APPLICATION OF MULTI-CRITERIA DECISION ANALYSIS METHODS TO COMPARATIVE EVALUATION OF NUCLEAR ENERGY SYSTEM OPTIONS

INPRO Collaborative Project "Key Indicators for Innovative Nuclear Energy Systems" KIND

EXECUTIVE SUMMARY

IAEA

INPRO

International Project on Innovative Nuclear Reactors and Fuel Cycles

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Summary

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was established in 2000 to help ensure that nuclear energy is available to contribute to meeting the energy needs of the 21st century in a sustainable manner. INPRO focuses on key issues of global sustainability of nuclear energy, with the aim of assisting in the development of long term nuclear energy strategies.

This brochure presents the main findings of the INPRO collaborative project 'Key Indicators for Innovative Nuclear Energy Systems' (KIND). It was undertaken within the INPRO area on 'global scenarios', which analyses regional and global nuclear energy scenarios to achieve a global vision of how nuclear energy could be sustainable within the present century.

The project was implemented in 2014–2017 by experts from 16 IAEA Member States. The final report of the project was published in the IAEA Nuclear Energy Series in 2019 [1].

The KIND collaborative project developed guidance and tools (the approach) for comparative evaluation of the status, prospects, benefits and risks associated with the development of innovative nuclear technologies for the more distant future. It also examined the applicability of such an approach to other problems, including those of interest to technology users and newcomer countries. The approach is based on a limited number of key indicators in subject areas of the INPRO methodology for NES sustainability assessment and the application of state of the art judgement aggregation and sensitivity/uncertainty analysis methods.

Within the KIND collaborative project, a number of case studies were carried out on comparative evaluations of hypothetical nuclear energy system (NES) options, namely, NESs based on pressurized water reactors (PWR), heavy water reactors (HWR), sodium cooled fast reactors (SFR), lead cooled fast reactors (LFR), molten salt reactors (MSR), accelerator driven systems (ADS) with associated fuel cycles, as well as on comparative evaluation of nuclear energy evolutions scenarios and nuclear versus non-nuclear energy options. These case studies demonstrated applicability of the KIND approach and toolkit for evaluation of merits and demerits associated with the energy system options under consideration.

1. Introduction

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), currently being implemented, is an integral part of the regular programme of the International Atomic Energy Agency (IAEA). Its objectives are to:

- help ensure that nuclear energy is available to contribute, in a sustainable manner, to the energy needs of the 21st century; and
- bring together technology holders and users to consider jointly the international and national actions required for achieving desired innovations in nuclear reactors and fuel cycles.

The INPRO's concept of a sustainable nuclear energy is derived from the United Nations (UN) sustainable development concept [2]:

> *"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs".*

Based on this concept, INPRO has developed a methodology for detailed assessment of sustainability of nuclear energy systems (NES), which helps identify the sustainability related gaps in the existing or planned NES. The key assessment areas include Economics, Infrastructure, Waste Management, Proliferation Resistance, Environment (Stressors and Resources), Safety of Reactors and Safety of Fuel Cycle.

A sustainable NES should be resource self-sufficient and cost-effective, have minimum burden of nuclear wastes, ensure effective proliferation resistance and maintain the appropriate level of safety, security and reliability, and is governed, regulated and managed by competent institutions, and supported by resourceful infrastructure and crosscutting research. Multiple opportunities exist in all these aspects to improve the sustainability of an NES. A comprehensive decision-making support is required for comparative evaluations the alternative options and selection of the most promising solution.

Assessments using the INPRO methodology require reasonably detailed design information for the components of a NES. For evolutionary systems, such information is typically available, whereas for future innovative NESs, that are still under development, sufficient information for a full-scope INPRO assessment is generally lacking. Moreover, the INPRO methodology is not intended for comparative evaluation of NESs.

To overcome this difficulty, the INPRO collaborative project *"Key indicators for innovative nuclear energy systems"* (KIND) developed guidance and tools for comparative evaluations of the status, prospects, benefits and risks associated with the different options for development of nuclear energy systems, including future innovative systems.

The KIND approach is based on the application of key indicators to reflect assessment areas of the INPRO methodology, and a multi-criteria decision analysis method to aggregate individual aspects to derive the overall evaluation of the alternatives. This leads to a comprehensive elaboration and understanding of the decision-making problem together with decision analysis by various mathematical methods and analytical tools. The project also explored application of the KIND approach to a variety of problems, including comparative evaluation of nuclear energy scenarios, and nuclear versus non-nuclear energy options.

The methodology for the KIND approach was selected by taking into account the lessons learned and the best practices in the multiple criteria decision-making applications for nuclear engineering as well as the most significant recent findings in decision support [3 – 9]. The KIND approach, thus, represent as a state-of-the-art method for comparative evaluations of NES options and related issues.

At the moment, the KIND approach is being extensively applied for comparative evaluations of various NES options at the scenario and technological levels, comparisons of nuclear fuel supply and waste management options, examination of cross-cutting issues that demonstrate the potential of the elaborated toolkit for decision support within a wide landscape of different practical nuclear engineering problems requiring expert judgment aggregations. The developed approach was found useful for establishing a productive dialogue between energy-option proponents and decision makers regarding sustainable nuclear energy options.

This brochure presents a short summary of the KIND approach and tools and the main conclusions of the KIND collaborative project.

2. Why is it important to perform comparative evaluation of NES/scenario options: Member States needs

One of the first activities of INPRO was to develop a detailed methodology for assessing the sustainability of a nuclear energy system (NESA). However, the INPRO methodology does not provide an approach for comparative evaluation of NES options.

A variety of innovative technologies to support future sustainable NESs are being developed in many countries worldwide. With multiplicity of such developments, the technology developer countries need to evaluate the performance of the innovative NES versus other innovative or established NES to prioritize/adjust the national efforts and R&D resource allocations for development of innovative nuclear technologies to support sustainable and cost-effective NES deployment. Such evaluations have to be performed for innovative technologies for which technical and economic data are not available in sufficient details. The evaluation, thus, has to be based on experts estimates and also by taking into account preferences of decision-makers and stakeholders. Different experts and stakeholders, however, may have different opinions which should be reflected in the evaluation process and methodology and aggregated to derive the overall evaluation of alternative options.

The technology user countries may be less interested in technical innovations and more interested in comparative choices of more mature evolutionary NES and relevant scenarios. However, if a technology user country performs R&D studies, it may have interest in some innovative elements. Newcomer countries typically need to make comparative choices of nuclear versus other means of energy production.

All countries may face a need to evaluate advantages and disadvantages of the various plausible NES options/scenarios compared under different circumstances and to derive their overall ranks, considering the NES performance, as well as experts' and decision makers' judgments and preferences.

Responding to Member States need, the KIND collaborative project developed guidance and tools for comparative evaluation of the status, prospects, benefits and risks associated with development of innovative nuclear technologies for a more distant future and examined the applicability of such approach to other problems, including those of interest to technology user and to newcomer countries.

3. Multi-criteria decision analysis

Multi-Criteria Decision Analysis (MCDA) is a method designed to help decision-makers conduct evaluations of alternatives characterized by numerous and conflicting factors influencing the status and evolution of a system and find compromises in the decision-making process. The MCDA problems include a finite number of alternatives explicitly known at the beginning of the decision-support process. Each alternative is represented by its performance in multiple attributes and respective criteria.

