

# A scenario study on the transition to a closed nuclear fuel cycle using the nuclear energy system modelling application package (NESAPP)

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**Abstract.** The paper presents the results of a case study on evaluating performance and sustainability metrics for Russian nuclear energy deployment scenarios with thermal and sodium-cooled fast reactors in a closed nuclear fuel cycle. Ten possible scenarios are considered which differ in the shares of thermal and sodium-cooled fast reactors, including options involving the use of mixed uranium-plutonium oxide fuel in thermal reactors. The evolution of the following performance and sustainability metrics is estimated for the period from 2020 to 2100 based on the considered assumptions: annual and cumulative uranium consumption, needs for uranium enrichment capacities, fuel fabrication and reprocessing capacities, spent fuel stocks, radioactive wastes, amounts of plutonium in the nuclear fuel cycle, amounts of accumulated depleted uranium, and the levelised electricity generation cost. The results show that the sustainability of the Russian nuclear energy system can be significantly enhanced through the intensive deployment of sodium-cooled fast reactors and the transition to a closed nuclear fuel cycle. The authors have highlighted some issues for further considerations, which will lead to more rigorous conclusions regarding the preferred options for the development of the national nuclear energy system.

## 1 Background

In the Russian Federation, the deployment of a two-component nuclear energy system (NES) based on the conjoint operation of pressurised light water reactors and sodium-cooled fast reactors in a closed nuclear fuel cycle is considered as one of the possible perspective ways to enhance the sustainability of national nuclear power. In this respect, different possible configurations of the NES are widely discussed. The two-component NES at various stages of its development may include thermal reactors (VVER type) with uranium oxide fuel, thermal reactors with partial or full loading of mixed uranium-plutonium oxide (MOX) fuel, and sodium-cooled fast reactors (SFR) with MOX fuel (Fig. 1) [1–4].

The timing and scales for commissioning different reactor units can differ in various scenarios for deploying this NES, depending on the overall objectives to be achieved by nuclear power, but the general principle is that all reactors in the system will be interconnected by a common closed nuclear fuel cycle in which the processed spent fuel products from some reactors are used to produce fresh fuel for other reactors.

Various possible configurations of the two-component NES can have certain similarities and differences, and respective merits and demerits associated with each specific NES configuration can be quantified through performance and sustainability metrics characterising resource consumption, material flows in the fuel cycle, needs for fuel cycle services, economic indicators, etc., which will evolve over time.

In this context, it becomes necessary to identify the most promising two-component NES configurations by carrying out scenario studies on the transition to a closed fuel cycle, in which the multiple representative and feasible scenarios for developing the national two-component NES with thermal and fast reactors are analysed using the transient scenario analysis codes. The primary purpose of such studies is to evaluate performance and sustainability metrics which can be used afterwards to carry out a multi-criteria comparison of the corresponding options on a quantitative basis using multi-criteria decision analysis tools which can also consider the time dependence of metrics resulting from the system evolution. An appropriate analytical framework can be used for providing recommendations regarding the most effective ways to enhance the sustainability of national nuclear power.

Following this action plan, the present case study demonstrates the first step of a related decision support

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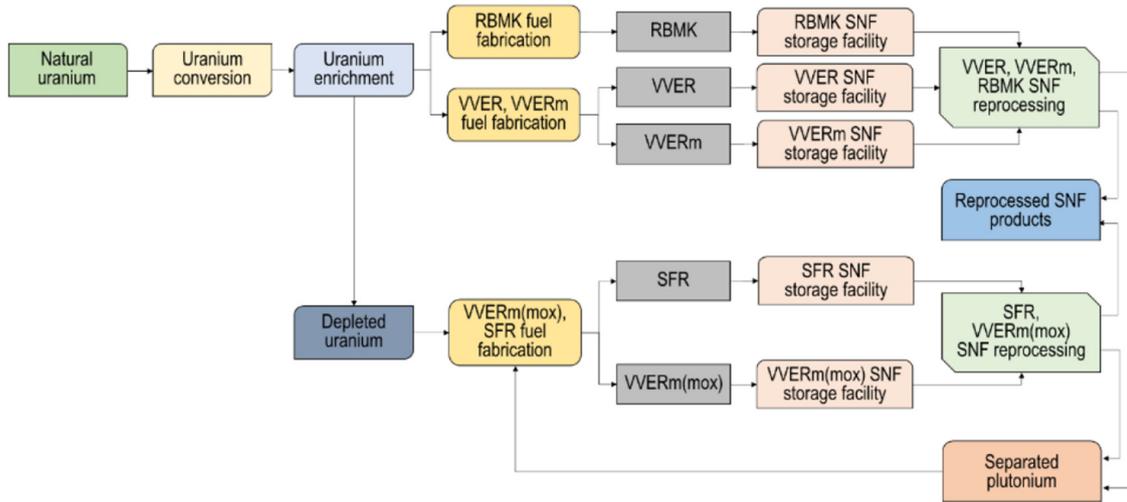


Fig. 1. Key components of the two-component NES infrastructure considered in the study.

process, in which some required metric data are prepared for further aggregation. For illustrative purposes, eight performance and sustainability metrics were considered and evaluated for ten possible deployment scenarios of the national two-component NES, the so-called NES options/configurations (see Tab. 1 and Fig. 2). These options include, in various proportions, thermal reactors (both with uranium fuel and with partial loading of MOX fuel — 1/3 MOX fuelled core) and sodium-cooled fast reactors (with MOX fuel). Of note, scenarios analysed in the present study do not imply consideration of other alternative technological options for the development of national nuclear power including lead-cooled fast reactors with nitride fuel, molten salt reactors, hybrid nuclear fusion-fission reactors, etc., which are also seen as promising advanced options for the development of nuclear power in the Russian Federation. Thus the study focuses specifically on the most technologically mature technologies that have already found industrial application.

