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Research Article

Multi-criteria evaluation and ranking of potential scenarios for the development of Russian two-component nuclear energy system with thermal and sodium-cooled fast reactors*

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Abstract

The paper presents the results from a multi-criteria comparative evaluation of potential deployment scenarios for Russian nuclear power with thermal and sodium-cooled fast reactors in a closed nuclear fuel cycle (the so-called two-component nuclear energy system). The comparison and the ranking were performed taking into account the recommendations and using the IAEA/INPRO software tools for comparative evaluation of nuclear energy systems, including tools for sensitivity/uncertainty analysis with respect to weighting factors. Ten potential Russian nuclear power deployment scenarios with different shares of thermal and sodium-cooled fast reactors were considered, including options involving the use of MOX fuel in VVER reactors. Eight key indicators were used, estimated as of 2100 and structured into a three-level objectives tree. The comparative evaluation and the ranking were carried out based on the multi-attribute value theory. The model for assessing the key indicators was developed using the IAEA/INPRO MESSAGE-NES energy system planning software tool. The information base for the study was formed by publications of experts from JSC SSC RF-IPPE, NRC Kurchatov Institute and NRNU MEPhI. The presented results show that it is possible to enhance significantly the sustainability of the Russian nuclear energy system, when considering multiple performance indicators, through the intensive deployment of sodium-cooled fast reactors and the transition to a closed nuclear fuel cycle. Tasks have been outlined for the follow-up studies to make it possible to obtain more rigorous conclusions regarding the preferred options for the evolution of a two-component nuclear energy system.

Keywords

Thermal reactors, fast reactors, closed nuclear fuel cycle, MOX fuel, MAVT, MESSAGE-NES

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Introduction

The starting point in discussing the potential ways for the evolution of nuclear power is normally an option with the extensive development of the existing system with thermal reactors and a once-through nuclear fuel cycle (NFC) as presently one of the most mature and cost-acceptable technologies. With regard for the fact that the plant life of current power units with thermal reactors, reaching 60 years now and expected to be increased in the future to 100 years thanks to the use of new materials, there is every reason to believe that thermal reactors will continue to account for a major share in the national nuclear power at least until the end of this century. However, the option with a nuclear energy system (NES) including only thermal reactors in a once-through NFC does not offer a solution to the nuclear power problems accumulated or anticipated in the decades to come and, in a long term, will cause the overall situation with nuclear power to worsen due to the growing problems with supply of resources, spent nuclear fuel (SNF) and radioactive waste (RW) management, economics, and some others, this to inevitably entail worsened public attitudes to nuclear technologies. It is already now that the combination of these factors has led to constraints for the development of national nuclear programs in a number of countries and to even the complete abandonment of nuclear power in some other countries.

In the Russian Federation, deployment of a two-component NES based on combined operation of thermal water-cooled water-moderated reactors and sodium-cooled fast reactors is looked upon as one of the possible ways to address the nuclear power challenges. There has been an extensive discussion of potential configurations for such a NES which may include, at different evolution stages, thermal reactors with uranium oxide fuel, thermal reactors with a partial or complete load of mixed uranium-plutonium oxide fuel (MOX), and sodium-cooled fast reactors with MOX fuel (Alekseev et al. 2011, 2016, 2017, Gulevich et al. 2018). All reactors in the system can be interlinked through a single closed NFC in which the products from reprocessing of SNF from one reactors are used to produce new fuel for the other reactors.

Varied potential configurations of a two-component NES have particular similarities and known differences, advantages and disadvantages expressed in quantitative terms via key performance indicators and characterizing the consumption of resources, economic performance, the material flows in the NFC, and others. Timely is this connection is to analyze comparatively and rank the most representative and probable evolution scenarios for a two-component national NES with thermal and fast reactors using multi-criteria decision analysis methods which will make it possible to compare, on a qualitative basis, costs, risks and benefits involved in each option and to provide recommendations with respect to the most effective ways to enhance the sustainability of the national NES. This paper presents an example of such an analysis using the IAEA/INPRO software tools and recommendations intended for a scenario analysis and a comparative evaluation of the NES options. The information framework for the study was formed by publications of experts from JSC SSC RF-IPPE, NRC Kurchatov Institute and NRNU MEPhI.

