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APPLICATION OF MULTI-CRITERIA DECISION ANALYSIS METHODS TO COMPARATIVE EVALUATION OF NUCLEAR ENERGY SYSTEM OPTIONS: FINAL REPORT OF THE INPRO COLLABORATIVE PROJECT KIND

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IAEA NUCLEAR ENERGY SERIES No. NG-T-3.20

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was launched in November 2000 under the aegis of the IAEA. Since then, INPRO activities have been repeatedly endorsed by the IAEA General Conference and by the General Assembly of the United Nations. The objectives of INPRO are to help ensure that nuclear energy is available to contribute, in a sustainable manner, to meeting energy needs in the 21st century, and to bring together technology holders and users so that they can jointly consider the international and national actions required to achieve desired innovations in nuclear reactors and fuel cycles.

One of the first activities of INPRO was to develop a detailed methodology for assessing the sustainability of a nuclear energy system (NES). However, trial applications of the methodology proved to be difficult for less mature NESs owing to a lack of data to support the detailed quantitative approach used. Moreover, the INPRO methodology does not provide for comparative evaluation of NESs.

To address this issue, in 2014 INPRO launched the collaborative project on Key Indicators for Innovative Nuclear Energy Systems (KIND). The KIND project, implemented in 2014–2017, developed an approach based on guidance and tools 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 uncertainty analysis methods.

This publication presents the results of the KIND collaborative project, including the above mentioned approach and several case studies performed by interested Member States to evaluate both evolutionary and innovative NES options, as well as to examine the applicability of the approach to other problems, such as those of particular interest to newcomer countries.

The IAEA officers responsible for this publication were V. Kuznetsov and G. Fesenko of the Division of Nuclear Power.

EDITORIAL NOTE

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1. INTRODUCTION

This report documents the scope and outputs of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) collaborative project Key Indicators for Innovative Nuclear Energy Systems (KIND). The KIND project was implemented in 2014–2017 by experts nominated by Armenia, Bulgaria, China, Croatia, France, Germany, India, Indonesia, Malaysia, Romania, the Russian Federation, Thailand, Ukraine, the United Kingdom, the United States of America and Viet Nam as participants or observers in the different tasks of the project. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.1. BACKGROUND

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. It is a mechanism for INPRO members to collaborate on topics of joint interest.

One of the first activities of INPRO was to develop a detailed methodology for assessing the sustainability of a nuclear energy system (NES). Initially published in 2005 [1.1], the INPRO methodology appears as a multivolume report that explains how to evaluate NES sustainability in the areas of safety, economics, infrastructure, waste management, proliferation resistance, physical protection and environment. The methodology was fully updated in 2008 [1.2], with more recent updates being produced in 2014–2016 [1.3–1.6].

One of the objectives of the INPRO methodology was to support sustainability assessment for advanced nuclear technologies and systems, as evidenced by the title of the 2008 update — Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems. However, trial applications of the methodology proved to be difficult for less mature designs owing to a lack of data to support the detailed quantitative approach applied in it. Additionally, the methodology does not provide for the comparative evaluation of different NES options.

The INPRO collaborative project KIND was chartered to develop guidance and tools for comparative evaluation of the status, prospects, benefits and risks associated with the development of innovative nuclear technologies for the more distant future and to examine the applicability of such an approach to other problems, including those of interest to technology users and newcomer countries. To achieve these objectives, the project undertook the following, based on a thorough review of relevant activities accomplished previously:

- Developed guidance on key indicator (KI) sets for comparative evaluation of different NES options;
- Adapted and elaborated the state of the art methods for expert judgement aggregation and uncertainty analysis methods to enable effective comparative evaluation of such options;
- Performed case studies on trial application of the KIND approach and explored the potential of this approach in application to both innovative nuclear energy systems (INESs) and other NES options, including those of interest to technology users and newcomer countries.

The project was implemented by experts nominated by several Member States representing technology holder countries with large nuclear energy programmes and active R&D projects, technology users and newcomer countries that are considering or are in the process of starting a nuclear programme.

The case studies illustrated a range of perspectives and indicated what it was important to consider as part of a comparative evaluation of performance and sustainability involving INESs. The technology developer countries were mostly focused on the performance of INESs versus other innovative or established NESs. The newcomer countries were less interested in technical innovations and more interested in comparative choices of nuclear versus other means of energy production. This resulted in the approval of a mid-course change in the charter of KIND by the INPRO Steering Committee to broaden its scope to include support for comparative evaluations across the range of options of interest to the represented Member States, including the original scope of less mature NESs, but also more mature NESs and non-nuclear energy options. The KIND project formulated general guidance on the selection of sets of KIs and developed tools capable of supporting a range of criteria and options, while the specific range of options to be included and the specific criteria to be used in an evaluation were left as a task for a Member State or an expert group conducting the comparative evaluation.

1.2. OBJECTIVE

The specific objectives of the KIND project were threefold. The first was to develop a theoretical basis and mathematical foundation for the comparative evaluation of options involving NESs. The nature of NESs requires the consideration of multiple areas: from economics and non-proliferation aspects through to public opinion issues, the technical details of reactor performance and waste generation. These indicators and attributes cannot easily be reduced to common units, such as monetary value, for comparison. Moreover, different groups of people with a stake in the results of the energy option analyses (stakeholders) will judge the importance of these areas differently. This leads to the need for the application of multi-criteria decision analysis (MCDA) methods and deep understanding of their strengths and limitations.

Given the range of options that could be evaluated comparatively and the availability of performance data, appropriate analytical techniques are required to analyse and use the specific measured performance data, expert opinion and survey information, which are input values for KI evaluations. The purpose for providing this information is to give the user the background needed to understand how the provided tools work and how to identify and separate the differences between options that are due to formal (artificial) factors versus the differences that are due to actual projected performance (real).

The next major specific objective was to provide background for and guidance on developing the inputs required to apply MCDA methods for a specific energy system evaluation. This includes guidance on how to develop a set of KIs; a system of value/utility functions for the indicators to express preferences and equate input data with indicator performance; a system of weight sets for rolling up the individual performance indicators into an overall indicator (figure of merit) for each evaluated option; and a sensitivity analysis to determine the uncertainty in the outcome and investigate how that outcome could vary with different stakeholders' views. This objective included providing information on potential KIs in each of the areas needed for the evaluation of an NES, covering different dimensions while emphasizing the primary attributes that need to be considered.

A graded approach to the number of indicators and the degree of detail of those indicators could be recommended based on the level of effort envisioned for the comparison. The type of indicator is to be tailored to the type of decision to be supported in the evaluation process, such as nuclear versus non-nuclear for a newcomer, or a technical evaluation of potential advanced nuclear options for an R&D programme. The purpose is to give users an open perspective on the range of possible evaluations and to instruct them on how to develop an appropriate system of KIs, value/utility functions and weights in order to perform the MCDA evaluation.

The final objective of KIND was to provide a software tool or set of tools, together with exhaustive user information; this includes the mathematical foundation of MCDA, the ability to furnish the tool with appropriate KIs and to customize inputs for the decision analysis to be performed, and information on how to use built-in graphics and tables to communicate the results of the evaluation.

Additional specific capabilities include the input and management of expert opinions for the evaluation of specific indicators when performance data are not available, and sensitivity analysis for examining the impact of uncertainty on KI input values, value/utility functions and weighting sets. The goal is to provide an easily accessible and simple to use tool that is capable of supporting the full range of comparative analyses covered by the KIND approach.

1.3. SCOPE

This report presents the outputs of the collaborative project KIND, the scope of which enveloped the following major tasks:

— *Development of guidance on KI sets, their scales and utility functions for comparative evaluation of performance and sustainability of different NES options*. The guidance provides recommendations on selection of the indicator set, the objectives tree structure and the scoring scale for indicator evaluation, as well as on identification of the weighting factors for the comparative evaluation process. The comparative evaluation approach developed employs and further elaborates on the concept of KIs introduced in the INPRO methodology for NES sustainability assessment and first implemented in the collaborative project Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS). The guidance includes general recommendations on the development of a KI set based on simple examples from the non-nuclear field and the evaluations involving an NES. It also includes a discussion on the attributes of sustainability in energy systems and explains how those attributes could be represented with the KIs.

— *Adaptation and elaboration of advanced methods of expert judgement aggregation and uncertainty analysis for effective comparative evaluation of NES options*. For this task, a large number of MCDA techniques and the broad experience of their application were reviewed, analysed and summarized. Multi-attribute value theory (MAVT) was recommended for comparative multi-criteria evaluation of NESs, as it is being widely used worldwide for different applied problems in general and in the nuclear engineering field in particular.

— *Application of the KIND approach to innovative nuclear energy systems and other NES options, including those of interest to technology users and newcomer countries*. For this task, a number of case studies were performed by project participants from IAEA Member States on the comparative evaluation of hypothetical NESs, national NESs (on a trial basis) and nuclear energy evolution scenarios. The technology holder countries were mostly focused on the technical performance of INESs versus other innovative or established NESs. The newcomer countries were more interested in comparative evaluation of evolutionary NESs or nuclear versus non-nuclear energy options. The case studies performed illustrate the effectiveness of the KIND approach in a broad variety of applications.

1.4. STRUCTURE

The report is structured as follows.

Section 2 provides background on the development of KIs for performing a comparative evaluation. This includes information on the main dimensions for energy sustainability and explanations on how those dimensions can be interpreted when applied to different types of evaluation, how to structure the criteria within each dimension and how to tailor the specific criteria based on the application. It provides examples of specific criteria, including those that have been used in prior evaluations involving NESs.

Section 3 presents information on frameworks for MCDA, including features and specifications of multi-attribute value/utility theory, and shows how to combine criteria to develop figures of merit for comparisons of different energy options. This section also addresses methods for treating uncertainty and the role of sensitivity analysis in examining the impact of uncertainty on option ranking order.

Section 4 provides information on scales for criteria and on the development of value/utility functions for judgement aggregation using KIs. This section covers statistical examination first, and then focuses on specific recommendations from the experts for performing evaluations within the framework developed by the KIND project.

Section 5 contains a number of case studies on trial application of the KIND approach for a variety of problems, performed by applying the specific tools developed for KIND. These case studies demonstrate the application range and reveal the application limits of the methods and tools discussed in the previous sections.

Section 6 documents the conclusions and recommendation of the KIND project.

The annexes provide an overview of previous NES evaluation studies (Annex I), the mathematical background and details of MCDA methods (Annexes II–IV), and a description of the KIND software tool that implements the MCDA approach for the performance of comparative evaluations according to the information given in this report, complete with an example of comparative evaluation (Annex V and the attached CD-ROM).

REFERENCES TO SECTION 1

[1.1] INTERNATIONAL ATOMIC ENERGY AGENCY, Methodology for the Assessment of Innovative Nuclear Reactors and Fuel Cycles: Report of Phase 1B (First Part) of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), IAEA-TECDOC-1434, IAEA, Vienna (2004).

[1.2] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems: INPRO Manual — Overview of the Methodology, IAEA-TECDOC-1575 (Rev. 1), IAEA, Vienna (2008).

[1.3] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Infrastructure, IAEA Nuclear Energy Series No. NG-T-3.12, IAEA, Vienna (2014).

[1.4] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Economics, IAEA Nuclear Energy Series No. NG-T-4.4, IAEA, Vienna (2014).

[1.5] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Environmental Impact from Depletion of Resources, IAEA Nuclear Energy Series No. NG-T-3.13, IAEA, Vienna (2015).

[1.6] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Environmental Impact of Stressors, IAEA Nuclear Energy Series No. NG-T-3.15, IAEA, Vienna (2016).

2. KI SETS FOR COMPARATIVE EVALUATION OF NESs

KIs could be used to evaluate different aspects of NES or strategy options (i.e. scenarios) in a comparative way. For comparative evaluation of NESs, the KIs could focus on NES sustainability objectives [2.1], and in particular on selected important aspects in areas such as safety, economics, resources, proliferation resistance and waste generation.

It needs to be noted that comparative evaluation is in its nature substantially different from mandatory regulatory assessments, such as safety and environmental impact assessments, as well as optional NES sustainability assessments using the INPRO methodology. The difference is that assessment allows one to prove compliance with the defined set of criteria and acceptance limits but incorporates no provisions for making a judgement that one assessed system is better than another on the basis of some system characteristics exceeding the defined acceptance limits. For a comparative evaluation, the latter is actually the principal point. Hence, for KIs, the only parameters or characteristics of an NES that need to be selected are those whose variations result in the tangible and well understood and interpreted changes of user oriented qualities.

Comparative evaluation of performance and sustainability cannot override, or substitute for, the compulsory safety and environmental impact assessments carried out on the basis of national regulations and IAEA safety standards. Comparative evaluation can only be complementary to the assessments, as it will support the selection of an NES that is preferable for a particular user out of those NESs that otherwise meet or, for still immature systems, are assumed to meet all of the regulatory and other mandatory criteria. Regarding comparative evaluations in the area of safety, only safe systems can be compared (e.g. by considering a possible increase of the compulsory safety level).

The KI concept was first introduced in 2008 as an option within the INPRO methodology for NES sustainability assessment [2.1]. The GAINS collaborative project applied this concept for the comparison of NES scenarios at the regional and global levels. The KIs for GAINS have been defined for selected INPRO assessment areas that reflect the focus areas of the GAINS project. KIND further elaborates upon a certain direction of the INPRO methodology; therefore, its outputs could provide inputs for further improvement of the INPRO methodology to enable its effective application for comparative sustainability evaluations of NESs, as well as transition scenarios to such systems.

This section starts with general information and considerations for developing a KI set based on simple examples from a non-nuclear field. After that, it elaborates on evaluations involving an NES. Finally, it proceeds with a discussion of the attributes of sustainability in energy systems and explains how these attributes could be represented with KIs.

2.1. CONCEPT OF KIs

A KI is a specific, usually measurable, indicator showing how a system performs in a particular area. For example, a KI for the fuel efficiency of an automobile is the average distance travelled per unit of fuel (kilometres per litre or miles per gallon)[1]. Several KIs may be needed to provide an evaluation of all of the attributes of the system.

Continuing with the automobile example, the payload of the vehicle can be measured by two KIs: the seating capacity and the cargo area size. These KIs measure different aspects of the payload and both are needed to fully evaluate this area. Depending on the use, a third KI may also be needed: the towing capacity. This illustrates the fact that the KI set may be dictated by the desired use as much as by the physical attributes of the system. Note that sometimes these additional indicators may be considered to be secondary indicators (SIs), especially if they are evaluating an optional rather than a mandatory aspect of the system. In this example, when an automobile would not be eliminated from consideration if it could not tow a trailer, but would be given extra credit if it could, then towing (pulling) capacity may be treated as an SI.

[1] In this section the example of a car is used because it represents a commonly encountered technology, while specific nuclear examples are deliberately avoided, taking into account the fact that some readers may not be technical experts and might be distracted by technological details. Technical details are then presented in the subsections that follow.

KIs need to be developed at the right level for the evaluation being performed. If the automobile is being evaluated for purchase by a family, then fuel efficiency and seating capacity would probably be examples of the level of detail needed. If instead the evaluation was of a technical nature, then the KI for fuel efficiency might be replaced by a more detailed group of KIs covering aerodynamics, engine efficiency, transmission gearing ratios and secondary energy loads (e.g. air conditioning). The average family may not understand these more detailed indicators, illustrating that the level of detail depends both on the evaluation needed and the audience for the evaluation results. The KIs are the 'key' indicators that best represent the entire system for the target audience with the fewest measurements.

Once a set of KI indicators has been developed, the next step is to consider how to evaluate them. For measurable KIs, this first involves taking the measurement and noting the accuracy of that measurement. The accuracy could later be used in sensitivity analyses to see if the comparative evaluation results change when the value used is the mean plus/minus the standard deviation. The goal to be achieved for each KI needs to be clearly indicated.

The next step is to convert the measurement into a valuation for the KI, using MCDA methods, for instance, based on a concept of 'value/utility function'. The value/utility function indicates how much a particular data value is worth in the evaluation process versus a standard scale (e.g. 0–10) and needs to cover the full local range of possible KI values. Often a linear value/utility function is used to convert the local range into the standard scale. However, non-linear value/utility functions could also be used to indicate values such as threshold values. For example, the value/utility function for the number of seats may give zero value for two or fewer seats, increasing value for three to six seats and no additional value beyond six seats. A value/utility function may be continuous, where, for example, a scale of 0–10 allows for a value of 6.32, or it may be discrete, such as having 'buckets', where each bucket includes a portion of the full range of possible valuations. The scale is arranged so that the 'worst' value is at the low end of the scale and the 'best' value at the high end, which may result in inverting the measurement data when smaller measured values are judged to be better (e.g. lower operating costs).

While the previous KIs were all measurable, some aspects of a system may be based instead on opinion. For example, a family may be interested in having an automobile that 'looks good'. This is a subjective or non-quantified KI and its value/utility function may be a set of several text descriptions and their associated numerical valuations. In such a system, 'ugly' may be assigned zero value, 'plain/boring' a 2, and so on, up to 'wow' being assigned a 10.

There are several ways to measure a subjective or non-quantified KI. One method is to have everyone agree on a consensus value for each automobile being considered, along with a consensus on the certainty of that value. Another is for each person to give his or her own value for each option and combine them into an average, noting the distribution of answers. Finally, this second approach may be modified to give more weight to the values from a subgroup of the family, such as the parents or those deemed to be the fashion experts in the family.

The next step is to combine the data values of the different KIs to come up with a figure of merit for the option. To do this, the valuations of the KIs are combined numerically using 'weights'. This may be a multi-tiered process, first combining the values in each area, and then combining the aggregated values across areas. The weights at each level add up to 100%, with some amount being allocated to each KI or subarea. For example, the importance of seating may be worth 60%, cargo area 30% and towing capacity 10% in determining the 'payload' area valuation. Each individual value is multiplied by its weight and then summed to obtain the total valuation for that area. The same process is then used to combine all of the evaluation areas to obtain the overall figure of merit for the option.

To the extent possible, KIs need to be independent. This is not always possible. For example, a KI for fuel efficiency and another KI for operating cost both include the amount of fuel used. When some amount of interdependence is identifiable in the KIs, this needs to be considered when developing the weights for combining them. Otherwise, this specific aspect is assigned hidden extra weight in the evaluation.

Different stakeholders in an evaluation may have differing opinions on weighting. For example, cost may be more important to one person, while available capacity is more important to the other. Groups of weights, or weight sets, may be developed to represent these different perspectives. One aspect of sensitivity analyses then becomes identifying what stays the same and what changes when the different weight sets are applied.

2.2. GENERAL CONSIDERATIONS IN DEVELOPING KIs

2.2.1. Overview

A number of nuclear energy assessments/evaluations have been conducted since civilian nuclear energy has become a significant contributor to total energy production. The most significant were probably the International Nuclear Fuel Cycle Evaluation (INFCE) [2.2], conducted between 1977 and 1980, the Generation IV Nuclear Energy Systems Roadmap (GEN IV) [2.3], conducted between 2000 and 2002, and the series of Nuclear Energy System Assessments (NESAs) conducted since 2003 using the INPRO methodology [2.4].

These assessments all included some form of KIs for evaluating NESs, and could be used as examples for developing KIs. Any evaluation of an NES needs initially to consider the main categories/areas/dimensions of indicators from sources such as those mentioned above. Different sources have their own definitions of categories. The United Nations Commission on Sustainable Development considered the dimensions of sustainability. The INPRO methodology introduced INPRO areas for NESA assessment (Fig. 2.1).

When looking at these sources, consider the type of decision they were supporting and how well it aligns with the evaluation you will be conducting. Many of the previous evaluations, such as INFCE and GEN IV, were technology focused. This makes them very good sources if you are conducting an evaluation of potential new technologies. However, they are less useful and possibly even distracting when performing other types of evaluations that are primarily considering currently deployed technologies.

The NESA evaluations are more focused on the readiness of a country to operate an NES and are not designed to compare NESs. This includes a broader assessment than the technology focused evaluations, including the status of institutions and human resources. The different focus results in a different emphasis on the evaluation areas. However, these evaluations are still only looking at NESs and may not include everything necessary to evaluate non-nuclear energy options.

The following discussion looks at the areas used in the INPRO methodology [2.1][2], the GEN IV roadmap and other sources (see Annex I), based on the main dimensions of sustainability identified by the United Nations Commission on Sustainable Development. Figure 2.1, taken from the overview volume of the INPRO methodology, is an example of how the United Nations dimensions and NES evaluation areas compare. Because the previous evaluations tended to focus solely on NESs, they do not map directly to the United Nations dimensions. For example, the Social dimension in the United Nations system [2.5] is focused primarily on social justice and may consider indicators such as “share of households without electricity” or “share of household income spent on fuel and electricity”. These indicators are not generally applicable to evaluations of NES options. That being said, it should be noted that the INPRO manual on infrastructure [2.6] presents basic principles and user requirements related to institutional, social and public acceptance aspects of NESs, and their application has already been demonstrated. This manual also makes a reference to the ‘Milestones’ document [2.7], which, inter alia, addresses issues of stakeholder involvement and public acceptance.

2.2.2. Economic dimension

Economic indicators include the cost to establish, operate and decommission energy systems. In some evaluations, this is extended to include dimensions such as life cycle costs, financing considerations and job creation.

Considerable up-front capital expenditure is required to establish all energy systems. Thus, financial risk is an important consideration [2.8]. Nuclear systems are generally much more capital intensive than other options, which could make financing more difficult to obtain. Factors that impact financial risk and may be candidates for KIs include the total capital cost versus the lines of credit available and the time that elapses between when capital costs are incurred and when revenue begins to be generated. If the parties involved are not in a position to take on the risk of the project, then it may not be a viable option.

Another important risk factor is the experience base for the project, including experience with the designs, the developer, the regulator and the operator. Some questions include the following:

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[2] Note that the INPRO methodology is currently undergoing a rolling revision of individual volumes. The discussion here is based on the previous (2008) version because it is the last complete version.

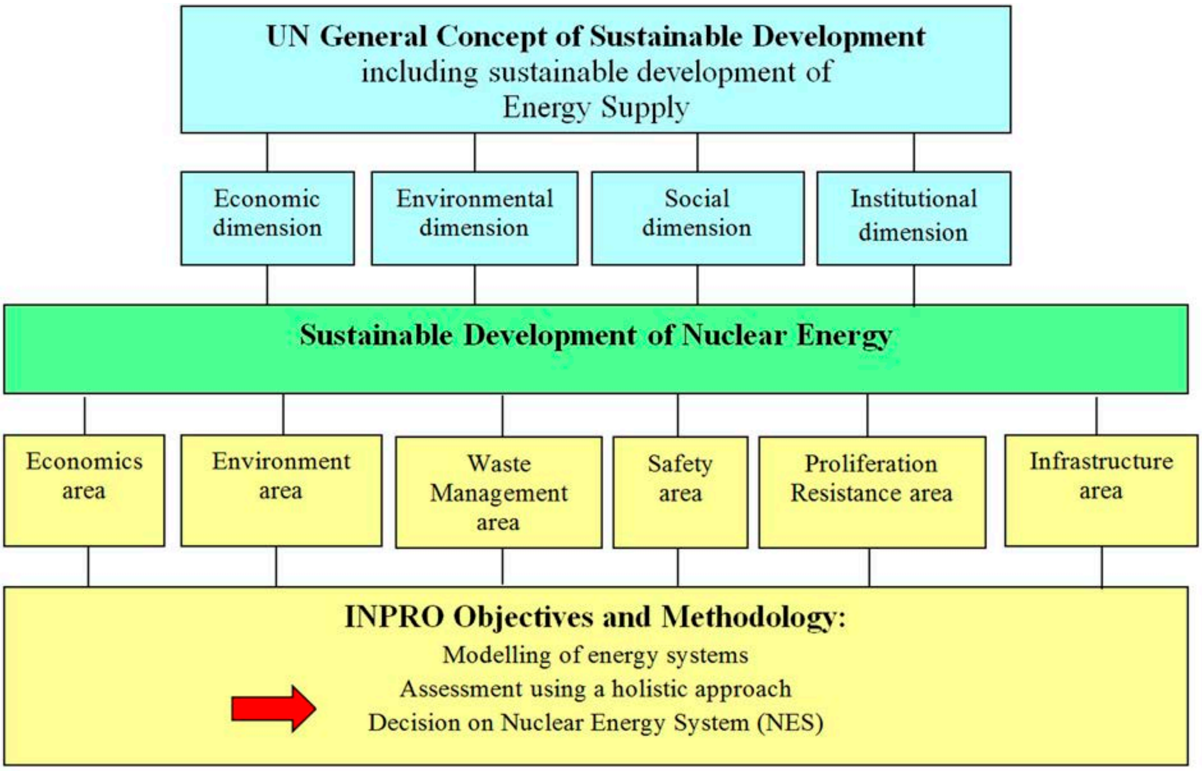

FIG. 2.1 . Interrelationship of UN concept of sustainability and INPRO areas [2.1].