## 2 Scenario assumptions and initial data used

Within the developed transient scenario models, all the existing thermal reactors were combined into two groups: RBMK and VVER. The following reactor types were considered as candidates for the deployment within the national NES: VVER, VVERm (modified VVER reactor with increased burnup), VVERm(mox) (modified VVER reactor with partial loading of MOX fuel—1/3 MOX fuelled core, single plutonium recycle) and SFR (sodium-cooled fast reactor with MOX fuel). It was assumed that VVER and VVERm could be commissioned from the first year of the forecast period, SFR from 2030, and VVERm(mox) from 2040. Exports of reactor technologies and fuel cycle services were not considered in the models.

The calculations were carried out with due account for the prehistory of the nuclear power deployment in the Russian Federation and based on the assumption that

there were no resource and infrastructure restrictions. It was assumed that the cooling time of spent fuel for all the reactor types before reprocessing would be 5 years, and reprocessing would be done on a centralised basis. The separated plutonium accumulated by 2020 (ex-weapon and reactor-grade plutonium) and plutonium contained in spent fuel are resources for producing nuclear fuel for SFR and VVERm(mox) (relevant data on stocks were taken from [5]).

The following assumptions were considered as the expected growth in overall NES capacities: approximately 40 GW in 2030, 60 GW in 2050 and 115 GW in 2100. To take into account the boundary effects, the prognosis horizon was extended up to 2150 (150 GW in 2150). Table 1 presents ten possible national NES options/configurations analysed in this study, which can be divided into 3 groups according to the implemented fuel cycle strategies: once-through, partially closed and fully closed fuel cycles.

Certainly, the entire set of possible feasible NES configurations cannot be reduced to only the ten alternatives considered in this study due to its illustrative scope, and a more thorough analysis should examine hundreds or even thousands of alternative options. To organise the systematic generation of feasible scenarios meeting the basic material balance equations, a simplified optimisation model was developed using the MESSAGE software tool [6], which makes it possible to identify the dynamics of commissioning various reactor units satisfying the basic constraints and restrictions engendered by the material balance equations for heavy nuclides. However, this model does not reproduce any structural or organisational details of the corresponding closed fuel cycle, which necessitates complimenting this model with another one for evaluating performance and sustainability metrics, developed based on the Nuclear Energy System Modelling Application Package (NESAPP). Due to the illustrative nature of this study, the results of considering only ten NES options identified in the course of the analysis, which were found to be the most representative ones, are presented

**Table 1.** Considered NES options.

NES option	Comments
Once-through fuel cycle	
NES option 1	Share of VVERm in the NES structure in 2100–100%
Partly closed fuel cycle	
NES option 2	Shares of VVERm and VVERm(mox) in the NES structure in 2100 – 90 and 10%, respectively
NES option 3	Shares of VVERm and VVERm(mox) in the NES structure in 2100 – 70 and 30%, respectively
NES option 4	Shares of VVERm and VVERm(mox) in the NES structure in 2100 – 50 and 50%, respectively
Fully closed fuel cycle	
NES option 5	Shares of VVERm and SFR in the NES structure in 2100 – 80 and 20%, respectively
NES option 6	Shares of VVERm and SFR in the NES structure in 2100 – 50 and 50%, respectively
NES option 7	Shares of VVERm and SFR in the NES structure in 2100 – 10 and 90%, respectively
NES option 8	Shares of VVERm, VVERm(mox) and SFR in the NES structure in 2100 – 70, 10 and 20%, respectively
NES option 9	Shares of VVERm, VVERm(mox) and SFR in the NES structure in 2100 – 30, 50 and 20%, respectively
NES option 10	Shares of VVERm, VVERm(mox) and SFR in the NES structure in 2100 – 40, 10 and 50%, respectively

here in order to highlight general trends associated with NES configurations based on the considered technological options. Details of the scenario generation approach applied can be found in [Appendix A](#).

All reactor values used in the calculations were annual average ones, i.e., they correspond to the steady-state reactor operating characteristics, the initial fuel loads and final spent fuel discharges were taken into account (in accordance with the technical data in [1], see [Appendix B](#)). The SFR was represented in the models separately by the core and the blanket. The service unit costs of fuel cycle services (average values) were taken from [1] (see [Appendix B](#)). Regarding the overnight cost of reactor installations, it was conservatively assumed that the specific overnight capital cost of SFR is by 10% higher than that of VVER (4 000 \$/kW). The discount rate was assumed to be 5% [1].