A large number of MCDA techniques (value-based, outranking, reference-based, other/hybrid methods) have been developed to deal with different kinds of decision-support problems, see Fig. 1a. These techniques help ranking and sorting the relevant options under consideration and selecting the most promising trade-off. Within the MCDA framework, special attention is paid to analysis of the solution's stability against variations of various parameters and the method used.

Within the MCDA framework, the decision support process starts with identification of the decision-maker, the group of subject-matter experts and the stakeholders (persons interested in a certain decision), and further goes through the following steps, Fig. 1b: problem formulation and structuring, formation of alternatives, identification and evaluation of criteria and attributes, selection of the MCDA method, performance of MCDA analysis to derive ranks of the compared NES/ scenario options, sensitivity/uncertainty analysis to clarify stability of the ranking results, final conclusions and recommendations.

Some MCDA methods

Elementary methods
- Simple additive weighting
- Kepner-Tregoe method
- etc.

Value-based methods
- MAVT
- MAUT
- AHP
- etc.

Outranking methods
- ELECTRE
- PROMETHEE
- QUALIFLEX
- etc.

Reference point based methods
- TOPSIS
- VIKOR
- BIPOLAR
- etc.

a)

b)

Fig. 1. Scope (a) and schematics (b) of multi-criteria decision analysis.

The KIND collaborative project, after reviewing the various MCDA methods for a comparative evaluation of the NES performance and sustainability [1, 4], selected the multi-attribute value theory (MAVT) as a basic method for NES comparative evaluations. A vast experience of applying this method exists for comparative evaluation of options on the basis of several attributes, as summarized in [1].

MAVT is a quantitative comparison method used for combining different measures of costs, risks and benefits as well as expert and decision-maker preferences into an overall score, i.e., a multi-attribute value function, see Fig. 2. The MAVT method is based on the use of single-attribute value functions. These functions transform diverse indicators evaluated in 'natural' scales to one common, dimensionless scale in accordance with expert judgments and decision-maker preferences. The single-attribute value functions are weighted according to the relative importance of their indicators. To identify the preferred alternative, the normalized score of each alternative is multiplied by the corresponding weighting factor to obtain the overall score, which indicates the overall rank of the alternative: the preferred alternative will have the highest overall score.

Since the MAVT method is easily adjustable and allows implementation of different approaches to comparison and differentiation of the alternatives, the KIND project developed an analytical tool based on the MAVT method, specially designed to support comparison of NES alternatives, named the KIND Evaluation Tool (KIND-ET) [1].

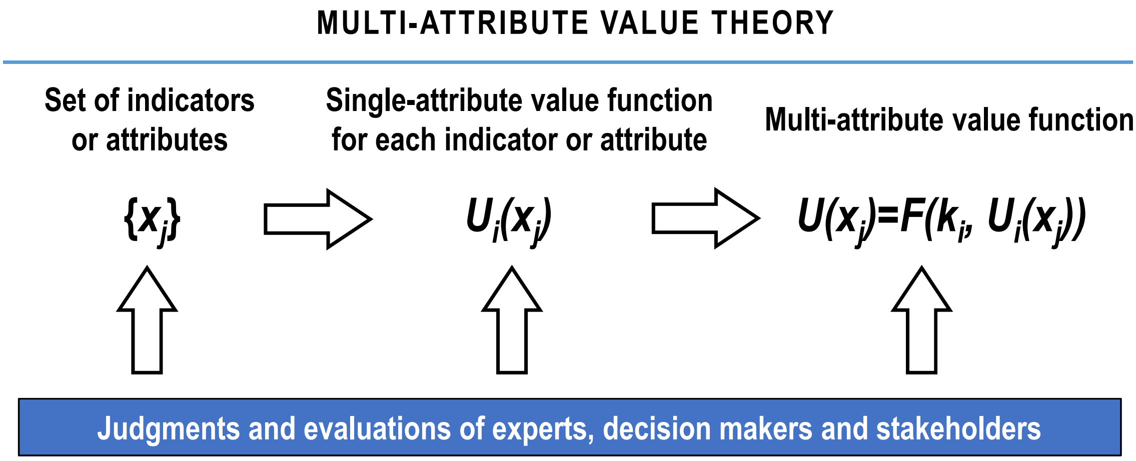


Fig. 2. Schematics of MAVT.

4. The approach to comparative evaluation of NES/ scenario options

The approach to comparative evaluation of NES/scenario options developed within the INPRO collaborative project KIND (hereinafter, the KIND approach) is an iterative procedure using the top-down and bottom-up perspectives. This approach as a decision support process begins with the identification of the decision-maker's problem and a group of subject-matter experts and stakeholders (persons interested in a certain decision) and iteratively goes through the following steps, Fig. 3:

- Problem formulation and goal definition;
- Formulation of alternatives (NES options);
- Identification of KIs (requirements for KI sets);
- Evaluation of indicators, including uncertainties, performance table formation;
- Selection of MCDA method or methods to be used;
- Objectives tree construction and weight assignments, including uncertainties;
- Alternative ranking determination based on the selected MCDA method or methods;
- Sensitivity and uncertainty analyses;
- Drawing conclusions and recommendations.

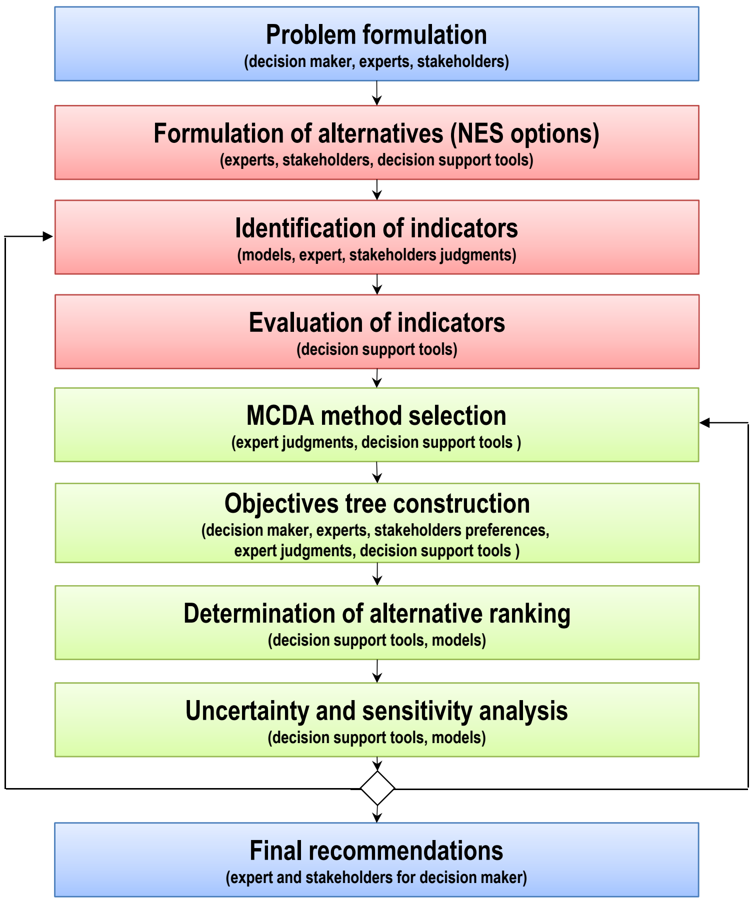


Fig. 3. Flowchart of MCDA application.