— Have the vendor's designs been built/operated elsewhere and if so how successfully? A first of a kind system carries higher risk. A system that has been built before, but has had construction or operations problems, will also represent a higher risk, especially if these problems are widespread across multiple facilities.
— How experienced is the developer and were previous projects finished on schedule? A solid record of on time and on budget development can reduce risk, while the opposite will increase risk. Prior successful experience with the specific system is a risk reduction indicator.
— Has this country built/operated this type of system before and does it have the institutions in place to regulate it? Lack of experience by any party in the process can increase the risk of schedule delays and rework.
— Does the utility or other organization that will own and operate the system have experience with the technology? A lack of experience can result in lower availability factors, impacting revenue generation.

Depending on when the evaluation occurs, some of the above may not be applicable or may be unknown.

The flexibility of the system may or may not be important, depending on the local situation. For example, the ability to produce not just electricity but also potable water or district heat depends on the local need for these alternative energy products. The ability to load follow is also potentially very important, depending on local conditions.

Another indicator that may be addressed through economics is the cost of carbon emissions or an associated credit for lack of emissions for nuclear systems.

Uncertainty is an important aspect of economics and applies to all types of evaluations, whether involving proven or less mature technologies or even nuclear versus non-nuclear options. The uncertainty for proven technologies is generally reduced if a specific site and project date are known, while more general evaluations include more uncertainty. The evaluation of economics for less mature technologies always involves considerable uncertainty.

The most common KI for economics is levelized unit electricity cost (LUEC). This is a general purpose indicator that covers most of the economics topic, but does not explicitly cover some of the specific dimensions mentioned above. Other indicators used in recent analyses include the overnight construction cost (a more direct measure of the capital at risk) and the annual production costs (which will include operating performance, fuel costs, taxes, payments into a development and demonstration fund, grid- and system-level costs, etc., and provide an indication of the expected cash flow). Cash flow analysis and relevant indicators are also used to evaluate the attractiveness of projects to potential investors. For systems that will develop and operate over long time periods, discount rate variations (e.g. declining discount rates) are used to evaluate the real life value of the long term consequences of present day decisions. These are all indicators that can be applied to both nuclear and non-nuclear energy generation systems.

2.2.3. Environmental dimension

The environmental dimension is applied differently in different evaluations and may or may not include specific areas. Here, we include resource utilization, land and water use, waste management, carbon emission, and radiological and chemical impacts.

Resource utilization includes materials that are consumed, such as fuel, and materials that may be recycled when a facility is retired. In general, resource utilization is concerned with materials that are rare or limited in supply (locally or globally). For most nuclear systems, the primary resource of concern is uranium (or thorium) used as fuel. Other energy systems may have different materials of concern, such as rare earth elements in the case of some renewables.

The general consideration is whether the material usage is sustainable, which is interpreted differently by different parties. How it is interpreted in an evaluation could introduce bias. For example, the INPRO methodology asks if there is a sufficient quantity of the resource to last through the end of the century, while some in the renewables community will say that any consumption of a resource is non-sustainable because the resource will eventually be consumed.

The Brundtland Commission report [2.9] provides a useful definition of sustainable development: “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

Using this definition, if the current usage, including consumption, does not compromise the resource for future generations, then it is sustainable usage. In application, this places most renewables in the sustainable dimension, while fossil fuels are more likely to be considered non-sustainable. Nuclear energy is generally viewed as sustainable on this basis, since the current rate of uranium usage is slower than the rate of the identification of new uranium resources and mining practices are reducing the energy required to mine uranium.

The KI typically used for NES resource utilization is the amount of U/Th used per unit of usable[3] energy produced (e.g. t/GW(e)·h). In comparisons of current proven nuclear technologies, this value varies by as much as 30%. However, there is a very large difference of up to two orders of magnitude in uranium usage between current and potential advanced nuclear fuel cycles (NFCs). Comparison of nuclear to renewable and fossil energy sources is more difficult, but it can be achieved using the Brundtland approach.

Land and water usage may also be included in resource utilization or may be considered separately. For land use, there may be small differences between NESs, but there can be large differences versus other energy sources. Land use needs to consider both temporary and permanent land use, where temporary use includes land for facilities such as reactors that can be reused when the facilities are retired, while permanent use includes any land required for disposal of wastes with long lived hazards such as long lived radioactive materials and toxic/hazardous wastes. Note that radioactive wastes are also generated from non-nuclear energy generators, including mill tailings from rare earths, technologically enhanced naturally occurring radioactive material (TENORM) from well drilling and mixed radioactive/toxic materials in coal ash. Land use can also vary based on what is disturbed versus what is undisturbed and what is required versus what is common practice. For example, the land use associated with a nuclear reactor will include a set back area that is often undisturbed land and in practice is often larger than required by regulations (e.g. an entire river island instead of just the portion where the reactor is located). The common KI for land use is the amount of land required per net unit of usable energy generated, including both temporary and permanent use.

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[3] ‘Usable’ depends on the application, with t/GW(e)·h mainly being applicable if the primary or sole product to be produced is electricity. If products other than electricity are to be produced, then another measure such as tonnes or British thermal units may be used.

The importance of water usage depends strongly on the location and secondarily on the amount of waste heat produced. In wet climates, water usage may not be an issue at all, while in dry climates it may be a KI. Light water reactors require water as a coolant moderator, and other steam turbine based electricity generation methods (coal, some gas, some concentrated solar, etc.) require water to cool the steam (waste heat rejection).

Several technologies are available, and both the amount of water withdrawn and the amount consumed vary considerably by technology. If water usage is important in the evaluation, the actual waste heat rejection technology needs to be identified. The commonly used KI is the amount of water consumed (evaporated) per net unit of usable energy generated, but in some cases the amount of water withdrawn may also be important.[4]

Waste management is a major area when comparing different advanced NES fuel cycles, but is of less importance when comparing current proven NESs. Advanced NESs with recycling of spent nuclear fuel (SNF) significantly modify the amount of waste generated and the characteristics and hazards associated with those wastes. When comparing different NFCs and technologies, typical indicators may include the total waste produced, the high level waste produced (including SNF destined for direct disposal), the decay heat load and the radioactivity of long lived radionuclides and radiotoxicity at different points in time (associated with fuel handling, ~10 years; waste disposal, ~100 years; and geological repository performance, ~100 000 to 1 000 000 years). If rated important for the purpose of comparative evaluation, the specific generation of intermediate and low level wastes could also be addressed though appropriately defined KIs. All are normalized to the net amount of useful energy produced.

When comparing NESs to other energy sources in the waste area, many of the detailed KIs mentioned above are not applicable because they do not apply to the other sources. Instead, wastes managed and disposed of need to be compared to wastes allowed to move into the environment without management (effluent and emissions) for their overall impact on populations and the biosphere. The types of waste to consider include radiotoxic, chemically toxic and elementally toxic materials. A highly hazardous material that is carefully managed results in a different environmental impact than a moderately hazardous material that is not managed. These evaluations are difficult to conduct, especially if local site considerations are included (wind direction, distance to population centres, sensitive species, etc.). For a generic site, some information is available in the literature, including health impacts from fossil fuel emissions.

Carbon emissions could be considered as a special indicator of emissions when comparing different energy sources, where life cycle emissions are normalized in tonnes of CO_2 per unit of net usable energy produced and credit is given for any management (carbon capture) and disposal (carbon sequestration). NESs are one of the lowest energy sources for life cycle carbon emissions per net unit of useful energy produced, and in a comparison of nuclear to nuclear, an indicator for carbon emissions is generally not useful because the differences are so small when considered in the context of other energy sources.

Finally, the thermal efficiency of a nuclear power plant (NPP) could be another KI to evaluate the waste heat rate (thermal footprint of the plant), and some advanced nuclear reactor concepts being developed or deployed currently offer higher rates of produced heat utilization through higher primary coolant temperatures or purposeful use of the reject heat. In this way, the thermal footprint of the plant could be reduced.

2.2.4. Social dimension

A number of indicators can be placed in the social dimension, depending on the type of evaluation and what issues are considered to be social issues. In this discussion, we include the typical NES areas of safety, proliferation resistance and physical protection, along with societal opinion/support for different energy generation technologies. Some evaluations also include environmental hazards that have been externalized (e.g. air pollution) as an additional indicator for social issues.

Safety is an area of high social concern. When considering KIs for safety, the purpose of the evaluation and the audience need to be considered, as technical safety analyses would use much different KIs than a more general analysis. In the technical area, difficulties include the claimed inherent safety of advanced systems that have not been approved by regulators. When these systems mature, they may be required to add additional layers of safety, as was done with current generation reactors, which will add cost, delays in construction and additional requirements for operation and maintenance.

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[4] Some advanced nuclear technologies presently being developed in the domain of small modular reactors consider the air cooling option.

For more general evaluations of safety, several approaches could be taken. One is founded on the actual performance of existing systems, while another is founded on the public perception of safety performance. Note that the root causes of the major nuclear accidents (Three Mile Island, Chernobyl and Fukushima Daiichi) have all been attributed to human error or omission rather than the technical design, although the designs did then contribute to the severity of the result [2.10–2.12]. When comparing one system to another, it is very difficult to determine the magnitude of differences in the potential for human error. Also, the public in general does not understand the technical details of reactor safety systems and so public opinion is likely to be based more on emotion than reason. However, this does not make public perception of risk any less meaningful — if people are afraid of something, they will not support it, and it does not matter why they fear it.

Finally, some evaluations may simply make the assumption that the system would not be allowed to operate by the regulator if the design was not sufficiently safe, and therefore all systems are equal in terms of safety. This approach may or may not be acceptable, depending on the audience, and depends heavily on how much the public trusts the regulators. However, in all cases, compliance with the IAEA safety standards [2.13] is a necessary requirement.

When considering possible improvements against the compulsory safety level, typical KIs in the safety area may vary by the level and type of analysis. A technical analysis may include summary level indicators of the main layers of probabilistic risk assessments, including the probability of core damage, the probability of a release and the need for evacuation. Unfortunately, a probabilistic risk assessment requires a mature design. It is also highly detailed, making it difficult to explain results to the public, including whether a difference is minor or major.

Innovative systems may promise real differences, including passive cooling and the absence of factors that can magnify an energetic release, that may be sufficient to avoid an accident, or significantly reduced source terms that could reduce the consequences of an accident. Until these systems are actually designed and independently evaluated by regulatory agencies, these promises cannot be taken as proven, which makes it difficult to weigh their importance versus other KIs.

Taking into account the fact that any comparative evaluations of NESs in the area of safety, targeted at additional safety improvement, could only complement (ideally, follow up) the mandatory regulatory assessments of safety, the KIs in the safety area could generically be viewed as attributes of NES acceptability, as well as of NES performance.

Proliferation resistance related KIs depend on factors such as whether the country is a weapons State and whether the country needs to deploy sensitive technologies of enrichment and reprocessing to support its NESs. The KIs can be binary (yes/no) at the basic (high) level of whether or not new enrichment or reprocessing facilities are included outside existing weapons States, as these two technologies are the only pathways to nuclear weapons.

Physical protection has been less likely to be a key issue with the public, but has increased in importance owing to concerns about terrorism. Physical protection is difficult to evaluate without a detailed design showing the defence in depth systems. For this reason, KIs may not be used for physical protection for less mature, advanced systems. KIs could include the presence of attractive materials in the fuel cycle in physical forms that can be stolen. Unlike with proliferation resistance, an attractive material from the physical protection viewpoint might only be attractive for making a ‘dirty bomb’.

Security of energy supply may also be a social dimension concern (or it could be in the institutional dimension). Security of supply may consider the number of independent suppliers, the amount of fuel or other key materials that can be stored economically, measured in days or months of supply, or other factors that address the risk of supply disruption. Long term supply security could be addressed under resource utilization.

The social dimension can also include factors such as the economic stimulation expected from an energy system option (jobs), the technical know-how required (good jobs) and other positive social impacts.

Owing to the diversity of indicators in the social dimension, one difficulty is how factors are combined. For example, how important is proliferation resistance versus economic stimulation? Different stakeholders may have very strong views in this regard, requiring sensitivity analyses to determine how sensitive results are to the weighting of the different indicators.

2.2.5. Institutional dimension

This dimension includes all the activities and agencies needed to develop, manage, operate and regulate an NES or the equivalent for non-nuclear energy systems. This can include different items, ranging from a regulatory agency to facilities in ports to training organizations. The most difficult aspect of developing KIs for the institutional dimension is in deciding what is truly important versus what can simply be noted or measured [2.7, 2.14, 2.15].

KIs in this dimension often evaluate what exists versus what is targeted to be developed. An existing system typically outperforms a new system of any type because the new system requires new institutional measures. How long it will take and how much it will cost to provide the missing institutional measures is often the main KI, but this can be broken down into separate indicators of this dimension based on stakeholder interest.

This dimension may also consider the supply chain for domestic content of facilities and equipment. However, having a domestic supply may be considered under the social dimension, or the impact of domestic content on economics may be considered under economics [2.16].

2.2.6. Other considerations

Some of the areas of evaluation for an NES may fit under more than one of the sustainability dimensions. Where they are placed can have an impact on the results of an evaluation because the weighting is often influenced by the name of the dimension or area. This can result in higher or lower weighting for a KI or set of KIs based on where it is placed in the overall structure. For example, gaseous emissions can be included under wastes or under environmental impacts. If they are included under wastes, then there will be a tendency to give more weight to high level waste and spent fuel and less to gaseous emissions. However, if they are included in environmental impacts then they may carry more weight in the environmental dimension because they are direct releases to the environment. They could also be included in both areas, as long as it is made clear that double counting is occurring and the weighting factors are developed with this in mind.

It should be noted that specific case studies can be based on the specific categories of the country, which in turn can be aggregated according to the high and intermediate level objectives, taking into account the national intentions and issues stated by a decision maker and the specifics of a decision making situation.

Based on such considerations, it seems important to propose and design the most suitable structure for an objectives tree, which is a key concept that is used in applied studies to support decision making by structuring the problem and simplifying the procedure for aggregating and processing expert judgements.

2.3. AGGREGATION OF EXPERT JUDGEMENTS AND COMPARATIVE EVALUATION PROCEDURE

The aggregation of experts' judgements for a comparative evaluation requires the application of mathematical methods and approaches to help individuals or groups in making decisions while considering several objectives. Such approaches combine objective measurements and the subjectivity of decision makers and help make it possible to understand and structure the problem, recognize the trade-offs and select the most preferred option. A comparative evaluation procedure based on judgement aggregation methods consists of the following main phases: problem structuring, model building and developing an action plan.

2.3.1. Problem structuring

In this phase, all the ideas about the problem and the corresponding solutions are discussed. First, the stakeholder groups have to be identified. A stakeholder is a person who has an interest or a stake in the object being evaluated. Individual stakeholders are likely to have different views on the problem, its surroundings and treatment. All stakeholders need to develop a common understanding of the problem and the objectives to be considered at the time the alternatives are evaluated.

It is advantageous to structure the problems in the form of objectives trees (or value trees, objectives hierarchies, hierarchies of attributes, etc.) which delineate the decision maker's preferences and represent hierarchies of objectives with evaluated KIs on the basis of which different alternatives can be easily evaluated. They are trees that map the decision maker's problems onto the structure of the options under evaluation. The key questions which arise while developing objectives trees are the following:

(a) What are the major objectives and concerns of the decision maker?
(b) What KIs differentiate the alternatives under evaluation?
(c) How can these KIs be measured?
(d) How are KIs and overall objectives related?

In general, the characteristics of objectives trees need to be comprehensive. A KI is defined as comprehensive if, by knowing the level of the KI in a particular situation, the decision maker has a clear understanding of the extent to which the associated objective has been achieved.

Some KIs are objective, that is, there is a commonly understood scale for such a KI and its levels are quantitatively measurable. When there is no objective index available (e.g. in the case of like or dislike judgements), subjective scales need to be constructed. It is important to note that although the preference comes with quantifiable values, many decision analysts admit that various KIs are not objectively measurable. The direct judgement on such KIs is a measurement procedure like any other. Faithful representation of an inherently subjective value structure, not objectivity, is the goal of structuring objectives trees. A KI can have the following characteristics:

— *Measurability*, which means that the possible levels of the KI can be assigned and the decision maker's preferences can be evaluated in terms of value/utility functions or rank ordering. In the decision analysis, measurable KIs are frequently called value relevant.
— *Evaluation relevance*, which means that if all alternatives under evaluation score the same on a given KI, that KI is not relevant to the evaluation and should not be part of the final calculation process.
— *Judgemental dependence*, if the evaluation of an alternative with respect to one KI depends on how the alternative performs with respect to the other.
— *Environmental correlation*, if the value of one KI strongly influences the value of another.

In principle, one could strive for a straightforward evaluation, avoiding problems such as judgemental dependence or environmental correlation. Often, difficulties can be removed by restructuring the parts of the tree that produce the problem. For instance, the problem of an environmentally correlated KI could be dealt with by combining the two correlated KIs into a new one.

When constructing objectives trees, the analyst needs to stop disaggregating when the dimensions at the lowest level are measurable and easy to evaluate judgementally.

When dividing an objective into sub-objectives, on the one hand, care must be taken to ensure that all of the important issues of the higher objective are accounted for in one of the sub-objectives, while on the other hand, a proliferation of the tree may be both unnecessary for the decision procedure and unmanageable.

The 'test of importance' is used to filter out those KIs that are not relevant to the particular decision process. The test of importance implies that before any objective is included in the hierarchy, the decision maker is asked whether he/she feels the best course of action could be altered if that objective were excluded. An affirmative response would imply that the objective needs to be included and a negative response that it does not need to be.

The relationship between the lower level dimensions and a higher dimension needs to be hierarchical and directed; it needs to avoid crosslinks with other higher level value dimensions and create an exhaustive and non-redundant list of explanatory value dimensions. The following, often conflicting, KIs are relevant to examining the validity of an objectives tree:

(i) *Completeness*: all relevant values are included;
(ii) *Operationality*: the lowest level values or KIs are meaningful and can be evaluated;
(iii) *Decomposability*: the KIs can be broken down into parts and are judgementally independent;
(iv) *Absence of redundancy*: no two KIs or values mean the same thing;
(v) *Minimum size*: the number of KIs is kept small enough to be manageable.

The quality of a tree might only become evident after evaluation of the numerical values. Generally, KIs are easiest to analyse if either more is preferred to less, or less is preferred to more. However, sometimes KIs may be non-monotonic, that is, they may have an ideal point or saturation level.

The use of objectives trees to evaluate options is straightforward: the analyst obtains values for the operational KIs (branches of the tree), converts the values to utilities, weights the KIs and carries out the judgement aggregation to obtain an overall evaluation of the option. In practice, however, this approach has difficulties. For instance, there may be too many branches to carry out a sensible evaluation, or some branches of the tree may be irrelevant because the options do not differ strongly enough in respect of them. The vertical depth of the proliferation of the hierarchy does not necessarily force the analyst to quantify preferences down to this level of detail. The hierarchy after a given level may serve merely as a qualitative checklist that helps facilitate clearer thinking about higher level KIs. The simplicity and ease of the judgement task need to be balanced against the operational ability of the KIs.

2.3.2. Model building

In this phase, a model of the preferences of the decision makers is developed based on a certain MCDA method. There are three important procedures to be completed during this phase:

(a) Specification of alternatives;
(b) Definition of KIs;
(c) Elicitation of values.

2.3.3. Developing an action plan

In this phase, the results of the previous phases are implemented through the development of an action plan and it is assumed that the following steps are undertaken:

(a) Synthesis of information;
(b) Sensitivity analysis;
(c) Robustness analysis;
(d) Creation of new alternatives.

2.4. SPECIAL CONSIDERATIONS FOR KIs

Different sets of KIs may be used within comparative evaluations of NES performance and sustainability that encompass different evaluation areas. Some of these KIs may be evaluated objectively to characterize reactor technology and NFC performance, material flows and requirements in NFC goods and services; others can only be evaluated qualitatively (in the form of descriptors) based on expert judgements; still others may be evaluated in terms of ‘go/no go’. Having been identified, an entire set of KIs provides an opportunity to evaluate and compare the performance and sustainability associated with the corresponding NES options.

2.4.1. Comparison of nuclear to nuclear systems, including options with different maturity levels

An NES comparison can be carried out at both the technological and scenario levels. This section discusses some specific issues related to the KI selection to compare NESs at the technological level. The next section will focus on issues related to the selection of KIs for an NES comparison at the scenario level. Creating a universal set of KIs for comparative evaluation of NESs is not possible owing to the need to take into account the specifics of the situation for which experts want to work out a decision, as well as the availability and affordability of appropriate information and data from experts and a decision maker.

Despite the fact that the specific sets of KIs can vary depending on the problem, it is possible to state that agreement on the evaluation areas that need to be considered within comparative evaluations of NESs is achieved among the different groups of experts involved in NES performance and sustainability evaluations. They are as follows: safety, economics, waste management, proliferation resistance and physical protection, environment, maturity of technology and country-specific area. For each of these evaluation areas, taking into account the available information and datasets, the KIs that best represent issues of practical interest for a specific problem need to be defined.

When comparing NESs at the technological level, it is crucial to keep in mind the maturity level of the options under consideration. It is necessary to distinguish situations in which several systems with the same maturity level are being compared and situations in which the experts compare systems with different maturity levels. Certainly, the less mature technologies are characterized by greater uncertainty than the more mature options; as a result, not all KIs can be quantified for less mature options owing to the lack of required information. Therefore, when forming the set of indicators, it is essential to recognize that consideration is only to be given to those indicators that can be adequately evaluated with acceptable accuracy for the entire set of alternatives. With technically less mature concepts, often the most knowledgeable experts are also the concept proponents.

When comparing NESs at the technological level, it is advisable to represent all NFC material flows in specific units (per unit energy production) in order to bring them to a comparable form (e.g. the specific cost of producing electricity, the specific natural uranium requirements, the specific rate of plutonium/minor actinide accumulation, etc.). NES comparisons at the technological level allow the peculiarities of the systems to be considered in selected areas; it is possible to evaluate the financial performance (net present value, internal rate of return, etc.), the likelihood and risks of unfavourable events arising from the commissioning, operation and decommissioning of the systems (e.g. the probability of a core meltdown, reactor core damage frequency, the risks associated with the theft of fissile materials or the misuse of NFC facilities, etc.) and R&D needs, as well as the utilization of NESs for different purposes and so on.

Because a number of KIs are evaluated solely in terms of scores (e.g. the technology maturity level), it is necessary to provide an opportunity to interpret the corresponding indicators and their values for the different alternatives being compared in areas and using concepts that are familiar to a decision maker (e.g. economic risks). The following is a concise general description of possible indicators for specific evaluations that were discussed by various expert groups within the framework of corresponding case studies on the comparative analysis and evaluation of the NES performance and sustainability.

2.4.1.1. Safety

In general, sustainability evaluations in the area of safety are applicable to more mature designs, and a given set of KIs for safety cannot be applied simultaneously to existing systems and innovative systems where many details are not well known. Proponents of innovative concepts speak about multiple inherent and passive safety features, but the absence of full safety analysis often makes it impossible to evaluate their importance. Should primary hazards and measures to cope with them be identified, the safety case for the system would be presented in the evaluation report, and compliance with the national safety norms and IAEA safety standards could then be used as a ‘go/no go’ KI for safety.

Such potential performance measures as ‘non-nuclear (mechanical, chemical) energy that is stored in and could potentially be released from the reactor system or fuel cycle system’, ‘time constants for transients’, ‘core damage frequency’, ‘large (early) release frequency’, ‘frequency of individual effective dose at site boundary’, ‘source term’, ‘dose versus distance curve’ and others may potentially be useful to specify KIs for sustainability evaluation in the safety area, but it may only be reasonable to use them in cases where all the options being compared may be evaluated by corresponding KIs. Additional indicators may also address other safety aspects: worker safety, public safety and investment safety (an event that leaves a facility useless, but harms no one, etc.).

