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Research Article

Multi-criteria analysis of the efficiency of scenarios for the development of the Russian nuclear industry in view of the uncertain prospects for the future*

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Abstract

Multi-criteria analysis is used in many areas of research where it is required to compare several alternatives according to a selected set of criteria. Of particular interest is the application of this method for a comparative assessment of the efficiency of scenarios for the development of innovative nuclear systems.

The article proposes an approach to the computational substantiation of the step-by-step transfer of the Russian nuclear industry to a two-component nuclear energy system (NES) with a centralized closed nuclear fuel cycle (NFC) based on the multi-criteria analysis method. At the same time, consideration is given to options for the development of the domestic nuclear industry in view of the uncertain prospects for the future. Taking into account various trends in the nuclear energy development, the authors identify the following three groups of possible scenarios. The first group includes 'growing' scenarios in which the number of units and their total installed capacity grow over time. The second group assumes that after a certain time of growth of the installed capacities, the stationary level will be reached, in which there will be no time-dependent capacity changes. The third group simulates a decrease in the installed nuclear energy capacities in the country after some growth.

To select the most preferable ways of technological development and assess the efficiency of a nuclear energy system, a limited set of selection criteria and performance indicators are used, covering the economy, export potential, competitiveness, efficient SNF and RW management, natural uranium consumption, and innovative development potential. An important part of this work was a detailed analysis of the uncertainties in the weights and input data used to derive the criteria.

Keywords

Thermal reactors, fast reactors, closed nuclear fuel cycle, MOX fuel, uncertainty, efficient SNF and RW management, export potential, competitiveness

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Introduction

The development of a nuclear energy system is a long and multi-stage process. The complexity of this process is determined by the need to consider not only the factors that are significant today or in the near future but also the uncertainty about the future conditions for developing the general energy system and the timeframe for adopting reactor and NFC technologies (Arzamastsev et al. 1987). The nuclear industry is a system with a deep division of labor, and many actors who often have diverging interests are involved in the decision-making process for its development. The relevance, importance and interest of the state and business in the adoption and implementation of fast reactor technologies is due to the fact that, in case of successful deployment of these technologies, it will be possible to solve the problems accumulated in the nuclear industry, expand existing markets and create new ones (Framework for Assessing Dynamic Nuclear Energy Systems 2013, Enhancing Benefits of Nuclear Energy Technology Innovation 2018, IAEA 2020, Egorov and Korobeynikov 2017b, Ponomarev-Stepnoy 2011).

The task facing the nuclear industry in adopting fast reactor and closed fuel cycle technologies is extremely difficult and has more than sixty years of history, which has not always been successful. The results of studies (Alekseev et al. 2016, 2018, 2019, 2020, Egorov and Korobeynikov 2016, 2017a, Egorov et al. 2017, Kalashnikov et al. 2016) of various scenarios for the development of the nuclear industry have shown that the technology of fast neutron reactors is a backbone for a closed fuel cycle of the two-component nuclear industry, providing reduced SNF and RW amounts.

Creating a two-component nuclear energy system (NES) based on VVER and fast reactors is defined as a key direction in the adopted Strategy for the development of nuclear energy in Russia up to 2050 and prospects for the period up to 2100.

The purpose of this work is to conduct a comparative multicriteria assessment of the efficiency of two-component nuclear energy systems with thermal and fast neutron reactors (BN-1200) with a closed NFC and reference systems of thermal reactors with an open NFC in view of the uncertain prospects for the future. To achieve this goal, a set of key criteria is used, covering the economy, export potential, safe SNF/RW management, natural uranium consumption and technology (innovative potential for development). In addition, the alternatives imply combinations of options: the development of a nuclear energy system with an increase in nuclear capacities, a stationary level and a decrease, over time, the capacities of nuclear power systems.

