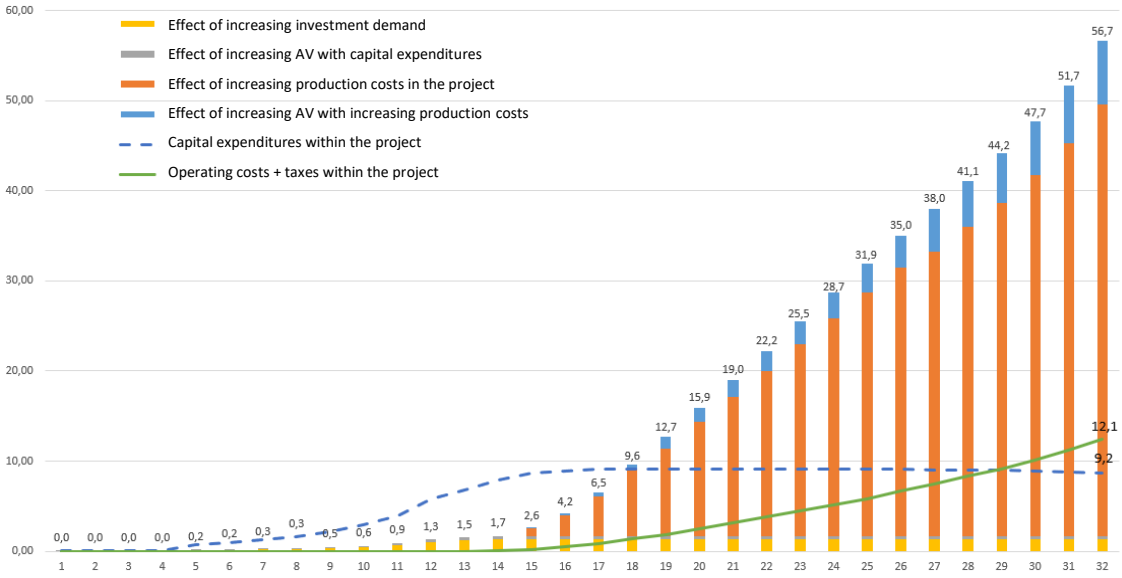

Figure 4: Estimates of the effects on production for the recipient country as a cumulative total (in constant prices in 2013, billion US dollars). Source: calculations by the Institute of Economic Forecasting of the Russian Academy of Sciences.

The main scenarios for the development of nuclear power industry, based on a systematic approach, in key areas.

So the first direction can be identified as the management of the development of nuclear power industry within the country.

The main condition for the growth of economic indicators in Russia is the development of the nuclear industry, which includes four large scientific and industrial complexes: first of all, this is nuclear engineering, then the nuclear fuel cycle and the nuclear environment complex and, most importantly,

R&D (namely, industry research institutes). Considering the operation of stations within the country, the following can be distinguished: 10 nuclear power plants operate 35 power units: 13 power units with channel-type reactors (10 power units with RBMK-1000 type reactors and 3 power units with EGP-6 type reactors); 20 power units with VVER type reactors (of which 13 VVER-1000 power units, 5 VVER-440 power units of various modifications and 2 VVER-1200 power units); 2 power units with fast neutron reactors (BN-600 and BN-800). The capacity of all power units is 29 GW. The introduction of new production capacities in the Russian Federation in 2018 made it possible to show record electricity generation. Thus, all Russian nuclear power plants have produced 204,6273 billion kWh (in 2017, 202,868 billion kWh).

Currently, the nuclear industry in Russia employs over 250 thousand people and includes over 400 enterprises and organizations. This industry employs highly qualified personnel who service nuclear power plants and implement their scientific developments in the field of designing nuclear reactors and disposing of spent nuclear fuel.

The temporary shortage of nuclear power plant generating capacities immediately affects the pace of development of the Russian economy. The commissioning of Novovoronezh NPP-2 and Rostov NPP will provide additional impetus for the further development of these subjects of the Russian Federation. There is also a rather promising project to launch a floating nuclear thermal power station in the northern territories of our country.

The second direction is the creation of a management model in the international market in the near future.