Problem statement

Three major problems need to be addressed to analyze comparatively and rank scenarios for the deployment of a two-component NES based on multi-criteria decision analysis methods (Kuznetsov et al. 2014, 2015, Schwenk-Ferrero and Andrianov 2017a, 2017b, Andrianov et al. 2019). First, a model of the NES shall be built taking into account the expected rate of the electricity generation growth and describing the key components of the industrial infrastructure including nuclear reactors and fuel cycle facilities with given performance. Second, a method shall be developed to estimate the key performance indicators that characterize the economics, the uranium consumption, the required capacity of the fuel cycle facilities, the amounts of SNF, RW and secondary fissile materials in the NFC, etc. Third, a model shall be developed for supporting multi-criteria decision-making.

The decision-making support model can be based on methods of the multi-criteria decision analysis where the scenario analysis results (values of the key indicators for each of the considered NES options) are used as the input. Such model, being complemented with information and data on the preferences of experts and decision makers, will make it possible to analyze comparatively and rank the options under consideration, as well as to identify the most effective ways for enhancing the sustainability of the national NES taking into account the results of the sensitivity/uncertainty analysis with respect to the all factors and aspects involved in the analysis.

Values of eight performance indicators were calculated as part of the study using MESSAGE-NES (Andrianov et al. 2012, IAEA Nuclear Energy Series 2016a, 2016b), the IAEA/INPRO energy system planning software tool, for ten expert-selected potential scenarios for the deployment of a two-component national NES containing, in different proportions, thermal reactors (both uranium fueled and with a partial load of MOX fuel) and sodium-cooled fast reactors based on MOX fuel (Figs 1, 2). The IAEA/INPRO software tool, intended for evaluating comparatively the sustainability of the NES options and performing the sensitivity/uncertainty analysis with respect to weighting factors, was adapted for comparing and ranking the scenarios (Kuznetsov et al. 2018, IAEA 2019).

Initial data and assumptions

The following assumptions were made to model the nuclear power capacity growth for the scenario analysis: 35 GW in 2030, 55 GW in 2050, and 103 GW in 2100 (Andrianov et