The transient scenario models developed in accordance with the recommendations [7,8] were verified by comparison with the results obtained using the original codes. These models make it possible to estimate the scale of material flows, needs for fuel cycle services and products as well as economic performance metrics. They can be used as a starting point for developing more rigorous models of the two-component NES. The evolution of the following performance and sustainability metrics were estimated for the period from 2020 to 2100 based on the considered assumptions: annual and cumulative uranium consumption, needs for uranium enrichment capacities, fuel fabrication and reprocessing capacities, spent fuel stocks, radioactive wastes, amounts of plutonium in the

nuclear fuel cycle, amounts of accumulated depleted uranium, and the levelised electricity generation cost (LGC).

### 3 Nuclear energy system modelling application package (NESAPP)

The models for assessing material flows, needs for nuclear fuel cycle services and economic performance metrics for given NES configurations were elaborated using the nuclear energy system modelling application package (NESAPP) [7]. NESAPP is a set of codes to support nuclear energy planning and nuclear fuel cycle transition scenario studies, including ([Fig. 3](#)):

- nuclear Data Processing Spreadsheets (NUDAPS) — a module for calculating thermal neutron cross-sections, resonance integrals and few-group neutron cross-sections and associated uncertainties;
- nuclide Evolution Exploring Tool (NUCLEX) — a module for calculating the evolution of the nuclide composition and characteristics of nuclear fuel in reactors and in the external nuclear fuel cycle;
- nuclide Composition Adjustment and Blending Tool (NUCAB) — a module for isotopic composition adjustment and blending;
- material Flow Analysis Data Integration Tool (FANES) — a module for material flow analysis and data integration in nuclear energy system evolution scenarios;

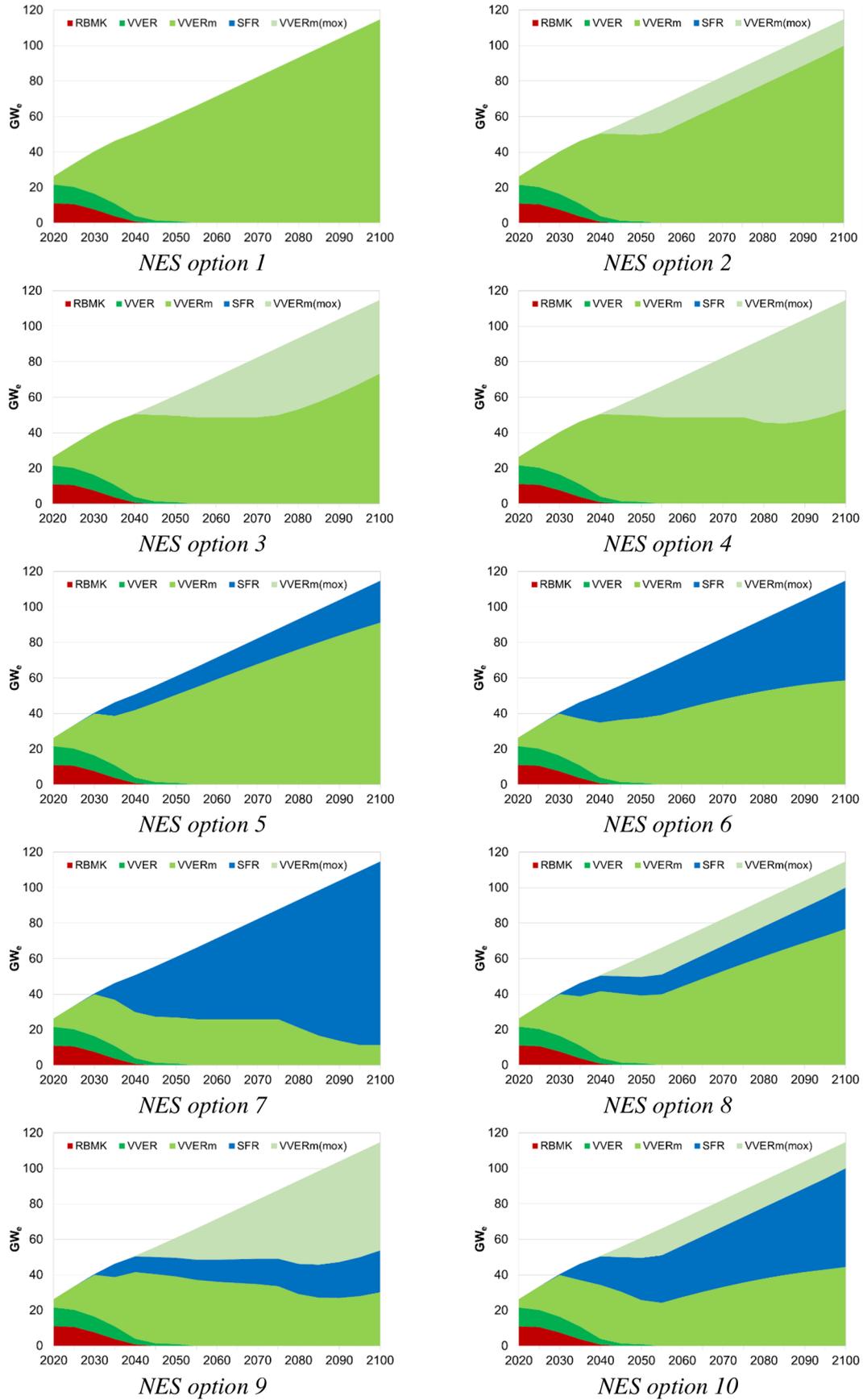
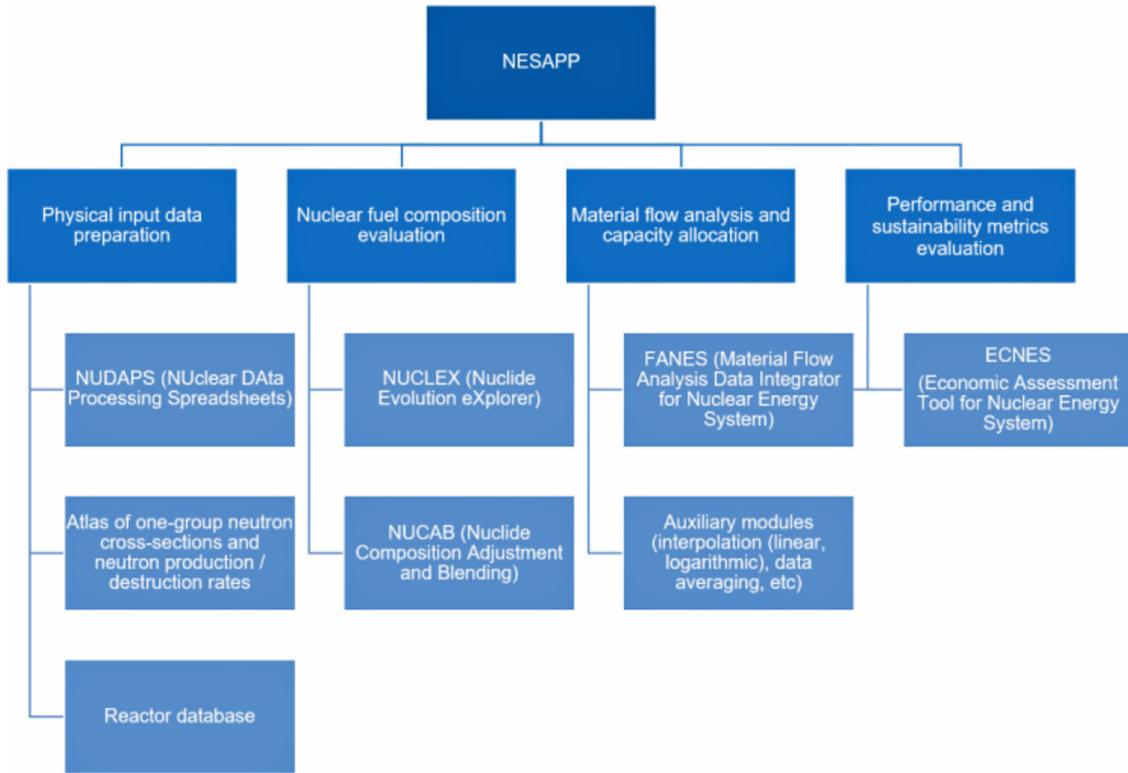