Nuclear energy is currently the basis for achieving sustainable development of the entire energy sector. As previously mentioned, the demand for electricity worldwide, and especially in developing countries, will increase by 30% by 2035. Accordingly, global investments in natural coal-fired power plants will decrease. When planning the construction of nuclear facilities within the framework of the implementation of the IAEA nuclear energy programs, representatives of the Rosatom State Corporation and the World Nuclear Organization should share their thoughts on the main directions for the development of nuclear infrastructure (NI). To organize, support and implement the national nuclear energy program, it is necessary to create a large-scale nuclear infrastructure that includes a large number of key instruments of influence. These include: minimization of administrative, financial, technical, regulatory and other risks. The implementation of this project will require huge efforts for all stakeholders (customer country, supplying country). Rosatom, in turn, offers its foreign partners corresponding packages for the creation and improvement of a national nuclear infrastructure program.

By 2030, the nuclear programs of Russia, India and China will play an important role in the implementation of Plan 303. It is recommended that small modular reactors and low-accident fuel types be introduced into practice more widely. Here it is important to note the existing global emission problems and constantly make every effort to cope with them.

By 2040, a decline in existing energy sources is expected and up to 200 GW of nuclear power plants should be decommissioned. However, various options are being considered to reduce this loss to 2.6 GW. But this will require significant efforts to extend the service life of existing reactors to 30 years. The IEA recommended that national governments lower unnecessary barriers to wider use of nuclear energy

The existing Harmony project proposes increasing the level of nuclear generation to 25% by 2050. This, in turn, is only possible with the commissioning of 1000 GW of new nuclear generating capacity. For this purpose, the World Nuclear Association has identified three areas of action – creating acceptable conditions in the electricity markets, a reliable safety system and improving regulatory processes. The Rosatom Production System (RPS) includes a set of measures for the culture of lean production processes, capable of providing competitive advantages at the global level. The RPS encourages employees of institutions and enterprises to develop a culture of communication with clients, promptly resolve emerging problems, pay close attention to the wishes of clients, end consumers, consumer workshops, try not to produce defective products, eliminate excess stocks, etc.

The third direction is safe and lean production management.

Currently, Russia is the only country that owns a functioning BN–600 fast neutron reactor, which was put into operation at the Beloyarsk NPP; a new BN-800 reactor is under construction; new reactors are planned to be commissioned – this explains the interest of the Americans in cooperation with Rosatom. (Zhukov, Kopytin, Popadko, 2022) The spent fuel of modern nuclear power plants is plutonium and uranium 238, which in the future can perfectly serve as fuel for reactors, which contributes to bringing nuclear energy to a higher level.

The fourth direction is the management of processes for maintaining the ecological system

But there are negative examples that carry the threat of shutting down nuclear power units due to a number of unresolved economic reasons. For example, the United States is holding back the development of nuclear power industry by promoting relatively cheap shale gas on the market. Since 2013, 4,674 MW of nuclear generating capacity has been shut down in the United States for this reason, and another 11,000 MW are at risk of closure. But based on the results for last year, the American nuclear power industry has had excellent results in terms of safety. They worked with a CUF of about 90% and provided the country with 2/3 of “carbon-free energy”. About half of U.S. nuclear power plants operate in regulated markets with fixed government rates.

The situation is more favourable in China, where cooperation with the French company EDF will allow the construction of two EPR-1600 units using the same fuel. This will be the first operational EPR nuclear power unit in the world. CGN is actively involved in the implementation of new projects in the UK, holding a 20% stake in the power unit construction project. It should be noted that the UK's exit from the EU will not affect the prospects for the development of nuclear power industry in the country. Thus, over the past 2018, CGN has signed more than 30 contracts with companies in the UK and the EU for a total amount of about 60 million pounds.

The following primary and essential tasks were set:

- limiting the increase in average global temperatures to "well below 2 degrees",
- cessation of greenhouse gas emissions,
- increasing access to energy in all regions of the world.

There are disputes about the safety of these power plants. A number of specific examples of serious accidents at nuclear power plants are given: accidents at power plants in Chernobyl, Three Mile Island and Fukushima, which led to very significant consequences for people's lives and had a negative impact on the environment. But despite this, nuclear energy is currently the only alternative to hydrocarbon sources, which makes it practically an unlimited reserve source for all mankind (Tay, 2019). Therefore, the long-term prospects for nuclear energy are positive. Taking into account both the low environmental impact of nuclear power plants and the limitation of hydrocarbon raw materials. As evidence of this, we can cite the example of the construction of 61 nuclear power units worldwide, and another 147 similar units are currently at the design stage.

