Performance and sustainability assessment of nuclear energy deployment scenarios with fast reactors: advanced tools and application

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Abstract. The paper presents the toolkit developed in the National Research Nuclear University MEPhI for a performance and sustainability assessment of nuclear energy deployment scenarios with fast reactors providing a solution to the problem of optimizing and comparing nuclear energy deployment scenarios with fast reactors in multiple criteria formulation. Some results of this toolkit implementation to assess the performance and sustainability of nuclear energy deployment scenarios with fast reactors demonstrate that technologically diversified nuclear energy structures in which several different fast reactor technologies are used may produce a synergetic effect in terms of nuclear energy system sustainability and performance improvement.

Key Words: fast reactors, nuclear energy system deployment scenarios, multi-objective decision-making

1. Introduction

A performance and sustainability assessment of nuclear energy system (NES) deployment scenarios with fast reactors is a multi-criteria problem determined by a wide spectrum of criteria characterizing resource consumption, economic performance, proliferation risks, safety and waste management aspects, etc. In determining the most promising scenario, it is necessary to consider the conflicting nature of the criteria because an improvement in one of the criteria causes, as a rule, a deterioration of values in the others. Thus, there is a need to use multiple criteria decision-making methods [1-4].

Multiple criteria decision making (MCDM) is a tool to help decision makers to highlight conflicts and perform proper trading-off during the decision making process [5,6]. A multi-criteria decision analysis (MCDA) and multi-objective decision-making (MODM) constitute the main components of multiple criteria decision-making. Although tasks that can be solved using these methods are different, their combined use seems to be appropriate to identify the most suitable and balanced NES deployment scenarios with fast reactors despite various contradiction criteria.

The both groups of methods may be applied to assess the performance and sustainability of NES deployment scenarios with fast reactors by searching for compromises between the conflicting criteria that determine the NES deployment scenarios and selecting the trade-off option to carry out multi-objective optimization of NES structures, taking into account the NES evolution, the structure and the organization of nuclear fuel cycle (NFC) and the most important system constraints and restrictions.

The paper presents the toolkit developed in the National Research Nuclear University MEPhI for a performance and sustainability assessment of NES deployment scenarios with fast reactors providing a solution to the problem of optimizing and comparing NES deployment scenarios with fast reactors in multiple criteria formulation. Some trial results of implementation of this toolkit for the performance and sustainability assessment of NES deployment scenarios with fast reactors are presented.

2. Complementary Application of Multiple-Criteria Decision-Making for Performance and Sustainability Assessment of NES Deployment Scenarios with Fast Reactors

MCDA and MODM constitute the main components of MCDM (Table I). The major distinction between MCDM problems is based on whether the solutions are defined explicitly or implicitly. Properly organized studies based on the multi-criteria decision making framework represent a complex practice not only formally operating with a set of mathematical methods and various analytical tools but also leading to a comprehensive understanding of the problem and its elaboration.

TABLE I: SOME OF THE MOST COMMONLY USED MCDM METHODS.

MCDA methods	MODM methods
Elementary methods ▪ Simple additive weighting ▪ Kepner-Tregoe method	No preference methods ▪ Global criteria ▪ Goal programming
Value based methods ▪ MAVT ▪ MAUT ▪ AHP	A priory methods ▪ Criteria constrains method ▪ The achievement scalarizing function ▪ The weighted sum
Outranking methods ▪ ELECTRE ▪ PROMETHEE	A posteriori methods ▪ ADBASE ▪ Normal constraint method ▪ Directed search domain
Reference point based methods ▪ TOPSIS ▪ VIKOR	Adaptive and interactive methods ▪ Genetic algorithms (NSGA-II, MOCHC, etc.) ▪ Feasible and Reasonable goals methods ▪ Parameter space investigation (PSI) method

In the MODM problems, the alternatives (NES deployment scenarios) are not explicitly known. An alternative can be found by solving a corresponding optimization problem. The number of alternatives may be either infinite or not countable (when some variables are continuous) or typically very large, if countable (when all variables are discrete). Essential to this family is the concept of a set of non-dominated alternatives. The non-dominated set of alternatives is informally defined as a set of alternatives for which the value of any one among the specific optimality criteria may only be improved by degrading at least one of the remaining criteria. Thus, any alternative belonging to the non-dominated set will not be improved by all the specific optimality criteria simultaneously.

The MCDA problems consist of a finite number of alternatives, represented by their performance on multiple criteria. The problem may be defined as searching for the best alternative from the decision-maker viewpoint or finding a set of suitable trade-off among alternatives. In general, MCDA will be applied to the following problem: given a set of M alternatives and N criteria for their assessment, where each of the alternatives is evaluated by experts or through objective calculations. A decision rule must be found based on the experts' preferences, which allows ranking all the alternatives according to their values and identifying the most suitable trade-off one among them.