Problem definition

Nobody knows exactly how the domestic nuclear industry will develop, but it is expected to be a long-term process that will make it possible to solve the problem of power supply for a long period of time. Such an energy system must be safe, economically viable, minimizing nuclear waste and excess plutonium as well as facilitating the export of Russian technologies to world markets. The system should provide for the possibility of its improvement (innovative potential). Besides that, the system must 'digest' what has been done in the past in the nuclear industry and, in particular, solve the accumulated (pending) problems, etc. To take into account the above requirements, it is currently assumed that a two-component system is most suitable for these purposes. In addition, the system must be resistant to 'fluctuations' in needs. This means that it must cope with the diversity in its pace of development, i.e., be manageable (flexible and sustainable).

Over the past decades, the requirements for the nuclear industry have been formulated repeatedly and are coinciding in many respects. Prospects for the development of nuclear energy often turn out to be over-glowing, which can be explained by the optimism of its developers. The requirements for nuclear energy are formulated as follows:

1. the consumer appeal:
   - guaranteed safety,
   - economic efficiency;

2. the production scale in the electricity market:
   - not less than 30% by the middle of the century;

3. the energy production structure:
   - should provide multipurpose use across application areas, i.e., expansion of sales markets and multi-component structure as factors of flexibility and resistance to possible risks;

4. the raw material base in the Russian territory:
   - should not have restrictions for a historically significant period of time (hundreds of years); and

5. the waste management:
   - must ensure safe final isolation of radioactive waste.

The paper analyzes not only the optimistic directions for the development of the nuclear industry in Russia but also rather pessimistic ones. This consideration is caused by the need to substantiate what to do 'tomorrow' and to be ready to ensure the solution of any problems that arise 'the day after tomorrow'. This, in our opinion, is very important in terms of strategically reasonable allocation of resources in such a slowly developing and financially costly area as the nuclear industry.

Therefore, the main features of tasks of this type include their systemic and 'dynamic' nature. To solve them, it is necessary to consider the entire NES (with more or less detail) and, moreover, for a certain long (calculated) period of time.

Selection and analysis of model scenarios for the development of the Russian nuclear energy system in view of the uncertain prospects for the future

At present, due to the large number of facts, both objective and subjective, it is impossible to predict with any certainty and confidence the direction for the future development of the Russian nuclear industry over a long period of time, but we can at least assume probable development trends. Under these conditions, it seems useful to perform a study comparing a number of model scenarios for the development of the Russian nuclear industry, representing a wide range of possible trends. Three groups of scenarios can be conventionally distinguished. The scenarios were built using the CYCLE code (Kalashnikov et al. 2016).

The first group includes 'growing' scenarios in which the number of units and their total installed capacity grow over time. At present, there is no way to predict the rate at which the capacity will grow and whether the derivative of the change in capacity over time will remain positive for the entire period under consideration. However, for simplicity, we will assume that it will be positive. Let us consider and compare the reference scenario with thermal reactors in an open fuel cycle with two-component scenarios with different start times for a series of fast neutron reactors. In the first case, the two-component scenario will simulate the option of 'timely' commissioning of fast reactors while, in the second case, a 'delay' in the time of commissioning of fast reactors will be implemented. The scenario of the timely commissioning of fast reactors will be further referred to as 'base'. Thus, the group of scenarios for the growth of Russian nuclear industry will include the following three scenarios: reference (Ref), two-component with fast and thermal reactors (Base), and two-component with a delay in the commissioning of fast reactors for 35 years (Delay). The scenarios in this group will be further referred to as 'growing'.

The second group assumes that after a certain time of growth of the capacities, the stationary level will be reached, in which there will be no time-dependent changes in the total installed capacity of the system. Within this group, there will also be three scenarios with the same change in installed capacities. The first scenario is a reference one with thermal neutron reactors. The other two are two-component, by analogy with the previous group with the timely and delayed commissioning of fast reactors. The notations used in the graphs and tables: RefS, BaseS and DelayS, respectively. The scenarios in this group will be further referred to as 'stationary'.

