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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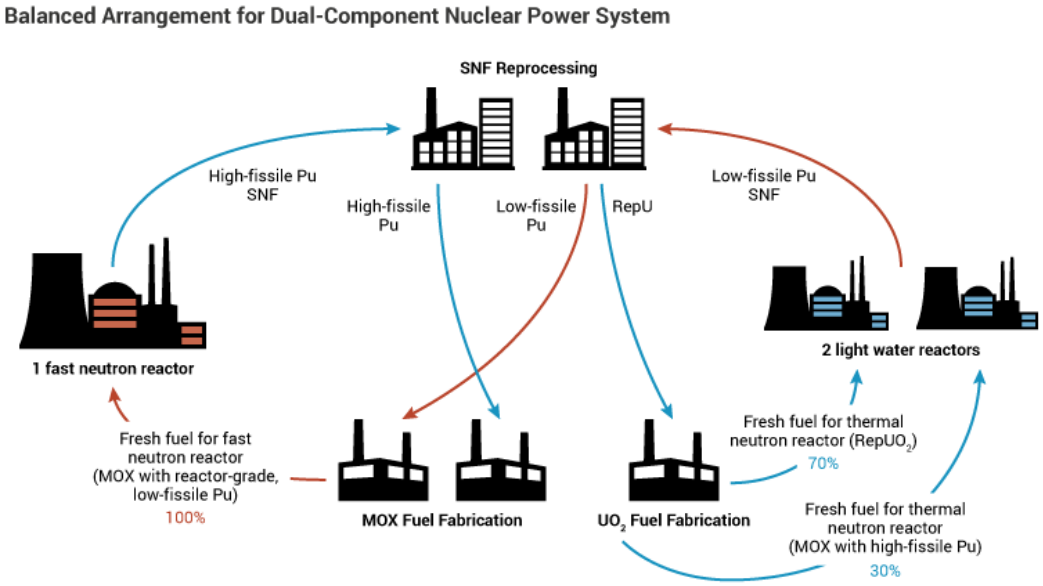
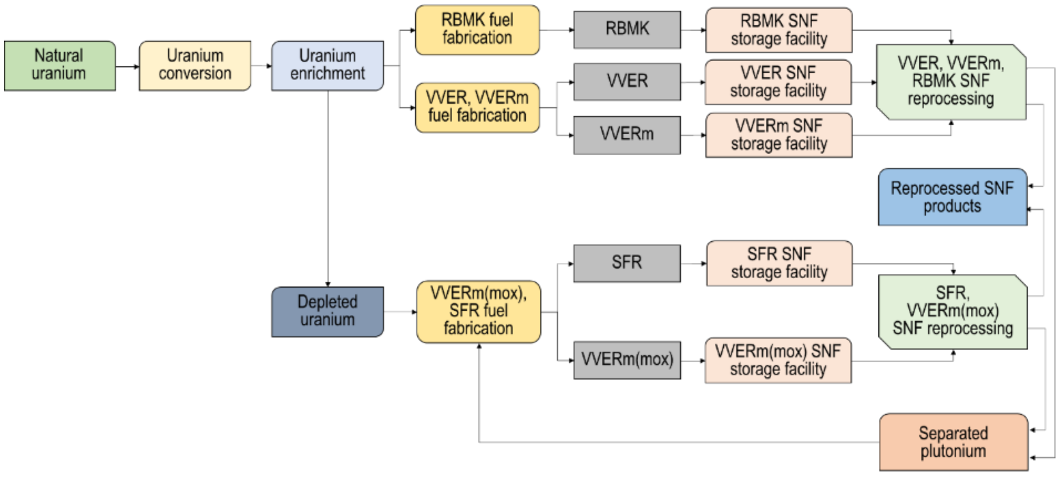
Two-component nuclear energy system

- 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.
- 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.



Source: Rosatom

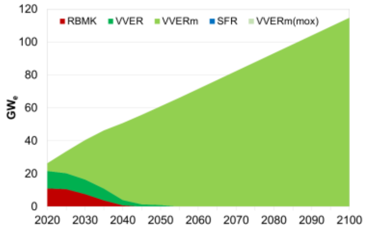


Problem statement

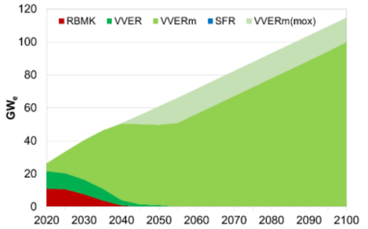
- Different NES configuration can have certain similarities and differences, and respective merits and demerits associated with each specific NES configuration can be quantified through performance and sustainability metrics characterising resource consumption, material flows in the fuel cycle, needs for fuel cycle services, economic indicators, etc., which will evolve over time.
- 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,
    - annual and cumulative needs for uranium enrichment capacities,
    - annual and cumulative needs for fuel fabrication and reprocessing capacities,
    - spent fuel stocks,
    - radioactive waste stocks,
    - amounts of plutonium in the nuclear fuel cycle,
    - amounts of accumulated depleted uranium,
    - the levelised electricity generation cost.
- Performances and sustainability metrics can be aggregated to carry out a multi-criteria comparison of the corresponding options on a quantitative basis using multi-criteria decision analysis tools.