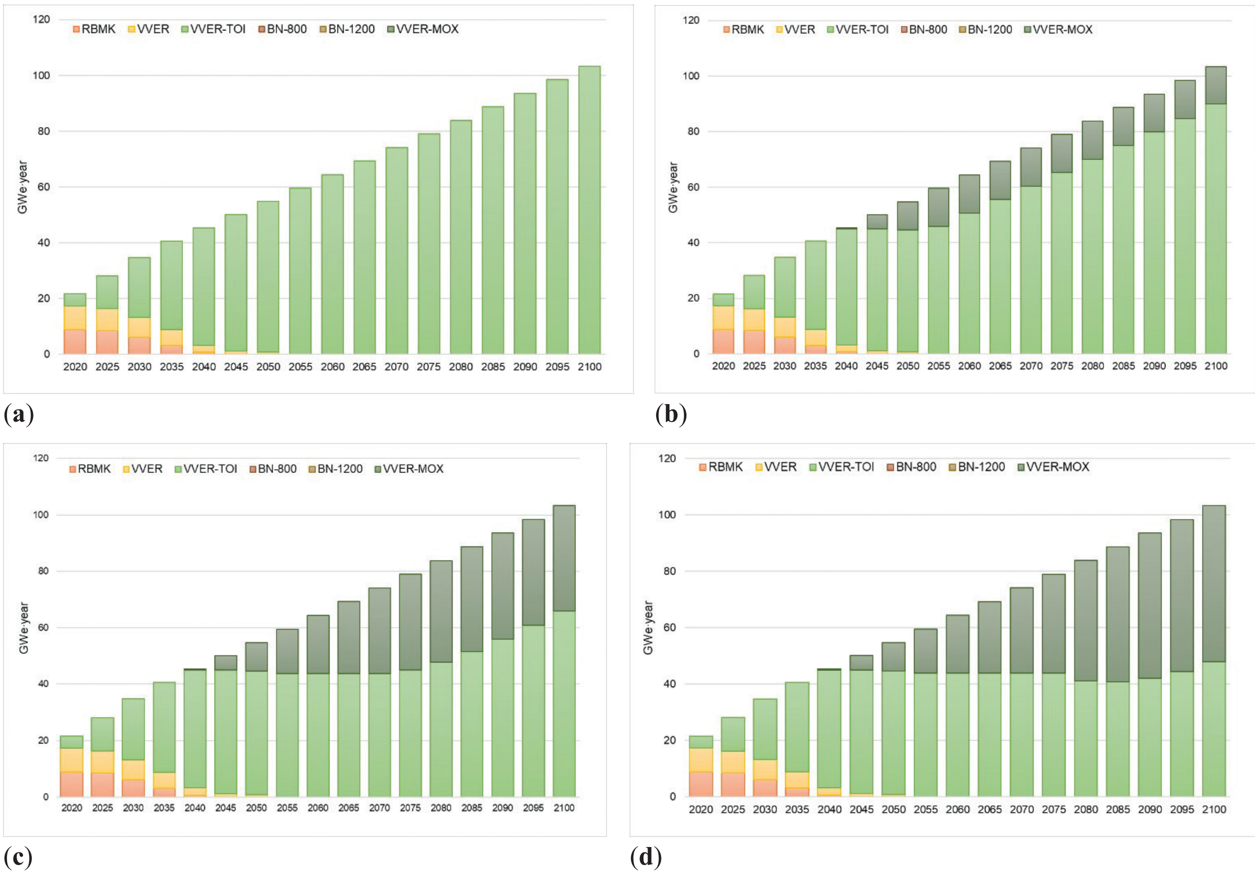

Figure 1. National NES deployment scenarios: **a**) VVER(100%); **b**) VVERmox(10%); **c**) VVERmox(30%); **d**) VVERmox(50%).

al. 2018). The considered candidate reactors for the NES included VVER, VVER-TOI (a modified VVER reactor with an increased burn-up), VVERmox (a modified VVER reactor with a partial load of MOX fuel), and BN-1200 reactors based on MOX fuel. VVERs and VVER-TOIs were assumed to be potentially commissioned beginning in the initial year of the considered period with BN-1200 and VVERmox reactors commissioned beginning in 2030 and 2040 respectively. Table 1 presents the ten options for the national NES deployment considered in the study, which can be grouped as follows: a once-through NFC, a partially closed NFC, a fully closed NFC.

The peculiarities of the calculation model are described in (Andrianov et al. 2018). The cost of the NFC services was taken from (Alekseev et al. 2016). It was assumed with respect to the cost of reactor plants that the specific capital costs for BN-1200s were 10% as high as for VVERs for which they amount to 4000 $/kW. The discount rate is 5% (Alekseev et al. 2016). The calculations took into account historical data on the evolution of nuclear power in the Russian Federation and assuming no resource or infrastructural constraints. The loading structure of the NFC facilities is determined by solving an optimization problem (minimizing the total discounted costs for the entire development program) provided the NES structure reaches the objectives shown in Table 1. It was assumed that it was possible to reprocess SNF from all types of reactors including RBMK. The SNF cooling period was assumed to be five years for all reactor types. The extracted plutonium (ex-weapon and reactor grade) accumulated by 2020 and the plutonium contained in SNF form the resource for the fast reactor fuel production.

Table 1. National NES deployment scenarios

Scenario	Reference designation	Brief description
Once-through NFC		
1	VVER(100%)	NES structure in 2100: VVER-TOI – 100%
Partially closed NFC		
2	VVERmox(10%)	NES structure in 2100: VVER-TOI – 90%, VVER-TOI MOX – 10%
3	VVERmox(30%)	NES structure in 2100: VVER-TOI – 70%, VVER-TOI MOX – 30%
4	VVERmox(50%)	NES structure in 2100: VVER-TOI – 50%, VVER-TOI MOX – 50%
Fully closed NFC		
5	BN(20%)	NES structure in 2100: VVER-TOI – 80%, BN – 20%
6	BN(50%)	NES structure in 2100: VVER-TOI – 50%, BN – 50%
7	BN(90%)	NES structure in 2100: VVER-TOI – 10%, BN – 90%
8	VVERmox(10%)BN(20%)	NES structure in 2100: VVER-TOI – 70%, VVER-TOI MOX – 10%, BN – 20%
9	VVERmox(50%)BN(20%)	NES structure in 2100: VVER-TOI – 30%, VVER-TOI MOX – 50%, BN – 20%
10	VVERmox(10%)BN(50%)	NES structure in 2100: VVER-TOI – 40%, VVER-TOI MOX – 10%, BN – 50%