The third group of scenarios simulates a decrease in the installed nuclear energy capacity within the country after 2025. It is assumed that this group will also have three scenarios with the same logic as in the previous two groups. The scenarios in this group will be further referred to as 'lowering'. The notations used in the graphs and tables: RefL, BaseL and DelayL, respectively.

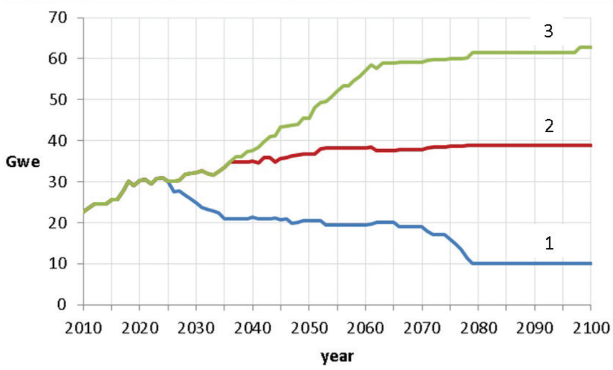

Figure 1. Changes in installed capacities for the groups of the scenarios under study: **1** – lowering; **2** – stationary.

Fig. 1 shows the changes in installed capacities for the model scenarios studied in this paper.

Each line in the figure shows the installed capacities achieved by a nuclear energy system for a particular group of scenarios using a set of appropriate reactor technologies, fuel production, processing and storage facilities.

The scenarios considered in this study were constructed according to the following conditions:

- the NES simulation horizon is up to 2100;
- the maximum possible utilization of SNF stocks in a two-component system (base scenarios) by 2100;
- the reserves of available natural uranium, which must ensure the operation of the thermal reactor fleet, are limited to 500 thousand tons and are not distributed by cost groups;
- plutonium from SNF reprocessing is stored and then spent on fuel supply, annual SNF reprocessing is carried out according to the need for plutonium, the balance of separated plutonium in the system should not exceed ~100 tons, excess separated plutonium does not accumulate in the system;
- reprocessed uranium is not recycled;
- the structure of the reactor fleet and the ratio between the numbers of reactors of various types are selected based on the requirement to achieve the specified installed capacity (IC) in the scenarios by the end of the period under consideration. In this study, the target ICs of a nuclear energy system are 62 GW, 39 GW and 11 GW for the 'growing', 'stationary' and 'lowering' scenarios, respectively.

A set of key criteria for multicriteria analysis

For the multicriteria analysis (MCA), a set of key criteria was used, shown in Table 1, which met the requirements for

Table 1. Set of key criteria.

No.	Criterion	Uncertainty
1	Economic (LCOE)	High
2	SNF and RW management	Low
3	Natural uranium consumption	Low
4	Plutonium production	Low
5	Export potential	Moderate

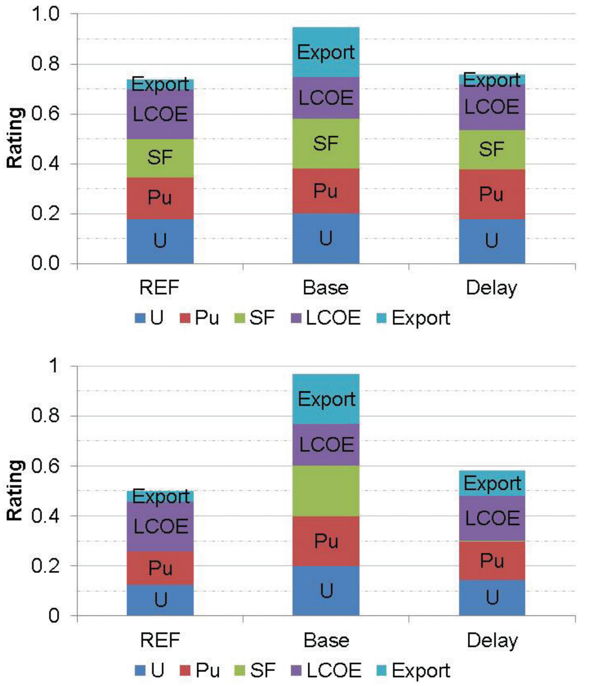

Figure 2. Ratings of the NES alternatives (the group of growing scenarios): **a)** – for 2050; **b)** – for 2100.