Considered NES options

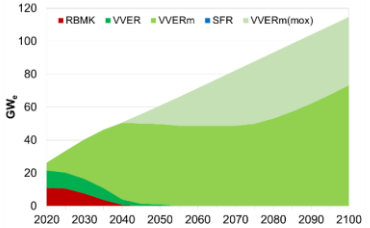
NES option	Comments
Once-through fuel cycle	
NES option 1	Share of VVERm in the NES structure in 2100 – 100%
Partly closed fuel cycle	
NES option 2	Shares of VVERm and VVERm(mox) in the NES structure in 2100 – 90 and 10%, respectively
NES option 3	Shares of VVERm and VVERm(mox) in the NES structure in 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



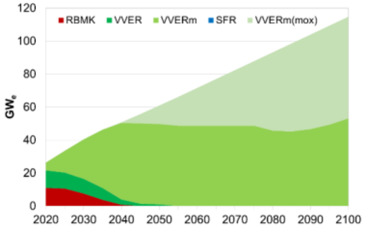
NES option 1



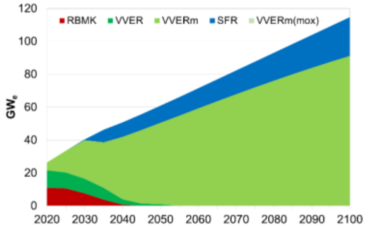
NES option 2



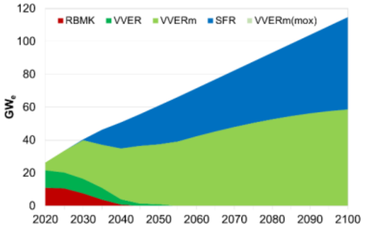
NES option 3



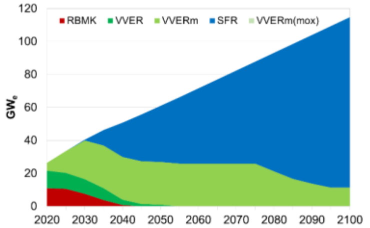
NES option 4



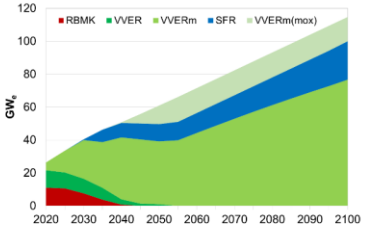
NES option 5



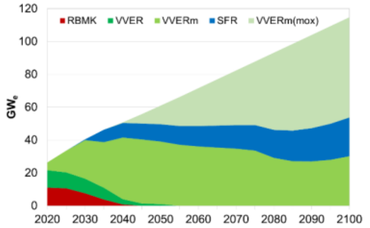
NES option 6



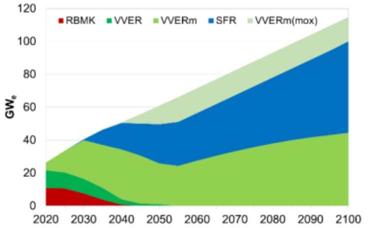
NES option 7



NES option 8



NES option 9



NES option 10

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)

Scenario assumptions

- The following assumptions were considered as the expected growth in overall NES capacities: 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).
- 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 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.
- 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. The SFR was represented in the models separately by the core and the blanket.
- The prehistory of the nuclear power deployment was accounted. No resource and infrastructure restrictions.
- The SNF cooling time is 5 years, and reprocessing would be done on a centralised basis.
- The separated plutonium accumulated by 2020 and the plutonium contained in spent fuel are resources for producing nuclear fuel for SFR and VVERm(mox).
- Regarding the overnight cost of reactors, it was 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%.

Scenario analysis approach

- To organise the systematic generation of feasible scenarios meeting the basic material balance equations, a simplified optimisation model was developed using the IAEA MESSAGE software tool. This tool 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.
- To reproduce structural or organisational details of the corresponding closed fuel cycles, another software was adapted for evaluating performance and sustainability metrics - Nuclear Energy System Modelling Application Package (NESAPP).
- The performance and sustainability metrics aggregation was carried out using the IAEA KIND-ET tool (this part of the study was carried out together with colleagues from IPPE, RF, Obninsk).

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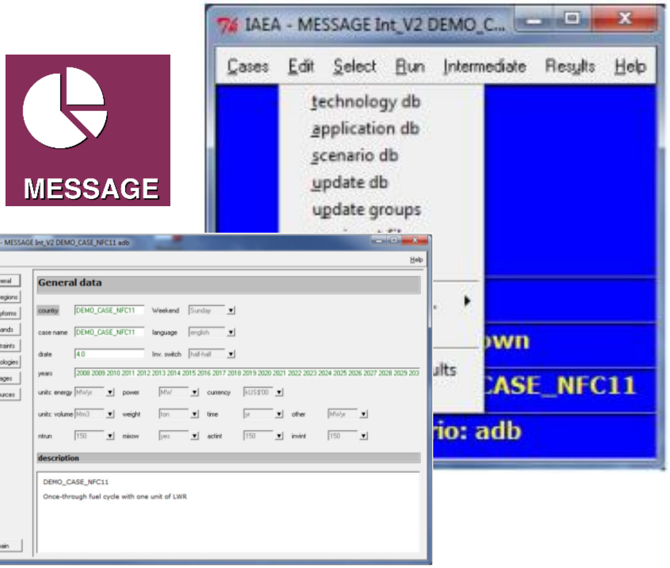


General data

country: DEMO_CASE_NFC11 — Weekend: Sunday
case name: DEMO_CASE_NFC11 — language: english
drate: 4.0 — Inv. switch: half-half
years: 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 203
units: energy: MWyr — power: MW — currency: kUS$'00
units: volume: Mm3 — weight: ton — time: yr — other: MWyr
ntrun: 150 — mixsw: yes — actint: 150 — invint: 150