2.4.1.2. Economics

The most often used economic KI is LUEC, which includes all the aspects that affect the total cost and views them over system commissioning, operation and decommissioning. At the same time, other economic or financial metrics may also be potentially interesting, such as net present value, total discounted cost, internal rate of return, discounted payback period and overnight capital costs. The need to utilize this kind of KI is caused by the fact that the liberalization of energy markets has given high decision making autonomy to business entities, which in the new conditions first of all seek to maximize their profits. The cash flow theory has come into use as the main tool for choosing efficient investment projects, where the mentioned KIs are used as the prime criteria for decision making efficiency.

Risks associated with the loss of capital investment may also potentially be interesting for decision makers. As a measure of the risk of capital investment loss, the concept of value at risk (i.e. a measure of loss that will not exceed the expected loss with a specified probability equal to a given confidence level) could be used. Other possible risks metrics (expected shortfalls, tail value at risk, etc.) may also be considered.

Risks associated with a long term burden for future generations resulting from decisions made in the present could be evaluated by cash flow analysis with declining discount rates.

2.4.1.3. Waste management

It is desirable to keep the generation of radioactive waste (measured, for instance, in tonnes or in volume units) by an NES and its impact (radiotoxicity, etc.) to the minimum practicable level. Different schemes of waste management may provide benefits to repository programmes, reducing the footprint of a repository. In this regard, the main contributors to heat load during different depletion periods of SNF (transuranic elements, fission products, activation product inventory) may also need to be characterized and taken into account.

Different KIs may be used to characterize waste management issues, such as ingestion radiotoxicity, radioactivity at 100 000 years after discharge (long term repository performance), radioactivity at 10 years after discharge (representative of handling issues), radioactivity at 100 years after discharge (decay storage thermal loading), high level waste (HLW) mass/volume, peak dose rate, decay heat or heat load, and time needed to reach a certain level of waste radiotoxicity. Some of these KIs may be represented per unit of energy produced by the system. The quantity of unique activation and chemically toxic waste products and unique waste forms may also be considered, if necessary, within comparative evaluations.

2.4.1.4. Proliferation resistance and physical protection

Proliferation resistance depends on intrinsic features and extrinsic measures that need to be implemented throughout an NES's full life cycle to ensure that the system will be an unattractive means to acquire fissile material for a nuclear weapons programme. Both intrinsic technical features and extrinsic institutional measures are essential and when applied to an NES can increase the difficulty of diversion of nuclear material and misuse of the NES on the part of the State. In comparison, physical protection and nuclear security are intended to counter threats from sub-State actors; these are the responsibilities of the host State and not a part of proliferation resistance.

Different metrics may be proposed to evaluate the material inventory and forms (unirradiated and irradiated direct use material, indirect use material, item or bulk form) that characterize the proliferation potential associated with the NES. From a marginal risk perspective, it is important that the host State being considered already possess sensitive technological capabilities for enrichment or separation that are physically capable of producing significant quantities (proliferation goal quantities) of unirradiated direct use material inventories. Metrics such as 'deployment of sensitive enrichment and reprocessing/separation technology' may represent a capability to produce unirradiated direct use material in a State.

Since high quality safeguards verification increases extrinsic proliferation resistance, such metrics as 'safeguards implementation considered from early design stage' represented by a 'go/no go' indicator may be valuable. International interdependence (bilateral cooperation agreement obligations), with non-proliferation assurances and obligations documented in cooperation agreements between States, is a legal requirement to increase extrinsic proliferation resistance.

In general, traditional physical protection metrics might be difficult to evaluate for non-mature NES systems owing to the necessity to have detailed designs for associated facilities.

2.4.1.5. Environment

The environment area traditionally covers aspects related to the utilization of natural resources and the impact of the NES on the environment (not directly related to nuclear waste issues), which may be specified by diverse metrics, such as: the amount of useful energy produced by the system (from mining until disposal, including enrichment, reactor operation and separation) per unit of mined natural uranium/thorium; the supply sufficiency of identified rare non-nuclear materials for a targeted deployment scale; and the amount of water (or other consumables) used or land potentially impacted per unit of useful energy produced.

2.4.1.6. Maturity of technology

The technology provided in an INES needs to be 'proven' or 'mature' before it is included in a proposed design. For a technology to be considered mature, it needs to have already been applied in a prototype (a system, subsystem, or component), tested in a relevant or operational environment, and found to have performed adequately for the intended application for a reasonable length of time, or be fully licensed and operated by a host country before export to another country. This implies a need for measuring or evaluating maturity and ensuring that only a sufficiently mature technology is included by the technology holders in proposed plant designs. In this regard, NESs that are involved in a comparison may be at different design stages (feasibility study, conceptual design, basic design, site selection, detailed design, pre-licensing) and different amounts of time will be needed to mature the technology.

Less mature technologies are characterized by greater uncertainty owing to insufficient detail in areas such as design information, operational data and cost information, but the expected performance characteristics of the less mature options are usually more attractive than those of the more mature ones. The greater the uncertainty is, the greater the risks associated with the project realization will be. The maturity of technology area characterizes an aggregated risk measure and in such a manner the results of a comparative evaluation of less and more mature options may be interpreted for decision makers. The risk terminology provides a good basis for judgements regarding the risks/benefits associated with less and more mature options to inform a decision maker who is responsible for decisions relating to clear recognition of the risks and risk acceptance.

The cost of the R&D and the research, development and demonstration needed to deploy an *n*th of a kind unit may be a performance measure of the maturity level of technologies. Other performance measures that may somehow qualitatively characterize the maturity level of technology are as follows: the degree of standardization and licensing adaptability, the degree of validation of basic processes (theoretical, process demonstration, pilot facility demonstration), the share of proven technology (in some innovative systems many proven systems and components might be used, such as standard turbine generators available on the market).

2.4.1.7. Country-specific area

Because some innovative technologies may contribute not only to sustainable energy production, but also indirectly (through spin-off enterprises) to other areas of the national economy for some studies, it may seem reasonable to use KIs characterizing the spin-off potential of an NES. Infrastructural (legal, institutional, industrial, human resource) capabilities, political support and public acceptance issues, flexibility for non-electrical services and energy products, and load following capability are other examples of potentially interesting aspects to be accounted for within comparative evaluations of NESs in different countries using corresponding metrics.

2.4.2. Comparison of NES deployment scenarios

Despite the possibility of a detailed specification of the NES features at the technological level, while remaining within the framework of such consideration, it is impossible to correctly reflect the functioning of a certain technology as part of a whole system. It is known that the same technological option may manifest different performance and sustainability in different environmental and infrastructural contexts. For this purpose, a comparative analysis of NES options at the scenario level has to be carried out. Specifics related to KI selection for this purpose are discussed below.

A comparative analysis of NESs at the scenario level enables comparison of the performance of various NESs in given economic, environmental and infrastructural surroundings, taking into account the pre-history of nuclear power deployment, forecasts of its development in the future, the accumulated stocks of nuclear materials and the corresponding infrastructural capabilities. Carrying out this kind of comparative analysis makes it possible to rank NES options in the light of how a particular system is capable of responding to the challenges that nuclear power is faced with (i.e. how efficiently every system will resolve the problems that arise and ensure effective and sustainable functioning in the future). Comparative evaluations of NESs can be carried out at the national, regional and global levels, in short, medium and long term contexts, depending on the specifics of the decision making problem.

It should be noted that the use of KIs that characterize the design measures of a particular system (financial schemes, probabilities and risks of unacceptable events, etc.) within the comparison of NESs at the scenario level is unsuitable. A comparative analysis of NESs at the scenario level focuses to a greater degree on how to evaluate the effectiveness of NESs in terms of efficient utilization of natural uranium or thorium resources, NFC capacities, and the accumulation rate of secondary fissile materials and radioactive wastes for the given scale of energy production. In this context, experts prefer to operate with functionals of the material flows in the NFC (integral amount over time, the annual needs and so forth). The preferred KIs are those characterizing the integral amount of a certain material flow over a given timeframe.

As an example, Table 2.1 lists the most commonly used KIs for a comparative analysis of NESs at the scenario level; these were considered within various IAEA INPRO endeavours and were reflected, in particular, in the reports of the GAINS and SYNERGIES collaborative projects [2.17].

The selection of a particular set of KIs needs to be configured while taking into account the fact that all of them have to be evaluated using various calculation tools. Therefore, the application of scores is less suitable for KI evaluation in this case. It is desirable that all relevant scenarios be calculated using the same methodological framework (the same model or software tool) and similar scenario assumptions in order to avoid discrepancies in KI values associated with the use of various toolkits and model hypotheses. Equilibrium modelling (based on equilibrium and steady state models) and dynamic modelling (using simulation and optimization models), as well as their combined application, can also be used to evaluate the KIs and form the evaluation tables.

Because different technological options may be combined into a system in different ways, as a rule, when comparing the NES deployment scenarios, the number of comparable options is much greater than for NES comparisons at the technological level. At the same time, an overall decrease is observed in the number of KIs used, but the KI values for different options are closer in magnitude to each other. This fact needs to be taken into account when selecting the judgement aggregation method and its adaptation to solve a particular decision making problem.

2.4.3. Comparison of nuclear to non-nuclear, including for newcomer countries

The development of KIs for NES vs NES comparisons is targeted for implementation in countries interested in the near term or medium term deployment of NESs, whether or not the country owns or is constructing NPPs. For newcomer countries where NPPs do not exist, and conventional energy and renewable energy system are widely used and familiarly operated, KIs designed for the comparative evaluation of NES and non-NES options may be more useful than KIs that are only designed for the comparison of two or more NESs. In this regard, specific KIs are needed for use in both technology developing countries and newcomer countries. The development of recommendations for KI selection for newcomer countries may also be based on the INPRO methodology and its extensions. KIs in certain areas need to be developed in conjunction with the national perspectives of newcomer countries.

There are three domains to which the newcomer countries normally pay close attention. First, only energy systems with proven and demonstrated safety are eligible for consideration. The second domain is economics and the third one is acceptability, which may be divided into the following areas: economics, energy security, public acceptance and infrastructure. Energy security is acceptability from the national point of view, while public acceptance is acceptability from the viewpoint of the public. Infrastructure determines the ability of the institutions and industries to accept the energy system. Different KIs under these areas need to be specified depending on the newcomer country.

The LUEC could be adopted as an economic indicator to evaluate the affordability (cost competitiveness) of the energy system, and the cash flow could be adopted as an economic indicator for availability. The two KIs in the area of economics, LUEC and cash flow, are described below.

LUEC is one of the best indicators for comparing the affordability of energy systems, taking into account the cost of the whole life of the NES, including the initial investment, fuel costs, operation and maintenance costs, and decommissioning costs. Since the external costs will be discussed further, they are not to be covered in the evaluation of LUEC in order to avoid double counting. On the other hand, if the energy system is a first of a kind plant, as in the case of NESs in newcomer countries, this may increase the LUEC (e.g. risk premium, construction delay, and increased operation and maintenance costs). In addition, headroom for higher cost could be provided for the preferable energy system in order to reflect any strategic considerations.

TABLE 2.1. KEY INDICATORS USED IN THE SYNERGIES SCENARIO STUDIES[a]

Area of interest	Key indicators	Units	Relevance to areas[b]
Power production	Per annum electric energy generation growth by reactor type	GW(e)·year	I
	Per annum thermal energy generation growth by reactor type	GW(th)·year	I
	Non-electrical production: (a) Hydrogen (b) Desalination (c) Heat	GW(e)·year	I
	Commissioning and decommissioning rates	GW(e)/year	I, WM
	Installed capacity	GW(e)	I, WM
Nuclear material resources	Natural uranium requirements: (a) Annual (b) Cumulative	kt HM	ER, WM
	Depleted uranium	kt HM	ES, ER
	Reprocessed uranium	kt HM	ES, ER
	Natural uranium savings due to: (a) Reprocessed U use (b) MOX use (c) Direct use of spent PWR fuel in CANDU (DUPIC)	kt HM	ER, PR, PP, WM
	Time of exhaustion of conventional natural uranium resource	Years	ER, PR, PP, WM
	Natural uranium exhaustion	t HM	ER, PR, PP, WM
	Plutonium: (a) Pu in the system (b) Reprocessed Pu (c) Reprocessed Pu use (d) Reprocessed Pu stock	t HM	ER, PR, PP, WM
	Thorium	t HM	ER, WM
Discharged fuel	Discharged fuel inventories: (a) Annual SNF generation (b) Long term SNF storage	kt HM + FPs	WM, I
Radioactive waste and minor actinides	Minor actinide inventories: (a) Reprocessed MAs (b) Used MAs (c) MA stock (e) MAs in long term storage	t HM	ER, WM
	Pu in long term SNF storage	t HM	ER, PR, PP, WM
	Reprocessed FPs	t	WM, I
	Radiotoxicity and decay heat	kW, Sv/kW·h	WM
	LLW/ILW/HLW disposal: (a) Volume (b) Area (c) Mass	(a) m^3 (b) km^2 (c) t	WM, I

TABLE 2.1. KEY INDICATORS USED IN THE SYNERGIES SCENARIO STUDIES[a] (cont.)

Area of interest	Key indicators	Units	Relevance to areas[b]
Fuel cycle services	Requirements in terms of NFC infrastructure, i.e. installed and new capacities for uranium: (a) Mining (b) Conversion (c) Enrichment (d) Fuel fabrication (e) Reprocessing of SNF, SNF temporary storages and final repositories	(a) t HM (b) t HM (c) SWU (d) t HM (e) t HM	PR, PP, I
	Annual quantities of fuel and waste material transported between groups	t HM	WM, PR, PP, I
	Transmutation rate	kg/TW(e)·h	WM, PR, PP, I
Costs and investment	Levelized unit of electricity cost (LUEC)	US $/MW(e)·h, mills/kW(e)·h	E
	Levelized fuel cycle unit of electricity cost	US $/MW(e)·h	E
	Annual and total investment (expenditure) in NPP	Billion US $, rel. value	E
	Annual and total investment (expenditure) in NFC	Billion US $, rel. value	E
	Annual and total discounted investment in NFC	Billion US $, rel. value	E
	Natural uranium cost prospective	US $/kg	E
	Economic value of reprocessed uranium	US $/kg	E
	Fuel cycle service cost: (a) Conversion (b) Enrichment (c) Fuel fabrication (d) Reprocessing	(a) US $/kg HM (b) US $/SWU (c) US $/kg HM (d) US $/kg HM	E
	Cumulative cost: (a) Enrichment (b) Reprocessing	US $	E
	SNF/HLW storage cost: (a) Interim (b) Final	US $	E
	Transmutation overcost (different approaches)	%	E

Note: CANDU — Canada deuterium–uranium, FPs — fission products, HLW — high level waste, HM — heavy metal, ILW — intermediate level waste, LLW — low level waste, MA — minor actinide, MOX — mixed oxide, NFC — nuclear fuel cycle, NPP — nuclear power plant, PWR — pressurized water reactor, SNF — spent nuclear fuel, SWU — separative work unit.

[a] Such important areas as safety and physical protection are not covered under the GAINS metrics, but are assumed to be thoroughly evaluated under other assessments based on the INPRO methodology for NES sustainability assessment [2.1, 2.17].

[b] E — economics, ER — environmental resource, ES — environmental stressors, PR — proliferation resistance, PP — physical protection, I — infrastructure, WM — waste management.

Energy (electricity) will only be available if the energy system is developed and deployed. The development and deployment of an energy system require substantial investment, and thus the owner has to convince a number of major investors that their investments would lead to acceptable profit. Cash flow is a good indicator to evaluate the quality of the investment, since it takes into account the whole life of the energy system, and it enables simultaneous consideration of multiple units in a specific timeframe. In order to evaluate the cash flow, several important conditions have to be determined (e.g. debt fraction, debt term, interest rate, expected return to equity investor, discount rate and the schedule for the introduction of the (series of) energy system(s)).

In cases where these conditions are still ambiguous, or the resource is not sufficient to perform a cash flow evaluation, several indicators may be used instead, for which the evaluations are much easier. Internal rate of return (IRR) and return on investment (ROI) are the two indicators that could be used to evaluate the attractiveness of the investment, and the comparison of investment to the investment limit is a way to evaluate the investment ability of the utility. However, there are some other aspects that could affect the attractiveness of investment in the energy system (e.g. banks and investors tend to perceive larger investment risk for larger projects; thus, the interest rate and the required rate of return on equity are normally higher for larger projects). The same conditions apply to projects with a long payback period. Therefore, the IRR and ROI are evaluated within the context of the weighted average cost of capital (WACC), which is the weighted average of the required rates of return for investors in the equity and debt of the project, where the weights are the shares of equity and debt in terms of total project value [2.8].

Energy security is of particular importance in the process of technology selection for energy systems. One way to strengthen energy security is to maximize the degree of localization. Based on this perspective, the degree of dependence on suppliers (overseas versus domestic) could be used as a KI for a comparative evaluation of energy systems.

The degree of dependence on supplier(s) is taken into consideration to evaluate the degree of localization of the energy system when introduced in the country, which reflects the sustainability of power utilization of the country. To generalize the degree of dependence so that it is applicable to all energy systems, the areas that need to be considered are determined based on the life cycle of the energy systems, for example, technology, construction, fuel supply, operation, maintenance, waste management and decommissioning.

Public acceptance is needed to initiate and sustainably use an energy system in a country. Public acceptance for an energy system may be achieved easily in some countries, but for others it may not be. Therefore, the evaluation of public acceptance is a crucial element for the evaluation of the ability to establish an energy system in a newcomer country (and to sustain an energy system in any country). The public acceptance survey is a metric that can reflect the acceptance of the public towards the energy systems [2.18]. In addition, there are several more concerns that can affect public acceptance; they may be characterized, for instance, by external cost and risk of accidents. External cost is the sum of the indirect costs estimated from the effects of the energy systems (e.g. greenhouse gas emissions and health effects caused by the operation of the energy systems).

Different approaches exist to evaluate the risk of accidents based on different criteria and thresholds to define a severe accident. The probability of a severe accident occurring could be evaluated by the accident rate (per GW(e)·year), which can be obtained by summing the severe accidents that have occurred in a specific energy system in the past and dividing the number by the total electricity generation (GW(e)·year).

To compare the degree of infrastructure readiness of a country with respect to the introduction of NESs with that for non-NESs, the measures of the status of the legal framework, the status of state organizations, the availability of infrastructure to support the owner/operator, government policy and the availability of human resources may be considered as KIs.

The national legal framework related to NESs or non-NESs in selected major areas of operational safety, environmental protection and waste management needs to be developed adequately to ensure that the development of the energy system, from construction until operation and decommissioning, will have no adverse effects on human health, the environment and infrastructure.

The term ‘state organizations’ covers all regulatory authorities of NESs or non-NESs that are responsible for controlling and maintaining operational safety, environmental protection and waste management.[5] As with the status of the legal framework, the state organizations need to be well developed to ensure that the development of the energy system, from construction until operation and decommissioning, will have minimal impacts on human

[5] For the nuclear option, safeguards and security measures are added by default.

health, the environment and infrastructure. The state organizations' degree of infrastructure readiness may be considered, based on whether the country has adequate state organizations with the above mentioned functions.

The infrastructure to support the owner/operator refers to any hardware, facilities or equipment needed to support the project during the installation, operation and decommissioning of the energy system. The industrial infrastructure to support the owner/operator can be equipment, machines, vehicles and related manufacturing capabilities, while the government infrastructure to support the owner/operator can be ports, roads and bridges related to the transportation of equipment or parts. In the case where there is no infrastructure to support the owner/operator, it will be imported from other countries [2.7].

The national energy policy issued by the government is a key part of establishing and maintaining NESs or non-NESs during their lifetime. The government is responsible for defining options for the energy system of the country to meet its growth in energy demand. The statement of government policy needs to define the role of NESs or non-NESs clearly as an energy source for the country for sustainable development. The policy may not be a commitment to use a specific energy system, but needs to provide details of the process and timeframe; the government will make a decision to use such an energy system as one of the energy sources in the country. It is noted that this KI may be eliminated or have a reduced weighting factor if there is a strong correlation between the areas of government policy and public acceptance in such a country, in order to avoid or reduce double counting in the scoring of those two areas.

Last but not least, the availability of human resources for the installation and operation of NESs or non-NESs is essential to ensure the safe, secure and economical operation of the NESs or non-NESs during their lifetime. The human resources need to be sufficient and qualified to be utilized for an energy system project. The human resources are necessary not only for the owner/operator of the energy system, but also for related organizations, such as the regulatory agency, governmental units, research institutes and industry.

REFERENCES TO SECTION 2

[2.1] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems: INPRO Manual — Overview of the Methodology, IAEA-TECDOC-1575 (Rev. 1), IAEA, Vienna (2008).

[2.2] INTERNATIONAL ATOMIC ENERGY AGENCY, International Nuclear Fuel Cycle Evaluation, Vol. 9: Summary Volume, IAEA, Vienna (1980).

[2.3] UNITED STATES DEPARTMENT OF ENERGY, GENERATION IV INTERNATIONAL FORUM, A Technology Roadmap for Generation IV Nuclear Energy Systems, USDOE and GIF, Washington, DC (2002).

[2.4] INTERNATIONAL ATOMIC ENERGY AGENCY, Lessons Learned from Nuclear Energy System Assessments (NESA) Using the INPRO Methodology: A Report of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), IAEA-TECDOC-1636, IAEA, Vienna (2009).

[2.5] INTERNATIONAL ATOMIC ENERGY AGENCY, UNITED NATIONS DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS, INTERNATIONAL ENERGY AGENCY, EUROSTAT, EUROPEAN ENVIRONMENT AGENCY, Energy Indicators for Sustainable Development: Guidelines and Methodologies, IAEA, Vienna (2005).

[2.6] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Infrastructure, IAEA Nuclear Energy Series No. NG-T-3.12, IAEA, Vienna (2014).

[2.7] INTERNATIONAL ATOMIC ENERGY AGENCY, Milestones in the Development of a National Infrastructure for Nuclear Power, IAEA Nuclear Energy Series No. NG-G-3.1 (Rev. 1), IAEA, Vienna (2015).

[2.8] INTERNATIONAL ATOMIC ENERGY AGENCY, Managing the Financial Risk Associated with the Financing of New Nuclear Power Plant Projects, IAEA Nuclear Energy Series No. NG-T-4.6, IAEA, Vienna (2017).

[2.9] BRUNDTLAND COMMISSION, Our Common Future, Oxford University Press, Oxford (1987).

[2.10] INTERNATIONAL ATOMIC ENERGY AGENCY, Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience, IAEA, Vienna (2006).

[2.11] INTERNATIONAL ATOMIC ENERGY AGENCY, The Fukushima Daiichi Accident: Report by the Director General, IAEA, Vienna (2015).

[2.12] KEMENY, J.G., et al., Report of the President's Commission on the Accident at Three Mile Island, US Govt Printing Office, Washington, DC (1979).

[2.13] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Standards, https://www.iaea.org/resources/safety-standards

[2.14] INTERNATIONAL ATOMIC ENERGY AGENCY, Building a National Position for a New Nuclear Power Programme, IAEA Nuclear Energy Series No. NG-T-3.14, IAEA, Vienna (2016).
[2.15] INTERNATIONAL ATOMIC ENERGY AGENCY, Integrated Nuclear Infrastructure Review (INIR) Missions: The First Six Years, IAEA-TECDOC-1779, IAEA, Vienna (2015).
[2.16] INTERNATIONAL ATOMIC ENERGY AGENCY, Industrial Involvement to Support a National Nuclear Power Programme, IAEA Nuclear Energy Series No. NG-T-3.4, IAEA, Vienna (2016).
[2.17] INTERNATIONAL ATOMIC ENERGY AGENCY, Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability: Final Report of the INPRO Collaborative Project GAINS, IAEA Nuclear Energy Series No. NP-T-1.14, IAEA, Vienna (2013).
[2.18] INTERNATIONAL ATOMIC ENERGY AGENCY, Stakeholder Involvement Throughout the Life Cycle of Nuclear Facilities, IAEA Nuclear Energy Series No. NG-T-1.4, IAEA, Vienna (2011).

3. THE APPLICATION OF JUDGEMENT AGGREGATION AND UNCERTAINTY ANALYSIS METHODS

3.1. MULTIPLE CRITERIA DECISION MAKING (MCDM) FRAMEWORK

A comparative evaluation of NESs requires judgement aggregation because of the multi-criteria character of the problem. Performance indicators characterizing different aspects associated with different evaluation areas are conflicting by nature: increasing a certain indicator may be associated with decreasing the other ones. The lack of common methodologies for decision making complicates the procedure for formulating a coordinated vision of preferable technological and institutional solutions balanced according to different costs, benefits and risks when it is necessary to take a set of contradictory indicators into account, as might be the case in the comparative evaluation of NES performance and, in particular, in the area of sustainability evaluations for NESs.