the scenarios for the development of Russian nuclear industry, taking into account the minimization of the SNF amount, saving natural uranium and reducing the cost of storing separated plutonium. The same table shows the qualitative level of uncertainty in the values of the corresponding indicators.

At the first stage of the MCA, it was assumed that all the five criteria were of the same importance, i.e., all the criteria had the same weight of 20%. The impact of 'violating' this assumption on the MCA results will be assessed in the next section.

Comparative multicriteria analysis for the different groups of scenarios

Multicriteria analysis was carried out for three periods: up to 2050, 2070 and 2100. For these periods, Tables 2–4 show the volumes of spent nuclear fuel and the amounts of consumed natural uranium and accumulated plutonium for all the groups of scenarios. The NES ratings for these characteristics were constructed using the information given in the tables.

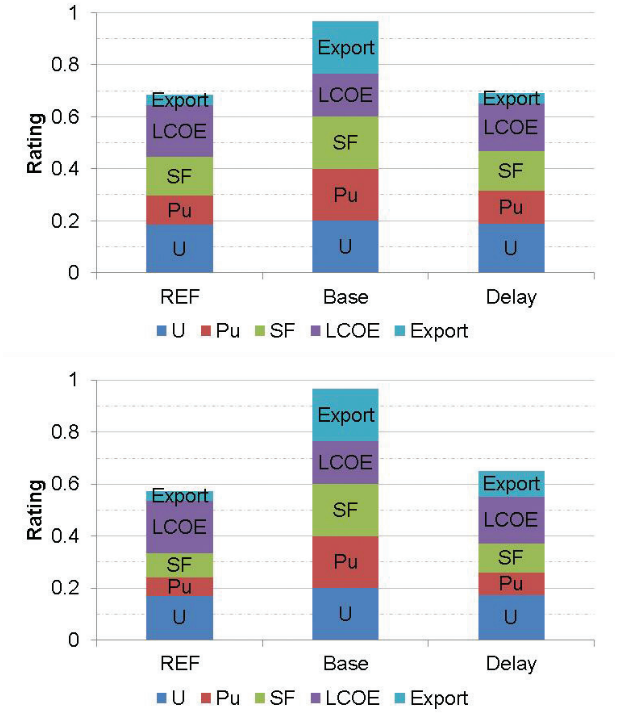

Figure 3. Ratings of the NES alternatives (the group of stationary scenarios): **a)** – for 2050; **b)** – for 2100.

Hereinafter, 'plutonium accumulated in the system' means plutonium produced by all reactors and contained both in spent nuclear fuel and separated plutonium in the system.

Figs 2–4 show the results of comparing the NES ratings in different groups of scenarios for different periods of time.

The results of the multi-criteria analysis for all the groups and time intervals showed a significantly higher rating for the two-component system with the timely commissioning of fast reactors. The option with the delayed commissioning of fast reactors had a lower rating among the two-component nuclear energy systems but a higher one in comparison with the reference system.

Sensitivity of the MCA results to the criteria and their weights

In the previous subsection (Comparative multicriteria analysis for the different groups of scenarios), we showed a significant advantage of the two-component system compared to the reference one when the equal importance of all the five criteria is taken into account. All the criteria had the same weight of 20%. At the same time, Table 1 shows that the economic criterion (LCOE) has the highest uncertainty for a nuclear reactor system. Therefore, in the study, the task was set to determine how changes in the weight of this criterion would affect the results of the multicriteria analysis. The weight of the economic criterion