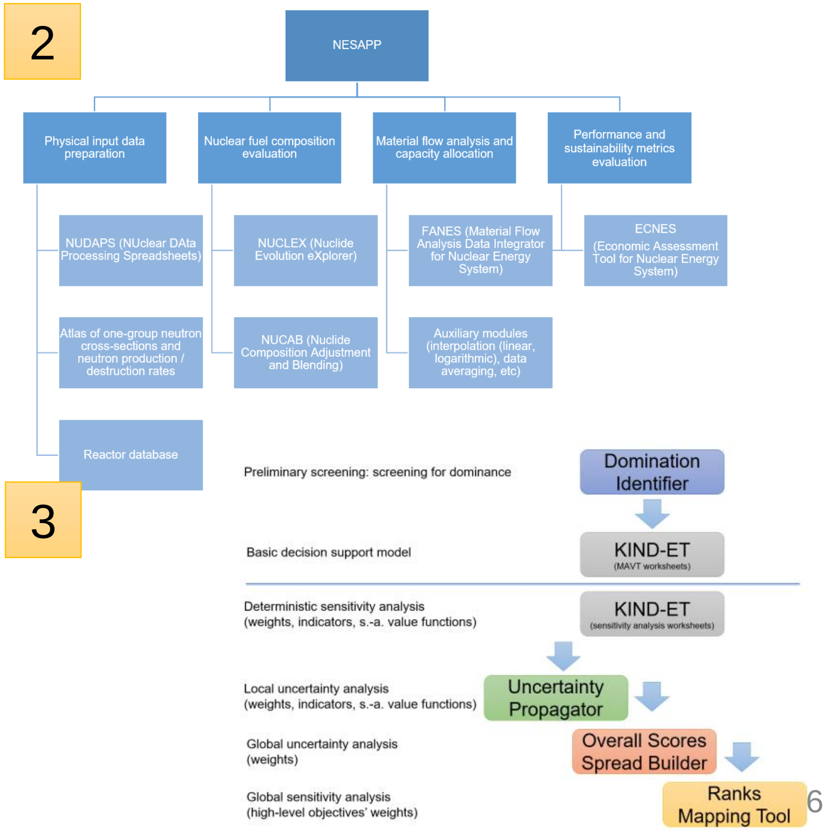
description

DEMO_CASE_NFC11

Once-through fuel cycle with one unit of LWR

2

3

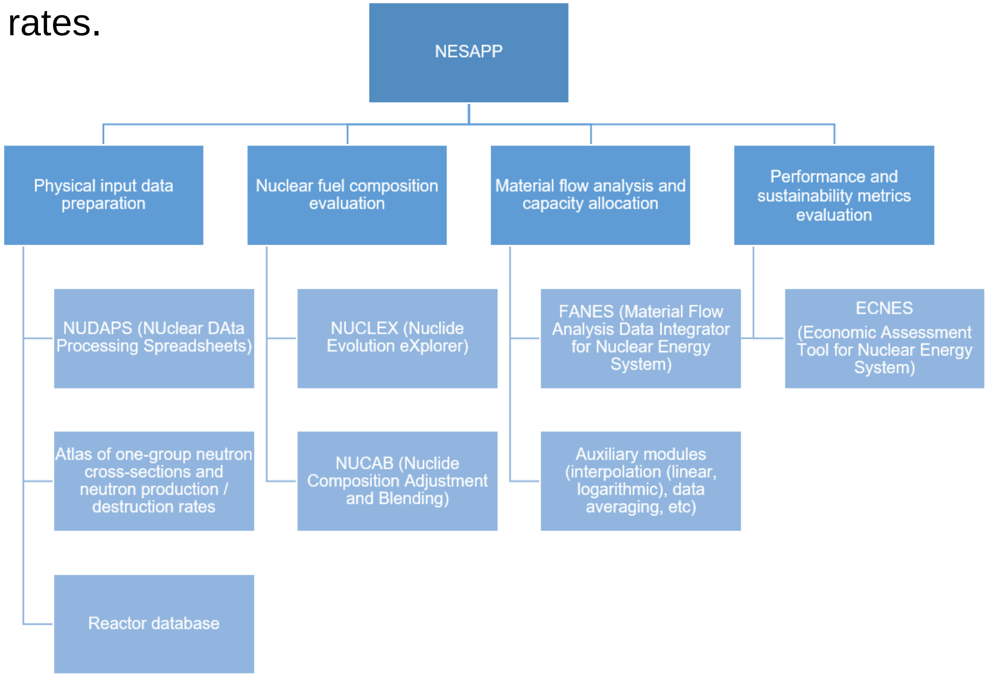

NESAPP

- Physical input data preparation
  - NUDAPS (NUclear DAta Processing Spreadsheets)
  - Atlas of one-group neutron cross-sections and neutron production / destruction rates
  - Reactor database
- Nuclear fuel composition evaluation
  - NUCLEX (Nuclide Evolution eXplorer)
  - NUCAB (Nuclide Composition Adjustment and Blending)
- Material flow analysis and capacity allocation
  - FANES (Material Flow Analysis Data Integrator for Nuclear Energy System)
  - Auxiliary modules (interpolation (linear, logarithmic), data averaging, etc)
- Performance and sustainability metrics evaluation
  - ECNES (Economic Assessment Tool for Nuclear Energy System)

Preliminary screening: screening for dominance	Domination Identifier
Basic decision support model	KIND-ET (MAVT worksheets)
Deterministic sensitivity analysis (weights, indicators, s.-a. value functions)	KIND-ET (sensitivity analysis worksheets)
Local uncertainty analysis (weights, indicators, s.-a. value functions)	Uncertainty Propagator
Global uncertainty analysis (weights)	Overall Scores Spread Builder
Global sensitivity analysis (high-level objectives' weights)	Ranks Mapping Tool

Software tool - Nuclear Energy System Modelling Application Package (NESAPP)

- **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;
- **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.