A consistent application of the MODM and MCDA methods makes it possible to realize a full cycle activities related to the identification of the most preferable NES options including the following two major steps (Fig.1).

Firstly, to identify the non-dominated (trade-off, efficient) NES structures based on given sets of restrictions, projections, and other model assumptions. These NES structures cannot be improved simultaneously on the whole set of performance criteria – absolutely unsatisfactory (worst) NES structures will be excluded from consideration and only non-dominated (trade-off, efficient) ones will be kept for further consideration. The number of such structures is in orders of magnitude less those ones which can be improved. Thus, MODM methods allow providing a primary screening of all options and dropping out undoubtedly unsatisfactory ones that narrow significantly the space of possible NES structures for a final examination related to selection of the most suitable NES structure or determine based on an information about trade-off curves the directions for structural changes in the NESs to increase their performance and sustainability. It should be noted that these directions are cost-effective (ensuring the maximum possible effect with minimum costs).

Secondly, to make the final selection of the most suitable NES structure from the primarily screened non-dominated ones by means of the MCDA methods taking into account experts and decision-maker judgments and preferences. Note that the MCDA does not provide the totally “best” structure because the structure can be more or less effective dependent on the stated objective. This two-step procedure is used within the NRNU MEPhI studies on performance and sustainability assessment of NES deployment scenarios with fast reactors.

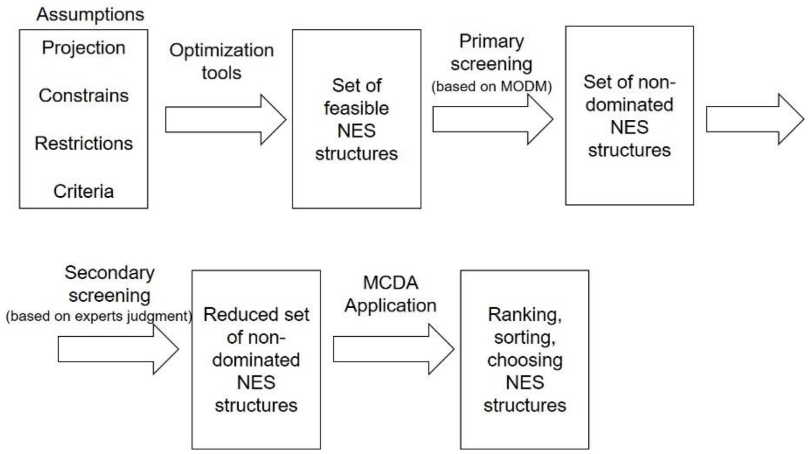

FIG. 1. Consistent approach to comparative evaluations of NES deployment scenarios based on combined use MODM and MCDA methods

3. Toolkit for Performance and Sustainability Assessment of NES Deployment Scenarios with Fast Reactors based on the Multi-Objective Analysis Framework

To implement the MODM methods for the dynamic optimization problems, serial calculations should be carried out with different NES model parameter values. Developing a dynamic NES model is a separate task to be solved using a large number of available software packages. One of such packages to be used for performing analytical studies in the area of NES performance and sustainability assessment is the IAEA software package MESSAGE. MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts) is a large-scale dynamic system engineering optimization model developed for middle- and long-term energy planning, energy politics analysis and scenario development [7]. This tool allows the users to formulate linear programming problems, find optimal solutions, and process the calculation results.

At the NRNU MEPhI, six additional modules were developed for multi-objective optimization and uncertainty accounting within the MESSAGE software package as stand-alone software products expanding the spectrum for possible MESSAGE applications [8]:

- Criteria constraints method (CCM) applying the method of criteria constraints
- Pareto set approximation module (ParSAM) implementing the reasonable goals method
- NES specification module (NESI) providing specification of NES components
- GRS module implementing an uncertainty analysis based on GRS method
- RFC module applying the stochastic approach to taking into account risks associated with cost underestimation for new technologies
- Robust optimization module (ROM) realizing the robust optimization method

The developed computational modules for the MESSAGE software package make it possible to determine compromise NES development strategies due to a combination of conflicting system factors and taking account of uncertainties in the main technical and economical parameters of a system. They provide the possibility of formulating more substantiated and balanced judgments about the attractiveness of possible NES structures due to taking account of all factors which produce both positive and negative effects on the NES deployment in the comparison of various development options.