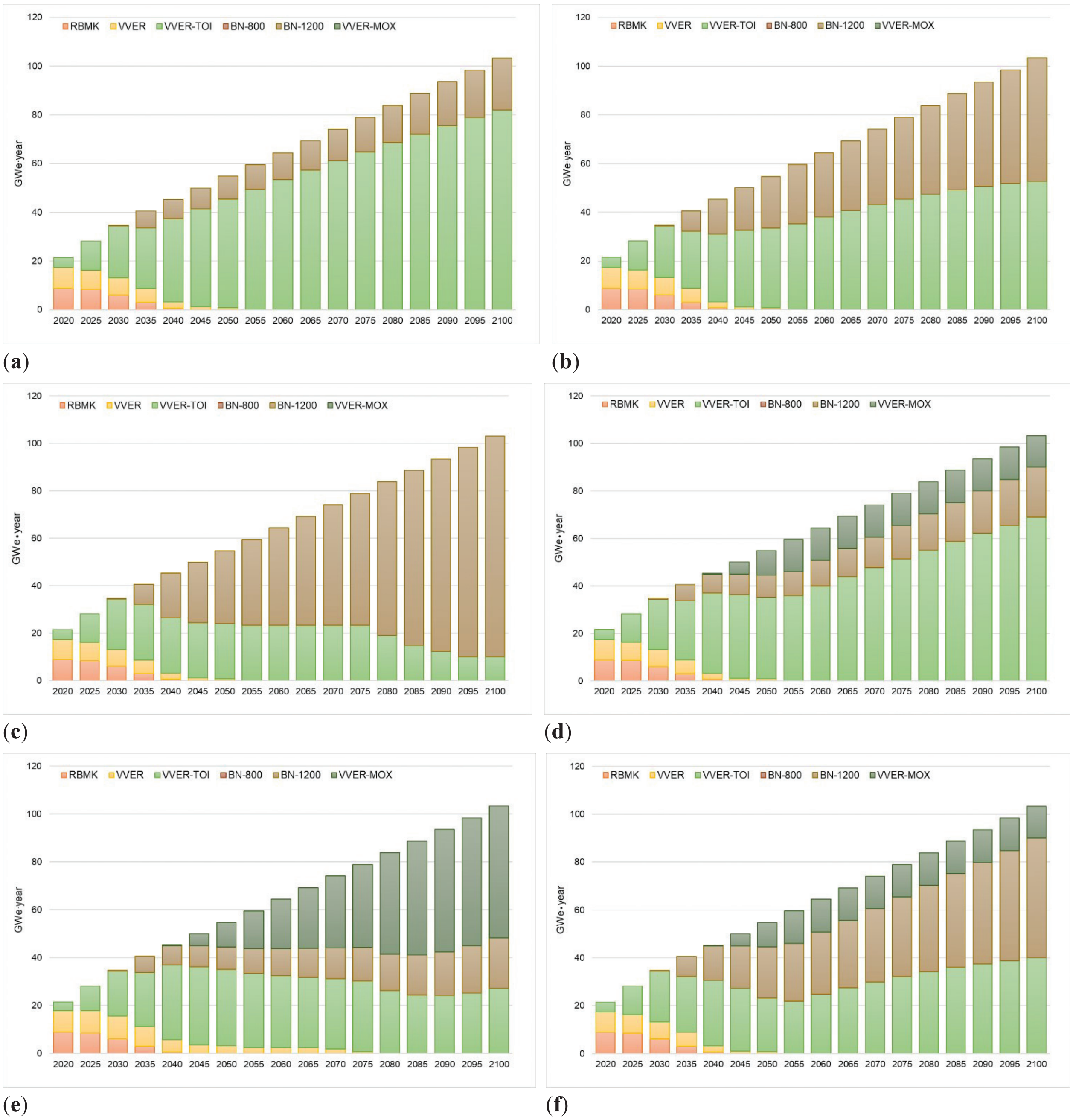

Figure 2. National NES deployment scenarios: **a**) BN(20%); **b**) BN(50%); **c**) BN(90%); **d**) VVERmox(10%)BN(20%); **e**) VVERmox(50%)BN(20%); **f**) VVERmox(10%)BN(50%).

Eight key indicators, estimated as of 2100, were used for the comparative evaluation: integral uranium consumption, needs for uranium enrichment and SNF reprocessing services, SNF amounts, RW amounts, plutonium amounts, depleted uranium stocks, levelized cost of electricity (LCOE) (Fig. 3). The lower is the indicator value, the higher is the score. All indicators are grouped by five evaluation areas (resource utilization, infrastructure, waste management, nuclear material stocks, and economics) which, in turn, are combined into three high-level objectives (resources, NFC performance, economics). The values of the indicators for the scenarios under consideration are given in Table 2 (all scenarios are non-dominated, that is, the scenarios do not include options which would be worse, in terms of the entire set of indicators, than one of the rest as a minimum).