The wide application of MCDA techniques makes it possible to search for compromises among the conflicting factors that determine NES performance and calculate the corresponding trade-off rates, carrying out a comparative evaluation of alternatives as well as choosing, ranking and sorting corresponding options. Uncertainty and sensitivity analyses based on state of the art methods also need to be included in the evaluations, providing better grounds for judgements and enabling the decision maker to reach a conclusion about the stability of the ranking results. The implementation of the MCDA methods might also add a new element to the INPRO methodology [3.1] on the facility level and the GAINS framework [3.2] on the scenario level, namely, ranking of the NES options based on a set of indicators using sets of preferences.

An expanded set of different MCDA tools (i.e. more representative ones) was considered within the KIND project framework that can be applied to perform comparative evaluations of NESs. In numerical studies, it would be rational to move from the application of the simplest methods to more complicated ones. Such a consistent approach simplifies the analysis of problems, providing a clear understanding of what results may be achieved based on the simplest assumptions, and then sequentially deepening the analysis by the application of more advanced tools. This approach provides an opportunity to analyse the use of more sophisticated MCDA methods versus the use of simpler ones and identify the most appropriate one. Particular attention needs to be paid to the analysis and comparison of the results that may be obtained using different tools with similar model assumptions to ensure that the application of different methods will not lead to conflicting results, but rather the obtained results will be well coordinated and consistent.

This section presents a general overview of the MCDA methods and general information on their application for comparative evaluations of NESs. Detailed consideration is given to the MAVT method, which was selected as a preferable method under the KIND project. The mathematical background and details for the MCDA methods are given in Annex II.

3.1.1. Implementation of MCDA for the comparison of NESs

Multiple criteria decision making (MCDM) techniques are a toolkit for supporting decision makers, who usually are faced with making numerous comparative evaluations. MCDM methods help to highlight conflicts and find compromises in the decision making process [3.3, 3.4]. Multi-criteria decision analysis (MCDA) and multi-objective decision making are the main classes of MCDM methods that help to solve difficult decision problems. The major distinctions between them are based on whether the solutions are defined explicitly or implicitly.

The MCDA problems are tractable if they are linked to a number of the alternative decision choices that are pre-specified (i.e. explicitly known). Each option is represented by its performance indicators, evaluated using multiple criteria. MCDA supports the decision process, facilitating finding the best solution or finding a set of acceptable trade-off choices. One may also be interested in ‘sorting’ or ‘classifying’ alternatives. Sorting refers to placing options in a set of preference ordered classes, while classifying refers to assigning alternatives to non-ordered sets.

Within the multi-objective decision making problems, the solutions are not explicitly known. An alternative (solution) can be found by solving a mathematical optimization problem. The number of alternatives is infinite or uncountable when some of the model's variables are continuous, or countable but very large when all of the model's variables are discrete.

MCDA methods are the most appropriate for the all-inclusive objective of the KIND approach. In a typical KIND-related case, there will be a finite number of alternatives that have been evaluated using a common set of multiple indicators; therefore, the MCDA approaches will be well suited for the comparison of alternatives for such a class of decision support problems.

The 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 then iteratively goes through the following steps (Fig. 3.1):

(a) Problem formulation and establishment of goals;
(b) Formulation of alternatives (NES options);
(c) Identification of indicators (requirements for sets of indicators);
(d) Indicator evaluation (including uncertainties) and performance table formation;
(e) Selection of an MCDA method;
(f) Construction of an objectives tree and weight assignments (including uncertainties);
(g) Determination of alternative ranking based on the selected MCDA method;
(h) Sensitivity and uncertainty analysis;
(i) Final conclusion and recommendations.

It should be noted that the KIND approach is an iterative procedure using top-down and the bottom-up perspectives.

The 'problem formulation' step offers an unbiased statement of the comparative evaluation problem, specifying its current state and a vision of the favoured result. Agreement needs to be reached regarding the problem statement to avoid potential misunderstandings in the next steps of the decision support process. While formulating a problem, it is necessary to specify all associated requirements, restrictions and conditions that need to be met by

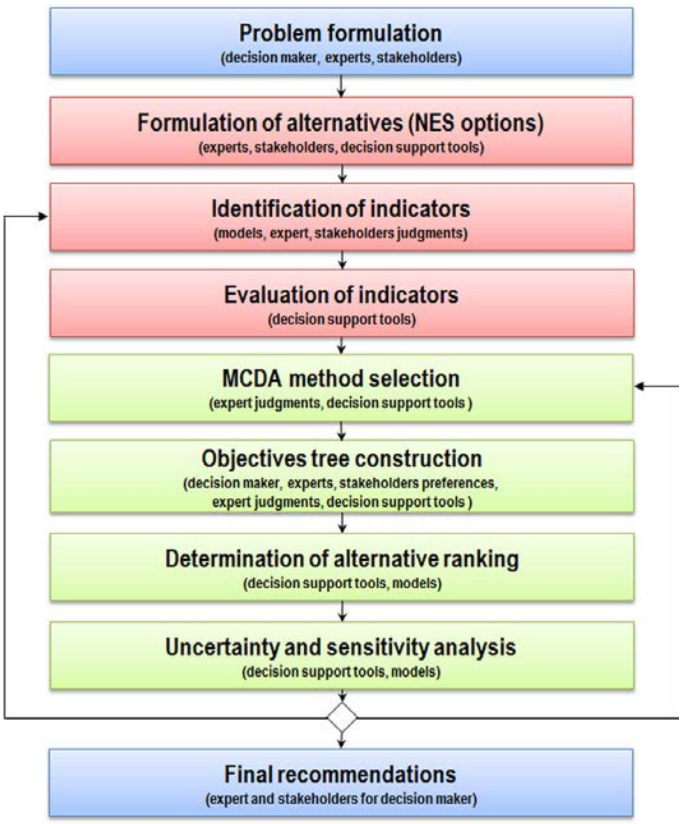


FIG. 3.1. The MCDA methods application flowchart.

any possible solution to the problem. Setting the overall objectives of the study is another important aspect of this step that determines directions in order to find the final solution.

The ‘formulation of alternatives (NES options)’ step involves identifying all of the potential options (solution, alternative, etc.) that satisfy all specified requirements, conditions and restrictions and have the potential to achieve the objectives of the study.

The ‘identification of indicators’ step involves formulating objective or subjective (i.e. quantitative or qualitative) key variables that are a performance measure for the criteria against which each option has to be evaluated. The indicators, either qualitative or quantitative, need to satisfy a certain set of requirements (not to be redundant, to be independent, etc.).

The ‘evaluation of indicators’ step provides an evaluation of the proposed indicator values for all options under consideration and leads to the formation of the performance table. The performance table is required for each MCDA method as input data.

The ‘MCDA method selection’ step looks at the nature of the problem to be solved and aims to identify the most appropriate MCDA method for its solution. Based on the method selected, a comparative evaluation of the alternatives can be carried out.

The ‘objectives tree construction’ step comprises structuring the problem in the form of a tree that also delineates the decision maker’s strength of preferences. Objectives trees are hierarchies of multi-level objectives ending up with evaluated indicators or attributes placed at the base level that serve as performance evaluation descriptors for different alternatives. Weights capture the essence of value judgements. Assigning the decision maker’s preferences for different possible values of attributes and weights at various vertical depths of the hierarchy proliferation helps to determine the relative importance of ‘and’ branches in the objectives tree.

The ‘determination of alternative ranking’ step combines indicators and their weights into overall scores/ranks among the options in order to identify the most preferred alternative for a given set of model parameters.

The ‘uncertainty and sensitivity analysis’ step provides additional information about the robustness of the ranking results, and this needs to be independent of whichever method was used or whatever model assumptions were chosen. It helps in identifying both the stability and robustness of ranks under specified uncertainties in the model parameters, as well as providing possible ways to revise and restructure the problem.

In the ‘final recommendations’ step, recommendations are given to decision makers regarding more appropriate trade-off solutions identified during the MCDA implementation.

Properly organized studies based on MCDA represent non-formal endeavours consisting of the application of different formal mathematical methods and analytical software tools, but support decision making through comprehensive elaboration and recognition of the decision problem. The MCDA does not provide the ‘best option’, rather it would be correct to talk about a trade-off option; therefore, special attention needs to be given to a sensitivity/uncertainty analysis (i.e. examination of the solution stability with respect to the various methods used and their model parameters).

3.1.2. Overview of relevant MCDA methods

The MCDA methods provide a means of analysis for hierarchy objectives trees with a predefined set of alternatives. MCDA is applied to the following problem: given *N* indicators for a comparison of *M* options, with each of the options having been evaluated either by experts or through objective calculations, derive a rule from the experts’ preferences that will allow the alternatives to be ranked according to their performance value and the best among a given alternative set to be identified.

A large number of different MCDA methods have been developed to deal with different kinds of problems [3.5–3.9]. Each method has its pros and cons and will be more or less useful depending on the situation. Until now, few approaches have been proposed to guide the selection of a technique that is adapted to a given situation.

The MCDA methods may be categorized into the following groups: value based, outranking, reference based and others. Value based methods (for instance, MAVT, multi-attribute utility theory (MAUT) and analytic hierarchy process (AHP)) are based on an evaluation of a single overall score for each alternative, and they are compensatory. In outranking methods (for instance, preference ranking organization method for enrichment evaluations (PROMETHEE), etc.), low scores for a certain indicator cannot be compensated by higher scores on another indicator; incomparability between the indicator scores of alternatives is, therefore, allowed. Reference based methods (for instance, technique for order preference by similarity to the ideal solution (TOPSIS), etc.)

determine the similarity of alternatives to an ideal and anti-ideal alternative. The comparative evaluations presented in different studies in the field of nuclear engineering have been carried out using the following well known MCDA methods: elementary methods, MAVT, MAUT, ELECTRE (which stands for élimination et choix traduisant la réalité, or elimination and choice expressing reality), TOPSIS, AHP and PROMETHEE (see Fig. 3.2).

Using several different MCDA methods within a certain case study may have a significant influence on a decision making process, since the decision making process supports a decision maker to understand and analyse the problem more thoroughly, to achieve consistency in the judgements and evaluations, and finally to obtain stable and robust ranking results. Although, in general, the ranks of options may differ for different methods, usually they provide non-contradictory results.

Most of the MCDA methods have been implemented in universal decision support software tools, such as Analytica, Criterium DecisionPlus, Decision Lab, Expert Choice, Logical Decisions or MakeItRational, which include extended options to perform both group analysis of decisions and uncertainty examination. Usually, the decision support software implements one, or more often two, MCDA methods.

3.1.2.1. Elementary judgement aggregation

Including a simple scoring model, this is the simplest MCDA method and is only applicable when all the data are expressed in exactly the same units. In this method, the overall score of an alternative is defined as the weighted sum of the alternative decision indicator or attribute values.

3.1.2.2. Multi-attribute value theory (MAVT)

This is a value based MCDA method that assumes judgement aggregation in terms of measured/evaluated costs, risks and benefits into an overall score using multi-attribute value functions that take expert opinion and decision maker preference strength into account. Within MAVT, single-attribute value functions are evaluated for each indicator, transforming the diverse indicators' local natural values to a universal, dimensionless scale, for example {0, 1}, reflecting the judgements of subject matter experts and the decision maker. The single-attribute value functions for each indicator are shaped over its variation range according to their significance for the evaluator. The overall (i.e. aggregated) scores indicate the ranks of the alternatives: the preferred alternative will have the highest overall score, which is the highest rank.

3.1.2.3. Multi-attribute utility theory (MAUT)

This is based on expected utility theory extending MAVT by using probabilities and expectations in order to incorporate uncertainties in indicator values into comparisons. Such uncertainty is characterized in MAUT by a random variable with a given probability density function. The overall utility function for each alternative is considered as a random variable as well. The ranking of alternatives within MAUT is based on the comparison

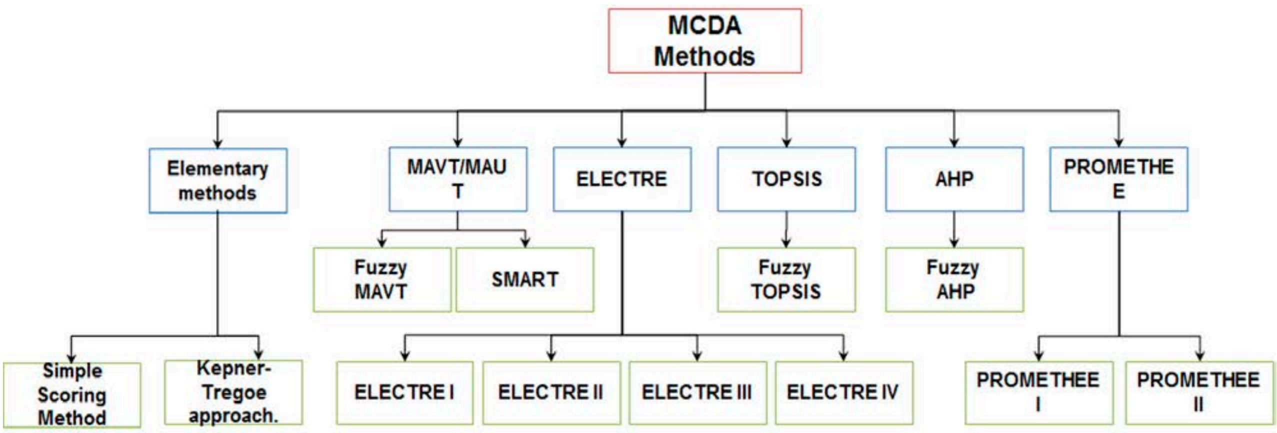


FIG. 3.2. The most commonly used MCDA methods.

of expected utilities: one alternative is more appropriate than the other if the mathematical expected value of the overall utility function for this alternative is greater than the corresponding expected values of the other ones.

3.1.2.4. Technique for order preference by similarity to the ideal solution (TOPSIS)

This is a reference based method for comparative evaluations that assumes compensatory judgement aggregation based on calculation of the geometric distance between each alternative and the most desirable (ideal or positive ideal) and the least desirable (anti-ideal or negative ideal) alternatives. TOPSIS is based on the idea that the preferred alternatives will have the shortest distance from the ideal option and the longest distance from anti-ideal one.

3.1.2.5. Élimination et choix traduisant la réalité — elimination and choice expressing reality (ELECTRE)

This is an outranking MCDA method that assumes the elaboration of outranking relations for the comparison of each pair of alternatives, with the procedure for choosing, ranking or sorting the options being considered working by means of the importance coefficients and the veto thresholds. It is based on the definition extension of preference and decision.

3.1.2.6. Preference ranking organization method for enrichment evaluations (PROMETHEE)

This belongs to the outranking group of MCDA methods, implying the extended definition of a criterion through the formation of an ordered relation of a given set of alternatives with intra-criterion preference degree functions (see Section 5.7.2 for details). Similar to other outranking methods, PROMETHEE is based on the pairwise comparison of alternatives for each indicator, with subsequent aggregation of the preferences. In this method, it is required that indifference and preference thresholds be specified and that selected preference functions be defined in the range from 0 to 1.

3.1.2.7. Analytic hierarchy process (AHP)

This is an approach to organize and examine multifaceted decisions that assumes the decomposition of the decision problem into a hierarchy of more easily comprehended sub-problems and applies pairwise comparisons to various hierarchy elements. Actual data for the elements or judgements for the elements' relative importance may be used within such pairwise comparisons. AHP transforms these evaluations into numerical values that are processed when solving the problem. A numerical weight is derived for each element of the hierarchy, allowing diverse elements to be compared to one another. Numerical priorities are calculated for each of the decision alternatives and represent the alternatives' relative ability to achieve the decision goal.

It has been shown that both elementary judgement aggregation methods and more sophisticated MCDA ones may be used for multi-criteria comparative evaluation of NES performance and sustainability at both the technology and the scenario levels. As has already been mentioned, selecting the best MCDA method for a given problem is a separate task. The final selection of the most appropriate method for a particular problem is to be made on the basis of problem context analysis and the quality of the initial information provided by the subject matter experts. For instance, depending on whether a detailed evaluation of all indicator values without uncertainty will be performed or the consideration will be limited to qualitative judgements regarding indicator values, different methods could be used. The MAVT, TOPSIS and PROMETHEE methods are more appropriate in the former case, whereas the AHP method may be more suitable in the latter. If it is necessary to consider the uncertainty in indicator values, the MAUT method is more suitable as compared to, for instance, MAVT or others.

Within the KIND project, it was shown that, despite the different theoretical frameworks, tools and algorithms, various MCDA methods for multi-criteria comparative evaluation of NES performance and sustainability lead to a similar final ranking of alternatives, providing detailed differentiation of the alternatives by indicators that are specific to costs, benefits and associated risks, and similar final identification of trade-off options.

Obviously, the content of the relevant method set is not to be limited to those considered previously. Experts may express their preference for other ranking/aggregation methods, but in this case, it is essential to verify their applicability and results. Moreover, it needs to be checked whether the results obtained using different methods are well coordinated and consistent under comparable conditions.

The use of MAVT based on simplified additive weighted aggregation was recommended for the needs of the KIND project because in KIND a universal tool that is able to compare mature nuclear technologies to other mature or less mature nuclear technologies, or even nuclear technologies to non-nuclear technologies, is required. MAVT has found wide application for different kinds of problems in the nuclear and non-nuclear engineering fields [3.10]. The wide experience of applying this method, as summarized in different publications, and the availability of an extensive set of recommendations and software tools for implementing it, are the main incentives and arguments for selecting MAVT. It has now been selected in KIND as a basic tool for the comparative evaluation of NESs. This recommendation, however, should not deter experts from implementing other MCDA methods in their studies.

3.2. FEATURES AND SPECIFICATIONS FOR MAVT/MAUT AS THE MAIN APPROACH FOR THE KIND OBJECTIVES

MAVT and MAUT have been applied to a wide range of decision making problems in the area of the multi-criteria comparative evaluation of nuclear reactors, with relation to NFCs and NESs [3.10–3.17].

Both MAVT and MAUT are quantitative comparison methods that are used to combine different measures in terms of costs, risks and benefits together with expert and decision maker preferences into high level aggregated performance scores. MAUT is de facto an extension of MAVT, based upon the expected utility theory. That is why the MAVT and MAUT methods are not always seen as being fundamentally different. MAUT extends MAVT in using probabilities and expectations to deal with uncertainties.

The problems considered by MAVT are typically stated as follows: given a set of *M* alternatives and *N* indicators for their evaluation, one needs to assume that each of the alternatives has been evaluated by each of the indicators, either by experts or through objective calculations. A rule must be derived from the experts' preferences, which will allow the alternatives to be ranked according to their value and the best among them to be identified. The use of multi-attribute and single-attribute value functions could be seen as the essence of the MAVT method. A multi-attribute value function represents a combination of indicators weighted according to the strength of expert and decision maker preferences to deliver an overall score (the value of the multi-attribute value function).

Single-attribute value functions can be used when quantitative information is known about the performance of each alternative. Every indicator has a single-attribute value function dedicated to express the expert judgement on its value level. These functions transform diverse indicators evaluated in their 'natural' scale to one common, dimensionless scale or score (from 0 to 1). These scores are then used in further evaluations.

The indicator values are weighted according to their importance over the ranges in which the indicators may vary. To identify the preferred alternative, experts use consistent scaling on each hierarchy level. The overall scores (the values of the multi-attribute value function) indicate the ranks of the alternatives. The preferred alternative will have the highest overall score.

3.2.1. Multi-attribute value functions

The fundamental concept of MAUT/MAVT is the decomposition of the multi-attribute utility into utility levels for all indicators with scaling constants (weights) and subsequent composition reassessment using aggregation models. The general form of the multi-attribute value function is:

$$u(x)=\sum_{i=1}^{n}k_i u_i(x_i)+k\sum_{\substack{i=1\\ j\rangle i}}^{n}k_i k_j u_i(x_i)u_j(x_j)+k^2\sum_{\substack{i=1\\ j\rangle i\\ l\rangle j}}^{n}k_i k_j k_l u_i(x_i)u_j(x_j)u_l(x_l)+\ldots$$
$$+k^{n-1}k_1k_2\ldots k_n u_1(x_1)u_2(x_2)\ldots u_n(x_n),\ \text{where}\quad 1+k=\prod_{i=1}^{n}(1+kk_i) \tag{3.1}$$

and where $u_i(x_i)$ is the single-attribute value function for indicator *i* scaled from 0 to 1, k_i is the weight for indicator *i* and *k* is a scaling constant that is a solution to an additional constraint equation.

The MAVT method is quite flexible; by factoring Eq. (3.1), both compensatory and complementary types of interactions between different indicators can be implemented, making simplifications to Eq. (3.1). Utilizing these simplified, additive or multiplicative forms of equation in KIND allows different possible decision maker preferences to be reflected in the process of the comparative evaluation of NESs (see Annex II).

The additive aggregation form may be considered as compensatory, allowing the low values of a certain indicator to be compensated by the higher values of another one. The multiplicative aggregation form is an extreme case of the complementary interaction between indicators in which, intuitively, the whole set of indicators is to work together to provide an effective score for system performance.

The multiplicative formulation requires preferential independence and utility independence conditions to be fulfilled, whereas the additive formulation is valid when the preferential, utility and additive independence conditions are satisfied [3.5]. Which type is to be used is a key decision to be made within a specific study. In a situation where multidisciplinary sets of indicators (assigned to different areas of interest) are considered simultaneously, it may be reasonable to implement the additive form of the multi-attribute value function. Intuitively, this simplification is justified in situations in which agreement among experts has been reached that the choice between two alternatives with common values for some attributes needs to focus solely on the remaining attributes that have different values. This intuition may be formalized as an ‘independence assumption’ that is often satisfied in practice. In studies related to safety and security aspects, the multiplicative form of the overall value functions is more likely to adequately reflect ‘the weakest link’ effect, which means that no indicator or attribute should take the lowest possible value, thereby dramatically reducing the system performance. The decision to use the additive or the multiplicative form of a multi-attribute value function depends on one’s readiness to accept fully compensatory versus non-compensatory aggregation. Nevertheless, provided that the MAVT method is applied correctly, it will identify all the strengths and weaknesses of the performance of the NESs being compared, independently in the form of a multi-attribute value function, resulting in a rankings system based on the experts’ and decision makers’ judgements and preferences.

The multi-attribute value function that is widely applied in many studies is the ‘additive model of multi-attribute value function’. It has the following form:

$$u(x)=\sum_{i=1}^{n}k_i u_i(x_i)\text{, where}\sum_{i=1}^{n}k_i=1 \tag{3.2}$$

Note that Eq. (3.2) is a special case of the general model given in Eq. (3.1) that comes about when the constant k that captures the interactions among the indicators is zero. The independence assumptions that justify the use of the additive model are reasonable for KIND type of analysis because of the relationships among the objectives and measures. As noted above, the indicators have been selected so that changes among common values for some indicators would not affect the ranking of the alternatives based on the other indicators. When the additive model is used, the results of the analysis are easier to interpret. However, the weight choice can change the ranking dramatically owing to compensation.

In conclusion, owing to the above mentioned arguments, the additive model was deemed to be reasonable for the implementation of judgement aggregations in the KIND approach.

3.2.2. Single-attribute value functions

A single-attribute value function represents a measure of the utility that a decision maker has assigned to a certain indicator value that is an argument of that function. A value function converts the indicator’s values as expressed in specific units into a dimensionless scoring scale within the range from 0 to 1. When applied to a multi-criteria comparative evaluation, a single-attribute value function describes the extent of a decision maker’s satisfaction with the relevant indicator’s value. Therefore, it is impossible to construct such a function based solely on objective evaluations. Instead, the construction of a single-attribute value function is achieved by relying on subjective evaluations obtained by interactions with a decision maker or with experts who have domain specific knowledge about the relative importance of different levels of specific indicators.

It is obvious that there can be different views about the values of different levels of an indicator, even among experts. Moreover, the selection made during questioning under simulated conditions may differ significantly from the decision that the same person will make under similar but real conditions. Therefore, it seems rather problematic to construct a single-attribute value function without uncertainty bias. Thus, even if it is possible to identify a single-attribute value function type with some precision, analysing sensitivity to the form of the single-attribute value functions is a necessary task.