The KIND approach has identified some specific considerations regarding development of a set of KIs for comparative energy system evaluations involving NESs. When developing a KI set it is important to:

- Determine the main areas to be evaluated and then assign KIs for those areas. The main areas could be based on what is important to different stakeholders in the evaluation and are to include all major perspectives;
- Not attempt to address every nuance of the system with a KI. It is to be remembered that these are 'key' indicators intended to address only the key elements of the system and the key issues to be considered in an evaluation. The total number of KIs needs to be limited, preferably not more than 15–20;
- Develop KIs, to the extent possible, that are independent from each other to avoid double counting same aspects of the system;
- To exclude the indicators included in national regulations. Comparative evaluation is deemed to support the selection of an NES that is preferable for a particular user from those that otherwise meet (or are anticipated to meet) all regulatory and other assessment criteria.

The objectives tree defines procedures of indicator aggregation and weighting factors evaluation and the ranking results interpretation. Such structuring makes it possible to simplify preparation of the indicator weights and provides a clear explanation of the ranking results. High-level objectives and areas weights could be obtained based on the input from decision-makers. The weighting factors for each indicator may be determined by soliciting input from subject matter experts in the corresponding nuclear engineering fields. Figure 4 illustrates construction of the KIND objectives tree as a three level hierarchical structure: the green and orange frames are indicators (key and secondary), the grey frames are evaluation areas and the blue frames represent high level objectives.

A comparative evaluation at the top aggregation level is not the final result, but rather an option to go down to lower aggregation levels and, when necessary, to particular indicators, sensitivities and uncertainties. Namely such down-to-the-bottom analysis and presentation could make a dialogue with decision makers useful and productive. Performing a detailed uncertainty/sensitivity analysis helps in significantly increasing the confidence level of results and conclusions, as this backs the judgments with conclusions on stability of the results.

The KIND approach provides a convenient and systematic way of performing all of the above-mentioned steps for a full cycle MCDA. The approach incorporates the specific features of an NES, including those for innovative systems that are considered for potential deployment in a more distant future. It also deals with the challenges related to the availability of data and the uncertainty in estimates and experts' judgement.

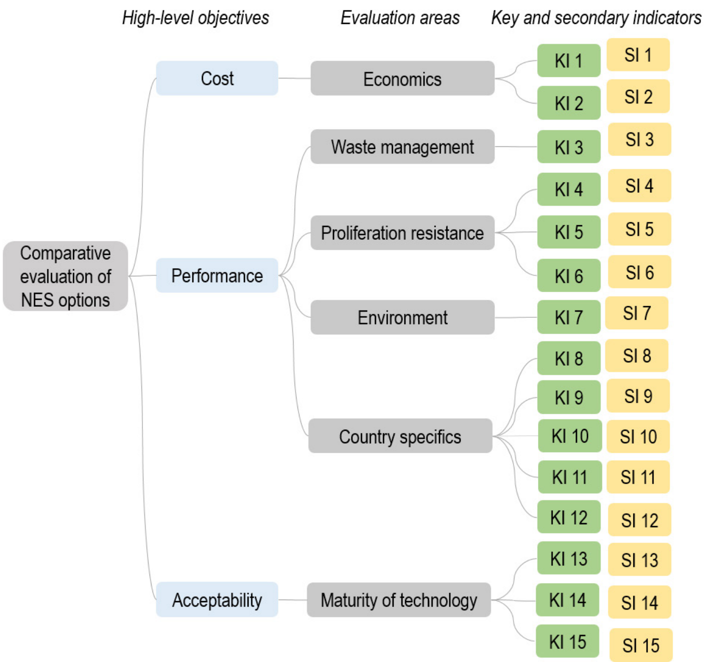


Fig. 4. Schematics of the objectives tree.

5. KIND Evaluation Tool (KIND-ET)

The KIND evaluation tool (KIND-ET) is a multi-attribute value theory (MAVT) based Excel toolkit developed within the INPRO collaborative project “Key Indicators for Innovative Nuclear Energy Systems” (KIND). KIND-ET was developed for the multi-criteria comparative evaluation of NES options or nuclear energy evolution scenarios in accordance with the approach and recommendations elaborated in the KIND project.

KIND-ET provides a solution for the comparative evaluation of the status, prospects, benefits and risks associated with development of nuclear technologies and deployment of nuclear energy systems. The architecture and functional capacities of KIND-ET allow users to modify the tool according to their needs. KIND-ET identifies the merits and demerits of the NESs or nuclear energy evolution scenarios being compared and evaluates their overall ranks based on their performance and experts and decision makers’ judgements and preferences.

The features of KIND-ET are quite flexible and allow the implementation of different approaches to compare and rank alternatives. The tables and graphs provide help to interpret the ranking results. KIND-ET users can utilize different approaches and techniques (e.g. choosing the shape of value functions) and perform other specifics for the implementation of the MAVT method as elaborated for the KIND objectives.

The default version of KIND-ET includes three-level objectives tree and 15 key indicators. This structure is suitable for defining several higher-level objectives, each with some evaluation areas and key indicators for each of the evaluation areas. The software follows basic requirements: problem-orientation and integration; user-friendliness and intuitive obviousness; automation and improvability. The tool was verified on a number of numerical examples by means of comparison with the calculations based on commercial decision-making software. The verification performed confirms that KIND-ET provides correct evaluations and can be used for relevant case studies.

KIND-ET provides for relatively easy performance of sensitivity and uncertainty analysis and modification to increase or reduce the number of high level objectives or/ and key indicators, alter the shapes of utility functions. A variety of graphical panels is provided to enable effective communication of the result of comparative evaluations.

The KIND-ET tools, user instruction and demo cases are provided with reference [1], either as a supplementary CD with a hard copy, or as an electronic attachment downloadable from the IAEA Web-site. Examples of the KIND inputs and outputs are given in Fig. 5 and Fig. 6.

High-level objectives titles	Areas titles	Indicators titles	Indicators abbr.	MIN score	MAX score	NES-1	NES-2
Cost	*Economics*	*LUEC*	*E1*	0	1	0	1
Cost	*Economics*	*Investment Level*	*E2*	0	1	1	0
Performance	*Waste Management*	*Waste Inventory*	*WM*	0	1	1	0
Performance	*Proliferation Resistence*	*Safeguards by Design*	*PR*	0	1	0	1
Performance	*Environment*	*Natural U Consumption*	*Env*	0	1	1	0
Acceptability	*Maturity of technology*	*Degree of Standardization*	*M1*	0	1	0	1
Acceptability	*Maturity of technology*	*World Record of Plant*	*M2*	0	1	1	0

Fig. 5. Inputs of KIND-ET (example).