NESAPP

Physical input data preparation

Nuclear fuel composition evaluation

Material flow analysis and capacity allocation

Performance and sustainability metrics evaluation

NUDAPS (NUclear DAta Processing Spreadsheets)

NUCLEX (Nuclide Evolution eXplorer)

FANES (Material Flow Analysis Data Integrator for Nuclear Energy System)

ECNES (Economic Assessment Tool for Nuclear Energy System)

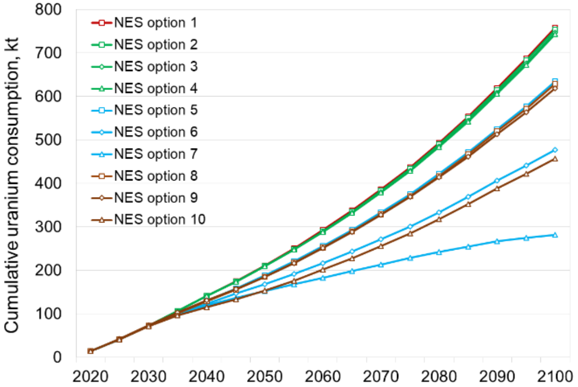
Atlas of one-group neutron cross-sections and neutron production / destruction rates

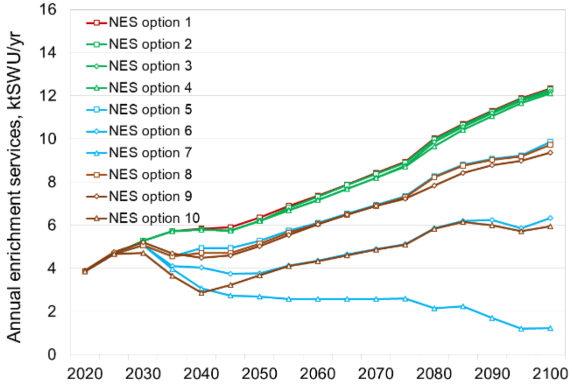
NUCAB (Nuclide Composition Adjustment and Blending)

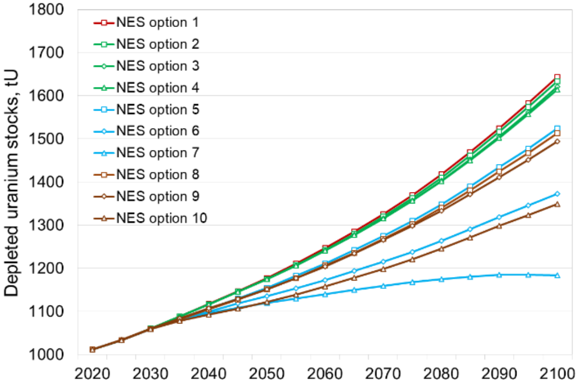
Auxiliary modules (interpolation (linear, logarithmic), data averaging, etc)

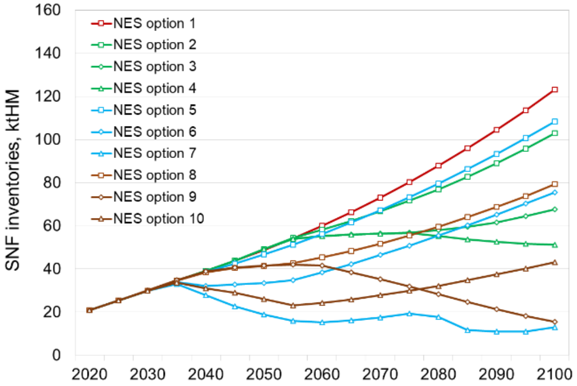
Reactor database

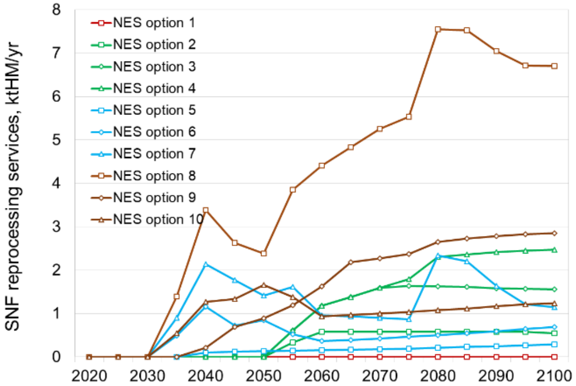
Material flows and needs for fuel cycle services