The single-attribute value function shapes may be evaluated by the subject matter experts appointed by the decision team. Some of these functions could be linear, some nonlinear, some piecewise continuous, and others may be based on categorical information. Different groups of experts may provide single-attribute value functions for indicators in their corresponding areas of expertise. It should be noted that the development of single-attribute value functions is potentially a sensitive issue.

As noted earlier, a multi-attribute value function (under MAVT) is appropriate when no significant uncertainty is associated with the levels of the indicator values. In that case, the shape of the single-attribute value functions will be determined by the decision maker's marginal value assigned to additional units of one indicator versus the other indicator. For example, if the decision maker has decreasing marginal value for additional units of an indicator, which is often the case, then the corresponding single-attribute value function will be concave to the origin. On the other hand, increasing marginal value of additional units of an indicator would imply a convex single-attribute value function.

If there is an uncertainty associated with the levels of the indicators, then the closely related multi-attribute utility function (under MAUT) will be appropriate, and the questions used for the assessment of the single-attribute utility functions need to include comparisons of alternatives that include risk, perhaps in the form of simple lotteries. In this step, a decision maker has to decide between two choices. The first one has a probability p of being the most preferred option or one of $1-p$ of being the least preferred one. The second choice is the absolute certainty of a particular option, or the certainty value between the most and the least preferred. The aim of the lottery is to determine a p value that makes the decision maker indifferent between the two choices. In this case, the shape of the single-attribute utility function will be determined by the combined influences of the marginal values of additional units of the indicator, along with the attitude of the decision maker regarding the risk associated with the lotteries. A concave single-attribute utility function will depict risk aversion, whereas a convex one will represent a risk prone attitude. A single-attribute utility function that is a straight line will be considered to be risk neutral.

In the case of the evaluation of a single-attribute utility function for the comparative evaluation of scientific or policy alternatives, the domain expert needs to be instructed to answer any lottery questions based on his or her professional opinion and subjective scientific judgement, without regard to personal attitude towards risk. Since the expert will not actually receive one of the alternatives that might be chosen from the ranking process, personal feelings regarding risk need to be irrelevant. In such a case, the expert's single-attribute utility function is to be identical to the single-attribute value function, which means that the appropriate evaluation techniques that seem most intuitively appealing and understandable to the respondent may be selected.

Examples of some common shapes of single-attribute value or utility functions are shown in Table 3.1. For ease of presentation, the descriptions of these functions indicate their interpretation with regard to attitude towards risk. As noted above, they could also be interpreted in terms of changes in the marginal value of additional units. In terms of the KIND project, losses and gains are related to a decision maker's desire to have larger or smaller indicator values.

Table 3.1 includes the most common types of single-attribute value functions, which have found wide applications in various applied studies (including nuclear engineering). These are mostly linear and exponential functions. Other popular types of single-attribute value functions are presented in Annex II.

3.2.3. Aggregation of indicators and the objectives tree

The objectives tree structure helps aggregation in the multi-level modelling of the evaluation process and, thus, is to be elaborated before performing a multi-criteria comparative evaluation. It defines the application rules for weighting factors and facilitates the interpretation of the ranking results.

Selection of the objectives tree structure is to be driven by the weighting factor evaluation in the various areas of expertise, which needs to be as simple as possible. A hierarchy structure with a three level objectives tree seems to be most appropriate for KIND owing to the simpler and more transparent procedure employed to obtain appropriate weighting factors from the experts' survey in different evaluation areas. Figure 3.3 illustrates

TABLE 3.1. SINGLE-ATTRIBUTE VALUE FUNCTIONS

Type	Increasing value functions	Decreasing value functions
Linear	$u(x)=\dfrac{x-x^{\min}}{x^{\max}-x^{\min}}$	$u(x)=\dfrac{x^{\max}-x}{x^{\max}-x^{\min}}$
	Attitude to risk: risk neutral trend	
Exponential	$u(x)=\dfrac{1-\exp\left(a\cdot\dfrac{x-x^{\min}}{x^{\max}-x^{\min}}\right)}{1-\exp(a)}$	$u(x)=\dfrac{1-\exp\left(a\cdot\dfrac{x^{\max}-x}{x^{\max}-x^{\min}}\right)}{1-\exp(a)}$
	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) Exponent power a may be called 'risk proneness level'	
$x^{\max}$ and $x^{\min}$ are the minimal and maximal domain values of a single-attribute value function, which it is reasonable to select to be as close to each other as possible to improve MAVT[a] resolution		

[a] MAVT — multi-attribute value theory.

the construction of the KIND objectives tree as a three level hierarchical structure: the orange frames are indicators (key and secondary), the green frames are evaluation areas and the blue frames represent high level objectives.

A multi-level evaluation might be simplified by focusing on a smaller number of major objectives. It is practical and reasonable to consider two or three objectives at most at the highest level, for example, 'cost', 'benefit' and 'risk' (most commonly used), or even better, 'performance', 'cost' and 'acceptability', which appear to be more appropriate for use in KIND.

Obviously, experts are free to choose indicator sets, evaluation areas and high level objectives to structure their comparative evaluation process. Based on decomposition determined by the tree structure, NES ranking results benefit from a clear and meaningful interpretation and the determination of a simple procedure for the evaluation of weighting factors. For the ranking results to be interpreted well, scores need to be calculated at each level across all evaluation areas in order to decompose a multi-attribute value function into individual contributions in accordance with the structure of an objectives tree.

3.2.4. Evaluation method for weighting factors

The representation of preferences among different indicators, evaluation areas and high level objectives (identification of weighting factors, w_i) is the most sensitive issue in the formal application of MCDA methods and requires accuracy and reasonableness. The weighting factors allow the relative importance of the indicators, evaluation areas and high level objectives to be taken into account, and reflect national preferences in nuclear energy development, as well as the international obligations of Member States. The weights in different aggregation rules and methods have different interpretations and implications, and can be identified in several ways by applying the direct method, the rating method, the ranking method, pairwise comparisons and the swing method (see Annex II).

For the representation of the additive multi-attribute value function in this publication, Eq. (3.2) is modified by replacing k_i with w_i and then used in the following form:

$$u(x)=\sum_{i=1}^{n} w_i u_i(x_i),\ \text{where} \sum_{i=1}^{n} w_i = 1 \tag{3.3}$$

The weighting factors for each indicator may be determined by soliciting input from subject matter experts in the corresponding nuclear engineering fields, for example, by means of a written questionnaire. The results of

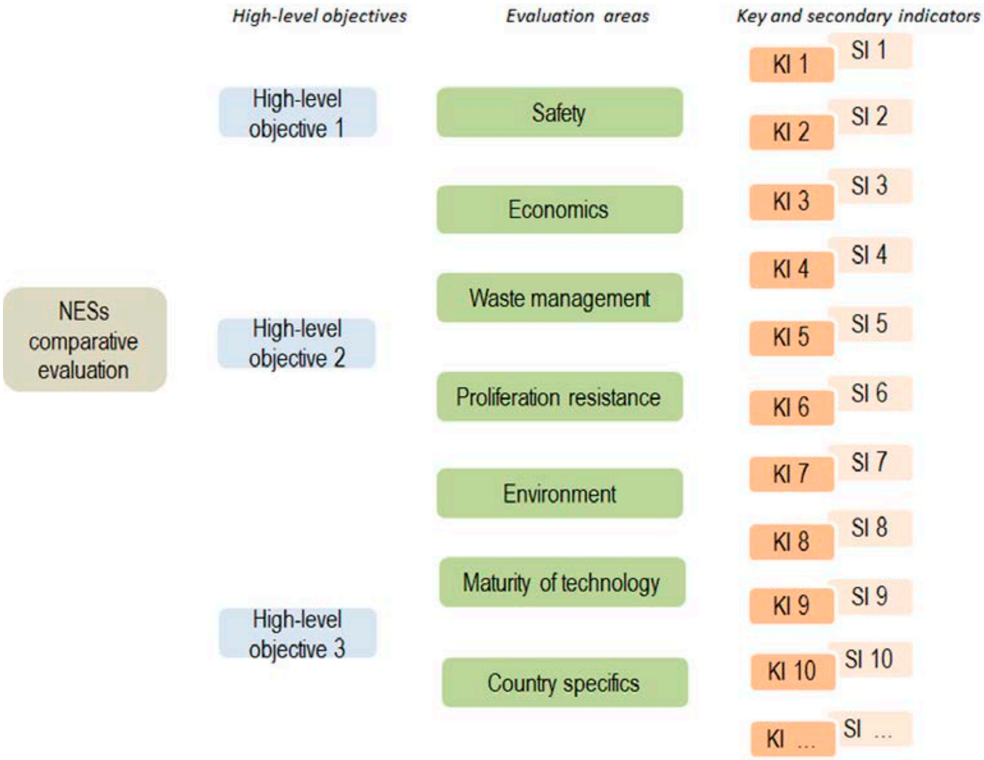


FIG. 3.3. The KIND objectives tree.

these questionnaires may be compiled to generate an unbiased set of weighting factors for use in the comparative evaluation approach. This process provides reliable data to elicit the weighting factors; however, the weighting factors are sensitive to both current trends and the bias of experts and stakeholders.

The simplest and most natural way to evaluate weighting factors is the direct method combined with a hierarchical weighting, which seems to be the most suitable approach for the KIND objectives (Table 3.2). To apply this method, weights in the range from 0 to 1 need to be estimated for all indicators across all areas and for each high level objective. To calculate the final weighting factors for the three level KIND objectives tree, three categories of weights need to be evaluated: the weights for the high level objectives (for instance, cost, performance and acceptability), the weights for each of the identified evaluation areas and, finally, the weights for the lowest level (i.e. the level of the key and secondary indicators).

Therefore, it is reasonable to implement a hierarchical weighting procedure. Experts have to set the weighting factors (real numbers from 0 to 1 at each hierarchy level), and owing to the normalization constraints at each branch of the objectives tree, the sum of the involved weighting factors should be equal to 1. Based on level weights, the final values of the weighting factors can be delivered, imposing the normalization constraints as follows:

(a) For the high level objectives (for instance, cost, performance and acceptability):

$$\sum_{i=1}^{N_h} w_h^i = 1 \tag{3.4}$$

where N_h is the number of high level objectives and w_h^i is a weighting factor for the *I* high level objective.

(b) For each identified evaluation area:

$$\sum_{j=1}^{N^i} w_a^{i,j} = 1 \tag{3.5}$$

where N^i is the number of evaluation areas within the *I* high level objective and $w_a^{i,j}$ is a weighting factor for the *j* evaluation area of the *I* high level objective.

(c) For indicators within a certain evaluation area:

$$\sum_{k=1}^{N^{i,j}} w_{\text{ind}}^{i,j,k} = 1 \tag{3.6}$$

where $N^{i,j}$ is the number of indicators within the *I* high level objective and the *j* evaluation area and $w_{\text{ind}}^{i,j,k}$ is a weighting factor for the *k* indicator for the *j* evaluation area and the *i* high level objective.

Thus, the final weighting factor for each indicator is determined as a multiplication of the above mentioned normalized level specific weights, used in Eq (3.3):

$$w_k = w_h^i \cdot w_a^{i,j} \cdot w_{\text{ind}}^{i,j,k} \tag{3.7}$$

The advantage of this approach is the possibility of subdividing the weight selection process into subject matter weight elicitation areas involving experts who only judge the indicator weights connected to that subject area. High level objective and area weights will be obtained based on the input from decision makers.

3.2.5. Interpretation and presentation of results

If the MAVT method has been recommended for use to support the comparative evaluation of options involving NESs (innovative, evolutionary) or even non-nuclear applications, then the important output to support decision makers is the quantification of benefits and risks (in a clear and understandable manner). The following options could be helpful:

(a) Result aggregation in high level objective categories;
(b) Colour codes for an understandable and clear representation of the results.

To make the presentation and explanation of ranking results more understandable, it is helpful to subdivide all indicators into a limited number of groups, for example, in accordance with the objectives tree, arranged hierarchically in the form of a three level structure, and then to aggregate them. Such aggregated group characteristics may serve as the high level objectives (e.g. three groups: cost, performance and acceptability) or evaluation area scores (e.g. groups corresponding to subject areas of the INPRO methodology).

Experts could then select visualization methods that provide high quality presentation of results, allowing for the easy drawing of conclusions. The four most commonly used methods for representing ranking results with visualization are shown in Fig. 3.4 (value path, radar chart, bar chart and pie chart). These examples do not limit any other ways in which the results can be presented.

TABLE 3.2. WEIGHTING FACTOR IDENTIFICATION METHOD

Weighting method	Evaluation algorithm	Illustration
Direct method and hierarchical weighting	An expert has to directly specify the weights for each hierarchical level and an analyst has to multiply them down to obtain the final lower level weights	$\left(w_1, w_2, ..., w_N\right), \sum_{i=1}^{N} w_i = 1$

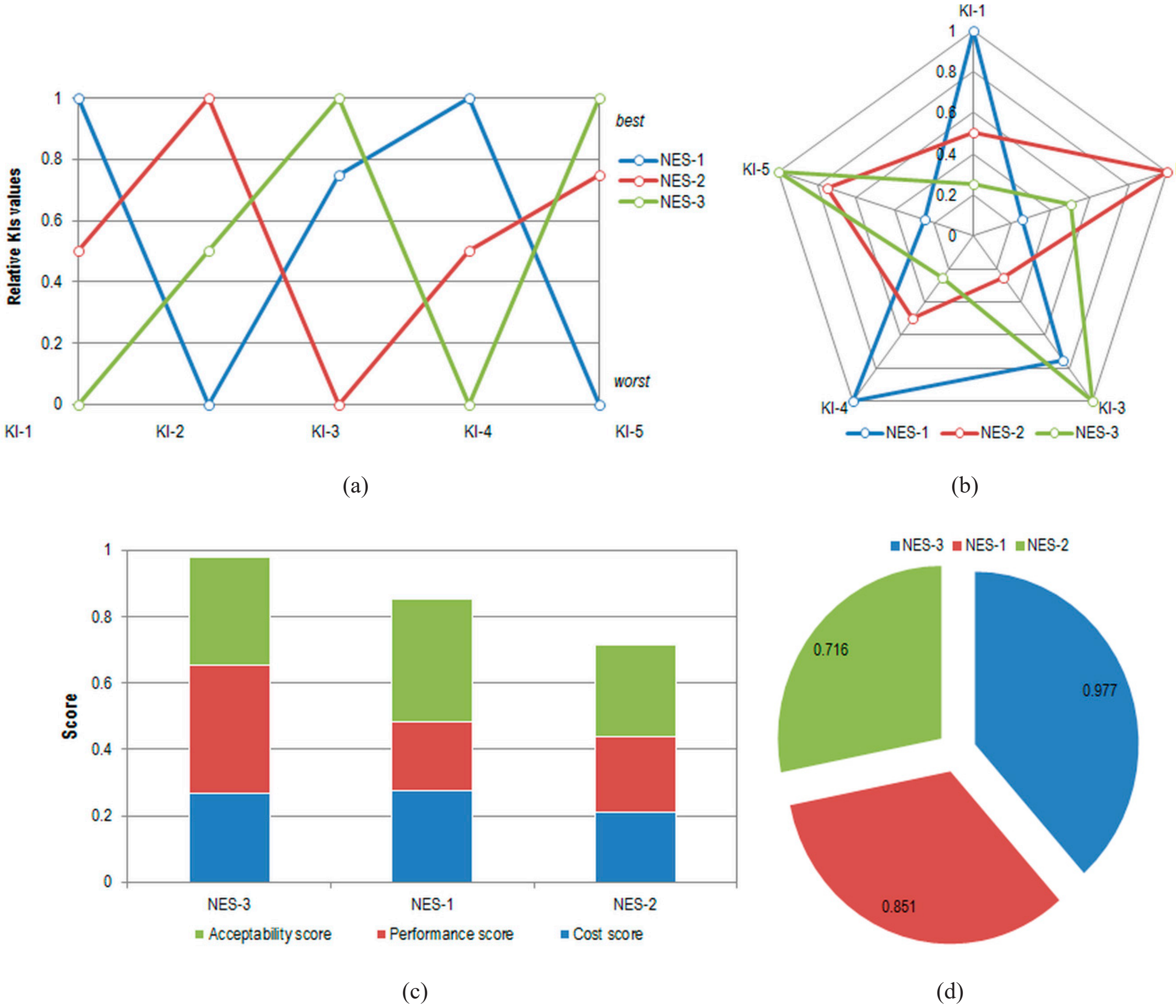


FIG. 3.4. Presentation of results. (a) Value path; (b) radar chart; (c) bar chart; (d) pie chart.

3.3. SENSITIVITY ANALYSIS AND UNCERTAINTY TREATMENT

There is a difference between an uncertainty analysis and a sensitivity analysis. An uncertainty analysis is performed in order to describe the range of possible outcomes for a given set of inputs (where each input has some uncertainty). A sensitivity analysis is performed in order to describe how sensitive the outcome variables are to the variation of individual input parameters. Since there may be multiple input parameters, a sensitivity analysis can help to determine which ones drive the majority of the variations in the outcome (for more details, see Annex III).

3.3.1. General comments on uncertainty treatment

Uncertainties in input data need to be accounted for in the KIND framework, in particular when the focus is on less mature technologies characterized by a lack of detailed data in some areas relevant to the design, operation and costs. There is no universal guidance on uncertainty treatment, but the widely implemented steps are: the identification and estimation of sources of uncertainty, and the evaluation of uncertainty in the results.

The sources of input uncertainties in the KIND approach can be objective, associated with indicator values, and subjective, associated with indicator weights. Additional uncertainty may be related to specific parameters used in a particular MCDA tool, for example, uncertainties associated with the shape of single-attribute value/utility functions (in MAVT/MAUT) or preference functions (PROMETHEE).

While evaluating the impact of uncertainty on the weighting factors' vector $w = (w_1, ..., w_m)$, the fact that w will satisfy the restrictions $0 \le w_i \le 1$ and $w_1 + ... + w_m = 1$ needs to be respected. In this regard, special procedures for generating weights have to be included within MCDA tools that allow a treatment of the weights' uncertainty with constraint.

The uncertainty in indicators needs to be evaluated correctly in cases in which they are objectively calculated versus evaluations based on subjective information elicited from experts. Large uncertainties in the initial data (for instance, NFC unit costs) will not always lead to large uncertainties in the indicators (for instance, LUEC); thus, an accurate evaluation of uncertainties is needed for a correct uncertainty treatment.

Sensitivity and uncertainty analyses are useful to evaluate the impact of uncertainty in input data on alternative ranking. Such analyses are used to increase the clarity of alternative selection; they enable decision makers to reach a conclusion regarding the stability and robustness of results and estimate risk. The purpose of a sensitivity analysis is to examine the change in model output values (ranking order) that results from modest changes in model input values (indicators, weights, value function). An uncertainty analysis is aimed at incorporating multiple uncertainty sources into comparative evaluations to provide overall ranking results with uncertainty.

The most widely known methods for evaluation of the impact of uncertainty on the results in MCDA based studies can be subdivided into two groups: deterministic and probabilistic sensitivity analyses. Both of them have their advantages and disadvantages. Some of them are more or less universal for application in MCDA tools requiring different time considerations and prerequisite knowledge for implementation. The deterministic approach is, in most cases, sufficient for the majority of decisions because of its low complexity and straightforward implementation.

The main advantages of a deterministic sensitivity analysis are: (1) it may be easily applied to uncertainty in both indicators and weights, because a corresponding model parameter (weight or indicator value) can be varied separately, and (2) little time is needed and additional information is not required when implementing such an analysis.

The main disadvantages of deterministic sensitivity analysis are: (1) the range over which weights or indicator values are varied is usually chosen arbitrarily and it is assumed that all parameter values in the range are equally probable, and (2) a large number of uncertain model parameters cannot be taken into account simultaneously, so it does not provide an evaluation of the cumulative impact of uncertainty on multiple model parameters.

Probabilistic sensitivity analysis requires the specification of probability distributions for model parameters of interest (for instance, based on objective statistics or by eliciting information from subject matter experts) and takes uncertainty from multiple model parameters into account.

It is important to note that the impact analysis for one variable at a time may mislead in the presence of dependences and correlations between input variables. Probabilistic analyses (e.g. techniques such as Monte Carlo simulations) could help to fix this problem.

Many other approaches and frameworks (such as fuzzy set theory, interval judgements, percentile uncertainty estimates, grey theory) may be used for uncertainty analysis within the MCDA, but they are not widely applied for decision support in the field of engineering and there is limited scope for their implementation in decision supporting tools. An extended description of the above mentioned approaches is given in Annex III and in Refs [3.18–3.20]. Examination of the impact of uncertainty on the ranking of the results has not been considered within this publication. It is planned to extend the KIND approach by providing guidance on uncertainty analysis within the follow-up collaborative project titled Comparative Evaluation of Nuclear Energy System Options (CENESO), which runs from 2017 to 2020.

3.3.2. Sensitivity to weights

Weight sensitivity analysis is a tool for understanding the influence of weights assigned to alternative ranking. This analysis evaluates the impact of weights' values on the outcomes (scores and ranks of alternatives). At the start, an expert may assign the appropriate weights to a base/reference case and then change any weight and compare the ranking results.

3.3.2.1. Direct approach

A direct approach to weight sensitivity analysis is a simple form of deterministic sensitivity analysis in which alternative ranking results are calculated for different weighting factor options. A possible weight sensitivity analysis within the direct approach may be realized in the following way: each weight is changed using an appropriate factor (for example, ±10% [3.21]) while maintaining the sum of the weights constant (equal to 1 or, equivalently, 100%). If there is no impact on alternative rankings, the decision support analysis is considered to be a stable and robust one. If an alternative ranking order will change owing to the weight variation, it is necessary to collect additional information or to explain the impacts that the potential errors in weighting factors have on the alternative selection to the decision maker.

An important condition to be satisfied while analysing the sensitivity to weight values is that the sum of all weights is to be equal to 1. Subject to this condition, it is possible to implement different methods of analysing the sensitivity to weight values, of which the most common one is modifying one of the selected weight values, provided that other weights vary proportionally (this approach is known as a ‘walking weights’ approach).

Another, more detailed, possibility for demonstrating the alternative ranking sensitivity to weighting factor values may be realized by using the ‘linear weight’ approach. In the linear weight approach, the expert can choose an indicator for which a weight sensitivity analysis will be performed and investigate how the ranking alternatives will change while a weighting factor varies from 0 to 1 (in this procedure, other weights are to be automatically proportionally adjusted so as to hold the weight sum equal to unity).

The linear weight approach is very effective. The graphs in Fig. 3.5 show, for each alternative, the variation of its overall score as a function of the corresponding weighting factor, keeping the value of other weighting factors unchanged. Based on this information, the ranks of alternatives may be identified for different weighting factor values, while the weighting factor areas may be obtained that deliver the same ranking result.

The uncertainty of decision makers’ preferences (uncertainty of weights) may be taken into account using, for example, the concepts of fuzzy numbers, probability theory or interval algebra. The applications of the MCDA methods allowing incorporation of uncertainties are realized in special versions of MCDA software (see Annex III and Refs [3.10–3.12]).

3.3.3. Sensitivity to single-attribute value functions

A single-attribute value function sensitivity analysis evaluates the impact on the final results (ranks of alternatives) with respect to changes in single-attribute value functions. A value function sensitivity analysis may only be implemented for value-based MCDA methods, such as MAVT or MAUT.