Unfortunately, these legislative requirements are not always and everywhere met and observed. Thus, in 2018, CO2 emissions increased by 1.4% compared to 2016. Only 4 nuclear power plants were able to switch to environmentally friendly energy, the rest have only made some progress in improving the technologies used

The fifth direction is the management of unified chains within the framework of the digitalization of the industry

In 2018 alone, the Government of the Russian Federation allocated 505 million rubles for the development, launch and targeted support in the field of “end-to-end” technologies (quantum technologies, artificial intelligence). Recently, digitalization has become one of the priority areas of state policy of the country and Rosatom in particular. It can be understood as a system for improving the efficiency of internal processes through the wider use of digital technologies. There is active development of own digital products, own advanced technologies for key sectors of the domestic economy, and automation of control systems. In recent decades, companies within Rosatom have been introducing digital products and technologies of their own development into their production and management processes. Modern approaches to managing processes and people require state-owned enterprises involved in the construction of nuclear power plants to provide an increasingly wide range of services: creating digital twins of facilities and other high-tech solutions. The most notable projects are being carried out at the Federal Nuclear Center in Saratov under the sign of the engineering division of Rosatom. All projects are implemented based on the general concept of development of the Russian Federation within the framework of digitalization of the country. This allows for access to new markets and the launch of new products through the use of advanced digital software products and technologies. This introduction into the energy sector allows for a reduction in production costs.

In the minutes of the meeting of the Board of Directors of Atomenergoprom JSC, it is reported that in order to digitalize the Russian nuclear industry, Rosatom State Corporation plans to create the Tsifrum company within its structure. Since December 2018, Rosatom has been carrying out “digital” uranium mining. All production processes are controlled from the main control center. Rosatom State Corporation, together with scientists from the National Research Nuclear University MEPhI, has

created an innovative intelligent technology that allows for the leaching of underground uranium. The implementation of this project makes it possible to significantly increase labor productivity, and at the same time, the economic efficiency of mining.

Atomenergoprom JSC (Nuclear Power Industry Complex) is a powerful integrated company that unites civil assets of the nuclear industry. In the nuclear energy sector, Atomenergoprom provides a full production cycle from uranium mining to the construction of nuclear power plants and their commissioning.

A single information platform created using Multi-D technology is one of the strategic components aimed at meeting construction deadlines and reducing the cost of nuclear power plants, achieving a competitive LCOE.

4 RESULTS AND DISCUSSION

There are several scenarios for the development of nuclear power industry. All scenarios are interconnected in terms of indicators and resources used in nuclear power industry. The indicators include LCOE and CO2 emissions, the resources include the total amount of water consumed due to electricity generation.

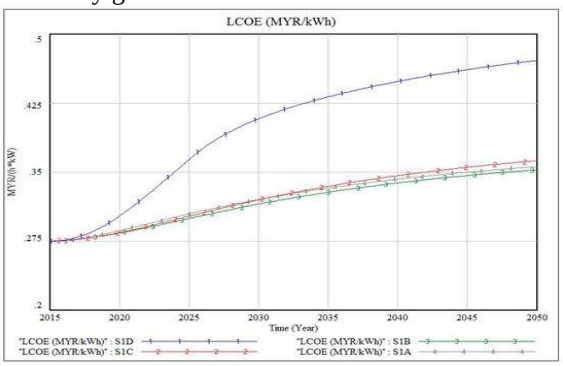

Figure 5: S1 - Levelised Cost of Energy (LCOE) (Demetriu, 2013).

The LCOE will be between S1B and S1C by 2050. Figure 5 shows that for S1B, S1C and S1D the LCOE will increase gradually, following an S-shaped curve, from approximately MYR 0.27 kWh to MYR 0.35 in 2050. S1 scenario - LCOE for solar power will be higher than for hydroelectric power. The significant difference in LCOE increase is due to the expansion of bioenergy, marine and wind energy.

Scenario S2 is presented in Fig. 6, where the LCOE behavior for scenario S2 is shown. Maintaining RE penetration at 5% without using nuclear energy would increase the LCOE to 0.35 MYR/kWh (S2A) and 0.53 MYR/kWh (S2B), respectively. S2B is significantly higher because diesel has a high LCOE. On the other hand, LCOE will be maintained at 0.27 MYR/kWh if nuclear penetration occurs as shown by S2C (10%) and S2D (20%). This is consistent with the fact that nuclear energy is significantly cheaper compared to other types of energy.