A set of basic MESSAGE-models was developed for evaluation of NES deployment scenarios based on once-through and closed NFCs adapted for multi-objective optimization problems and material flow calculations in the NFCs of steady-state and developing NESs at the national levels. The elaborated MESSAGE NES models were discussed at the IAEA workshops on analytical tools for development of sustainable energy strategies; they allow evaluating the NFC material flows, requirements for NFC goods and services, economic performance indicators; they can also be used for multi-objective, robust and stochastic optimization which allows us to solve problems on nuclear energy planning in multi-objective formulation taking into account associated uncertainties.

In addition, a set of classical MCDA methods (simple additive weighting, MAVT/MAUT, AHP, TOPSIS, PROMETHEE) were adapted for comparing NES deployment scenarios and selecting the most attractive option taking into account the recommendations of the INPRO/IAEA project on Key Indicators for Innovative Nuclear Energy Systems [3]. These methods are widely used to support decision-making in different subject areas, including nuclear engineering and, in particular, for a comparative analysis of NES deployment scenarios.

4. Trial Results of the Toolkit Application

In this paper, the trial results of the proposed consistent approach and software tools for a comparative evaluation of the NES deployment scenarios with fast reactors are presented in order to demonstrate the potential of the toolkit for screening and ranking of the NES options on the example of a hypothetical Russian NES model. Fig. 2 shows the structure of a hypothetical Russian NES model with different fast reactors in the closed NFC. Based on this model, a search for balanced NES structures was carried out according to a set of conflicting criteria which may determine cost-effective NES structures facilitating natural uranium saving and reducing SNF volumes and proliferation risks associated with fissile materials and capacities for their production. All the assumptions made (electricity demand, uranium ore resources, NFC specific features, etc.) are described in [9].

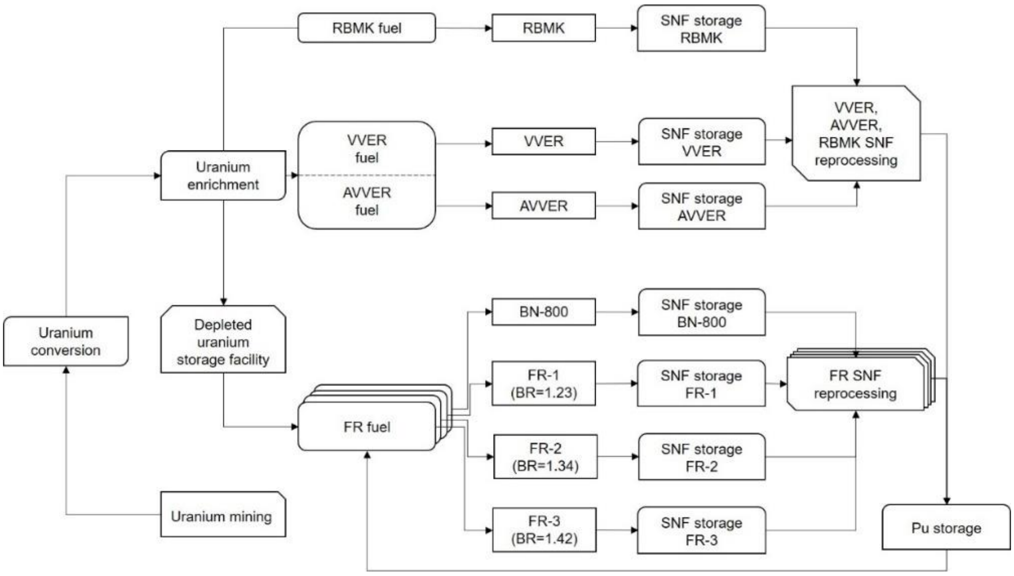

FIG. 2. Flowchart of a hypothetical Russian NES with different fast reactors.

Applying different approaches to multi-objective optimization of NES structures, non-dominated scenarios were identified for different scenario assumptions and criteria (consumption of natural uranium, accumulated volume of SNF, levelized unit electricity cost, proliferation risk index, capacities of enrichment and reprocessing facilities), it was observed that the majority of non-dominated NES structures are technologically diversified. It means that, in such NES structures, several different fast reactor technologies are present which produce a synergetic effect in terms of NES sustainability and performance improvement.

The technologically diversified NES structures with different fast reactor types seem to be trade-off options balanced for different costs and risks which can provide cost-effective risk mitigation measures (ensuring the maximum possible effect with minimum costs) without any external constraints added to the model. In general, the technologically diversified NES structures include a larger number of reactor technologies as compared with the NES structures resulted from the deterministic approach and they are more stable towards uncertainties in the model parameters. Fig.3 demonstrates six different examples of possible non-dominated scenarios: I is a reference once-through NFC option, II-VI assumes closed NFC and fast reactors.