Fig. 2. NES configurations under consideration.



**Fig. 3.** Nuclear Energy System Modelling Application Package (NESAPP).

- economic Assessment Tool (ECNES) — a module for assessing economic performance metrics for nuclear energy system evolution scenarios;
- local reactor database including an atlas of one-group neutron cross-sections and neutron production/destruction rates.

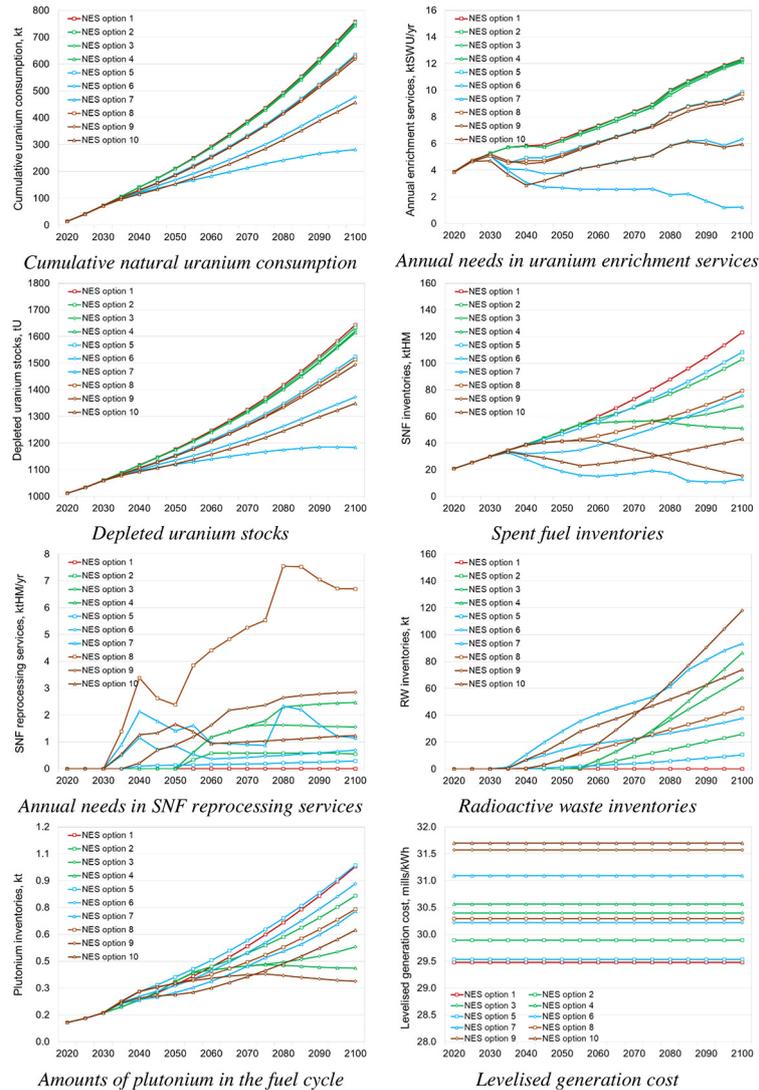
The elaborated NES models considers the expected growth rates of electricity production and describes the main components of the industrial fuel cycle infrastructure, including nuclear reactors and fuel cycle facilities with specified technical and economic parameters. At various stages, the considered scenarios include thermal reactors with uranium oxide fuel, thermal reactors with partial loading of MOX fuel and SFRs with MOX fuel.