The scenarios were comparatively evaluated and ranked based on the multi-attribute value theory (MAVT) with the additive form of the multi-attribute value function and decreasing linear functions used as single-attribute value functions for all performance indicators (Kuznetsov et al. 2014, 2015, Schwenk-Ferrero and Andrianov 2017a, 2017b). The “equal weights” was used for the analysis starting point assuming that all performance indicators are equally important. Such approach can be applied when there is no sufficient

Table 2. Key indicators for considered scenarios

Scenario	Integral uranium consumption, kg	Integral needs for uranium enrichment services, ktSWU	Integral needs for SNF reprocessing services, kt h.m.	Amounts of SNF in 2100, kt h.m.	Amounts of RW in 2100, kt	Amounts of plutonium in NFC in 2100, kt	Amounts of depleted uranium in 2100, kt	LCOE, mills/kWh
VVER(100%)	787.65	666.75	0	126.98	0	1.09	1669.03	29.48
VVERmox(10%)	782.92	662.72	27.36	106.12	26.92	0.84	1658.34	29.89
VVERmox(30%)	776.18	656.97	71.81	69.11	70.76	0.54	1644.80	30.40
VVERmox(50%)	772.07	653.46	92.71	51.06	91.42	0.41	1638.11	30.57
BN(20%)	658.10	556.25	12.15	111.54	10.96	1.02	1544.24	29.53
BN(50%)	492.27	414.81	41.77	77.70	38.93	0.91	1384.26	30.22
BN(90%)	284.97	237.99	100.28	13.96	95.37	0.76	1184.07	31.09
VVERmox(10%)BN(20%)	651.51	550.63	346.08	81.58	46.76	0.77	1531.93	30.29
VVERmox(50%)BN(20%)	640.97	541.64	126.27	14.46	123.68	0.34	1511.78	31.57
VVERmox(10%)BN(50%)	470.99	396.66	79.63	44.59	76.26	0.65	1359.36	31.70

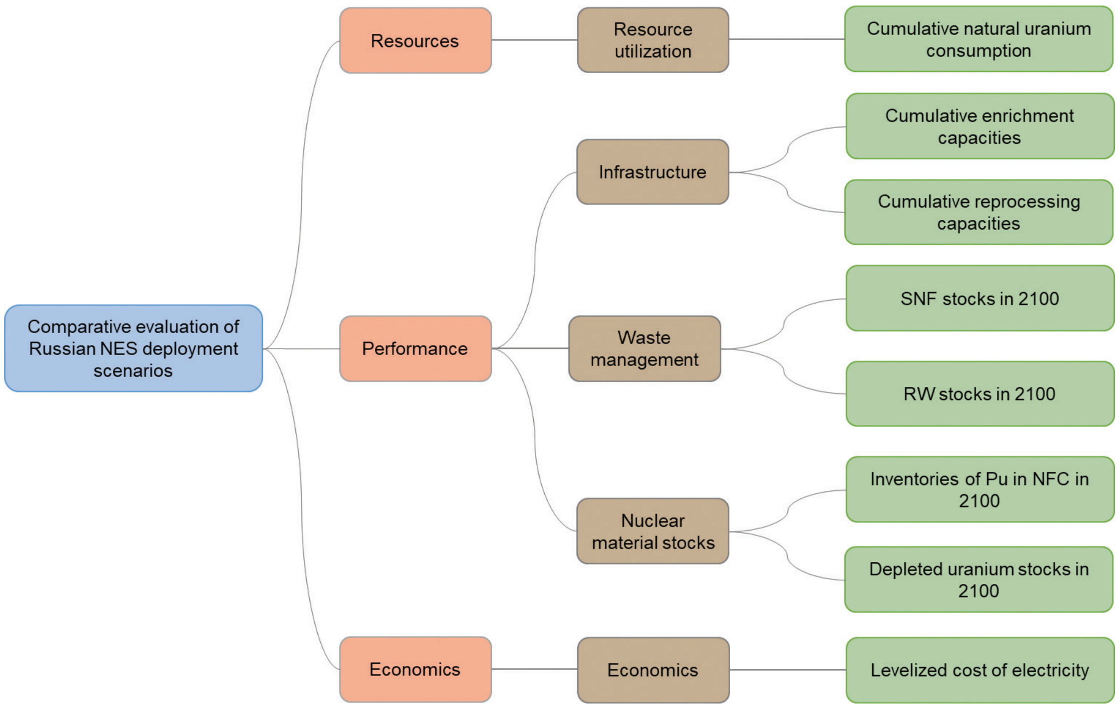

Figure 3. Objectives tree.

information on the relative importance of the performance indicators, which is quite natural in considering a long-term period (Zardari et al. 2015, IAEA 2019). The "equal weights" approach in combination with an expanded sensitivity/uncertainty analysis with respect to weight factors, makes it possible to conclude in general on the attractiveness of the compared options in different potential situations.