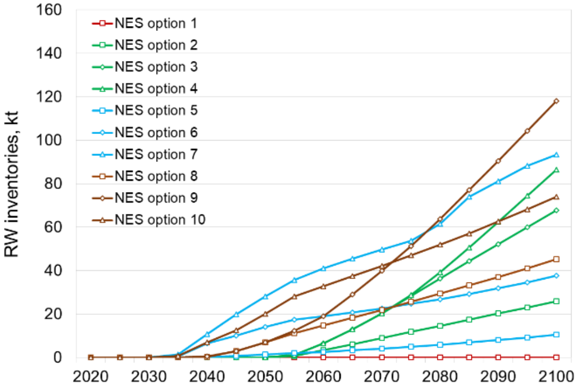


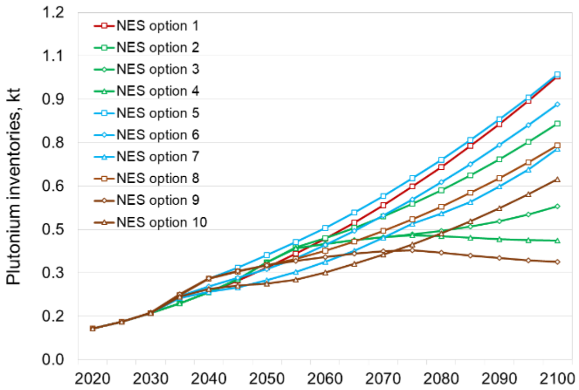


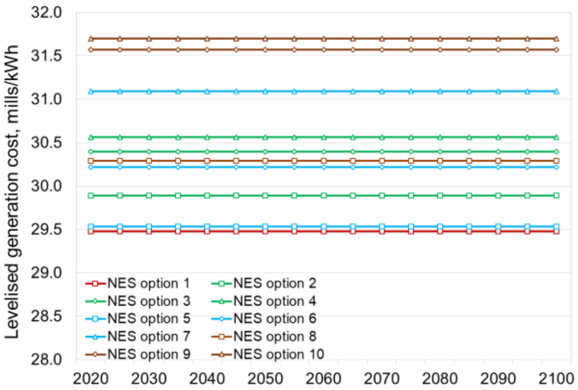




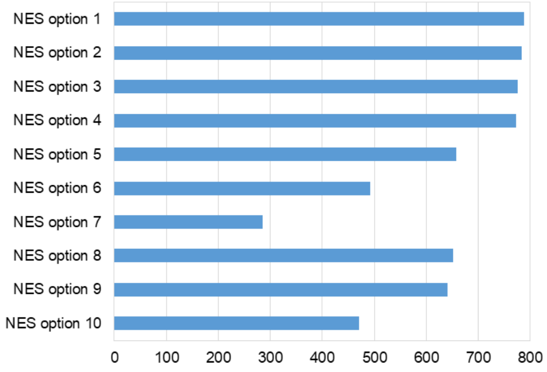




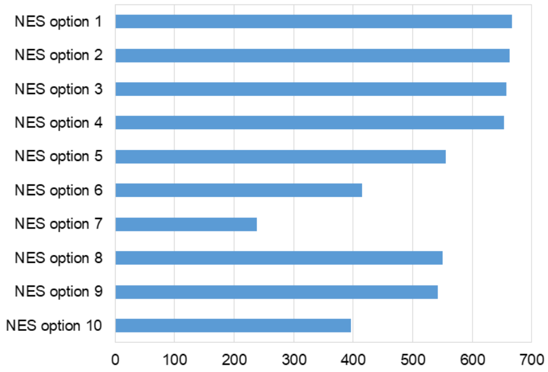




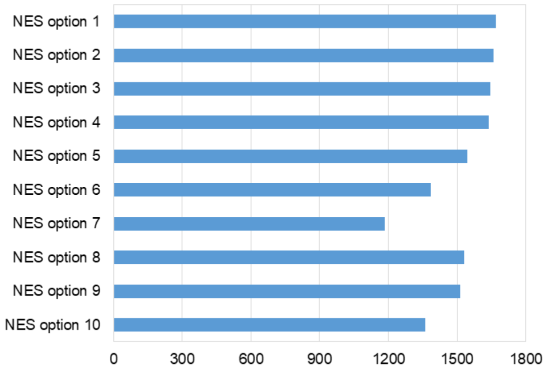
Cumulative performance data as of 2100



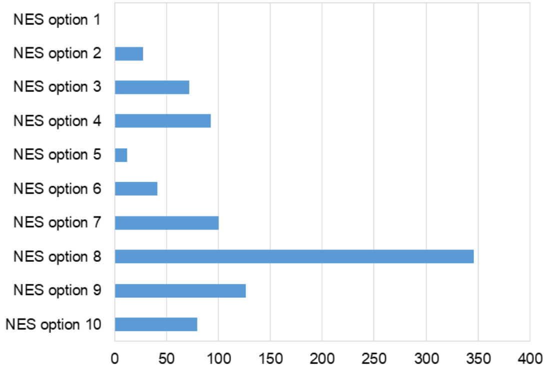
Cumulative uranium consumption, kt



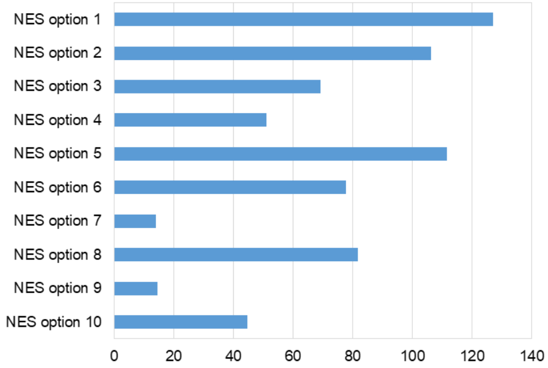
Cumulative enrichment capacities, ktSWU



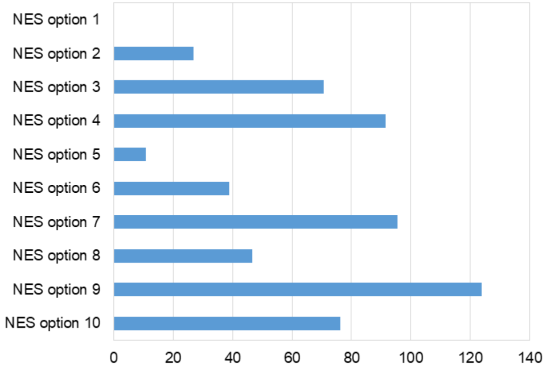
Depleted uranium stocks in 2100, kt



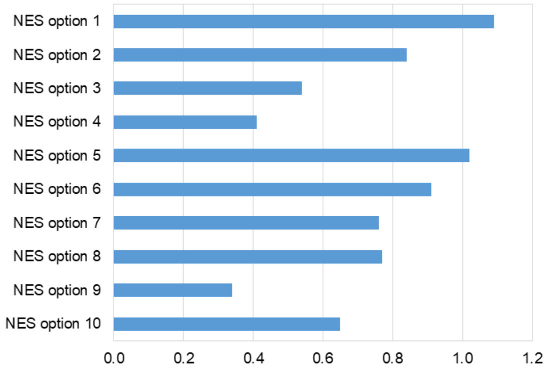
Cumulative reprocessing capacities, ktHM