## 4 Results and analysis

The evolution of material flows and needs for fuel cycle services as well as economic performance for the considered NES configurations are presented in [Figure 4](#) (annual data were converted to 5-year averaged interval data for better representation). Cumulative performance data as of 2100 are shown in [Figure 5](#). It is obvious that, in the process of searching for the most preferred NES configuration, the priority should be given to those NES options for which all the metrics will have the minimum values. Analysing the generated performance data, one can see that there is no option that can be considered the best for the entire set of metrics. Moreover, it should be noted that the time dependence of metrics in the general case does finally lead

to ambiguity in recommendations for different timeframes: some configurations can demonstrate, for instance, an improvement in long-term performance while reducing short- or medium-term ones. It is clearly shown by the following metrics from the considered list, such as spent fuel inventories, annual needs in SNF reprocessing services, radioactive waste inventories, or amounts of plutonium in the fuel cycle (see, for instance, [Fig. 4](#) where NES option 7 produces the highest radioactive waste inventories up to 2075 while, after 2075, NES option 9 starts leading on this metric).

The following observations can be made: (1) NES option 1 is the most favourable in terms of economic performance and due to the fact that there are no needs for spent fuel reprocessing services while other metrics take the highest values among all the other options; (2) NES option 7 is the most promising in terms of uranium consumption, needs for enrichment services, depleted uranium stocks, and spent fuel inventories metrics while for the other metrics it demonstrates mediate performance; (3) NES option 9, involving both SFRs and MOX-fuelled thermal reactors, is the most promising in terms of the amount of plutonium in the fuel cycle metric (so the preference can be given to this option if no other metrics are considered) but the other metrics become sufficiently less attractive in contrast to the options that involve utilisation of plutonium only in SFRs (this is also relevant for other options involving utilisation of plutonium in both thermal and fast reactors). Worth noting is that there is no new separated plutonium accumulation in the scenarios considered: all needs in plutonium are covered on a fly



**Fig. 4.** Material flows and needs for fuel cycle services.

to feed the plutonium utilised reactors (without the need to store separated plutonium). Of note, the more rigorous decision support analysis requires consideration and detailed tracking of plutonium of different quality using specific performance metrics which are not evaluated here due to the preliminary character of the study.

All the other options do not provide any improvement in the performance metrics as contrasted with the options previously considered, and their performance metric data are within the metric values for the abovementioned options. Both groups of options involving utilisation of plutonium in thermal reactors (i.e., NESs consisting of MOX-fuelled thermal reactors with or without SFRs) do not provide better performance for the overall NES performance in terms of evaluation metrics used, unlike the options in which the fuel cycle is closed only for the SFR reactor type.

The demonstrated time-dependence of the metric data can lead to a change in the recommendations for selecting the most preferred NES configuration for different timeframes.

In such cases, it is desirable to find configurations that balance the system performance within different timeframes. It is necessary to develop and test appropriate guidelines for selecting the most promising trade-offs meeting short-, medium- and long-term objectives. Another aspect that should be mentioned is that the levelised generation cost spread for the considered options is characterised by the minimum uncertainty (about 7.3% among all the considered scenarios) in contrast to the other performance metrics for characterising mass flows, for which the values may differ up to several times.