Ranking results

Fig. 4 presents the results of ranking the scenarios based on the MAVT method for the base option of weights (the overall scores for the scenarios are decomposed into individual components in accordance with the high-level objectives). As shown by the results of assessing the scenarios under consideration, the BN(90%) scenario with the 90% share of sodium-cooled fast reactors in the NES structure in 2100 has the highest score for the base weighting option. Considerably behind in overall scores are the following scenarios: BN(50%), VVERmox(10%)BN(50%), BN(20%), and VVERmox(50%)BN(20%). The VVERmox(50%), VVERmox(30%), VVERmox(10%), VVER(100%) and VVERmox(10%)BN(20%) scenarios had the smallest overall scores with a narrow margin between.

For the resources objective, with the scenario scores considered for each high-level objective, the BN(90%) scenario has evidently the highest score, while the VVER(100%) and VVERmox(10,30,50%) options have the smallest scores. For the NFC performance objective, the BN(90%) option also has the highest score, while the VVER(100%) and VVERmox(10%)BN(20%) options have the smallest. For the economics objective, the highest score is for VVER(100%) with BN(20%) being slightly behind, while the VVERmox(10%)BN(50%) and VVERmox(50%)BN(20%) options had the small-

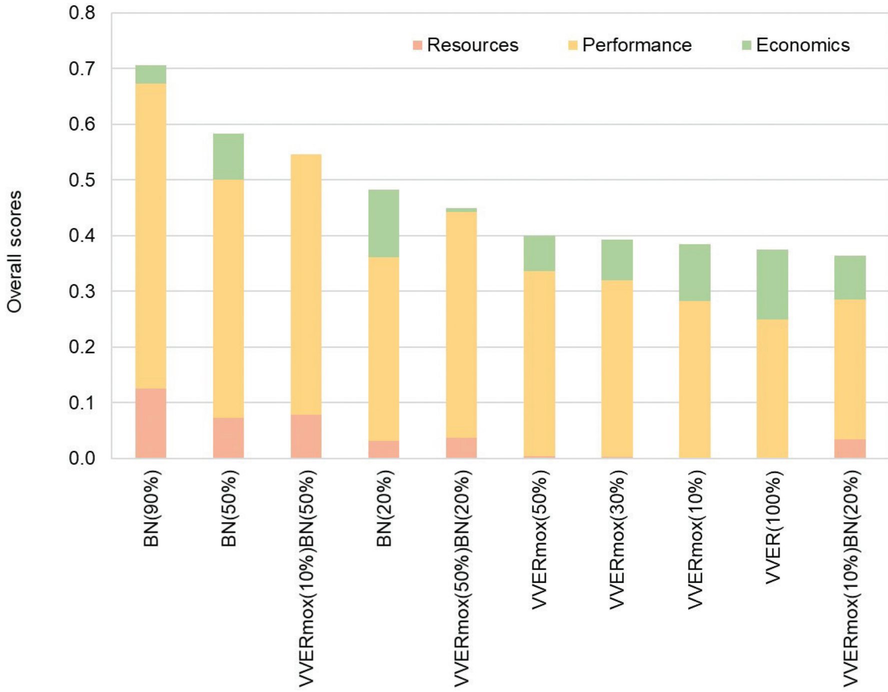

Figure 4. Ranking results for the base weighting option.

est scores for this objective. Despite the fact that the BN(90%) scenario scores are not the highest for the economics objective, the best performance this scenario showed for the resources and NFC performance objectives has made it, as a result, the most attractive option in conditions with an equal relative significance of the performance indicators. The VVERmox(10%)BN(50%) option, which suggests that some 20% of MOX fuel is used in VVER, was the third highest-rated option despite a minor decrease in the amount of consumed uranium and a more expensive NFC due to the MOX fuel production and thermal reactors SNF reprocessing. As follows from Table 2, specific to this option, as well as to other options with the use of MOX fuel in VVER reactors, is the possibility for reducing the amount of plutonium in the NFC.