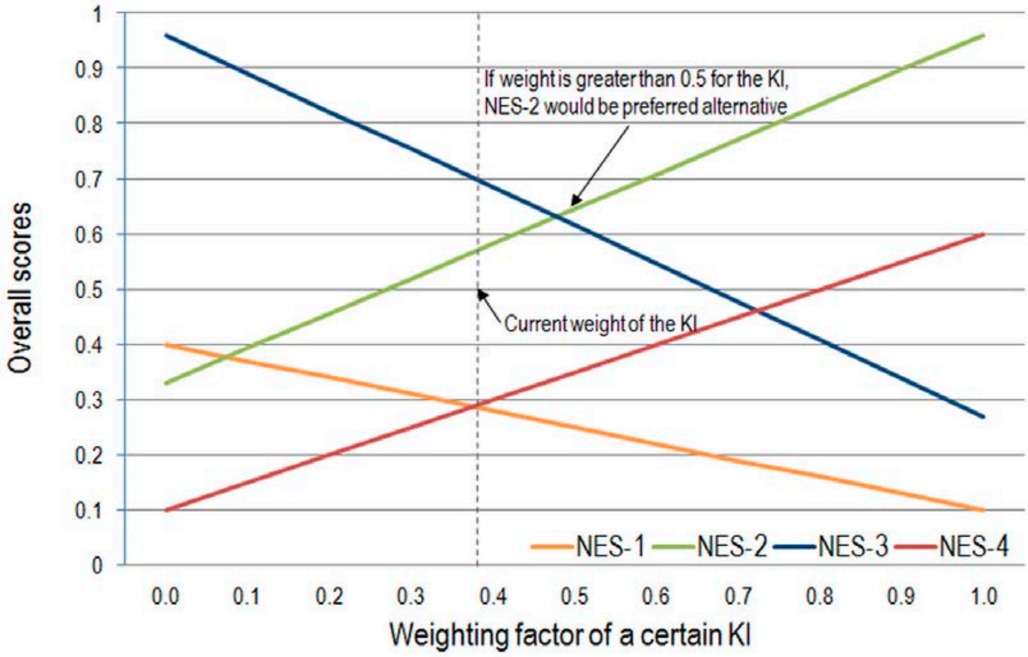


FIG. 3.5. Linear weight approach to weight sensitivity analysis.

3.3.3.1. Direct approach

A direct approach used to determine the sensitivity of the ranking results with respect to a value function type involves direct observation of how the ranking results are affected by a change in one or more value functions, the type of which varies within certain limits. This approach provides many opportunities for analysing sensitivity to a value function type, for example by simultaneous variation of several value functions or by a change in the value function parameters defining it.

Generally, this analysis is applied for a qualitative (often visual) check: an expert modifies a value function type and observes the changes in the order of the alternatives' ranking, as well as the values of the multi-attribute value function. In this way, a posteriori knowledge can be gathered that reveals the main components affecting the ranking results. However, in this case, a smart strategy is required to determine how to modify value function types in order to find a quantitative description of the observed regularities.

Given the multi-factorial character of the evaluation of the sensitivity to value function types in the decision support systems, implementing the direct approach to sensitivity analysis is a common practice. However, other approaches are potentially realizable, including those based on the statistical approach, as well as improved analytical methods which suggest incorporating uncertainties caused by value function types directly into the analysis (i.e. design of the decision rule).

3.3.3.2. Statistical approach

The statistical approach to value function sensitivity supplements the direct approach. It is reasonable to implement this approach in situations where the form of single-attribute value functions is not well understood. This approach assumes the random generation of a set of single-attribute value functions from a certain set of functions, and the identification of alternative ranks while applying them. Based on this information, the rank distribution of alternatives may be evaluated for each alternative (Fig. 3.6).

The probability rank distributions of each alternative can be constructed based on this analysis in order to determine the most probable rank values as well as their mean values, variance, and so on. As a whole, this information characterizes the degree of alternative rank sensitivity to a value function type. Based on this information, it is possible to make quantitative judgements on the attractiveness of an alternative with due account of uncertainties in the form of value functions.

It should be noted that using this approach may cause the alternatives to be seen as indistinguishable. This is due to the variation of a value function type over an unnecessarily wide range, which will lead to the alternative rank probability distribution being close to equally probable. Therefore, such an approach requires special attention when determining the boundaries of a value function shape variation; they should be neither too narrow nor too wide.

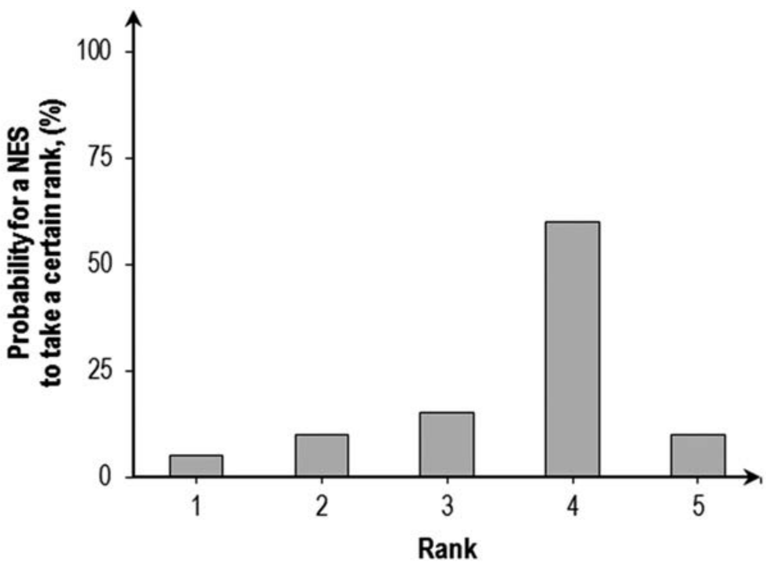


FIG. 3.6. NES rank distribution: illustration of statistical approach to value function sensitivity analysis.

3.3.4. Sensitivity to and uncertainty of KIs

As a rule, the exact values of indicators are unknown; instead, the indicators are characterized by a certain range of values. This statistical dispersion may be caused, for example, by an error bias of measured value. In cases when an indicator is evaluated qualitatively, for example, based on expert judgements, the uncertainty in the indicator value may be caused by the ambiguity of reflecting expert qualitative judgements in a score scale. Thus, analysing sensitivity to a scatter of possible indicator values might be important.

It should be noted that evaluations of the impact with respect to indicator uncertainties may be reduced when analysing sensitivity to other model parameters while implementing one or another MCDA method (for example, within the MAVT method, indicator uncertainty may be reduced to the uncertainty of a value function type). However, it is necessary to clearly identify the cause of uncertainty (the objective or subjective nature of the uncertainty) to avoid double counting its impacts when performing an analysis.

3.3.4.1. Direct approach

A direct approach to determine the sensitivity of ranking results to indicator values may be a direct observation of the impact of indicator value changes within certain limits. The direct approach may be based on techniques such as the simultaneous variation of several indicators within specified boundaries or the generation of indicator values in accordance with a specific rule.

This approach is used for a qualitative (often visual) analysis: an expert modifies the indicator values and directly observes changes in the ranking results and in the values of multi-attribute value functions. Based on this procedure, a posteriori experience is gained that enhances our understanding of the sensitivity of ranking results to indicator values. In order to reflect certain quantitative regularities, a strategy for modifying indicator values needs to be set up so as to enable quantitative description of the observed regularities.

In decision support systems, a sensitivity analysis with respect to indicator values is, as a rule, not realized as a separate functional module. If necessary, an analysis of this kind can be carried out by modifying the basic calculation model, making a series of variant calculations with different indicator values and then analysing the results.

3.3.4.2. Advanced MCDA methods

Another possible option for considering uncertainties in indicator values is to apply advanced MCDA methods that provide such a capability, for instance, MAUT or methods from the fuzzy MCDA toolkit.

As discussed in Section 3.1.2, MAUT is an extension of MAVT that allows the indicator value uncertainty represented by a random variable with a given probability density function to be accounted for. The single-attribute and overall utility functions for each alternative are also, as a result, random variables with corresponding probability distributions. The alternatives' ranks are determined within MAUT based on a comparison of the expected overall utilities of the considered options that allow incorporation of the uncertainties in the indicator values.

Fuzzy MCDA methods involve considering uncertainties in the indicator values by using fuzzy numbers (singleton, triangular, trapezoidal and piecewise are the most commonly used). Indicators, like other elements of fuzzy sets, have a given degree of membership in distinction from the binary (yes/no) membership used in the regular sets within point estimations. It is deemed that a fuzzy approach corresponds better to individual judgements regarding indicator values characterized by uncertainties, and allows, within decision models, the incorporation of relevant uncertainties. In such models, the conventional crisp judgement scale is replaced with fuzzy numbers to indicate the fuzziness of judgements regarding indicator values.

3.3.5. Comparison with other MCDA methods

Comparing the results obtained using different MCDA methods is another possible option to examine the overall stability and robustness of the ranking results, significantly increasing the confidence level.

In the general case, the ranks of alternatives may be different when using different MCDA methods. Differences in the rank order may occur owing to different representations of a performance table demonstrating the performance of the alternatives in terms of the chosen criteria; the results from evaluating weights using different procedures (e.g. swing and pairwise) and realized via different MCDA methods may vary significantly; and the decision rules implemented in the MCDA methods may have a significant impact on the ranking order. There are no specific rules for conversion among different variants of the model parameters used in different methods. Notwithstanding, the different theoretical frameworks applied in different MCDA methods lead to well coordinated and similar outcomes that allow the overall stability and robustness of the results to be examined.

3.3.6. Summary

Uncertainty and sensitivity analysis approaches need not to be limited to those considered in this section. The selection of the most suitable approach depends on the scope of the specific case study and the related audiences and expert preferences, which should be mentioned in the case study reports.

The uncertainty treatment for both the indicators and the weights and their consideration in the framework of the decision making model related to the comparative evaluation of NESs is a significant problem because there are no universal ready-made recommendations. In this regard, it is helpful to thoroughly analyse the application feasibility of existing approaches within a case study in order to treat uncertainties.

The MCDA methods applied to a multi-criteria comparative evaluation of NESs' performance need to include uncertainty analyses with respect to weights, indicators and other model specific parameters (for example, single-attribute value functions within the MAVT method). Uncertainty treatment evaluates the impact of model parameter uncertainties on the overall scores. A balance needs to be reached between elimination of the uncertainty sources and overestimation of the uncertainties, which may lead to the alternatives becoming indistinguishable.

For most problems, simple approaches within a deterministic sensitivity analysis are sufficient to examine the impact of uncertainties, owing to the advantages of straightforward implementation, intuitive appeal and ability to be implemented within different MCDA methods. With these approaches, the weights or indicators are varied as a single value. Within the MAVT method, the sensitivity analysis explores the impact of changes in indicators, weights and value function on ranking results.

At the same time, more sophisticated methods may be required in cases where multiple sources of uncertainty are to be taken into account simultaneously, where dependence relations exist among the input data and where there are no time constraints for uncertainty modelling. Such approaches seem most appropriate if only the lower and upper bounds are known (interval or grey approaches) or if experts' opinions are characterized by specific distributions (probabilistic or fuzzy set approaches) in a group decision process.

In the framework of the KIND approach, it is reasonable to examine, as the basic option, the impact of uncertainties in indicators, weights and method parameters through a deterministic sensitivity analysis. For more sophisticated users, additional options may be interesting in order to provide robust judgement aggregation in which the weights are not determined by their average values, but are distributed within certain intervals or characterized by distributions. This option has not yet been performed at full scale.

REFERENCES TO SECTION 3

[3.1] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems: INPRO Manual — Overview of the Methodology, IAEA-TECDOC-1575 (Rev. 1), IAEA, Vienna (2008).

[3.2] INTERNATIONAL ATOMIC ENERGY AGENCY, Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability: Final Report of the INPRO Collaborative Project GAINS, IAEA Nuclear Energy Series No. NP-T-1.14, IAEA, Vienna (2013).

[3.3] FIGUEIRA, J., GRECO, S., EHRGOTT, M., Multiple Criteria Decision Analysis: State of the Art Surveys, Springer, Boston, MA (2005).

[3.4] BELTON, V., STEWART, T., Multiple Criteria Decision Analysis: An Integrated Approach, Kluwer Academic Publishers, Dordrecht (2002).

[3.5] KEENEY, R., RAIFFA, H., Decisions with Multiple Objectives, John Wiley & Sons, New York (1976).

[3.6] VON WINTERFELDT, D., EDWARDS, W., Decision Analysis and Behavioral Research, Cambridge University Press, Cambridge (1986).

[3.7] HWANG, Ching-Lai, YOON, Kwangsun, Multiple Attribute Decision Making: Methods and Applications, Springer, Berlin (1981).

[3.8] BRANS, J.P., VINCKE, P., A preference ranking organisation method: (The PROMETHEE method for multiple criteria decision-making), Manage. Sci. **31** 6 (1985) 647–656.
[3.9] SAATY, T.L., The Analytic Hierarchy Process, McGraw-Hill, New York (1980).
[3.10] DYER, J., BUTLER, J., EDMUNDS, T., JIA, J., A multivariate utility analysis of the alternatives for the disposition of surplus weapons-grade plutonium, Oper. Res. **46** 6 (1998) 749–762.
[3.11] KEENEY, R., NAIR, K., Evaluating Potential Nuclear Power Plant Sites in the Pacific Northwest Using Decision Analysis, International Institute for Applied Systems Analysis, Laxenburg (1976).
[3.12] NIREX, Review of 1987–1991 Site Selection for an ILW/LLW Repository, Nirex, Didcot (2005).
[3.13] HÄMÄLÄINEN, R.P., LINDSTEDT, M.R.K., SINKKO, K., Multi-attribute risk analysis in nuclear emergency management, Risk Anal. **20** 4 (2000) 455–467.
[3.14] BUTLER, J., et al., The United States and Russia evaluate plutonium disposition options with multiattribute utility theory, Interfaces **35** 1 (2005) 88–101.
[3.15] CHARLTON, W.S., et al., Proliferation resistance assessment methodology for nuclear fuel cycles, Nucl. Tech. **157** 2 (2007) 143–156.
[3.16] KIM, S.K., PARK, H.S., LEE, K.W., JUNG, C.H., "MAUT approach for selecting a proper decommissioning scenario", Proc. Waste Management Symp. 2007, Tucson, 2007, Curran Associates, Red Hook, NY (2008).
[3.17] INSTITUTE OF STUDIES FOR THE INTEGRATION OF SYSTEMS, NEEDS — New Energy Externalities Developments for Sustainability: Publishable Final Activity Report, ISIS, Rome (2009).
[3.18] DURBACH, I.N., STEWART, T.J., Modelling uncertainty in multi-criteria decision analysis, Eur. J. Oper. Res. **223** (2012) 1–14.
[3.19] BROEKHUIZEN, H., GROOTHUIS-OUDSHOORN, C.G.M., VAN TIL, J.A., MARJAN HUMMEL, J., IJZERMAN, M.J., A review and classification of approaches for dealing with uncertainty in multi-criteria decision analysis for healthcare decisions, PharmacoEconomics **33** 5 (2015) 445–455.
[3.20] WIGELAND, R., et al., Nuclear Fuel Cycle Evaluation and Screening: Final Report, FCRD-FCO-2014-000106, United States Department of Energy, Washington, DC (2014).
[3.21] UNITED STATES DEPARTMENT OF ENERGY, Guidebook to Decision Making Methods, WSRC-IM-2002-00002, USDOE, Washington, DC (2001).

4. SELECTION OF SCALES AND VALUE FUNCTIONS FOR KEY INDICATORS

The MAVT method is quite flexible because it allows the implementation of different approaches to compare and differentiate alternatives as well as interpret the ranking results. Therefore, it is helpful to have information on the application of MAVT to the comparative evaluation of NESs, including: the selection of scoring scales for the evaluation of indicators; the identification of a risk attitude parameter; the evaluation of single-attribute value function shape; the identification of weighting factors; uncertainty and sensitivity analysis and presentation of results. This section provides the experts' recommendations (both general and specific) in these areas.

4.1. STATISTICAL ANALYSIS OF THE KIND APPROACH

Statistical examination of the KIND approach based on Monte Carlo simulation was carried out to provide general recommendations aimed at increasing the resolution of the MAVT method. The statistical analysis contributed to the formulation of a consolidated set of recommendations on how to reduce the risk of the indistinguishability of the alternatives and the sensitivity of the ranking results to the model parameters.

Based on this analysis, it was possible to formulate recommendations on how to implement the comparative evaluation procedure, regardless of the number of alternatives being compared. Moreover, it was possible to indicate directions for modifying the model assumptions to provide better differentiation among the alternatives. Such modifications may become necessary when some of the alternative performance indicator values being compared are close to each other. Details on analysis of the KIND approach using statistical treatment are provided in Annex IV.

The goal of the statistical analysis was to provide recommendations concerning the following:

— Selection of scoring scales for evaluation of indicators;
— The role of SIs in the comparative evaluation of NESs;
— The impact of the shape and domain of the single-attribute value functions;
— Ways of aggregating the indicators in high level objectives for evaluation of the weighting factors;
— Interpretation and explanation of the ranking results.

The following options were examined to support the recommendations:

(a) Different sets of indicators (15 and 30 indicators);
(b) Different sets of comparable NESs (2, 5 and 10 systems);
(c) Different scoring scales to evaluate indicators (3, 5 and 10 point scoring scales and a continuous scale);
(d) Different types of single-attribute value functions and their domains (end points, global and local domains);
(e) Linear and exponential single-attribute value functions.

To make judgements and conclusions regarding the impact of model assumptions, two statistical indices were used:

(1) 'Maximal variation in scores' — a statistical index characterizing the resolution of alternatives (capability to make a differentiation between the compared alternatives).
(2) 'Rank reversal index' — a statistical index characterizing alternatives' rank stability and robustness depending on the model assumptions.

An explanation of these statistical indices is presented below. The 'maximal variation in scores' is the difference between the maximum and minimum values of multi-attribute value functions for a given set of alternatives (see Fig. 4.1(a)). It is used as a measure of the distinguishability of alternatives. The higher this value is, the more distinguishable the alternatives will be. This analysis is informative but must be applied with considerable care. These recommendations should not be used directly without proper consideration for the user-specific problem, and making a premature decision by amplifying an apparent difference should be avoided. In practice, a multi-step process can be applied by first narrowing the alternatives and then researching the remaining ones in more detail and possibly using a modified set of KIs (see Sections 4.4 and 4.5).

To evaluate the impact of the forms of the single-attribute value functions on the ranking results, an additional statistical index called the 'rank reversal index' was used. This index represents a measure of the maximum possible change in the ranks of the alternatives due to the switch from one form of single-attribute value function to another, averaged over the entire set of the considered (randomly generated) NESs (Fig. 4.1(b)).

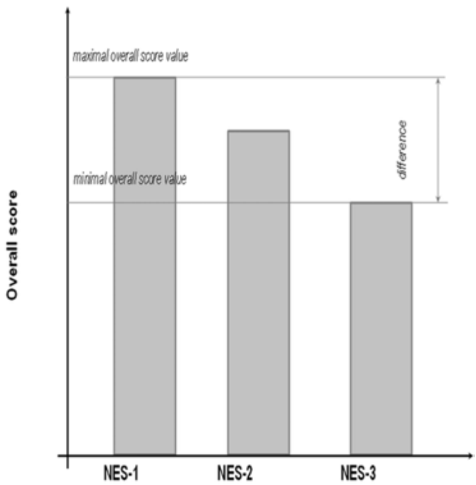
To determine the changes of ranks for each alternative resulting from a modification of the single-attribute value functions, the maximum value of this index is selected, and then this index value is averaged for the entire set of the considered (randomly generated) NESs. Note that this value cannot exceed $N - 1$, where N is the number of systems being compared (it corresponds to the case where the best alternative becomes the worst one).

The 5th and 95th percentiles, median and mean[1] of the statistical indices used were evaluated for corresponding statistical distributions [4.1]. The difference between the 95th and 5th percentiles is a measure of statistical dispersion. The median is the measure of the central tendency. For some cases, probability distributions of statistical indicators have been built. Graphical representations of the statistical measures used are given in Fig. 4.2. More details on statistical analysis are provided in Annex IV.

4.1.1. Assumptions made for the statistical examination of the KIND approach

Owing to the limited scope of the study, Monte Carlo simulation was performed under the following restrictions:

(1) The sensitivity analysis for the single-attribute value function forms was performed on a restricted scale and was limited to the consideration of linear and exponential single-attribute value functions with exponent powers lying in the range from –10 to +10.
(2) Two types of single-attribute value function domains (end points of indicator score ranges) were considered: global and local domains. A local domain assumes that the minimal and maximal domain values of a single-attribute value function are equal to the minimal and maximal KI values specified in the performance table for considered NESs. A global domain of the single-attribute value function is specified from 1 to the maximal scoring scale value.



NESs	Ranks of NESs		Differences in ranks
	Linear value functions	Exponential value functions	
NES-1	1	3	2
NES-2	2	N	N-2
...	...	...	...
NES-N	N	1	N-1
Rank reversing index:			N-1

(a) (b)

FIG. 4.1. Explanation of the statistical indices used. (a) Maximal variation in overall scores; (b) rank reversal index.

[1] A percentile is a measure used in statistics to indicate the value below which a given percentage of observations in a group of observations falls. For example, the 5th percentile is the value (or score) below which 5 per cent of the observations may be found. The median is the 50th percentile. The mean is the average value.

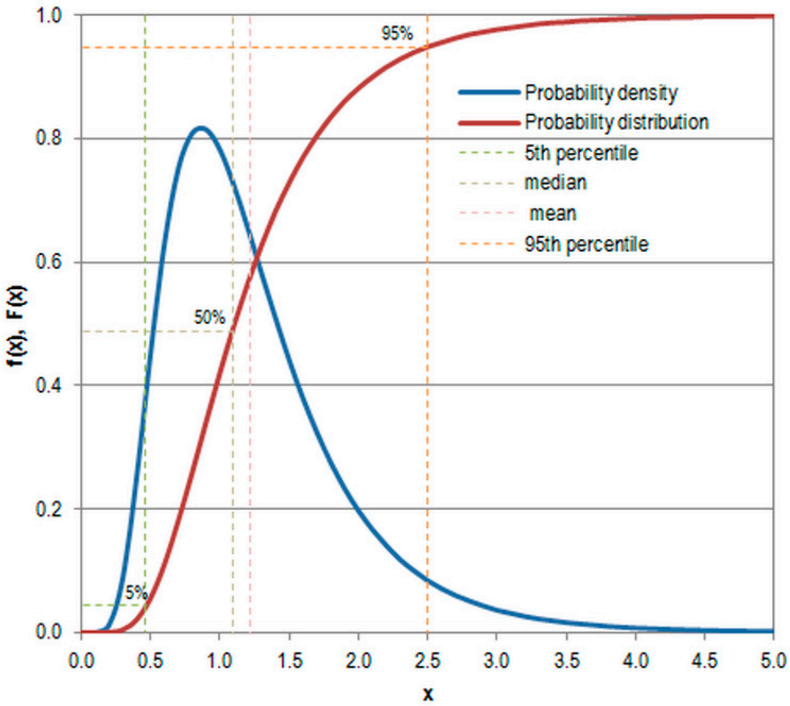


FIG. 4.2. Explanation of the statistical measures used.

(3) Equal weights for all indicators were considered. Thus, according to the requirement that the sum of all the weighting factors be equal to unity, these weighting factors were assumed to be equal to $1/N$, where N is the number of indicators.

(4) Ten thousand randomly generated uniformly distributed NES performance indicators were considered for each case. Each set of model parameters used for performing the statistical analysis was examined 10 000 times to provide good statistics. These runs correspond to 10 000 hypothetical NESs.

4.1.2. Impact of MAVT parameters on the resolution of alternatives and the sensitivity of the ranking results

This section describes the regularities identified during the statistical examination of the KIND approach. Based on them, recommendations were formulated for detailing the KIND approach. The goal is to reduce the risk of indistinguishability among alternatives and the sensitivity of the ranking results to model parameters.

4.1.2.1. The number of NESs analysed

As the number of NESs being analysed increases, the comparative evaluation by means of the MAVT method becomes more complicated. Such sophistication arises from the increase in the quantity of the initial data to be gathered and handled, the increased number of assumptions and model parameters to be selected and implemented, and the greater complexity of performing the sensitivity and uncertainty analysis and interpreting and representing the ranking results. Notwithstanding, the general tendency accompanying these difficulties is that the distinguishability of alternatives becomes more pronounced and the ranking results demonstrate reduced sensitivity to model parameters. In such cases, it is reasonable to consider an appropriate selection of simplified MAVT model parameters and assumptions to reduce the initial data preparation in order to achieve an acceptable resolution of alternatives.

The number of NESs analysed and their maturity level and similarity are the main aspects influencing the selection of the appropriate MAVT model assumptions and parameters. A large number of NESs requires the pre-sorting of alternatives into groups using ‘rough’ assumptions, and afterwards ranking of the NESs in relation to different groups, making more refined assumptions.

In the national case studies, the comparison of two alternatives is often applied and represents a sensitive situation because the ranking result has the following characteristics:

- — It does not depend on the form of single-attribute value functions.
- — It does not require a precise evaluation of the indicator values (i.e. it is sufficient to assign 0 to the NES option with the lowest performance or 1 to the best performing one).
- — It does not depend on the scores assigned to an indicator when both NESs perform identically (e.g. both may be allocated 0 or 1). The ranking results will depend on neither the indicator value nor the corresponding weighting factor.