## 5 Discussion

The performed evaluations clearly indicate significant advantages of the scenarios with a large proportion of SFRs (NES option 7) compared to NES option 1, but the role of MOX-fuelled thermal reactors in the two-component NES was not clearly revealed. To ensure the specified growth

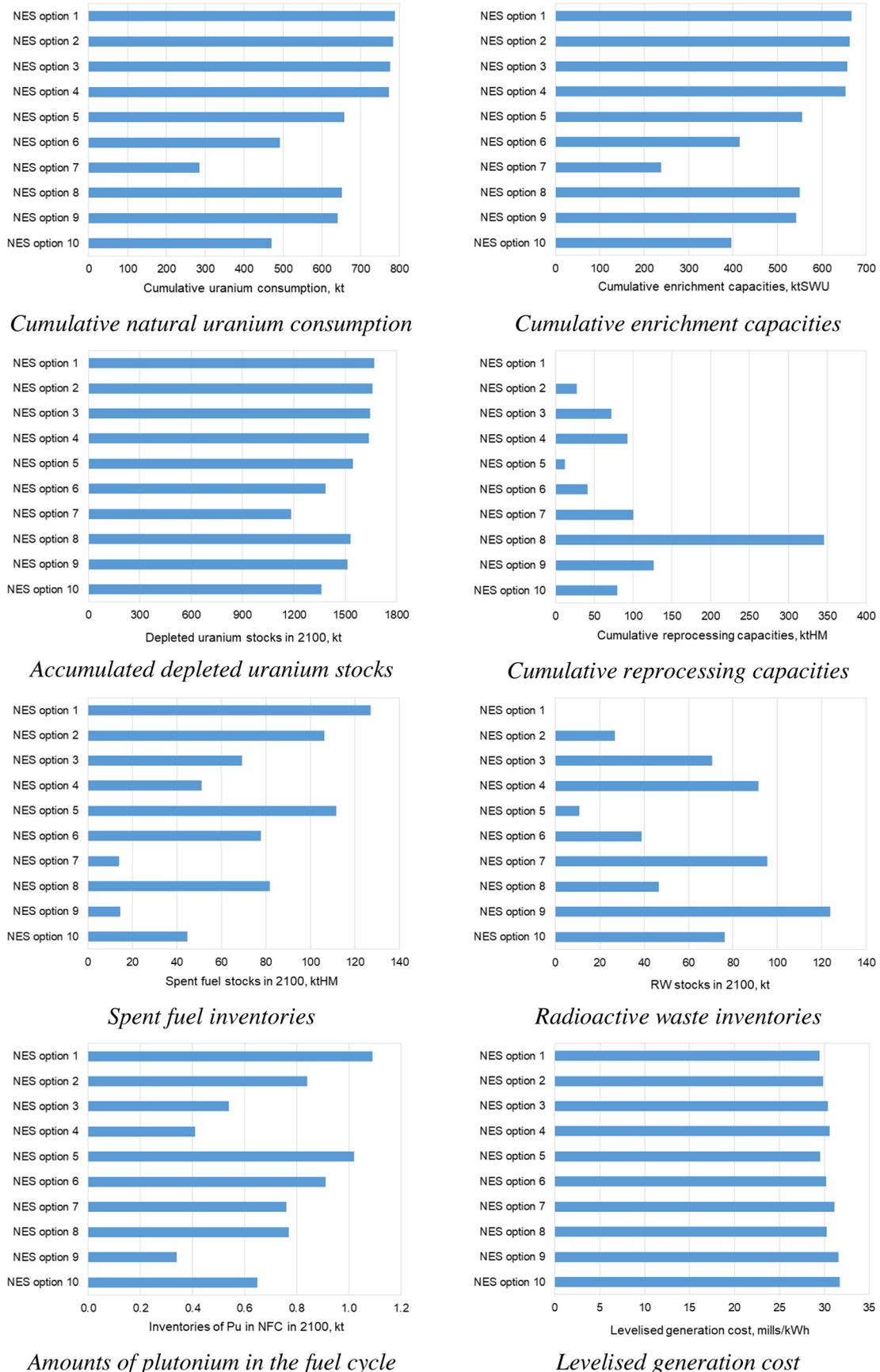


Fig. 5. Cumulative performance data as of 2100.

rate of the NES capacities in the current national conditions, there is no need for a fast reactor with high fuel breeding parameters and, as a result, there is no economically justified need to utilise excess plutonium in thermal reactors (other considerations that can make this technological option reasonable are not discussed). The results confirm the thesis that, if fast reactors are expected to be introduced in the future, the issue of using plutonium in thermal reactors requires a detailed examination, since there are no irrefutable arguments proving the feasibility of this option. This points to the need for further studies on the role of MOX-fuelled thermal reactors in the two-component NES, since it is a commercially mature technology that can burn excessive plutonium providing a plutonium balance (i.e., plutonium production is equal to its consumption) in the system.

NES option 7 is the most attractive among all the considered alternatives if the importance of achieving the goals for the resource utilisation and fuel cycle performance prevails even in case of slight deterioration in economic performance for the corresponding NES configuration (levelised generation cost for NES option 7 is 5.5% higher as compared to the cheapest NES option 1, which, however, is within the uncertainty range produced by the service unit cost data [9]). All the other options with SFRs can be seen as less attractive but trade-off ones which may become more attractive if the importance of improving economic performance and, at the same time, the relevance of keeping the improved fuel cycle performance and the resource utilisation still remain. NES option 1, implying the commissioning of only VVER reactors with uranium oxide fuel in a once-through fuel cycle, can take the first place if it is not intended to enhance the fuel cycle performance (including minimisation of the amounts of spent fuel and plutonium in the nuclear fuel cycle, etc.) and resource utilisation.