The ranking results described are given for the base weighting option. At the same time, it is clear that there is a major uncertainty in the priorities of the NES long-term deployment and, therefore, a major spread in the weighting factors exists. Of interest in this connection is to assess how the uncertainty in weights affects the final scores for the options under consideration. The spread in scores due to the uncertainty of weights was estimated in accordance with the methodology proposed in one of the studies undertaken under a program of the US Department of Energy (Wigeland et al. 2014). This methodology allows one to rank scenarios in conditions of lacking information on the significance of the performance indicators and to identify the probability for a particular scenario to be chosen. This method suggests that nothing is known about the priorities (weights) and is assessed as if the scenarios were ranked by different expert groups having different views on the significance of the performance indicators. This information can be presented in the form of statistical distributions (e.g., using a box-and-whiskers plot), and the most attractive scenario can be selected on its basis and the stability of this scenario and the probability for it to be opted for can be evaluated.

The spreads in the final scenario scores due to the uncertainty of the weight values is shown in Fig. 5 (the number of the combinations of weights analyzed was 10 000, and the weights were assumed to be distributed uniformly in the interval [0, 1], provided the sum of the weights in each sample is equal to unity). The BN(90%) scenario is characterized by the most attractive spread in the final scores among the entire set of options. The BN(20%) scenario can also be highly attractive in certain conditions; it is expected to be more attractive than all other options which suggest BN and VVER joint operation based on MOX fuel. The VVER(100%) and VVERmox(10,30,50%) scenarios can be considered statistically indistinguishable. The BN(50%) scenario has the smallest spread in scores but this scatter is overlapped by the scatter of the scores for the BN(20%) and BN(90%) scenarios.

The uncertainty with respect to the weights of the high-level objectives was analyzed to identify the scenarios which may potentially be ranked first (provided the weights at the lower levels of the objectives tree are equal). The analysis makes it possible to identify the intervals of the weight values with which the respective option may be rated first (possible weight values for the resources high-level objective are on the abscissa axis, the weight values for the NFC performance are on the ordinate axis, and the weight values for the economics objective are on the applicate axis, the total of the weights being equal to unity).

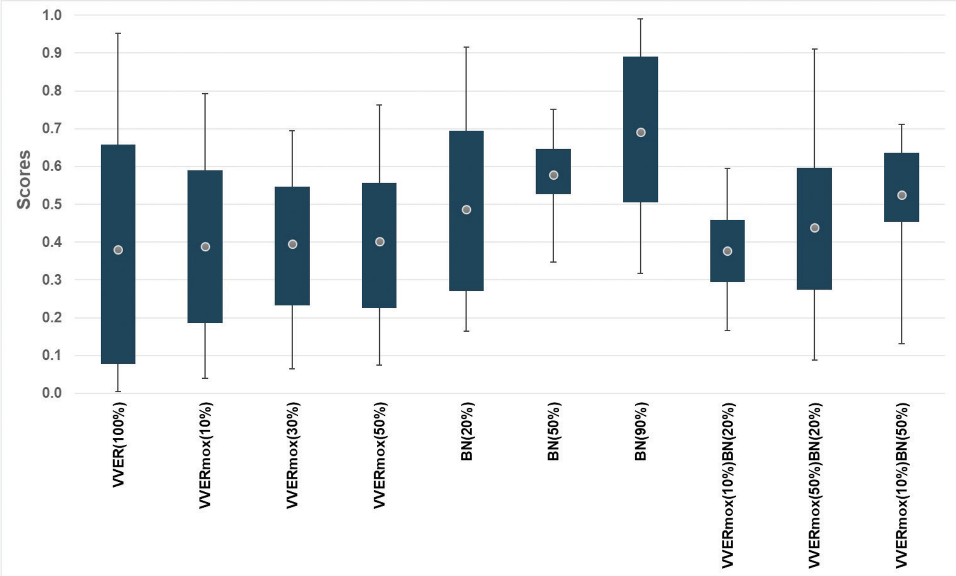

Figure 5. Spreads in the scenario scores due to the uncertainty of weights (average values, 5, 25, 75 and 95% percentiles are shown).