Levels	1a	1b	1c	2a	2b	2c	2cV	3a	3b	3bV	3cV	3cV2
Multi-attribute value function	0.346	0.433	0.395	0.465	0.465	0.772	0.761	0.664	0.639	0.484	0.792	0.844
Areas scores												
Resource utilization	0.000	0.037	0.033	0.044	0.003	0.187	0.187	0.124	0.117	0.080	0.333	0.323
Waste management	0.013	0.112	0.085	0.170	0.296	0.312	0.310	0.297	0.306	0.300	0.328	0.322
Economics	0.333	0.284	0.277	0.251	0.166	0.272	0.264	0.243	0.216	0.103	0.130	0.199
Total	0.346	0.433	0.395	0.465	0.465	0.772	0.761	0.664	0.639	0.484	0.792	0.844

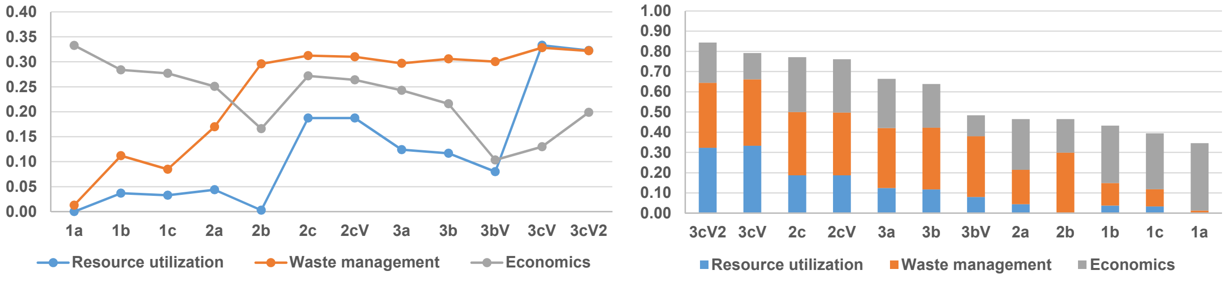


Fig. 6. Outputs of KIND-ET (example).

6. Case studies on trial application of the KIND approach

6.1. Scope and content of the considered problems

Based on the KIND approach, several trial case studies have been performed related to comparative evaluations of hypothetical NESs, NESs based on different types of evolutionary and innovative reactors, nuclear and non-nuclear energy systems, and NES deployment scenarios. These case studies were carried out for the purpose of testing the KIND approach and were not deemed to adequately reflect any developments or official plans adopted in corresponding Member States. In some cases, the results of these studies were presented to and discussed with decision makers, just to understand how useful the KIND approach could be to maintain the corresponding dialogue.

The case studies have demonstrated the applicability of the recommendations and tools developed within the KIND project to comparative evaluations of NES options. They also proved that the approach can reflect the merits and demerits associated with the various energy system options under consideration.

It is important to emphasize that the key indicator approach does not provide for the identification of KIs in each and every evaluation area. Every single case study presented below provides an example of a different selection of evaluation areas and the relevant KIs to reflect the specific concerns and priorities of a particular country.

Altogether, seven case studies were performed in the report including:

- Generic case studies of hypothetical NESs;
- Innovative versus innovative NESs;
- Evolutionary versus innovative NESs;
- Evolutionary versus evolutionary NESs;
- Nuclear versus non-nuclear energy systems;
- Nuclear energy deployment scenarios.

Their detailed reports are provided in reference [1]. The scope to the performed studies is illustrated in brief by several examples provided in the following two sub-sections.

6.2. Case studies on comparative evaluation of NES options

Case study from Romania: evolutionary versus innovative nuclear energy systems

The study performed by the expert team from Romania had the following specific objectives:

- To evaluate the considered NES together with the already existing/operating NES technology (CANDU 6), based on specific KIs and taking into consideration the country specifics;
- To validate the obtained results by performing sensitivity analysis.

The case study considered three NES technologies: CANDU NES technology (two CANDU 6 reactors presently operating at the Cernavoda NPP; the electricity generated comprises approximately 20% of Romania's total electricity production); an evolutionary NES, the Generation III+ enhanced CANDU technology — ENES; and an innovative NES, the Generation IV lead cooled fast reactor technology — INES.

Three high level objectives were chosen and the evaluation areas were grouped, as shown in Fig 7:

(a) Economics (E), corresponding to the cost high level objective;

(b) Safety (S), waste management (WM), environment (ENV) and proliferation resistance (PR), corresponding to the performance high level objective;

(c) Maturity of technology (M) and country specifics (CS), corresponding to the acceptability high level objective.

Two KIs were selected for the evaluation in the area of economics: Levelized energy product or service cost (E1) and R&D cost (E2). The evaluation in the waste management area has been performed by considering specific radioactive waste inventory (WM1) and spent nuclear fuel management costs (WM2). The evaluation of NESs in the area of proliferation resistance has been performed by means of the following three KIs: attractiveness of nuclear material (PR1); attractiveness of technology (PR2); safeguards approach identified (PR3). For the environment area, the following KI has been chosen: amount of useful energy produced by NES from a unit of mined natural uranium (ENV1). Five KIs were chosen for the evaluation of considered NESs in the safety area, namely: potential to prevent release (S1); design concept specific inherent and passive safety features and systems (S2); core damage and large early release frequencies (S3); source term (S4); short term and long term accident management (S5). For the evaluation of considered NESs in the maturity of technology area, three KIs have been selected: design stage (M1); time needed to mature the technology (M2); degree of standardization and licensing adaptability (M3) (higher value was rated better in evaluation).

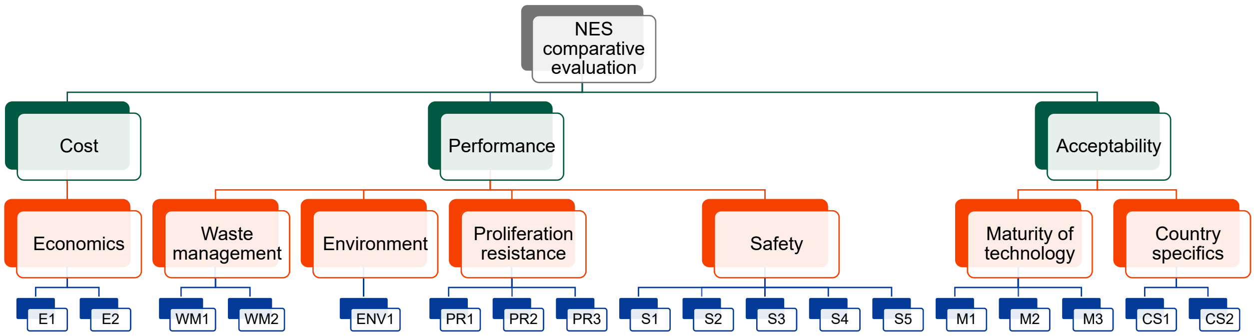


Fig. 7. Structure of the objectives tree in the case study from Romania.

The results were obtained for different weights at the objectives tree level:

- Case 1 — weights for high level objectives: cost 50%, performance 30%, acceptability 20%;
- Case 2 – weights for high level objectives: cost 30%, performance 50%, acceptability 20%;
- Case 3 – weights for high level objectives: cost 40%, performance 40%, acceptability 20%.

For the main working cases considered (cases 1, 2 and 3, with different sets of weights for high level objectives), the overall scores obtained for the INES suggest that it is more attractive (better in terms of performance in the safety, waste management and environment areas, and also superior in the country specifics area under the high level objective ‘acceptability’), Fig. 8.