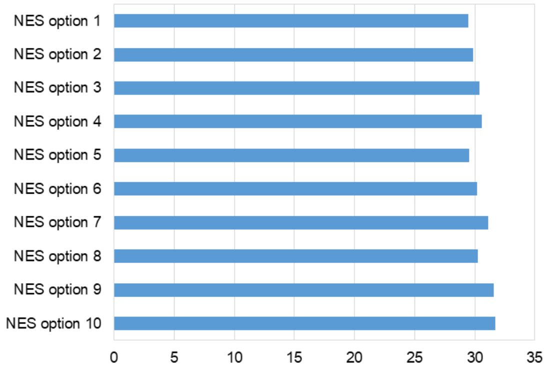
Spent fuel stocks in 2100, ktHM



RW stocks in 2100, kt

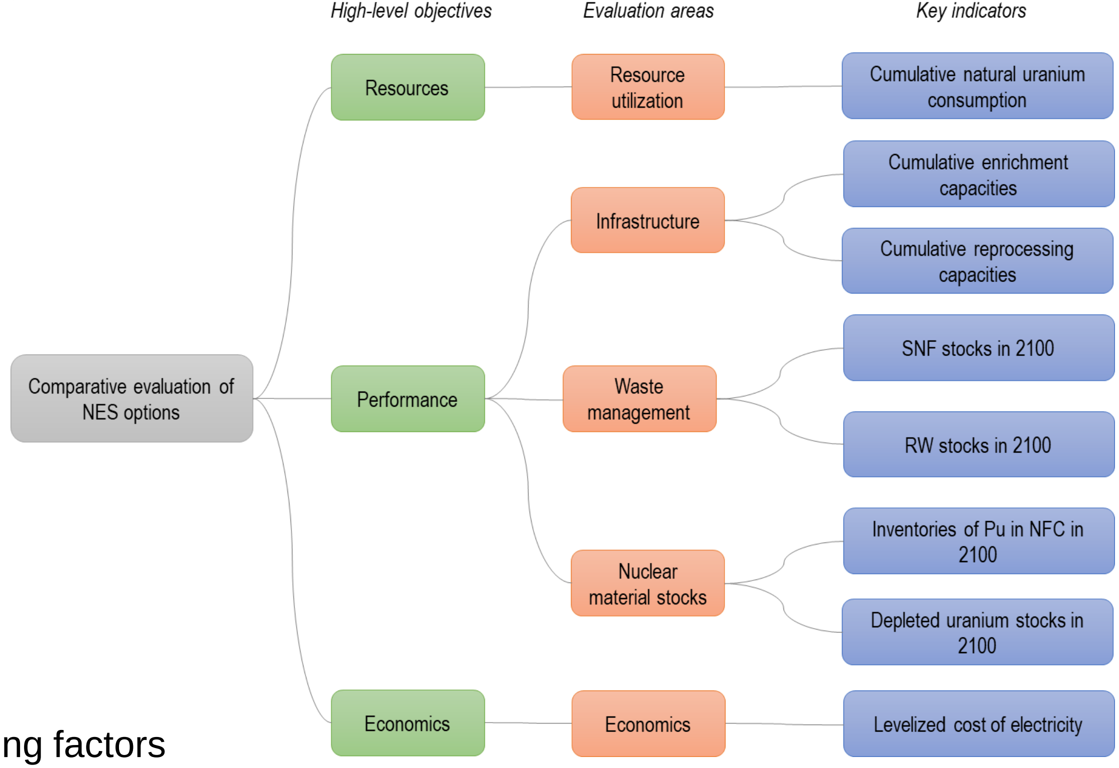


Inventories of Pu in NFC in 2100, kt



Levelised generation cost, mills/kWh

Aggregation of performance metrics



High-level objectives *Evaluation areas* *Key indicators*

Comparative evaluation of NES options

Resources

Resource utilization

Cumulative natural uranium consumption

Performance

Infrastructure

Cumulative enrichment capacities

Cumulative reprocessing capacities

Waste management

SNF stocks in 2100

RW stocks in 2100

Nuclear material stocks

Inventories of Pu in NFC in 2100

Depleted uranium stocks in 2100

Economics

Economics

Levelized cost of electricity

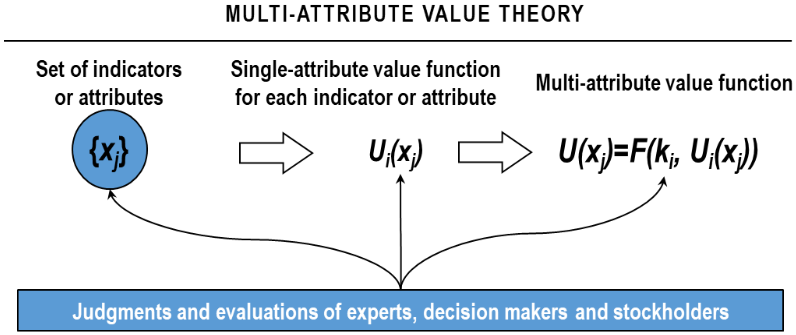
Base case weighting factors

High-level objectives	High-level objectives weights	Evaluation areas	Area weight	Key indicators	Indicator weights	Final weights
Resources	0.125	Resources	1	Cumulative uranium consumption	1	0.125
Performance	0.75	NFC capacities	0.333	Cumulative enrichment capacities	0.5	0.125
				Cumulative reprocessing capacities	0.5	0.125
		Waste management	0.333	SNF stocks in 2100	0.5	0.125
				RW stocks in 2100	0.5	0.125
		Nuclear materials stocks	0.333	Inventories of Pu in NFC in 2100	0.5	0.125
				Depleted uranium stocks in 2100	0.5	0.125
Economics	0.125	Economics	1	LGC	1	0.125