As it was shown in different studies, for example [10], the results of the evaluations indicate that the comparison of the NES deployment scenarios on the basis of only economic indicators, without considering the rational use of resources, effective nuclear fuel cycle organisation and radioactive waste management objectives, provides a one-sided picture giving preference to the NES option based on thermal reactors and a once-through fuel cycle. The multi-criteria decision analysis framework for comparing and ranking alternatives offers solutions different from those obtained by using the approaches based on pure economic considerations: preference is given to energy production options that have the highest system efficiency, taking into account the Sustainable Development concept requirements.

In this regard, future work should also be focused on performing a multi-criteria comparative analysis and ranking of NES deployment scenarios using the multi-criteria decision analysis framework. The decision support model can be based, for example, on the multi-criteria decision analysis methods, where the initial data are the scenario analysis results, i.e., values of the key indicators for each of the considered NES options. Using an appropriate decision support model, supplemented with data on the experts/decision makers' preferences, it is possible to perform a multi-criteria comparative analysis and ranking of the options under consideration. Taking into account the results of the sensitivity/uncertainty

analysis of the main factors, this model can also be helpful in determining the most effective directions to enhance the sustainability of national nuclear power.

Of course, the results obtained in this study are illustrative and cannot form the basis for management decisions: it would make sense to consider many more possible configurations of the two-component NES, different growth rates of installed NES capacities and other sets of performance indicators. It should also be borne in mind that sodium-cooled fast reactors can be used not only for producing electricity on a commercial scale but, due to their neutron excess, for burning off minor actinides and producing isotopes for their subsequent use in medicine and industry. In particular, the tasks of considering the possibility of plutonium multi-recycling in thermal reactors after 'improving' the quality of plutonium in SFRs and assessing the impact of exported reactors and fuel cycle services on the national two-component NES structure may be important for future research.

## 6 Summary

The presented results of the transient scenario study involving ten possible national NES configurations characterised by various proportions of thermal and sodium-cooled fast reactors, including options for using MOX fuel in thermal reactors, allow us to discuss preliminary observations regarding the development of national nuclear power as a sustainable energy supply option. It is shown that it is possible to significantly increase the sustainability of the national NES by the intensive and large-scale deployment of sodium-cooled fast reactors and gradual transition to the closed nuclear fuel cycle. These considerations have demonstrated the need for further detailed studies on the possible role of MOX-fuelled thermal reactors in the two-component NES, since this commercially mature technology can burn excessive plutonium providing a plutonium balance (i.e., plutonium production is equal to its consumption) in the system.

## Author contribution statement

All the authors were involved in the preparation of the manuscript. All the authors have read and approved the final manuscript.

## Appendix A: Scenario generation approach applied

NES scenario studies using simulation software tools start with defining the prospective reactor fleet structure for the entire considered time horizon. Based on this information, material flows and needs for fuel cycle goods and services can be evaluated using sophisticated fuel cycle codes which may include, among other functions, tracking the nuclide composition evolution in reactors and in the external nuclear fuel cycle. The prospective NES structure can be qualitatively defined on the basis of expert judgments reflecting the visions of experts regarding the most promising nuclear energy configuration in the future or,

alternatively, the dynamics commissioning various reactor plants can be determined more formalistically based on the solution of the respective optimisation problem. The latter option assumes that the corresponding single-objective or multi-objective or stochastic or robust optimisation problem should be formulated and then solved using optimisation software tools. The optimisation problem can consider a variety of resource and infrastructural constraints and restrictions which will specify the system evolution with respect to a given objective (or objectives). More sophisticated optimisation models can also take into account uncertainties associated with technical, economic, or scenario data. Such models can be developed as extensions of the classical single-objective optimisation paradigm by introducing additional constraints on model variables or by elaborating respective statistical sampling models based on the primary single-objective optimisation model.

Within the present study the following approach was applied to identify the list of NES configurations for their follow-up analysis using a simulation fuel cycle analysis code: – taking into account the uncertainties in the cost data (see [Appendix B](#)), one thousand samples of fuel cycle cost combinations were generated and sequentially used to populate the NES optimisation model. For each cost combination sample, the reactor plant commissioning was determined based on the optimisation problem solution using the pre-elaborated MESSAGE model. Calculations were made based on the assumption that the natural uranium reserves are unlimited (it is possible to use non-conventional uranium resources), and there are no constraints on the capacities of fuel cycle facilities.

The loading structure for spent fuel reprocessing plants is determined based on the relevant optimisation problem solution. The optimisation criterion is the minimisation of the total discounted cost for the development programme.

- having the information about the feasible reactor fleet structures for one thousand generated NES deployment scenarios, a simple screening procedure was applied to select ten options from this scenario list which meet the pre-defined target shares of different reactor types in the NES structure at 2100 (see [Tab. 1](#)).
- these ten selected NES configurations and the basic cost data were then used to populate the NESAPP models to perform more rigorous fuel cycle analysis on evaluating material flows, needs for fuel cycle goods and services as well as economic performance metrics.