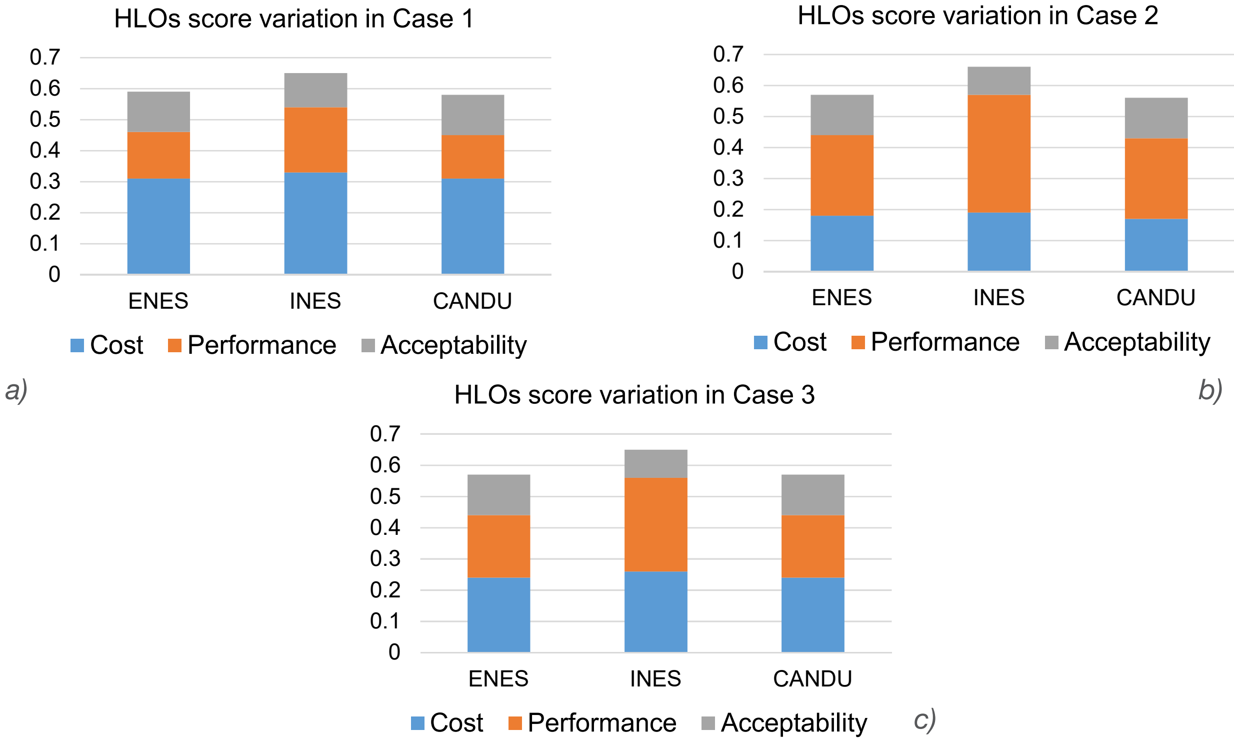


Fig. 8. High level objectives (HLO) scores for: (a) case 1; (b) case 2; (c) case 3.

The case study from Romania has concluded that innovative technology could offer an opportunity for Romania to enhance its participation in the world's most advanced scientific studies. The impact might not be restricted to the development of local scientific communities, but it could also create numerous opportunities for technological collaboration and knowledge transfer between the research community and industry.

Case study from Thailand: nuclear versus non-nuclear energy options

The objective of the study was to apply the set of KIs developed for newcomer countries to a case study for Thailand, whose main objective was the comparative evaluation of energy system scenarios with an NES and a non-NES. The options under consideration included an NES (evaluated using data for the Generation III+ pressurized water reactors of interest (i.e. AP-1000, APR1400, ACPR and VVER)) and a coal power plant (CPP).

The KI set belongs to four areas: economics, energy security, public acceptance and infrastructure. There are two KIs in the area of economics: levelized unit electricity cost (LUEC) and cash flow. The degree of dependence on suppliers is the only KI in the area of energy security. The area of public acceptance has three KIs: survey of public acceptance, external cost and risk of accidents. Infrastructure is the area with the largest number of KIs. The five KIs in this area are status of legal framework, status of state organizations, availability of infrastructure to support owner/operator, government policy and availability of human resources.

Ranking results of the comparative evaluation show that CPP is more attractive than NPP for Thailand, with them receiving the scores of 0.468 and 0.412, respectively, for the ratio of the HLO weighting factors 'Economics' to 'Acceptability' 0.3/0.7, as shown in Fig. 9. The results indicate that the score that has a significant impact on the NES is from the area of public acceptance, while the attractiveness of CPP is mainly derived from the areas of economics and infrastructure. The sensitivity analysis was performed by varying the ratio of the high-level objective weighing factors. For the fixed evaluation area weighting factors and indicator weighting, increasing the weight of 'Economics' with decreasing the weight of 'Acceptability' down to approximately 0.4 could result in making NES more attractive than CPP. The results indicate that NES attractiveness overcomes that of CPP when the weighting factor of 'Acceptability' is less than 0.4, Fig. 10.

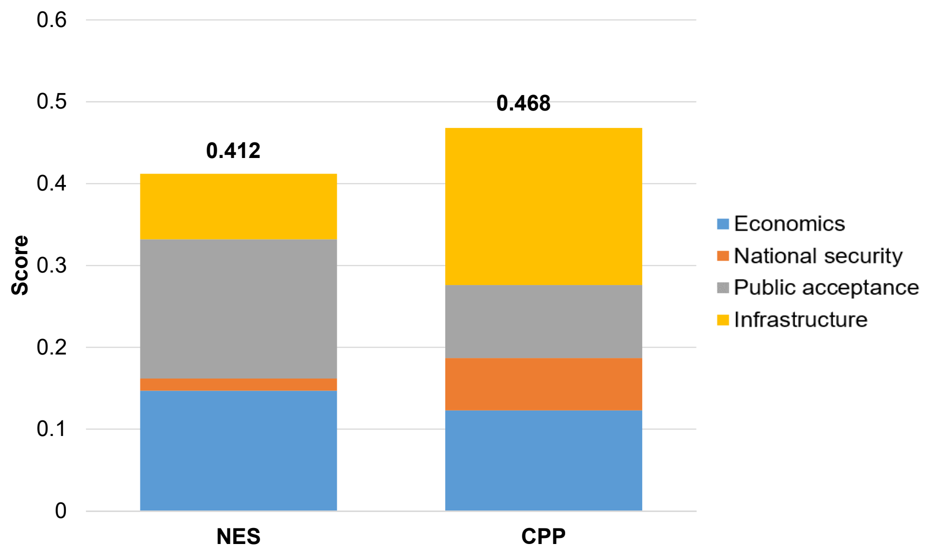


Fig. 9. Ranking results for comparative evaluation of an NES and a CPP (base case).

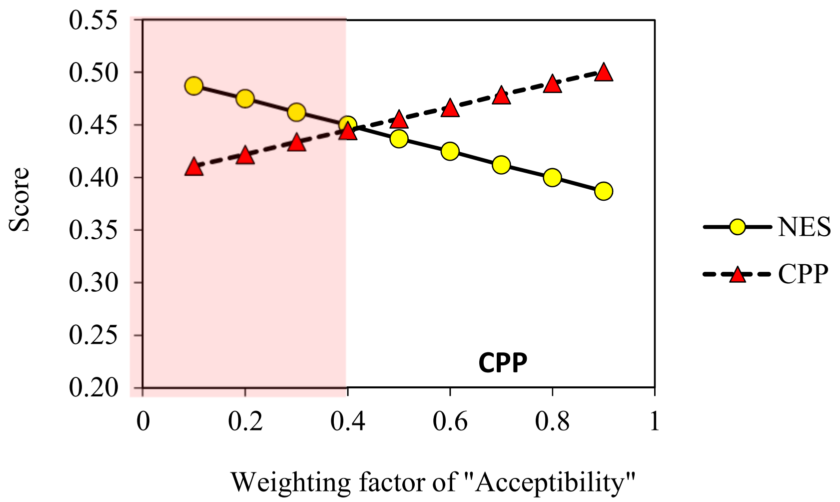


Fig. 10. Sensitivity analysis for NES and CPP performed by varying the acceptability weighting factor.