Among non-dominated technologically diversified NES deployment scenarios with thermal and fast reactors for illustration of the next step of the consistent approach, the following four options are considered with different SNF management options taking into account an approach and data presented in [10]:

- Thermal and fast reactors without thermal reactors SNF reprocessing
- Thermal and fast reactors with only VVER SNF reprocessing
- Thermal and fast reactors with only VVER SNF reprocessing delayed by 30 years
- Thermal and fast reactors with complete thermal reactors SNF reprocessing

The following six performance indicators were assessed and used for the comparison:

- Integral consumption of natural uranium
- Accumulated volume of SNF/HLW for final disposal
- Integral SNF reprocessing volume
- Integral absolute expenditures
- Reserve for handling the SNF/HLW
- Fuel component of the levelized unit electricity cost

A comparative evaluation was performed based on different MCDA methods (simple scoring Model, MAVT/MAUT, AHP, TOPSIS, PROMETHEE) in accordance with the recommendations elaborated within the INPRO/IAEA project on Key Indicators for Innovative Nuclear Energy Systems [3].

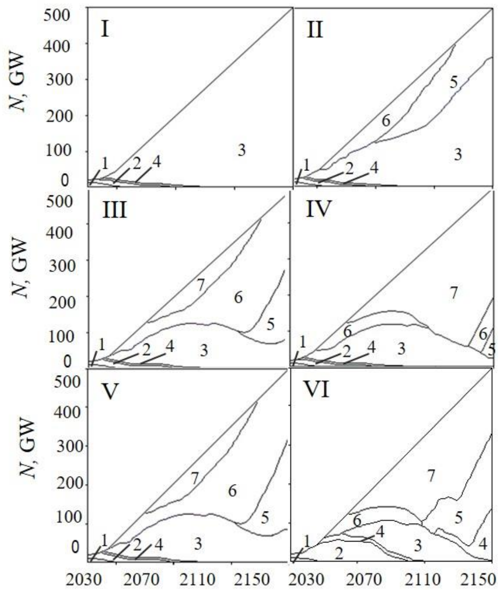

FIG. 3. Example of six non-dominated technologically diversified NES structures: 1 – RBMK, 2 – VVER, 3 – AVVER, 4 –BN-800, 5 – FR-1, 6 – FR-2, 7 – FR-3.

Within the MCDA-based comparative evaluation of four options for SNF management in the closed NFC, it is observed that only VVER SNF reprocessing options seem to be more promising ones in comparison to others under the assumptions made. In the case of increasing the importance of economic performance indicators in comparison with other ones, it seems reasonable to delay the large-scale VVER SNF reprocessing. Taking into account the uncertainties in the weights within a multi-attribute model made it possible to rank the scenarios in the absence of information regarding the relative significance of performance indicators and determine the preference probability for a certain NES deployment scenario (Fig.4).

It is also observed that the use of different MCDA methods (simple scoring Model, MAVT/MAUT, AHP, TOPSIS, PROMETHEE) to compare the NES deployment scenarios, despite some differences in the rankings, leads to well-coordinated and similar results. Based on the sensitivity analysis results and additional analysis of alternatives as well as the whole set of graphical and attribute data, it is possible to identify the most promising NES deployment scenario.

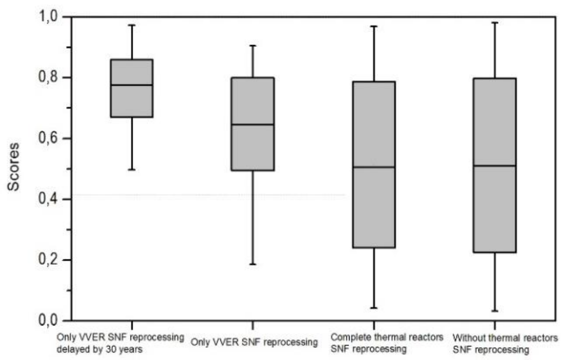

FIG. 4. Ranking results for SNF management in the closed NFC taking into account uncertainties.

5. Conclusion

The paper presents the toolkit developed in the National Research Nuclear University MEPhI for a performance and sustainability assessment of NES deployment scenarios with fast reactors providing an examination of the problem on optimizing and comparing NES deployment scenarios with fast reactors in multiple criteria formulation. Some results of implementation of this toolkit for the performance and sustainability assessment of NES deployment scenarios with fast reactors are presented which demonstrate that technologically diversified NES structures in which several different fast reactor technologies are used may produce a synergetic effect in terms of nuclear energy system sustainability and performance improvement.

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