This approach is scalable: there are no restrictions on its application to generate several thousand scenarios, to examine multivariable impacts, or to consider alternative performance metrics. The developed optimisation model was prepared in full compliance with the IAEA recommendations on the specification of nuclear energy systems in the MESSAGE software tool and verified by comparison with the results obtained using original codes; it has also been discussed and tested at IAEA workshops on analytical tools for sustainable energy development strategies, (see IAEA, Modelling Nuclear Energy Systems with MESSAGE: A Users' Guide, IAEA Nuclear Energy Series No. NG-T-5.2, IAEA, Vienna (2016)).

## Appendix B: Reactor, fuel cycle and cost data

**Table B.1.** Reactor and fuel cycle data.

Item	Units	RBMK	VVER	VVERm	VVERm(mox)	SFR
Reactor data						
Plant lifetime	yr	50	50	60	60	60
Reactor thermal output	MW <sub>th</sub>	3200	3000	3300	3300	2800
Reactor electric output	MW <sub>e</sub>	1000	1000	1250	1250	1250
Auxiliary power consumption	%	6.5	6.0	6.5	6.5	5.0
Average load factor	%/100	0.8	0.9	0.93	0.93	0.90
Construction time	yr	–	–	5	5	5
Capital investments schedule		–	–	uniform	uniform	uniform
Fuel cycle data						
Thermal reactor fuel cycle data						
Initial core inventory	tHM	134.4	75	77	77	–
Enrichment (initial loading)	%	2.4	3.3	3.9	3.9	–
Equilibrium loading (UOX)	tHM/yr	44.8	20.5	23.4	13.7	–
Enrichment (eq.loading)	%	2.4	4.70	4.74	4.86	–
Equilibrium loading (MOX)	tHM/yr	–	–	–	9.7	–
Pu content in MOX fuel (eq.loading)	%	–	–	–	9	–
Annual Pu production	tHM/yr	0.22	0.24	0.27	0.76	–
Tail assay	%	0.2	0.2	0.2	0.2	–
Fast reactor fuel cycle data						

**Table B.1.** (continued).

Item	Units	RBMK	VVER	VVERm	VVERm(mox)	SFR
<i>SFR initial core inventory:</i>						
core, MOX/U/Pu	tHM/tHM/tHM	–	–	–	–	41.6/34.2/7.4
axial blanket, UOX/ <sup>235</sup> U	tHM/%	–	–	–	–	20.2/0.2
radial blanket, UOX/ <sup>235</sup> U	tHM/%	–	–	–	–	44.4/0.2
<i>SFR equilibrium loading:</i>						
core, MOX/U/Pu	tHM/tHM/tHM	–	–	–	–	7.6/6.2/1.4
axial blanket, UOX/ <sup>235</sup> U	tHM/%	–	–	–	–	3.7/0.2
radial blanket, UOX/ <sup>235</sup> U	tHM/%	–	–	–	–	5.0/0.2
<i>SFR annual spent fuel discharge:</i>						
core, MOX SF/Pu	tHM+FP/tHM	–	–	–	–	7.6/1.3
axial blanket, UOX SF/Pu	tHM+FP/tHM	–	–	–	–	3.7/0.17
radial blanket, UOX SF/Pu	tHM+FP/tHM	–	–	–	–	5.0/0.13
Other data						
Average discharged burnup (UOX/MOX)	MW day/kgHM	20.0	48.0	47.9	49/46	113
# of refuelling batches,core/ax.bl./rad.bl.	#	3	3	3	3	5/5/8
Cooling time,core/ax.bl./rad.bl.	yr	5	5	5	5	5/5/3

**Table B.2.** Reactor costs.

Item	Unit	Reactor type	Range	Basic value
Overnight construction cost	US \$/kW(e)	VVER SFR	3500–6300	4000
			3600–6600	4400
Fixed O&M cost	US \$/kW/year	VVER, RBMK SFR	60–87	70
			65–92	75
Variable O&M cost	US \$/MW h	VVER, RBMK SFR	0.8–2.7	1.14
			1.1–2.9	1.16

**Table B.3.** Fuel cycle service unit costs.

Fuel cycle step	Unit	Range	Basic value
Uranium mining/milling	US \$/kg U	50–300	100
Uranium conversion	US \$/kg U	5–15	10
Uranium enrichment	US \$/kg SWU	85–150	110
Fuel fabrication for VVER, RBMK (UOX)	US \$/kg HM	240–420	350
Fuel fabrication for SFR, VVER (MOX)	US \$/kg HM	1000–6000	3500
Fuel fabrication for SFR (blanket fuel)	US \$/kg HM	200–500	300
Spent fuel reprocessing for VVER, RBMK (UOX)	US \$/kg HM	460–900	600
Spent fuel reprocessing for SFR, VVER (MOX)	US \$/kg HM	640–1000	770
Spent fuel reprocessing for SFR (blanket fuel)	US \$/kg HM	460–900	600
RW treatment for VVER, RBMK	US \$/kg HM	150–350	250
RW treatment for SFR	US \$/kg HM	250–1000	860
Spent fuel direct disposal for VVER, RBMK	US \$/kg HM	270–1580	850
Pu storage	US \$/kg Pu	2000	2000

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