To evaluate the overall MAVT scores of the two alternatives, it is sufficient to sum up the weighting factors of the indicators that perform better for a certain alternative, providing the maximum resolution between alternatives. Thus, the evaluation result depends solely on the weights for the indicator values being equal to 1. This effectively reduces the evaluator's effort to define single-attribute value functions.

4.1.2.2. Structure of the objectives tree

Selection of an appropriate structure for the objectives tree is an important task in multi-criteria problems with which a structural uncertainty is associated. The assumptions regarding the structure of the objectives tree are inherent to the decision model, and adequate elaboration of the objectives tree structure, depending on the decision problem, lies in the area of responsibility of the experts carrying out a study. Structural uncertainties arise when experts or decision makers are uncertain as to whether all relevant indicators are being considered and how these indicators are structured. To cope with structural uncertainty, different options for the objectives tree need to be considered, and a more suitable option may be selected based on a posteriori experience obtained after examining the decision problem from different perspectives.

The larger the number of attributes involved in the evaluation within a certain category, the smaller the contribution of each single attribute to the overall scores. Therefore, the objectives tree needs to be balanced in such a way that each attribute or indicator provides an adequate contribution to the overall scores.

In KIND, the central part of the objectives tree covers the INPRO areas. Thus, all indicators are to be mapped into these areas. To simplify an evaluation of weights, it is reasonable to select no more than five to seven indicators per area. At the upper tree level, two or three high level objectives need to be generated that specify broader evaluation areas.

4.1.2.3. The number of indicators used and scoring scales for indicator evaluation

A large number of indicators reduces the distinguishability (resolution) of alternatives. This is caused by the self-compensating merits and demerits of a certain NES, and it degrades the resolution.

Furthermore, the use of a large number of indicators requires more effort to form a performance table containing the indicator performance scores. Therefore, it is reasonable to keep the number of indicators relatively small (preferably no more than 15–20) and, in case the overall scores of some alternatives are close to each other, to implement a comparative evaluation procedure for a second time by introducing SIs (see Sections 4.4 and 4.5) into the evaluation process[2].

In MAVT based comparisons, scoring scales starting from the simplest two-point scale and ending with a continuous scale may be used. It is impossible to say a priori which scale is the best. Selecting a scoring scale for the comparison of NESs is to be based on the task context analysis (the number of analysed systems, similarity between systems, NES maturity level, possible quantitative evaluation of indicators) and aim at finding a balance between a slightly more complicated procedure in the preparation of a performance table and a significant differentiation of the alternatives.

[2] This works better for mature NESs. For less mature NESs, it may be necessary to use an initial comparison to narrow the alternatives, followed by a period of additional R&D prior to a second comparison. This was the approach used in the GEN-IV roadmap, where the intention was to narrow the alternatives to a smaller set that would require fewer R&D resources.

A natural scale is the most suitable for indicator evaluation, since a number of indicators can be evaluated on the basis of calculations. It should be noted that transfer to another scoring scale entails the inclusion of additional uncertainty arising from the procedure.

The statistical analysis performed has shown that when 'natural' (continuous) indicator evaluation scales are used, the sensitivity of the ranking results to the form of the single-attribute value functions becomes less pronounced if global value function domains are used as compared to local ones. However, in this case, the risks for the indistinguishability of the alternatives are significantly increased (the final scores become closer to each other). Therefore, it is reasonable to only use natural (continuous) scales for the assessment of indicators in combination with local single-attribute value function domains.

The selection of a suitable number of scores is an important independent task, as not all indicators can be quantified on a continuous scale. When selecting the number of scores, one needs to consider that, if a scoring scale for indicators is excessively large, the risks for the indistinguishability of the alternatives will be increased, making the ranking results more sensitive to model parameters.

When comparing two NESs using a local domain for single-attribute value functions, the opposite trend is observed. An extended scoring scale is preferable, since it enables a more precise differentiation of the alternatives. It is less likely to have the same value of a certain indicator for these two alternatives when the scale is broader.

In general, the exact values of indicators are not explicitly known, as they are often biased with uncertainties. In a situation where the indicators depict a certain measured value, the nature of the uncertainty may be related directly to the measurement or indirectly to the data processing. For qualitatively evaluated indicators, for example, those based on expert judgements, the uncertainty is caused by the ambiguity of mapping expert or qualitative judgements onto the scoring scale used. Uncertainties may arise owing to the conversion of indicators from a natural scale to a scoring scale.

In a situation when there are no specific conversion rules (both linear and non-linear transformations may be used), the conversion itself may lead to different scores and, ultimately, to different ranking results.

In general, in order to minimize uncertainties, it is helpful to use, if possible, a natural scale of indicators without any conversion to scoring scales in the evaluations.

It should be noted that the incorrect application of any MCDA method can lead to the creation of artificial differences or a reduction of real differences between the compared options. This means that slight differences in the values of indicators in the compared options may lead to large differences in the overall scores of the aggregated options, and vice versa — large differences in the indicators may not make a significant difference in the overall scores. This can change the real picture of the attractiveness of the compared options and, therefore, needs to be taken into account by experts when conducting an examination and interpretation of the ranking results.

The interpretation of differences is an area that is the responsibility of experts and it needs to be analysed when a decision model is created. Within the MAVT method, this problem may be a priori controlled by selecting appropriate domains of single-attribute value functions to provide an adequate contribution from each individual indicator to the overall scores.

4.1.2.4. Domains of single-attribute value functions

The 'domain' is the set of all valid values for the 'independent' variable. The 'range' is the set of values for the resulting 'dependent' variable. Consequently, the domain of single-attribute value functions can be a range of indicator values if the indicator represents a dependent variable. The domain of a single-attribute value function may be selected in various ways. When choosing the domain, the fact that the indicator values for all of the alternatives must be within the range needs be taken into account; if a range is wide, it will be difficult to discriminate between alternatives, whereas if the range is narrow, the scores of the alternatives may be outside the range.

The domains are to be chosen in such a way that the maximum distinguishability of alternatives is achieved and the sensitivity of the ranking results to the forms of the single-attribute value functions is reduced. Two options may be considered to identify the domains of single-attribute value functions: (1) local domains and (2) global domains (see Fig. 4.3).

A local domain means that the minimum and the maximum argument values of each single-attribute value function (corresponding respectively to 0 and 1 in the value range of a single-attribute value function) are equal to the minimum and maximum values of the related indicator for each considered set of NESs defined in the

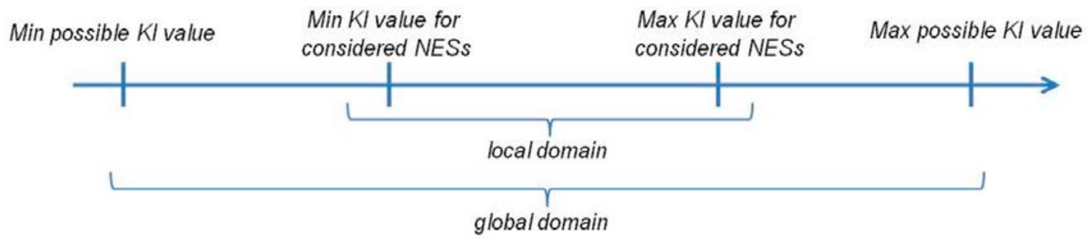


FIG. 4.3. Single-attribute value function domains.

performance table. However, this may complicate the problem solution to some extent, as it is necessary to identify these areas for each indicator separately.

A global domain is determined by an analyst (i.e. without reference to the performance table for a certain problem). It needs to include all values from the minimum possible score to the maximum possible score that the analyst is ready to assign as the best and the worst values for the domain.

The use of a local domain for single-attribute value functions enhances the distinguishability of alternatives as compared to the global one. In particular, the selection of local domains for single-attribute value functions is especially important in the case when there are few alternatives, where the risk of observing indistinguishable alternatives is relatively high. At the same time, if the number of alternatives is large enough, the selection of the global domain may be more suitable owing to the reduction of the effort required for the solution of the problem.

Local domains are most appropriate in the majority of cases, but their utilization may artificially enhance (maximize) differences between the alternatives. Due to these phenomena, it may be reasonable to use global domains for some indicators. Also, global domains are applicable in situations where it is necessary to perform a sensitivity analysis regarding indicator values.

It makes sense to use the global domains of single-attribute value functions in cases where, besides answering the question ‘Which of the systems under consideration is more attractive?’, it is necessary to find an answer to another question: ‘In what areas do we need to improve the system of interest so as to enhance its attractiveness compared to its alternatives?’ Thus, it is advisable to use the global domains of single-attribute value functions, which would reflect improvements in the performance of the system more informatively by gradually improving the values of the indicators used in the evaluations.

Statistical analysis of ranking in the KIND approach shows sensitivity to the form of single-attribute value functions. At the same time, the ranking results do not dramatically depend on the forms of single-attribute value functions. This fact allows the efforts related to the preparation of single-attribute value functions to be reduced. It should be stated that for the comparison of NESs’ performance, linear functions may be used as a first approximation for single-attribute value functions for all indicators.

The decision maker and experts may disagree with the linear form of single-attribute value functions, because, in their view, different levels of indicator values may carry different significance. In such cases, the construction of single-attribute value functions for each indicator is performed while reflecting the experts’ preference strength. Section 4.3 provides a description of the steps that experts need to pass through for the elicitation of single-attribute value functions reflecting the risk attitude.

4.2. SELECTION OF SCORING SCALES IN THE EVALUATION OF INDICATORS

When selecting scoring scales for evaluation of indicators, the fact that the fewer the number of points used on the scoring scale, the simpler the rules for scoring will be, needs to be taken into account. Conversely, if the number of points on the scoring scale is large enough, the scoring rules become more complex. Any scoring scales from the two-point one to a continuous one may be used for indicator evaluation in the comparative evaluations of NESs. In any case, for the rational selection of the most suitable scoring scale, context analysis is to be carried out for a problem.

The following three aspects determine the selection of the scoring scale for the evaluation of indicators: the maturity level of the NESs, the similarity of the NESs and the number of NESs being compared. The main rules that provide acceptable resolution of alternatives and ranking stability and robustness are the following (see Fig. 4.4):

— The lower the maturity level of the NESs being compared, the narrower the scoring scale.
— The larger the number of NESs being compared, the narrower the scoring scale.
— The greater the similarity between the NESs being compared, the wider the scoring scale.

The selection of scoring scales for the evaluation of indicators needs to be based on trade-offs among the trends outlined above. Some comments and explanations are given below to clarify these trends.

When comparing a small number of NESs (e.g. up to five), it seems appropriate to use a wider scoring scale (e.g. a 10 point scoring scale). When comparing a large number of NESs, it makes sense to use a narrower scoring scale (e.g. a three point scoring scale), because the benefits of using a wider scoring scale will be counterbalanced by the increased complexity of the indicator evaluation procedure.

It is reasonable to use different scoring scales at different stages of technological development (design stages), which characterize the maturity level of the NESs being compared, because less mature technologies are characterized by features such as insufficiently detailed design information, operational data and cost information, whereas for more mature options more detailed information is available (see Section 2.4.1).

To provide an acceptable resolution for the performance of similar NESs (e.g. for NESs based on similar reactor technologies), a wider scoring scale could be used, which would help to highlight differences.

Another important aspect is the choice of well balanced scoring scales for the whole set of indicators (for both key and secondary ones), which would guarantee an adequate share of each attribute in the multi-value score. Within the MAVT method, this problem may be solved by an adequate selection of the single-attribute value function domains (their end points), to be chosen to be as close to each other as possible.

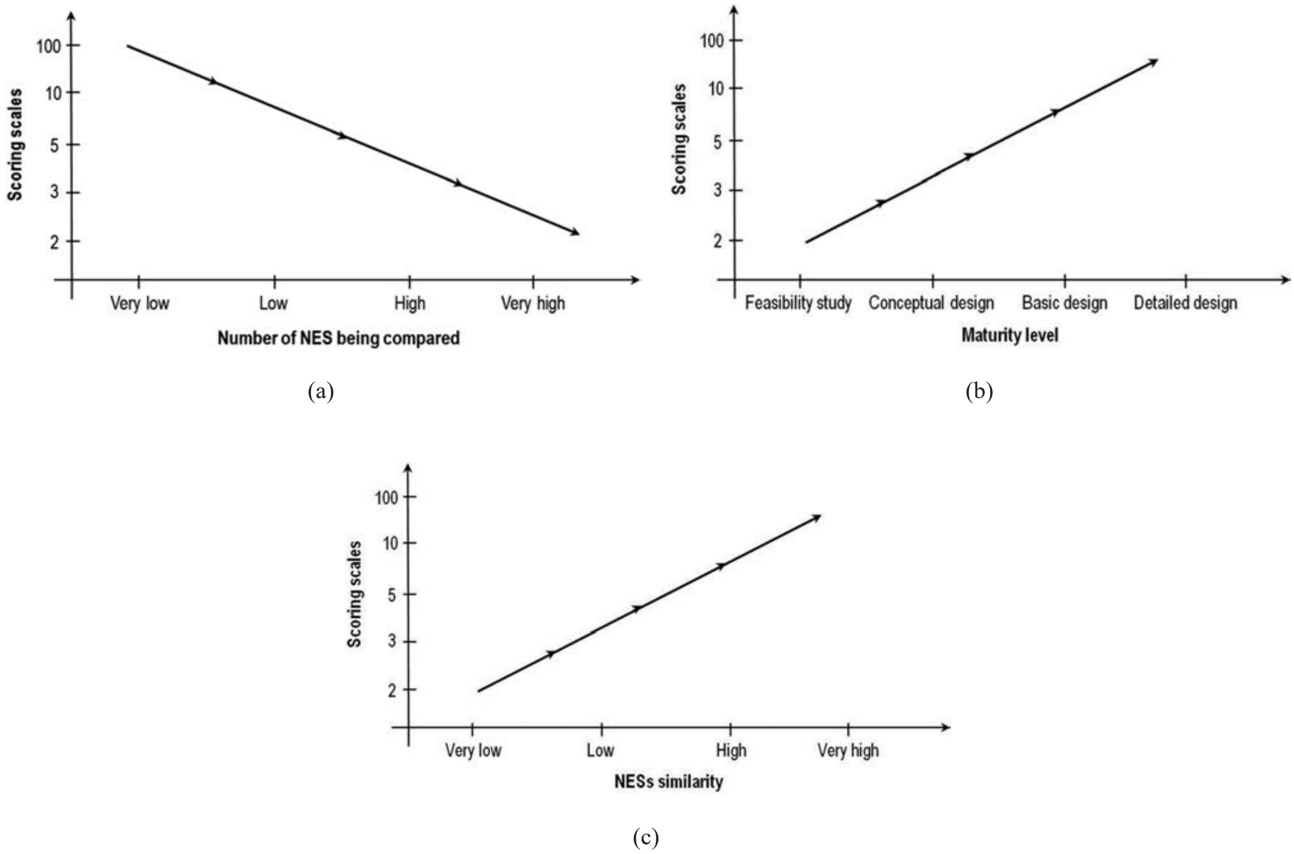


FIG. 4.4. *Illustration of the main trends to be taken into account for the selection of a scoring scale.*

4.3. ELABORATION OF SINGLE-ATTRIBUTE VALUE FUNCTIONS

The elicitation of single-attribute value functions requires the direct involvement of the decision makers and experts, who have to prepare questionnaires and apply other means to gather the necessary information, which needs to be processed afterwards. Taking into account the specificity of the KIND approach aimed at solving the applied problems in the nuclear technology domain, where the main users are technical experts not skilled in performing multi-criteria decision analyses, it seems favourable to develop a simple and fast pilot method for evaluating the single-attribute value function types and the parameters. Such a method could have the following features:

(a) As the form of single-attribute value functions reflects the risk attitudes, it is helpful to use exponential functions as the most common ones in making comparative evaluations of alternatives based on the MAVT method. In cases where the decision maker considers the increments in indicator values to be of equal preference, the corresponding single-attribute value function will be linear.

(b) It is necessary to determine an increasing or a decreasing function expressing the maximization or minimization preference. The selection will depend on how the indicator characterizes an 'increase' in system performance: if higher values of the indicator correspond to a more attractive system condition, the single-attribute value function will be increasing, otherwise, it will be decreasing. It is assumed that the single-attribute value functions are monotonic over the entire domain. The increasing single-attribute value function (Eq. 4.1) and the decreasing single-attribute value function (Eq. 4.2) are assumed to be represented as follows:

$$u(x) = \frac{1 - \exp\left(a \cdot \dfrac{x - x^{\min}}{x^{\max} - x^{\min}}\right)}{1 - \exp(a)} \tag{4.1}$$

$$u(x) = \frac{1 - \exp\left(a \cdot \dfrac{x^{\max} - x}{x^{\max} - x^{\min}}\right)}{1 - \exp(a)} \tag{4.2}$$

where a is the exponent characterizing the function curvature; the closer it is to zero, the smaller the exponent curvature and the nearer its shape is to the straight line. The exponent value measures the 'risk proneness level'. The risk proneness level characterizes the degree of risk proneness: positive a values correspond to risk proneness, while negative a values correspond to risk aversion. Moreover, $x^{\max}$ and $x^{\min}$ are the minimal and maximal values in the domain of a single-attribute value function.

Note that the same functional forms may be used for the single-attribute value function even if there is no uncertainty associated with the indicator values. In this case, the convexity of the function may be interpreted as a measure of the increase or decrease of the marginal preference value associated with the incremental unit variation of the indicator value. As mentioned earlier, this discussion will interpret the curvature of the single-attribute function in terms of risk proneness, since this is a common explanation for the concavity or convexity of a utility function[3].

(c) If the values of the corresponding indicator are uncertain, then the evaluation of the single-attribute value function needs to incorporate questions involving lotteries or gambles. For example, the exponent power in Eqs (4.1) or (4.2) may be evaluated using the lottery method, determining the certainty equivalent in an assumption of a 50/50 gamble. The certainty equivalent is the amount of payoff that a decision maker would have to receive to be indifferent between that payoff and a given gamble. The certainty equivalence (*CE*)[4] of the lottery is a classic elicitation method assuming equal (50/50)[5] probabilities of obtaining each of the two

[3] The difference between a multi-attribute value function (under MAVT) and a multi-attribute utility function (under MAUT) is a subtle one, and relates primarily to which single-attribute assessment methods should be used.

[4] Many elicitation methods may be used to measure a value/utility function to determine a decision maker's attitude to risk based on risk attitude evaluation lotteries (for example, the certainty equivalence method, the probability equivalence method, or the lottery equivalence method).

[5] It should be noted that the procedure can be added to by including the lottery probability parameters, which will somewhat complicate the procedure for polling decision makers. For this reason, it is not presented here. Nevertheless, it could be used as an additional option for advanced users.

outcomes (indicator values) [4.2, 4.3]. To perform single-attribute value function identification within this method, three values need to be specified for the 50/50 lottery: the better outcome, the worse outcome and the certain equivalent (Fig. 4.5).

The implementation of this method assumes that a series of questions is answered: do you prefer the lottery in order to obtain a 'better outcome' (*BO*) and 'worse outcome' (*WO*) with 50% probability each (indicated as <better outcome, worse outcome>) or a guarantee of a 'certainty equivalent' of the lottery. Usually, a better outcome will be the highest outcome in the decision problem and a worse outcome will be the lowest outcome. In any case, these outcomes need to be far enough apart for the decision maker to perceive a definite difference between them. These three values are related as follows: $u(CE) = 0.5 \cdot u(BO) + 0.5 \cdot u(WO)$. If the exponential form of a single-attribute value function is used with certain parameters specifying x^{min}, x^{max} values, as well as the exponent power *a*, then, after simplification, an expert may observe that the exponent power *a* must satisfy the following transcendental equation:

$$\exp\left(a \cdot \frac{CE}{x^{\max} - x^{\min}}\right) = 0.5 \cdot \exp\left(a \cdot \frac{BO}{x^{\max} - x^{\min}}\right) + 0.5 \cdot \exp\left(a \cdot \frac{WO}{x^{\max} - x^{\min}}\right) \tag{4.3}$$

where x^{max} and x^{min} are the minimal and maximal domain values of a single-attribute value function (end points of the single-attribute value function). Given the values for *CE*, *BO* and *WO*, an expert could find the value of the exponent power *a* that satisfies the equation exactly. This equation is used to parameterize the exponent power identification within the express method.

(d) This procedure is to be applied to single-attribute value functions attributed to each indicator, whereas estimations involving different scores can be used for different indicators. Based on these procedures being applied to all selected indicators, it is possible to create a set of single-attribute value functions for the entire set of indicators.

(e) After obtaining the result for the alternative ranking, it may be desirable to analyse the sensitivity to the single-attribute value function type by varying the exponent within certain limits from the selected basic value. Should the ranking results not be modified, the solution could be considered as stable. Otherwise, it is necessary to ascertain the risk attitude and its parameters in order to interpret the ranking results.

4.4. ROLE OF SIs

The concept of SIs was introduced in Section 2.1 to supplement the set of KIs. The SIs may be used within single or two tier evaluation procedures (Fig. 4.6). A single tier evaluation procedure assumes that SIs (or a part thereof) are used to carry out a comparative evaluation on a par with the KIs. Then, the objectives tree becomes a four level one that requires the identification of weighting factors for the KIs and SIs. A two tier evaluation procedure assumes that SIs can be used at the final selection stage to eliminate the indistinguishability of the alternatives that was not resolved by KIs.

Implementation of the first option for SIs in general complicates the evaluation process because of the increased volume of information required for the preparation of the initial data to perform evaluations, such as additional weighting factors and single-attribute value functions. At the same time, it increases the risks of making alternatives less distinct.

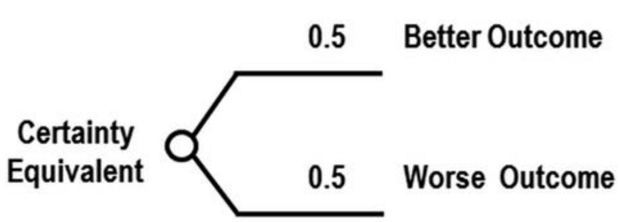


FIG. 4.5. Certainty equivalence method.

The second (two tier) option is preferable. It simplifies the evaluation process, as it requires less information for the preparation of input data to perform evaluations and avoids the elicitation of additional weighting factors, single-attribute value functions, and so on. At the same time, using fewer indicators in a comparative evaluation decreases the risks of making the alternatives less distinct.

Potentially, other options concerning the comparative evaluation procedure may be proposed, taking into account the context of the problem being considered (depending on the available data, study objectives, project time and resources, etc.). Preferably, any possible comparative evaluation procedure should not lead to overcomplicating the objectives tree structure and the weighting factors evaluation procedure, and should allow proper distinguishability of the compared alternatives. Resolving structural uncertainties through considering the problem from different perspectives makes it possible to determine which KI and SI application option is most suitable for a particular task. Usually, within several cycles of consideration and analysis of the decision making problem, an understanding is developed, together with suggestions on how to update the comparison procedure, if there is reason to, and, on this basis, continue to the next cycle of solving the problem.

4.5. PERFORMING COMPARATIVE EVALUATIONS

The experts' recommendations for selecting MAVT model parameters to be implemented in an NES comparative evaluation procedure within the KIND approach are summarized in Table 4.1. These recommendations are aimed at reducing (1) the risks of the alternatives being indistinguishable and (2) the sensitivity of the ranking results to model parameters, and have been tested in a number of case studies to demonstrate their effectiveness [4.4, 4.5].

In conclusion, it should be noted that the above-stated recommendations by no means limit the possibility of choosing any other model assumptions in conducting a comparative evaluation of NESs. Since these recommendations were formulated based on a statistical analysis of a large number of systems, it cannot be excluded that a deviation from them will reduce the distinguishability of the alternatives in some cases and make the ranking results more sensitive to model parameters. In each particular case, the model parameters need to be selected based on a comprehensive analysis of the problem.