6.3. Case studies on comparative evaluation of deployment scenarios

Comparative evaluation of scenarios considered in the collaborative project "Global Architecture of Innovative Nuclear Energy Systems with Thermal and Fast Reactors and a Closed Nuclear Fuel Cycle" (GAINS) [10]

The KIND approach can also be used for comparative evaluation of nuclear energy deployment scenarios. To demonstrate such an application, a case study was conducted to compare eleven scenarios (Table 1) considered in the GAINS collaborative project. The nine key indicators listed in Table 2 were used to present important aspects of the NESs considered in these scenarios. The following weighting options were considered reflecting possible experts' preferences: equal significance of all KIs; expert preferences based on the questionnaires of the INPRO meetings; preference to investments minimization; and preference to wastes minimization.

Based on the KIND approach, it was possible to rank the scenarios from the most preferred NES to the least preferred NES, as shown in Fig. 11. It was also possible to identify potential merits and demerits of the relevant nuclear technologies within the NES and draw recommendations for improvement of the technologies.

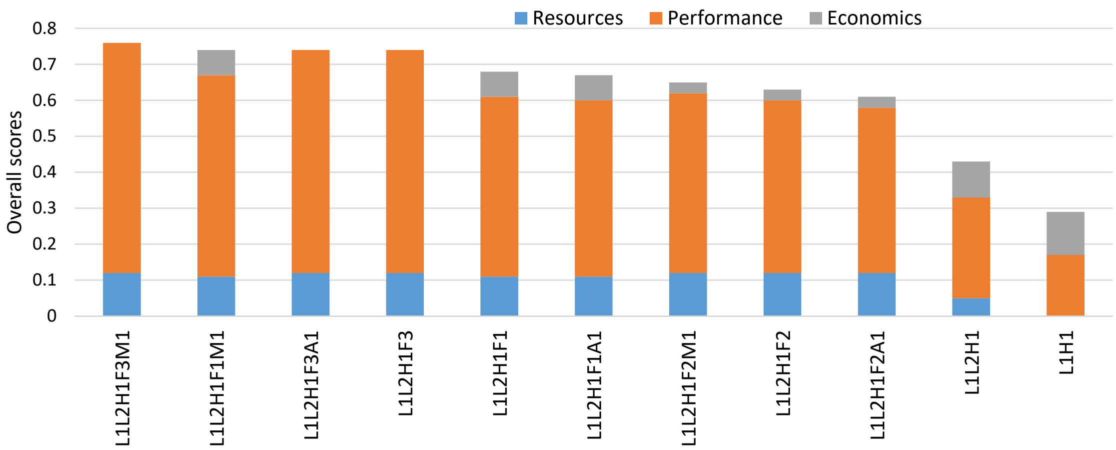
Table 1. NES deployment scenarios

NES deployment scenario	Denotation[1]
BAU	L1H1
BAU+	L1L2H1
BAU+, FR 'break-even'	L1L2H1F1
BAU+, FR 'medium-BR', medium burn-up	L1L2H1F2
BAU+, FR 'medium-BR', high burn-up	L1L2H1F3
BAU+, FR 'break-even' and ADS	L1L2H1F1A1
BAU+, FR 'medium-BR', medium burn-up, ADS	L1L2H1F2A1
BAU+, FR 'medium-BR', high burn-up, ADS	L1L2H1F3A1
BAU+, FR 'break-even' and MSR	L1L2H1F1M1
BAU+, FR 'medium-BR', medium burn-up, MSR	L1L2H1F2M1
BAU+, FR 'medium-BR', high burn-up, MSR	L1L2H1F3M1

Table 2. Key indicators

Key indicators
Natural uranium consumption
Annual spent nuclear fuel generation
Total spent nuclear fuel in long term storages
Minor actinides in nuclear fuel cycle
Plutonium in nuclear fuel cycle
Total enrichment capacities
Total reprocessing capacities
Total uranium cost
Total investments in NPPs

Fig. 11. Ranking of the NES deployment scenarios.



[1] L1 – LWR with low burn-up (45 GW·day/t); L2 – LWR with high burn-up (60 GW·day/t); H1 – HWR; F1 – "break-even" FR with breeding ratio BR~1.0; F2 – FR with medium BR (BR~1.2), medium burn-up (~31 GW·day/t); F3 – FR with medium BR (BR~1.2), high burn-up (~54 GW·day/t); A1 – ADS for MA burning; M1 – MSR for MA burning.

Comparative evaluation of the OECD/NEA advanced nuclear fuel cycles

Another similar application of KIND was for the OECD/NEA study on "Advanced Nuclear Fuel Cycles and Radioactive Waste Management" [11] which was devoted to an evaluation of the impact of nuclear fuel cycle strategies on the uranium consumption and waste management. The nuclear fuel cycle options analyzed included once-through, recycling in thermal reactors, sustained recycle with a mix of thermal and fast reactors, and sustained recycle with fast reactors.

The objective was to identify those nuclear fuel cycles which provide benefits to the spent nuclear fuel (SNF)/ high level waste (HLW) repository programme, reduce the depletion of uranium resources and enhance the prospects for nuclear power. Altogether, 12 nuclear fuel cycle (NFC) options (Table 3) were considered which were evaluated by 8 key indicators (Table 4). The comparative evaluation (Fig. 12) has shown that some partly closed nuclear fuel cycles represent trade-off benefits for the repository programmes and enable more efficient use of natural uranium, but at some additional costs.

Table 3. NFC options

NFC options	**Comments**
Current industrial practice and extensions	
NFC 1a "Once-through NFC"	*reference NFC*
NFC 1b "Current reprocessing NFC"	*Pu is recycled once in the form of MOX*
NFC 1c (Variant of Scheme 1b)	*avoids the separation of pure Pu by recycling Np and Pu together*
Partially closed NFC	
NFC 2a "Pu burning in LWR"	*uses LWRs only, MOX fuel with enriched uranium (MOX-UE)*
NFC 2b "Pu and Am burning in LWR"	*requires two types of MOX-UE fuel, Am-Cm separation (Cm decay products are either disposed or recycled as MOX)*
NFC 2c "Heterogeneous Am recycling"	*Am is recycled in targets which are disposed after irradiation*
NFC 2cV (variant 2c)	*Am and Cm go to storage facility (decay products are either disposed or recycled as MOX fuel)*
Closed NFC	
NFC 3a "TRU burning in FR"	*based on integral FR concept, avoids separation of pure Pu*
NFC 3b "Double strata NFC"	*burns all Pu in conventional LWRs and FRs*
NFC 3bV (variant 3b)	*circumvents the FR stage by transferring the Pu from the PWR-MOX stage directly to the ADS NFC*
NFC 3cV1 "All-FR strategy"	*based on Gen-IV gas-cooled FRs*
NFC 3cV2 (variant 3c)	*based on EFR using MOX, UREX+, uranium is not recycled*