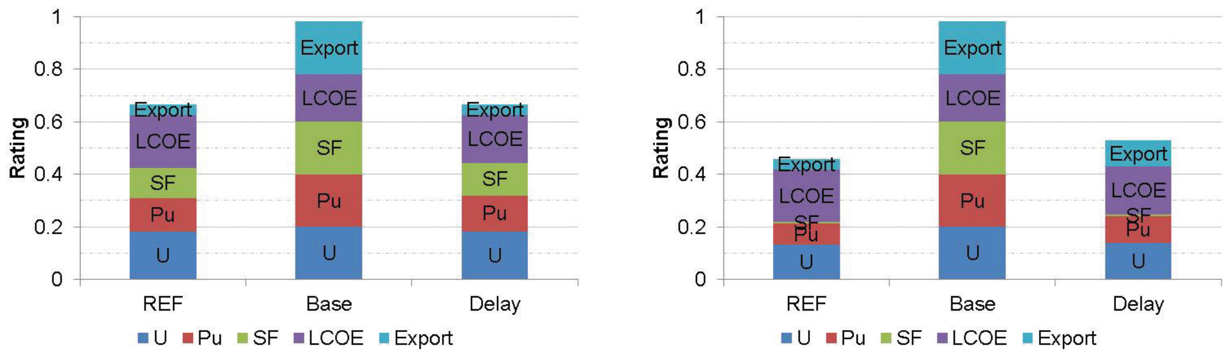

Figure 4. Ratings of the NES alternatives (the group of lowering scenarios): **a)** – for 2050; **b)** – for 2100.

Table 2. SNF volumes, natural uranium consumed and plutonium accumulated in the system for the group of growing scenarios.

Scenario	By 2050.			By 2070.			By 2100.		
	^{nat}U, т	Accum Pu, т	SNF volume, т	^{nat}U, т	Accum Pu, т	SNF volume, т	^{nat}U, т	Accum Pu, т	SNF volume, т
Ref	211 387	546	47 413	384 709	966	68 545	636 451	1 451	99 997
Base	188 332	507	36 331	296 092	730	34 603	394 102	970	326
Delay	211 387	458	46 352	379 545	695	62 185	547 837	1 264	47 233

Table 3. SNF volumes, natural uranium consumed and plutonium accumulated in the system for the group of stationary scenarios.

Scenario	By 2050.			By 2070.			By 2100.		
	^{nat}U, т	Accum Pu, т	SNF volume, т	^{nat}U, т	Accum Pu, т	SNF volume, т	^{nat}U, т	Accum Pu, т	SNF volume, т
RefS	195 618	791	46 300	310 450	1 355	61 334	476 396	1 867	81 853
BaseS	181 883	441	34 369	264 038	481	28 668	327 888	210	0
DelayS	194 507	679	45 210	304 232	1 102	52 423	410 434	1 790	14 197

Table 4. SNF volumes, natural uranium consumed and plutonium accumulated in the system for the group of lowering scenarios.

Scenario	By 2050.			By 2070.			By 2100.		
	^{nat}U, т	Accum Pu, т	SNF volume, т	^{nat}U, т	Accum Pu, т	SNF volume, т	^{nat}U, т	Accum Pu, т	SNF volume, т
RefL	145 615	495	41 619	202 819	661	50 230	248 328	934	56 930
BaseL	132 819	312	24 317	162 368	347	17 414	165 609	371	1 412
DelayL	145 615	455	39 069	200 446	571	44 154	236 878	742	35 465

changed upwards, and the weights of the remaining criteria were 'adjusted' to this change in such a way that the sum of all the weights remained equal to unity.

The results show the advantage of the two-component scenario with the timely commissioning of fast reactors over the reference one until the weight of the economic criterion is about 0.65. Note that the total weight of the other four criteria becomes 0.35. At the same time, the value of the economic criterion for the two-component system 'worsened' by 30% in comparison with the reference scenario. The scenario with the delayed commissioning has an advantage over the reference one only if the weights of the economic criterion are sufficiently low. The advantage of the two-component scenario turned out to be quite stable in the group of lowering scenarios as well.