This part of the study was carried out together with colleagues Dr V. Usanov etal from IPPE, RF, Obninsk

Aggregation results

Multi-attribute value theory (MAVT) is a quantitative comparison methods used to combine different measures of costs, risks and benefits along with expert and decision-maker preferences into the high-level aggregated performance index.



MULTI-ATTRIBUTE VALUE THEORY

Set of indicators or attributes

Single-attribute value function for each indicator or attribute

Multi-attribute value function

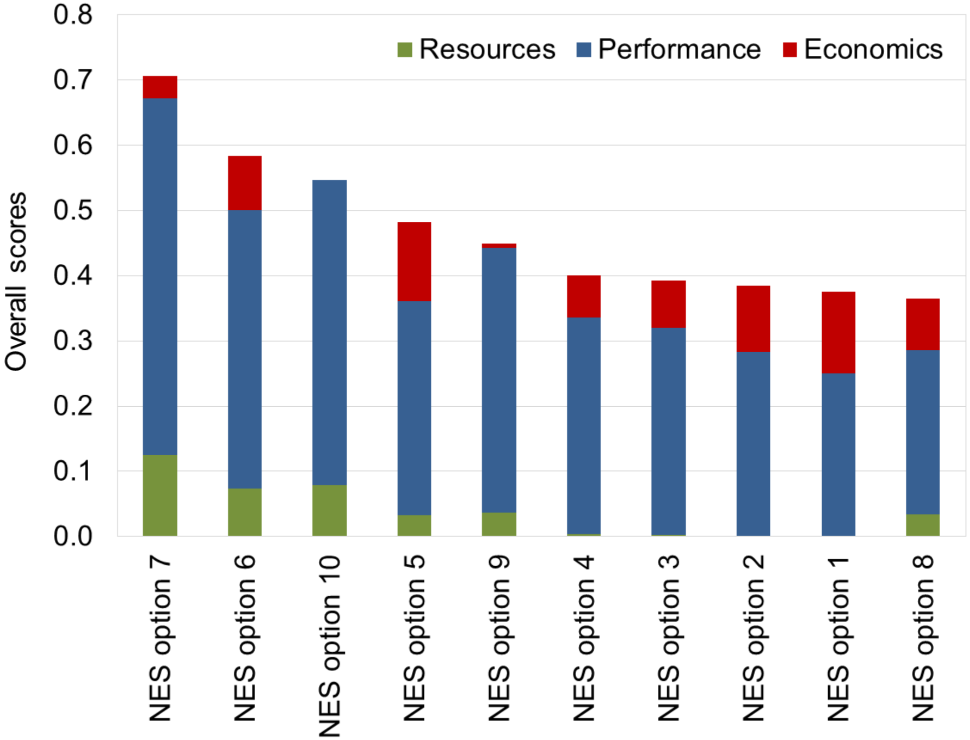
$\{x_j\}$ → $U_i(x_j)$ → $U(x_j)=F(k_i, U_i(x_j))$

Judgments and evaluations of experts, decision makers and stockholders

Type	Decreasing value functions	Increasing value functions
Linear	$V(x)=\frac{x^{\max}-x}{x^{\max}-x^{\min}}$	$V(x)=\frac{x-x^{\min}}{x^{\max}-x^{\min}}$
	Attitude to risk: risk neutral trend	
Exponential	$V(x)=\frac{1-\exp\left(a\cdot\frac{x^{\max}-x}{x^{\max}-x^{\min}}\right)}{1-\exp(a)}$	$V(x)=\frac{1-\exp\left(a\cdot\frac{x-x^{\min}}{x^{\max}-x^{\min}}\right)}{1-\exp(a)}$
	Attitude to risk: if a>0 – risk proneness trend (convex downward (concave upward) function) if a<0 – risk aversion trend (convex upward (concave downward) function)	
x^{max} and x^{min} are the minimal and maximal domain values of a single-attribute value function, which is reasonable to select as close to each other as reasonably possible to improve MAVT resolution		