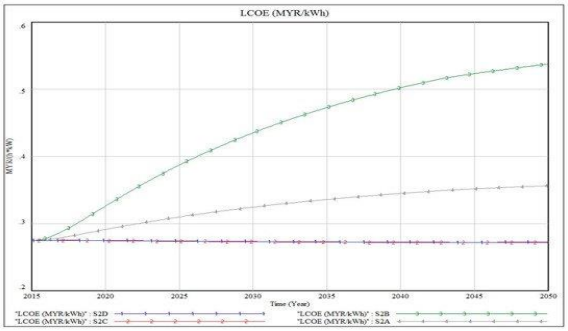

Figure 6: S2 - LCOE (Demetriu, 2013).

For the second scenario, the projected CO_2 emission figures are 112,000–114,000 $KtCO_2e$/year. Nuclear power emits much less into the environment than in the first scenario.

Considering the LCOE level, CO_2 emissions and water use in energy production, nuclear power is recommended worldwide.

Misnon et al. (Misnon, Hu, Rahman, YAsir, 2017) suggested that organizations and the public in many countries are generally willing to accept nuclear energy projects, but not everyone is aware of the benefits of this industry. However, there are risks of accidents such as Chernobyl, Fukushima, which increases the time frame and leads to some protests about nuclear energy (Misnon, Hu, Rahman, YAsir, 2017).

5 CONCLUSIONS

There are currently 436 nuclear power units in the world. Their total capacity is 369,818 MW. Countries with low AC use are noted. As an example, we can cite France, where 74% of electricity is generated by nuclear power plants, in South Korea - 35.48%, in Belgium - 51%, and 29.21% in Japan. The record holder for low use of AC is the United States, where the total capacity of power plants is 101,240 MW (about 20% of the total amount of electricity generated in the country).

A broad and detailed analysis of the prospects of energy markets is carried out, with mandatory consideration of demographic, technological, economic, political, climatic and other factors. There was a slight increase in the share of nuclear energy in electricity consumption from 10.5% in 2015. Up to 11.0-11.4% in 2040. These indicators may be different for developed and developing countries.

Scientists from many countries predict a decrease in the share of nuclear power plants in electricity production in OECD countries by 0.3% by 2040, that is, to the level of 17.7%. However, the share of nuclear power outside the OECD could rise significantly to 7.9%, or 3.4% by 2040.

The European continent, due to various political decisions taken, may significantly reduce its nuclear capacity (by 20%) by 2040. These are France, Germany, Belgium, Spain, Sweden, Great Britain, Switzerland. In North America, over the same period under review, under favorable circumstances, the volume of nuclear capacity will increase by 3%, and under unfavorable circumstances, it will decrease by 0.2 and 1.8%, respectively. Countries such as Poland, Lithuania, and Turkey are aiming to increase nuclear generation. However, the current trends will not give the expected effect. Electricity production at nuclear power plants will be carried out, which will lead to a reduction of 15% in a favorable scenario and 27% in an unfavorable scenario.

The Russian government plans to increase the share of nuclear energy from 20% to 25% in the country's energy balance by 2045. Achieving this indicator indicates the commitment to maintaining carbon neutrality, as outlined in the low-carbon development strategy of the Russian Federation. Rosatom is actively engaged in the most promising areas of nuclear energy development, which allows Russia to remain a key growth point for nuclear generation. Despite the high capital intensity of NPP construction, the significant cost of conservation of first-generation nuclear power plants, the extremely high efficiency of NPPs (up to 86%) indicates the prospects for the further development of nuclear power industry in the country.

Given the influence of a huge number of factors on the economy of the country and regions, it is impossible to definitely predict the future direction of nuclear energy development in the long term, but it is possible to compare model scenarios of development, conditionally identifying five groups of scenarios.

The first direction is a growing one, which is based on the use of innovative technologies to achieve the priority goals of the Russian Nuclear Energy Sector. The second direction is focused on the development of international nuclear energy: today, Rosatom is building 58 facilities in 18 countries around the world (regions of East and South Asia, the Middle East, Africa). OPEC experts predict that by 2045 the share of nuclear energy in the energy balance will grow to 6.6% (compared to 5.3% in 2022). The third development scenario is based on the thesis that nuclear energy has been legally recognized by a number of countries as environmentally friendly, and the Russian Federation and the People's Republic of China consider nuclear generation as a "green" project. The fourth group of scenarios is based on the development of nuclear energy - IV generation reactors with a closed nuclear fuel cycle. Russia is already a world leader in low-power reactor technology. And the fifth group of scenarios suggests the introduction of unified supply chains as development priorities in the implementation of the national digitalization project of the industry. It is obvious that nuclear energy is aimed at achieving environmental goals, supporting efforts to combat climate change and ensuring national energy security.

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