Table 4. Key indicators

Area	**Key indicators**
Resource utilization	Natural uranium required per energy generated
Nuclear waste management	Mass of TRU loss transferred to waste
	Activity of SNF and HLW at 1000 years
	Decay heat loading of SNF and HLW at 50 years
	Decay heat loading of SNF and HLW at 200 years
	Volume of HLW and SNF
Economics	NFC costs
	Costs of electricity at equilibrium

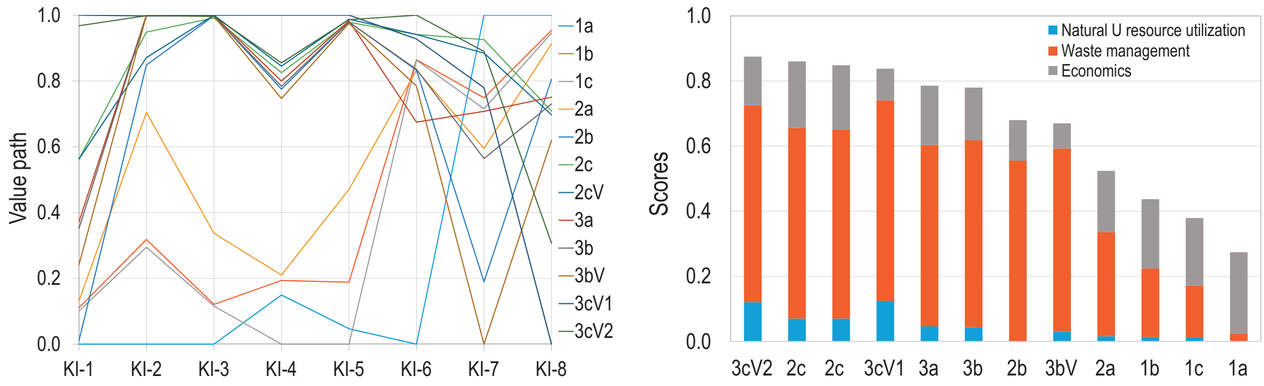


Fig. 12. Performance and ranking results for advanced NFC options.

6.4. Lessons learned from trial applications of the KIND approach

The KIND collaborative project participants confirmed that the approach could be effective in practical comparative evaluations of not only less mature innovative NESs but also other energy options and nuclear versus non-nuclear energy system options. The lessons learned from these trial case studies are:

- The problem elaboration and the objectives tree need to be prepared through consultative and iterative process. A comparative evaluation problem can be simplified by focusing on a fewer number of major high-level objectives. It is practical and reasonable to consider at most two/three highest level objectives, e.g., ‘cost’, ‘benefit’ and ‘risk’ (commonly used) or ‘performance’, ‘cost’, and ‘acceptability’, depending on specifics of the considered comparative evaluation problem. These high-level objectives need to be linked with relevant evaluation areas according to the INPRO methodology, and suitable indicators need to be assigned to each of the areas.

- The determination of relative importance (weighting factors) among different indicators, evaluation areas or high-level objectives needs to be rational and reasonable, and reflect national preferences for nuclear energy development, as well as international obligations of Member States. Weights for indicators need to be determined by soliciting input from subject matter experts in the corresponding nuclear engineering fields. Weights for evaluation areas and high-level objectives can be determined by soliciting input from decision makers.

- To avoid utilization of an excessive number of indicators, a multi-stage evaluation may be applied. The first stage reduces the total number of options using key indicators while the second stage goes into more detail in a couple of areas using the so-called secondary indicators, where it is difficult to separate the remaining options with the original key indicators.

- For interpreting the ranking results, it is necessary to decompose the overall scores into individual components in accordance with the specified structure of the objectives tree. Based on this decomposition, the status of the NES options may be explained for the decision makers and stockholders.

- The results of sensitivity and uncertainty analysis would help achieving a productive communication by pointing to those cases where compared options are undistinguishable and by identifying certain changes in attitudes and policy that can overturn the originally obtained conclusions regarding the comparative evaluation.

7. Conclusion summary for the INPRO collaborative project KIND

The INPRO collaborative project KIND has done the following:

- Developed guidance on the elaboration of KI sets for comparative evaluation of the performance and sustainability of different NES options;
- Adapted and elaborated advanced methods of expert judgement aggregation and sensitivity/uncertainty analysis to enable effective comparative evaluation of such options;
- Conducted case studies on trial application of the KIND approach;
- Explored the potential of the developed approach in application to both INESs and other NES options, including those of interest to technology users and newcomer countries.

The project has identified a number of specific considerations regarding the development of a set of KIs for comparative energy system evaluations involving NESs. When developing a KI set it is inter alia important to do the following:

- Identify the target audience for the evaluation and select KIs that will be understandable to that target audience.
- Determine the main areas to be evaluated and then assign KIs for those areas. The main areas could be based on what is important to different stakeholders in the evaluation and are to include all major perspectives.
- Develop KIs with full consideration of which data are available for all of the options using the least detailed option as the basis. If using a quantitative KI, first verify that quantitative data are available for every option to be evaluated. If using a qualitative KI, verify that unbiased experts are available to provide the qualitative input.
- Note that if large numbers of experts are involved in one area of evaluation, it may result in excessive number of KIs in that area, since they know their domain in detail, and will opt to have numerous KIs to measure every aspect. This does not necessarily improve the overall evaluation as the clarity of priorities can be lost in the 'forest' of KIs.
- Fully describe and document each KI, so that everyone involved can understand what is included, and how it is to be evaluated.

The selection of the MCDA method that is most suitable for a given problem is a separate task that needs to be based on examination of the problem context and the information provided by the subject matter experts and a decision maker.

To structure a dialogue based on MCDA methods, it is necessary to describe all of the assumptions that have been made accurately to avoid misunderstandings in interpretation of the results. These assumptions then need to be analyzed within a sensitivity analysis. A detailed explanation of the selected model assumptions in the case study report is an area of responsibility for experts carrying out MCDA based studies.