Fig. 5 shows a graphical dependence of the ratings in the group of growing scenarios for 2100, depending on the economic criterion and its weight for the two-component scenarios with the timely commissioning of fast reactors. The same graph shows the weight dependence of the ratings for the reference scenario and

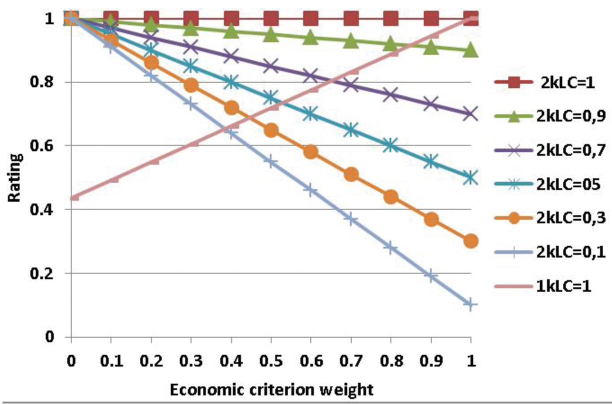

Figure 5. Sensitivity of the ratings to changes in the LCOE criterion depending on weight. The notations used: 2kLC are the dependences of the rating of a two-component system at different values of the economic criterion LCOE (1, 0.9, 0.7, 0.5, 0.3, 0.1); 1kLC = 1 is the dependence of the rating of the reference system with the value of the economic criterion LCOE = 1; SC is the dependence of the sensitivity coefficient on the weight of the economic criterion.

the weight dependence of the coefficient of sensitivity to the economic criterion.

It follows from the results shown in Fig. 5 that if the economic criterion increases in weight, its sensitivity to changes becomes higher.

Conclusion

Due to the large number of facts, both objective and subjective, it is impossible to predict with any certainty and confidence the direction for the future development of Russian nuclear industry over a long period of time, but we can consider probable development trends.

In order to take into account various development trends in the nuclear industry, three groups of development scenarios were identified. The first group includes ‘growing’ scenarios in which the number of units and their total installed capacity grow over time. The second group assumes that after a certain time of growth of the installed capacities, the stationary level will be reached, in which there will be no time-dependent changes in power. The third group simulates a decrease in the installed nuclear power capacities in the country after some growth. It was assumed that each group would include three types of scenarios with the same capacity changes. The first scenario was a reference one with thermal neutron reactors. The other two were two-component: with the ‘timely’ commissioning of fast reactors (base scenarios) and the ‘delayed’ commissioning of fast reactors.

The results of the multicriteria analysis for all the scenario groups revealed the greatest potential in the two-component system. The option with the delayed commissioning of fast reactors had a lower rating among the two-component nuclear energy systems but a higher one in comparison with the reference single-component system. The inclusion of fast reactors in the nuclear energy system for all the considered development options will make it possible to solve its systemic problems, including the most important ones, such as reducing RW amounts from traditional nuclear power plants, saving natural resources, etc.

An important part of this work was a detailed analysis of the uncertainties in the input data used to derive the criteria and their weights.

The research results showed the stability of the ratings of two-component systems in different groups of scenarios to sufficiently significant changes (deterioration) in the values of the economic criterion and its weight.

The results of the analysis of the two-component scenario with the timely commissioning of fast reactors showed the highest rating in comparison with the reference scenario and the scenario with the delayed commissioning of fast reactors for all the groups of scenarios, including (it should be specially emphasized) the group of lowering scenarios. This means that the best way to solve the accumulated problems of nuclear power, namely to reduce the amounts of spent nuclear fuel, save natural uranium, improve the export potential, and reduce the amounts of accumulated plutonium, is to switch to a two-component system with fast and thermal reactors. At the same time, the timely commissioning of fast reactors shows the best results in all the groups of scenarios.

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