Exponent power ***a*** is the ***risk proneness level***

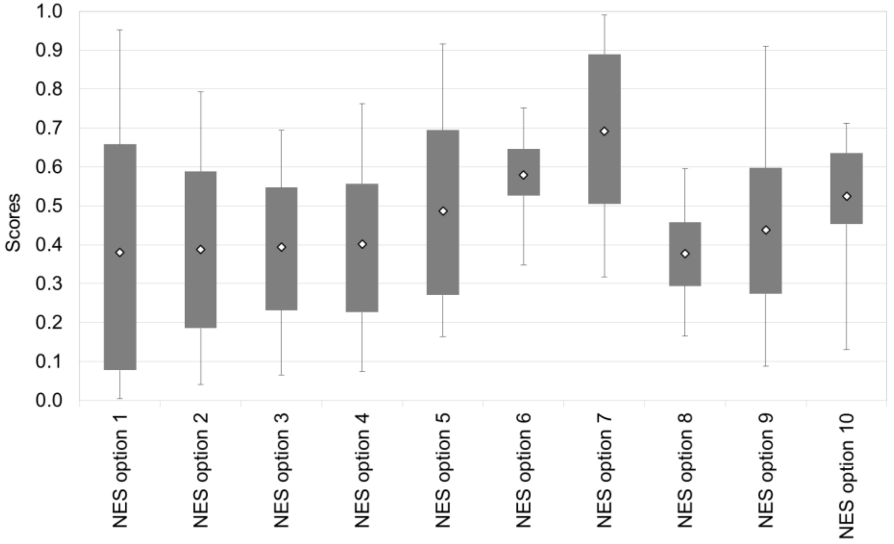
Scores for high-level objectives and overall scores



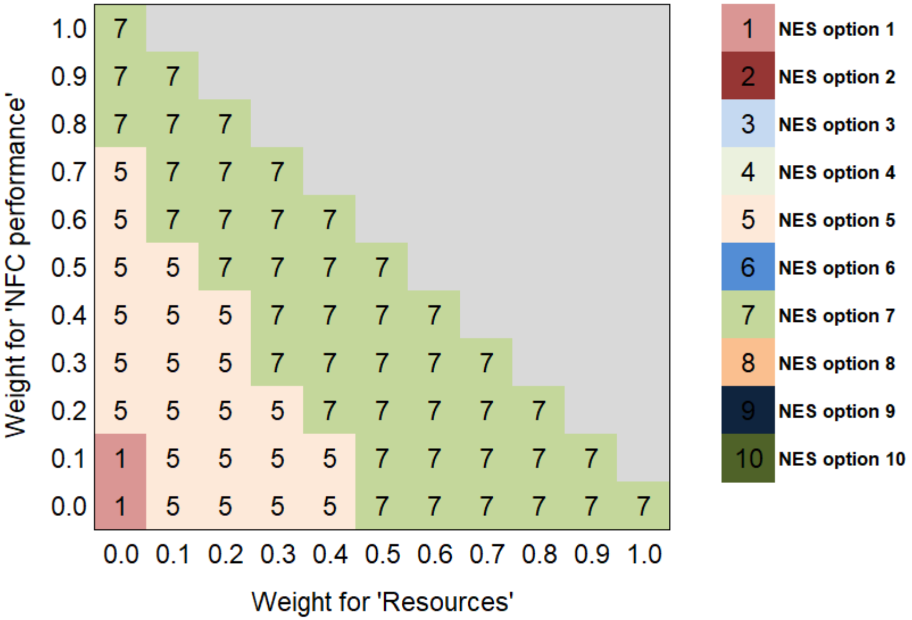
Sensitivity and uncertainty analysis

- The global uncertainty analysis was performed with respect to weights. The number of analysed weight combinations was 10 000 and it was assumed that all the weights are uniformly distributed within [0,1], provided that the sum of the weights for each combination is unity.
- The global sensitivity analysis was performed in regard to the weights of the high-level objectives in order to identify scenarios that could potentially have the first rank. The performed analysis indicates areas of the weights of the high-level objectives for which the corresponding option can take the first place in the ranking.

Spreads in overall scores



Mapping the first-rank options



Weight for 'NFC performance'	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1.0	7										
0.9	7	7									
0.8	7	7	7								
0.7	5	7	7	7							
0.6	5	7	7	7	7						
0.5	5	5	7	7	7	7					
0.4	5	5	5	7	7	7	7				
0.3	5	5	5	7	7	7	7	7			
0.2	5	5	5	5	7	7	7	7	7		
0.1	1	5	5	5	5	7	7	7	7	7	
0.0	1	5	5	5	5	7	7	7	7	7	7

Weight for 'Resources'

1	NES option 1
2	NES option 2
3	NES option 3
4	NES option 4
5	NES option 5
6	NES option 6
7	NES option 7
8	NES option 8
9	NES option 9
10	NES option 10

Results (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.
- NES option 7 is the most promising in terms of uranium consumption, needs for enrichment services, depleted uranium stocks, spent fuel inventories metrics while for the other metrics it demonstrates mediate performance.
- 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 but the other metrics become sufficiently less attractive in contrast to the options that involve utilisation of plutonium only in SFRs (this observation is also relevant for other options involving utilisation of plutonium in both thermal and fast reactors).
- All the other options do not provide any improvement in the performance metrics.
- 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.

Results (2)

- The role of MOX-fuelled thermal reactors in the two-component NES was not clearly revealed. The results confirm the thesis that, if fast reactors are expected to be deployed 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.
- 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).
- 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.
- 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 performance, taking into account the Sustainable Development concept requirements.

Conclusion

- 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.
- Some issues for further considerations were highlighted, which will lead to more rigorous conclusions regarding the preferred options for the development of the national nuclear energy system.

Thank you for your time!