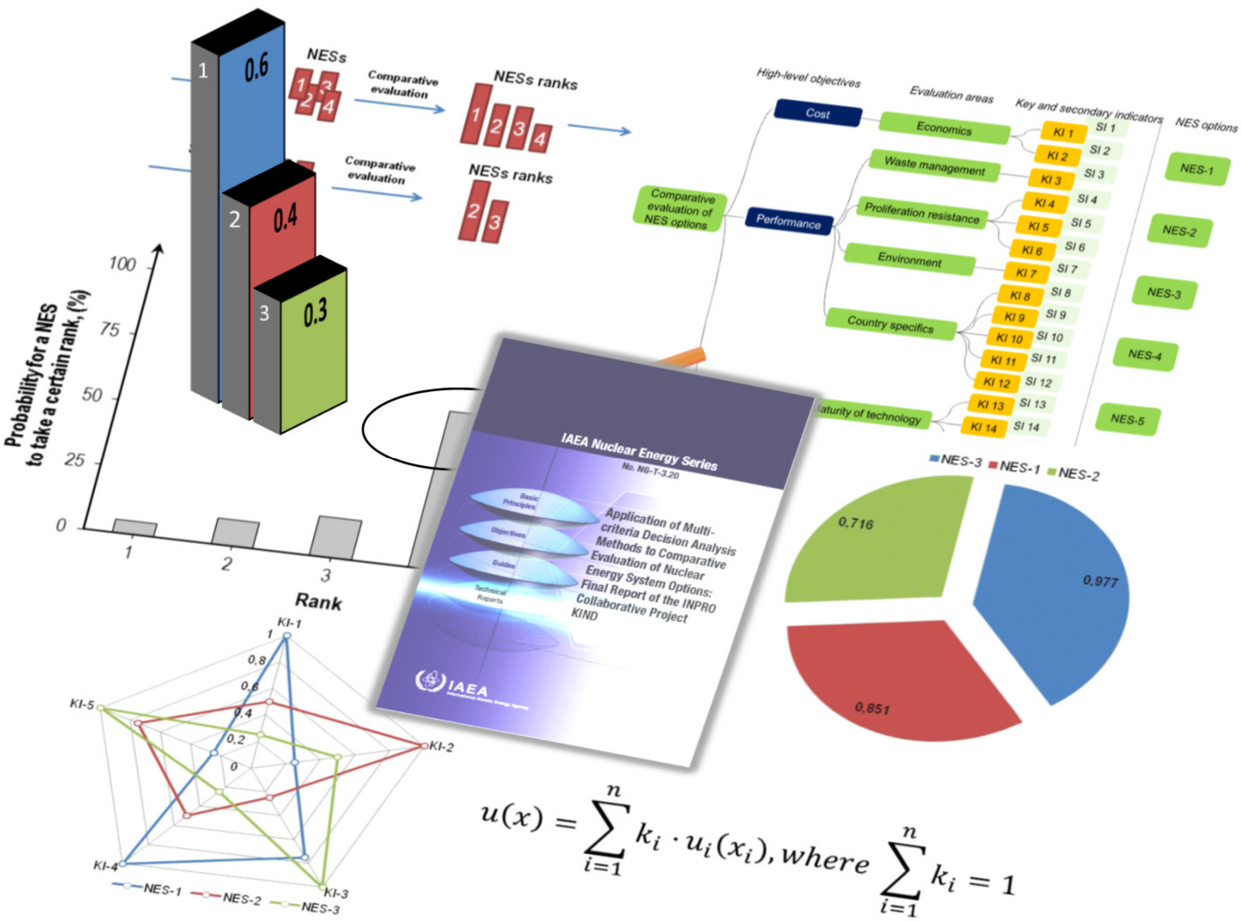
Properly organized case studies based on the KIND approach represent a complex endeavour, not only operating formally with a set of analytical tools, but also helping to understand explicitly what could support the decision making process.

Experts are responsible for the quality of MCDA based studies conducted to support the establishment of a certain recommendation and inform a decision maker about the merits and demerits (costs, benefits and risks) of the options considered. The decision maker takes responsibility for the final decision, taking into account the results of MCDA based studies, and this decision needs to be accepted with a clear recognition and acceptance of the associated risks.

Performing a detailed uncertainty/sensitivity analysis helps to increase the confidence level for the results and conclusions significantly, as this backs the judgements with information on the stability of the results. One of the important areas for further development of the comparative evaluation approach for NESs is the extension of judgement aggregation methods to problems with uncertainties that are relevant to most of the real world problems.

The elaboration and trial applications of the KIND approach to date have indicated that it can not only be effective in practical comparative evaluations of less mature INESs, but also other energy options and, specifically, NES evolution scenarios and NES versus non-nuclear energy options.

Further steps in the elaboration of the KIND approach will be linked to applications of the developed toolkits to practical problems that address a variety of issues that interested Member States rate as important. This is being accomplished within the on-going follow-up INPRO collaborative project on Comparative Evaluation of Nuclear Energy System Options (CENESO). The KIND toolkit will be used to streamline such systemic activities and formulate specific guidelines with respect to particular approaches aimed at improving the performance and sustainability of national, regional and global NESs.



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Abbreviations

ADS	Accelerator driven system
AHP	Analytic hierarchy process
BR	Breeding ratio
CANDU	Canada deuterium–uranium reactor
CENESO	Comparative evaluation of nuclear energy system options
CPP	Coal power plant
EFR	European fast reactor
ELECTRE	Elimination et choix traduisant la realite
ENES	Evolutionary nuclear energy system
FR	Fast reactor
GAINS	Global architecture of innovative nuclear energy systems based on thermal and fast reactors including a closed fuel cycle
HLO	High level objective
HLW	High level waste
IAEA	International Atomic Energy Agency
INES	Innovative nuclear energy system
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
KIND	Key indicators for innovative nuclear energy systems
KIND-ET	KIND-Evaluation Tool
LWR	Light water reactor
MA	Minor actinides
MAVT	Multi-attribute value theory
MAUT	Multi-attribute utility theory
MCDA	Multi-criteria decision analysis
MOX	Mixed oxide fuel
MOX-UE	Uranium enriched MOX fuel
MSR	Molten salt reactor
NEA	OECD Nuclear Energy Agency
NES	Nuclear energy system

NFC	Nuclear fuel cycle
NPP	Nuclear power plant
OECD	Organization for Economic Co-Operation and Development
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
HWR	Heavy-water reactor
PWR	Pressurized water reactor
SNF	Spent nuclear fuel
TOPSIS	Technique for order preference by similarity to the ideal solution
TRU	Transuranium elements
UN	United Nations

Glossary

Key indicator is a specific, usually measurable, indicator showing best how a system performs in a particular area.

KIND collaborative project was the IAEA/INPRO collaborative project with the overall objective to develop guidance and tools for comparative evaluation of the status, prospects, benefits and risks associated with the development of innovative nuclear technologies and to explore the potential of such an approach in application to other problems, including those of interest to technology users and newcomer countries.

KIND approach is a set of actions intended to deal with comparative evaluation of NES or scenario options based on the selection and use of a limited number of key indicators along with the state-of-the-art judgment aggregation and sensitivity/uncertainty analysis methods.

KIND evaluation tool (KIND-ET) is an MAVT based Excel tool for multi-criteria comparative evaluation of NES or scenario options in accordance with the approach and recommendations elaborated in the KIND collaborative project.

KIND recommendations are a set of specific directions on selecting model parameters to be implemented in an NES/scenario comparative evaluation procedure within the KIND approach aimed at reducing the risks of alternatives' indistinguishability and ranking results' sensitivity to model parameters.

Multi-Attribute Value Theory is a quantitative comparison method used to combine different measures in terms of costs, risks and benefits, using single-attribute value functions together with expert and decision-maker preferences, into overall performance score.

Multi-Criteria Decision Analysis is an area of multiple criteria decision-making in which a number of the alternative decision choices are explicitly pre-specified: each option is represented by its performance indicators evaluated on multiple criteria.

Nuclear energy system is a complete system, including reactors, nuclear fuel cycles, nuclear infrastructure and legal and institutional arrangements

Objectives tree is a hierarchical structure facilitating aggregation in multi-level modelling of the evaluation process and, therefore, is to be elaborated before performing a multi-criteria comparative evaluation.

Secondary indicator is an additional indicator evaluating an optional rather than a mandatory aspect of the system; can be used to increase resolution among compared NESs or scenarios.

Single-attribute value function is a function to be evaluated for each indicator, which transforms diverse indicators' local natural values to universal, dimensionless scale, for example [0, 1], reflecting judgments of subject matter experts and decision-makers.

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