Discussion

Fig. 6 allows one to make preliminary conclusions as to the most effective ways to improve the sustainability of the national NES in the multi-criteria evaluation conditions. As shown in the figure, the VVER(100%) scenario with uranium-oxide fuel in a once-through NFC has been ranked first in the space of weights for the high-level objectives provided the economic assessment criteria predominate and there is no need for minimizing the use of natural uranium resources and the SNF and plutonium amounts. It is for quite a time that economy will remain the key criterion in deciding in favor of any reactor technology or fuel cycle option to be included in the effective NES. This result therefore confirms the timeliness of the further VVER-type reactor evolution with regard for current and future safety and competitiveness requirements. The BN(20%) scenario becomes more attractive with the increased significance of

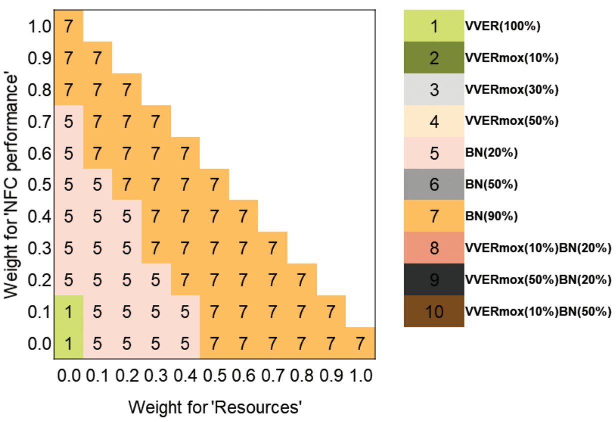

Figure 6. Mapping of the scenarios ranked first in the space of weights for the high-level objectives. The applicate axis (the weight of the Cost Effectiveness high-level objective) is assumed to be directed at the reader.

the cost effectiveness, while increasing the NFC performance and use of resources remain pending issues.

With the resources and NFC performance objectives being highly significant, the BN(90%) scenario, in which the share of BN reactors grows gradually and reaches 90% only by the end of the century, is the most attractive of the considered scenarios.

While the estimates made indicate quite expressly that the options with a large share of BN reactors are highly advantageous as compared with the VVER(100%) option, the role of thermal reactors with MOX fuel in a two-component NES has not shown itself distinctly. In particular, no MOX fuel options were ranked first (see Fig. 6) in the space of weights for the high-level objectives despite the fact that the VVERmox(10%)BN(50%) option took the third place in the total rating (see Fig. 4). This contradiction shows the need for further studies to be undertaken with respect to the role of thermal reactors with MOX fuel in a two-component NES.

The obtained substantial dependence of the reactor fleet structures for the modeled NES on the extent of the objectives under consideration, including rational use of resources, efficient NFC arrangement and radioactive waste management, demonstrates that the nuclear power efficiency assessment methods based only on economic performance, tending to a system of thermal reactors, gives a one-sided picture. Multi-criteria methods for evaluating alternatives offer solutions differing from solutions based on economic approaches and provide for the system efficiency of energy generation and an improvement in its environmental performance with regard for the Sustainable Development concept requirements.

Evidently, the findings are of an illustrative nature. It makes sense to consider a large number of potential configurations for the two-component NES, different growth rates of the NES installed capacity, and other sets of performance indicators, with regard for the fact that sodium-cooled fast reactors can be used not only for commercial generation of electricity but also as facilities the excessive neutrons in which make it possible to burn minor actinides and produce isotopes to be further used in medicine and industry. It may potentially become important for future studies to take into account the possibility for the repeated recycling of plutonium in thermal reactors following the "refinement" of plutonium in BN-type reactors (Gulevich et al. 2018) and to assess the influence of the export supplies of reactors and the NFC services on the Russian NES structure.

Conclusions

The paper presents the results of a multi-criteria comparative evaluation for ten potential deployment scenarios for Russian nuclear power with different shares of thermal and sodium-cooled fast reactors, including options which involve the use of MOX fuel in VVER reactors. The eight key performance indicators were used within the study which were estimated as of 2100. The study allows one to make preliminary conclusions on the ways for the evolution of the national NES as a sustainable energy source to provide a balanced combination of technical, economic and environmental factors. The results demonstrate that the sustainability of the national NES through a balanced combination of the cost effectiveness, effective use of resources and fuel cycle performance objectives based on the reactor technologies, demonstrated to date, can be enhanced through the large-scale deployment of sodium-cooled fast reactors and the transition to a closed fuel cycle. The results have shown the need for further studies to be undertaken with respect to the place of thermal reactors with MOX fuel in a two-component nuecler energy system as a commmercially mature technology capable to "burn" excessive plutonium and provide its balanced production and consumption in the system.

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