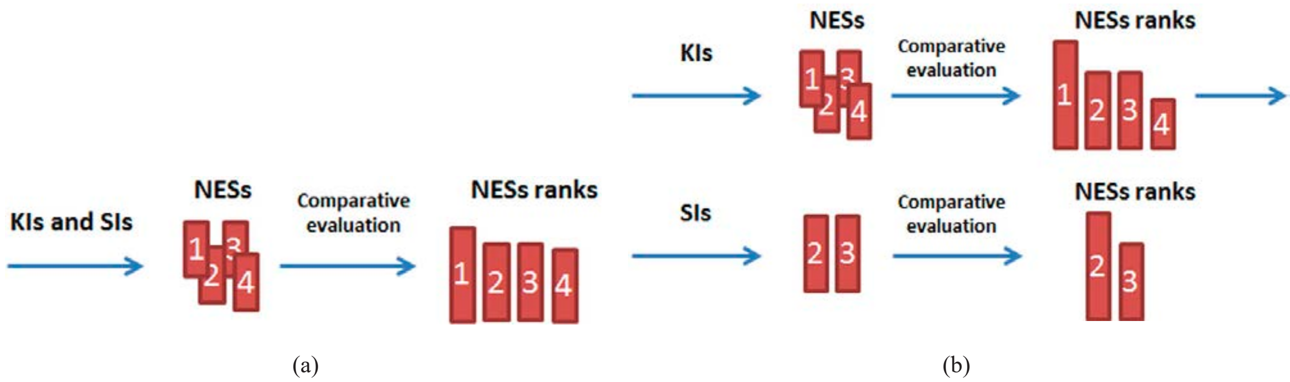


FIG. 4.6. Possible options for a comparative evaluation procedure within the KIND approach. (a) Single tier evaluation procedure; (b) two tier evaluation procedure.

TABLE 4.1. EXPERTS' RECOMMENDATIONS

Small number of NESs being compared	Large number of NESs being compared
Number of NESs being compared	
Up to five	More than five
Number of indicators used in a comparative evaluation	
Fewer than 20	
Role of SIs	
SIs may be used to improve the resolution in cases of uncertainty within a second iteration focusing more on a detailed two tier comparative evaluation procedure if a 'winner' among the alternatives is required	
Scoring scales	
Wide scoring scale or continuous scale are preferable (e.g. 10 point scoring scale)	Narrow scoring scale is preferable (e.g. 5 point scoring scale)
Objectives tree and weighting factors	
Three level objectives tree, direct method and hierarchical weighting	
Domains of single-attribute value functions	
Local domains for single-attribute value functions are preferable	Local domains for single-attribute value functions are preferable, but global domains provide acceptable resolution of NESs
Form of single-attribute value function	
Linear form is acceptable for single-attribute value functions as a first approximation. Risk attitudes may be accounted for by using the exponential form of the value functions (with identification of proper risk level by means of 50/50 lottery).	

REFERENCES TO SECTION 4

[4.1] UPTON, G., COOK, I., Understanding Statistics, Oxford University Press, Oxford (1996).

[4.2] KEENEY, R., RAIFFA, H., Decisions with Multiple Objectives: Preferences and Value Tradeoffs, John Wiley & Sons, New York (1976).

[4.3] VON WINTERFELDT, D., EDWARDS, W., Decision Analysis and Behavioral Research, Cambridge University Press, Cambridge (1986).

[4.4] KUZNETSOV, V., FESENKO, G., ANDRIANOV, A., KUPTSOV, I., INPRO activities on development of advanced tools to support judgment aggregation for comparative evaluation of nuclear energy systems, Sci. Technol. Nuclear Install. **2015** (2015).

[4.5] KUZNETSOV, V., FESENKO, G., ANDRIANOV, A., "INPRO collaborative project on key indicators for innovative nuclear energy systems (KIND)", Innovative Designs and Technologies of Nuclear Power, Proc. IV Int. Scientific and Technical Conf., Moscow, 2016, JSC NIKIET, Moscow (2016) 292.

5. CASE STUDIES ON TRIAL APPLICATION OF THE KIND APPROACH

5.1. OVERVIEW OF CASE STUDIES

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 has the ability to 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.

The summaries of the case studies provided in this section are grouped as follows:

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

The case study summaries include the following sections (corresponding to the flowchart given in Fig. 3.1):

(a) The ‘Introduction’ section presents the background of the case study and its relevance to the objective of KIND.
(b) The ‘Objective and problem formulation’ section describes the objective of the case study and the formulation of the questions to be answered.
(c) The ‘Formulation of alternatives (NES options)’ section identifies and describes a list of NES options to be evaluated in the study.
(d) The ‘Identification of indicators’ section defines KIs and SIs, with the objectives tree, and includes a detailed description.
(e) The ‘Evaluation of indicators, including uncertainties’ section specifies the input data used and details the evaluation of selected indicators and their uncertainties, together with performance table formation.
(f) The ‘Selection of an MCDA method’ section justifies the selection of the most suitable method or methods (MAVT recommended).
(g) The ‘Determination of weights, including uncertainties’ section identifies weights according to the objectives tree and KI weight calculation.
(h) The ‘Ranking alternatives (NES options) with the selected MCDA method and interpretation of results with relevance to objectives at different levels’ section contains tables, graphs and text presenting the results of the study, together with interpretation of the results in natural (substantive, not related to the KIND method) terms.
(i) The ‘Sensitivity and uncertainty analysis’ section analyses weight sensitivity, value function sensitivity, the uncertainty of KIs and their impact on NES ranking, and the results of comparative evaluation.
(j) The ‘Conclusion’ section contains the main conclusions of the case study, presented as a summary.

5.2. GENERIC CASE STUDIES OF HYPOTHETICAL NESs

5.2.1. General assumptions and comments

Consideration of hypothetical systems is quite a common approach in various subject areas, eliminating the need to prepare tables of characteristics of real systems that might require significant time and effort for their formation. This approach seems appropriate for application in the early stages of any activities related to a methodology elaboration, because it provides an opportunity to carry out and demonstrate the procedure for performing comparative evaluation. Such an approach also helps to identify the bottlenecks and likely problems that potential users will encounter in the detailed analysis of real NESs throughout relevant case studies.

5.2.2. Comparison of five hypothetical NESs

This section presents an example of the comparative evaluation of five hypothetical NESs, demonstrating the comparative evaluation procedure in accordance with the KIND recommendations. This example illustrates the basic steps that need to be completed for the comparison of real systems: the formation of a performance table, the evaluation of weighting factors and other model parameters, the performance of evaluations and sensitivity analysis, and the interpretation of the evaluation results.

Within the study, for illustrative purposes, it is assumed that a set of 15 unnamed KIs and 15 secondary (additional) indicators are given, each of which can be evaluated either in scores or in natural (physical) units. These performance indicators can be grouped into six evaluation areas and will be used to test the NES comparative evaluation procedure on hypothetical NESs. Figure 5.1 demonstrates the arrangement of the indicators in a hierarchical structure that is known as an objectives tree.

A performance table was formed at random and model parameters were selected in line with the recommendations made in the previous section:

(a) A set of 15 KIs and 15 SIs (all indicators need to be minimized) was used within the first and second tiers of the comparative evaluation procedure, respectively.
(b) Linearly decreasing single-attribute value functions were applied with the end points defined from the performance table.
(c) The indicators were evaluated using 5 and 10 point scoring scales within the first and second tiers of the comparative evaluation procedure, respectively.

5.2.2.1. Performance table

The values of all the KIs for the considered NESs are presented in the performance table (Table 5.1) for the problem. In accordance with the assumptions regarding the objectives to be achieved with each indicator (all indicators need to be minimized), an indicator value score of 1 is the best possible value, while an indicator value score of 5 is the worst one. The performance table is presented in the form of a value path in Fig. 5.2. This figure shows variations in the values of all KIs for the entire set of NESs and demonstrates how an improvement in a certain KI value reduces the other KI values due to the transition from one NES to another.

In the most evident form, the procedure for the comparative evaluation of NESs may be formulated by ranking NESs according to the closeness of each NES to the upper limit of a graph from a set of KIs. This closeness will depend on the metric type, which is a measure of the distance to the upper limit.

5.2.2.2. Weighting factors

The only assumption that was made to evaluate the weight values was that at each level of the objectives tree, the significance or importance of all the high level objectives, the areas of evaluation and the indicators are identical. This option assumes that the experts and the decision maker agree that high level objectives characterized by aggregated goals of cost, performance and acceptability are equally important.

Each evaluation area within the high level objectives (cost (economics), performance (waste management, proliferation resistance, environment, country specifics) and acceptability (maturity of technology)) was assigned an equal weighting factor. The sum of all the weighting factors for each of these areas was also required to be equal to unity.

At the final level (the level of the KIs), the weighting factors for each indicator included in the corresponding evaluation area were assumed to be equal. The final weighting factors calculated in accordance with the described assumption for each indicator are shown in Table 5.1.

5.2.2.3. Ranking results and interpretation of the results

The alternative ranking results are shown in Fig. 5.3 and the scores of the multi-attribute value functions are presented in Table 5.1. Of all the options considered, the NES-3 is the most preferred alternative. The alternatives NES-1 and NES-5 are close to each other according to the scores of the multi-attribute value functions and take the second and third places, respectively. The alternatives NES-4 and NES-2, despite the slight difference in the values of the multi-attribute value functions, may be considered as indistinguishable and will be evaluated further.

To interpret the ranking results, the multi-attribute value functions may be decomposed into individual components in accordance with the specified structure of the objectives tree. Depending on the depth and level of detail the interpretation requires, this decomposition may be performed at different levels in accordance with the structure of the objectives tree.

Table 5.2 shows the values for the high level objectives (cost, performance and acceptability), which determine the final scores. Based on this decomposition, the superior attractiveness of alternative 3 (NES-3) may be explained in the following manner: despite the mediocre scores for the high level objectives acceptability and cost, this alternative provides the best score for the high level objective performance. For this reason, this alternative takes the first place. The ranking results for the other alternatives can be interpreted in a similar way.

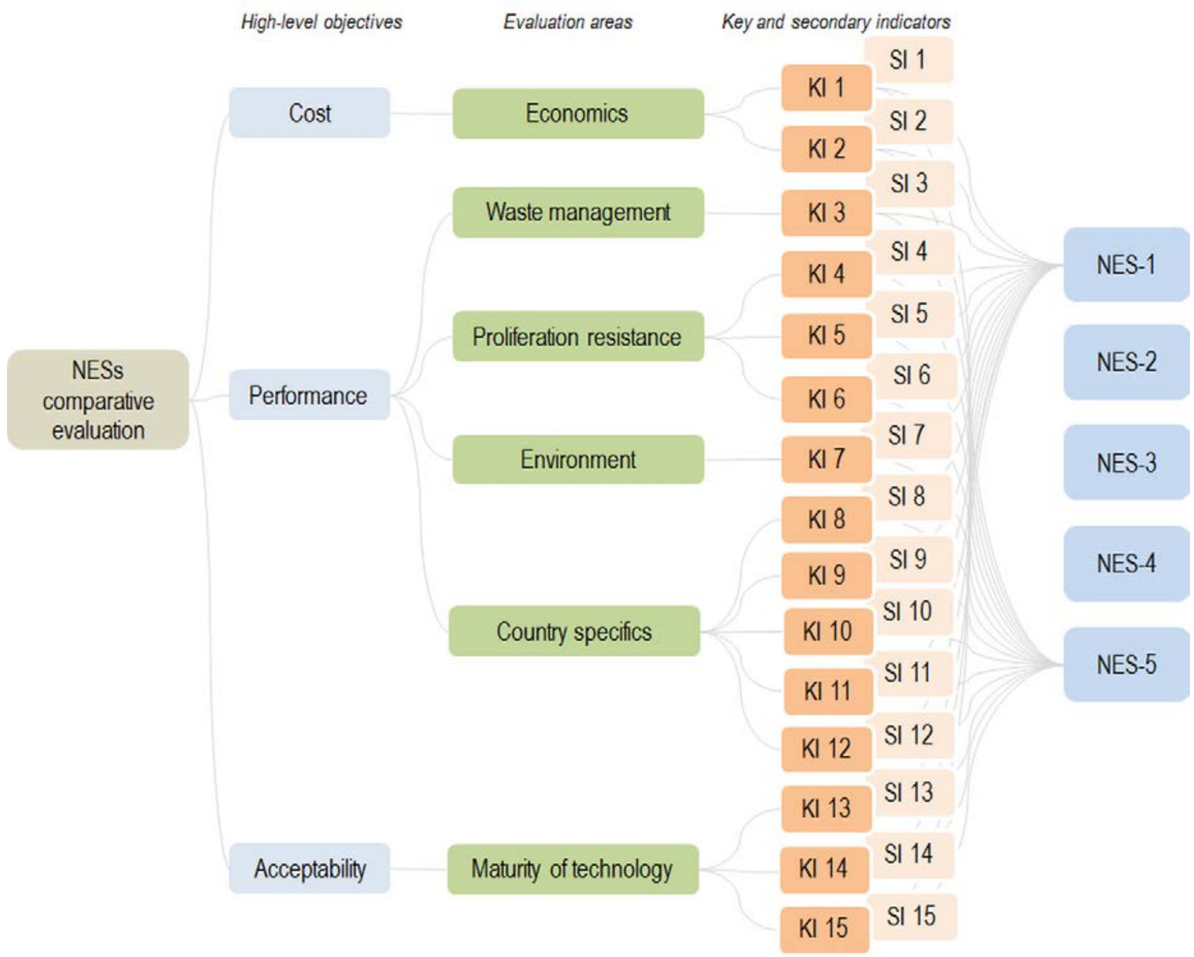


FIG. 5.1. The objectives tree.

TABLE 5.1. PERFORMANCE TABLE

High level objectives	Evaluation areas	KIs	Weights	NES performance				
				NES-1	NES-2	NES-3	NES-4	NES-5
Cost	Economics	KI-1	0.167	1	2	3	2	4
		KI-2	0.167	2	4	2	1	2
Performance	Waste management	KI-3	0.083	5	1	1	3	3
	Proliferation resistance	KI-4	0.028	2	3	1	4	3
		KI-5	0.028	5	5	3	3	4
		KI-6	0.028	4	5	3	2	4
	Environment	KI-7	0.083	3	4	1	2	3
	Country specifics	KI-8	0.017	4	3	4	3	4
		KI-9	0.017	3	4	3	2	3
		KI-10	0.017	3	4	2	3	4
		KI-11	0.017	2	2	4	3	5
		KI-12	0.017	2	4	2	4	2
Acceptability	Maturity of technology	KI-13	0.111	4	2	4	4	1
		KI-14	0.111	4	3	3	5	3
		KI-15	0.111	3	4	3	5	4

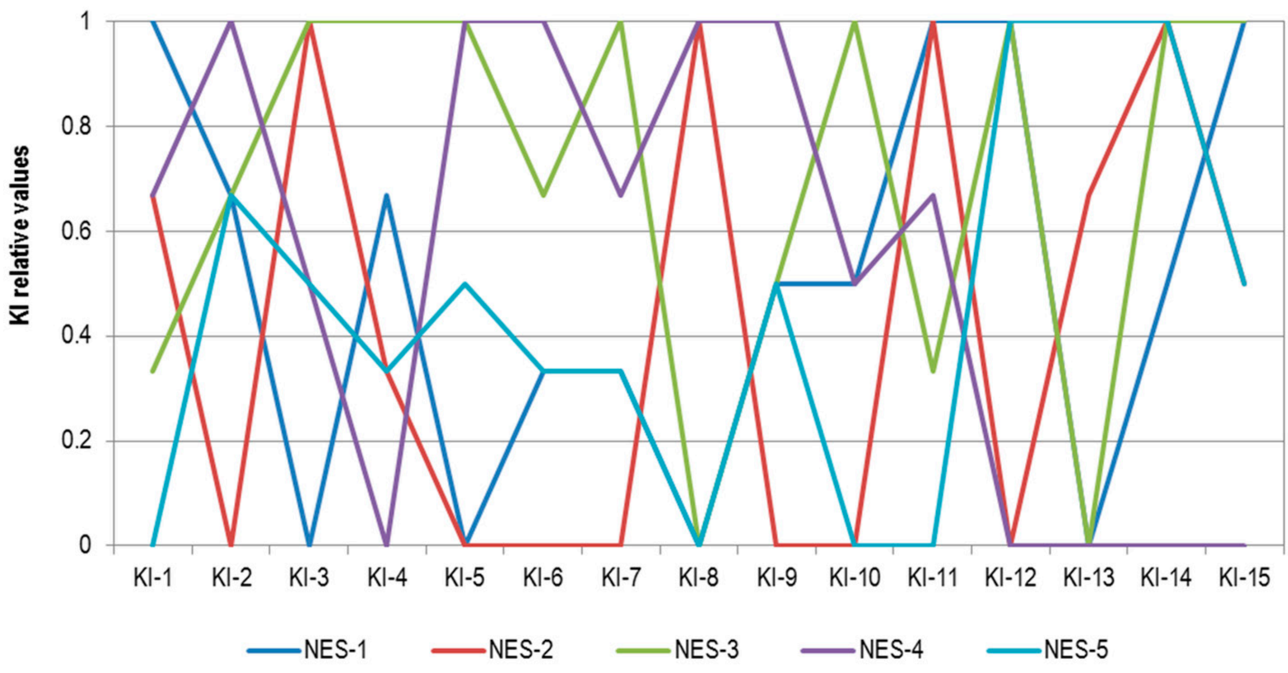


FIG. 5.2. Value path.

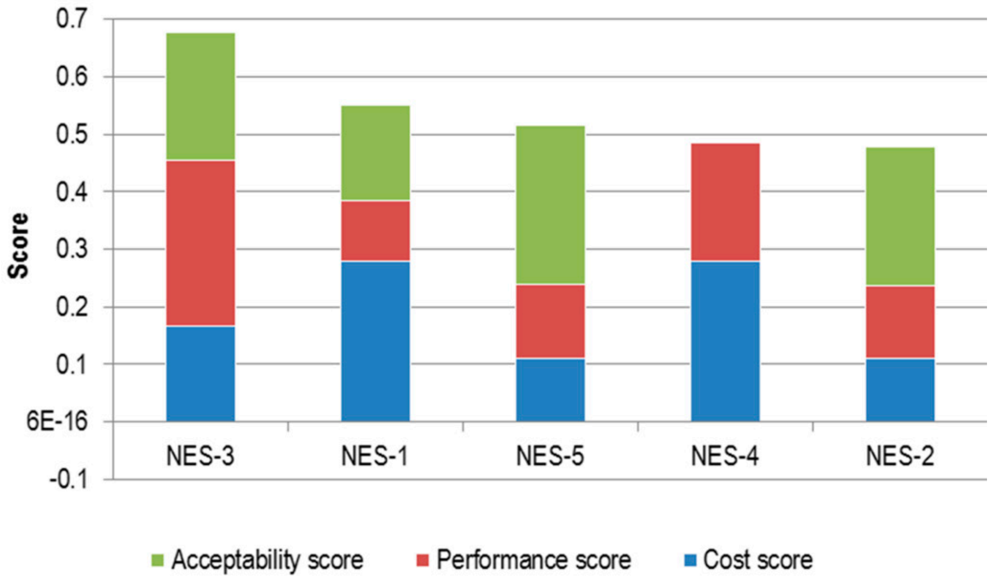


FIG. 5.3. Ranking results.

TABLE 5.2. HIGH LEVEL AGGREGATED OBJECTIVE SCORES

	Cost score	Performance score	Acceptability score	Overall score
NES-1	0.278	0.106	0.167	0.55
NES-2	0.111	0.126	0.241	0.478
NES-3	0.167	0.288	0.222	0.677
NES-4	0.278	0.206	0	0.483
NES-5	0.111	0.127	0.278	0.516

TABLE 5.3. SECOND LEVEL SCORES

	Economics	Waste management	Proliferation resistance	Environment	Country specifics	Maturity of technology
NES-1	0.278	0	0.028	0.028	0.05	0.167
NES-2	0.111	0.083	9.259×10^{-3}	0	0.033	0.241
NES-3	0.167	0.083	0.074	0.083	0.047	0.222
NES-4	0.278	0.042	0.056	0.056	0.053	0
NES-5	0.111	0.042	0.032	0.028	0.025	0.278

In this case, if the decision maker and experts want a more detailed explanation of the reasons that led to the dominance of one alternative over another, the multi-attribute value function needs to be decomposed into components that correspond to each evaluation area. Table 5.3 shows the scores for alternatives for each of the evaluation areas. In particular, it is clear from these figures that NES-3, in almost all areas within the category of performance, surpasses all of its competitors, which ultimately leads to the conclusion that this alternative is the best one.

5.2.2.4. Sensitivity analysis

A sensitivity analysis has been performed for the weighting factors and shapes of the single-attribute value functions. In general, it should be noted that the selected model parameters, in accordance with the recommendations presented in the previous section, have shown the stability and robustness of the ranking results.

(a) Impact of single-attribute value function forms

Sensitivity analysis is a tool for evaluating the impact of assigned single-attribute value functions on the final results (ranks of alternatives). To demonstrate the sensitivity of the ranking results to the forms of the single-attribute value functions, a special statistical analysis was carried out by using randomly generated single-attribute value functions and building a statistical rank distribution for each alternative considered. The most likely ranks for each alternative and their statistical distributions are shown in Fig. 5.4. The analysis has shown that the most likely ranks of alternatives coincide with the ranks obtained using linear single-attribute value functions. The analysis confirms the reduced sensitivity of the ranking results to the form of the single-attribute value functions, which was possible through the selection of appropriate assumptions regarding the model parameters.

(b) Weight sensitivity

A weight sensitivity analysis provides an understanding of the influence of the assigned weights on the ranking of the alternatives. In the framework of the linear weight approach to the weight sensitivity analysis, experts have to select an indicator for the sensitivity analysis and analyse how the ranking alternatives will change with the weighting factor varying from 0 to 1 (other weights are automatically changed proportionally, keeping the weight sum equal to unity). Such analysis can be carried out for the weighting factors at each level of the objectives tree: the high level aggregated objectives, the evaluation area level and the individual indicator level. In the present study, this approach was applied for the high level of the objectives tree for illustration.

Figure 5.5 shows the overall scores (multi-attribute value functions) for each alternative as a function of the corresponding weighting factor value and the base case value for this weighting factor. Based on this information, the ranks of alternatives may be identified for different weighting factor values, while the weighting factor areas may also be obtained, providing the same ranking result. Based on this analysis, it may be concluded that the ranking results are not very sensitive to the weighting factor values and may be considered as stable, because they satisfy the following sensitivity test: a 10 per cent change in all weighting factors does not affect the ranks of the alternatives.

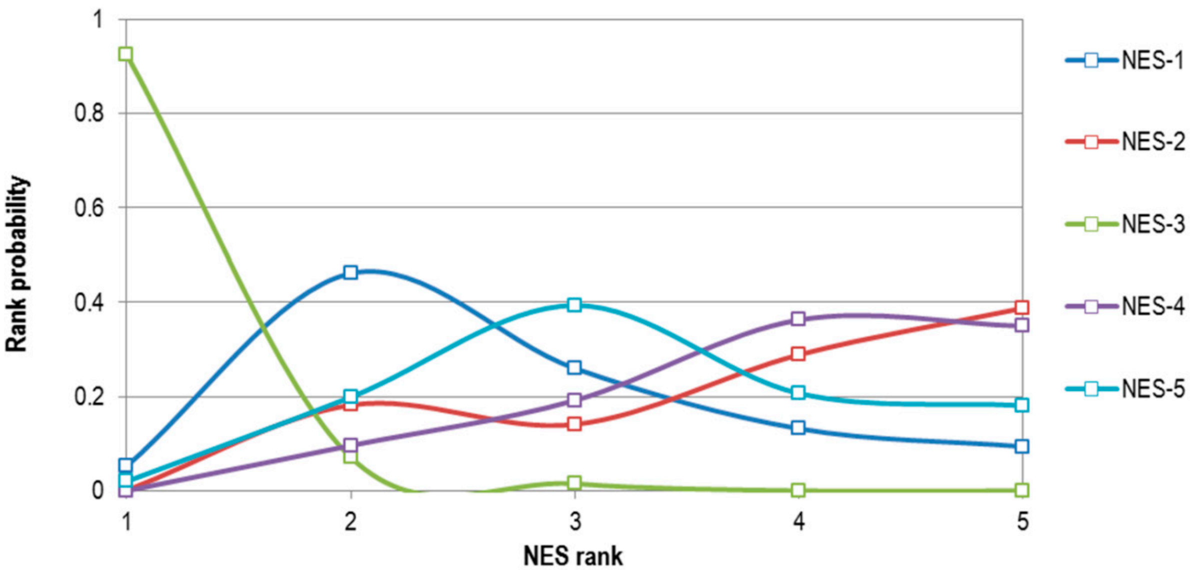


FIG. 5.4. Rank distributions.

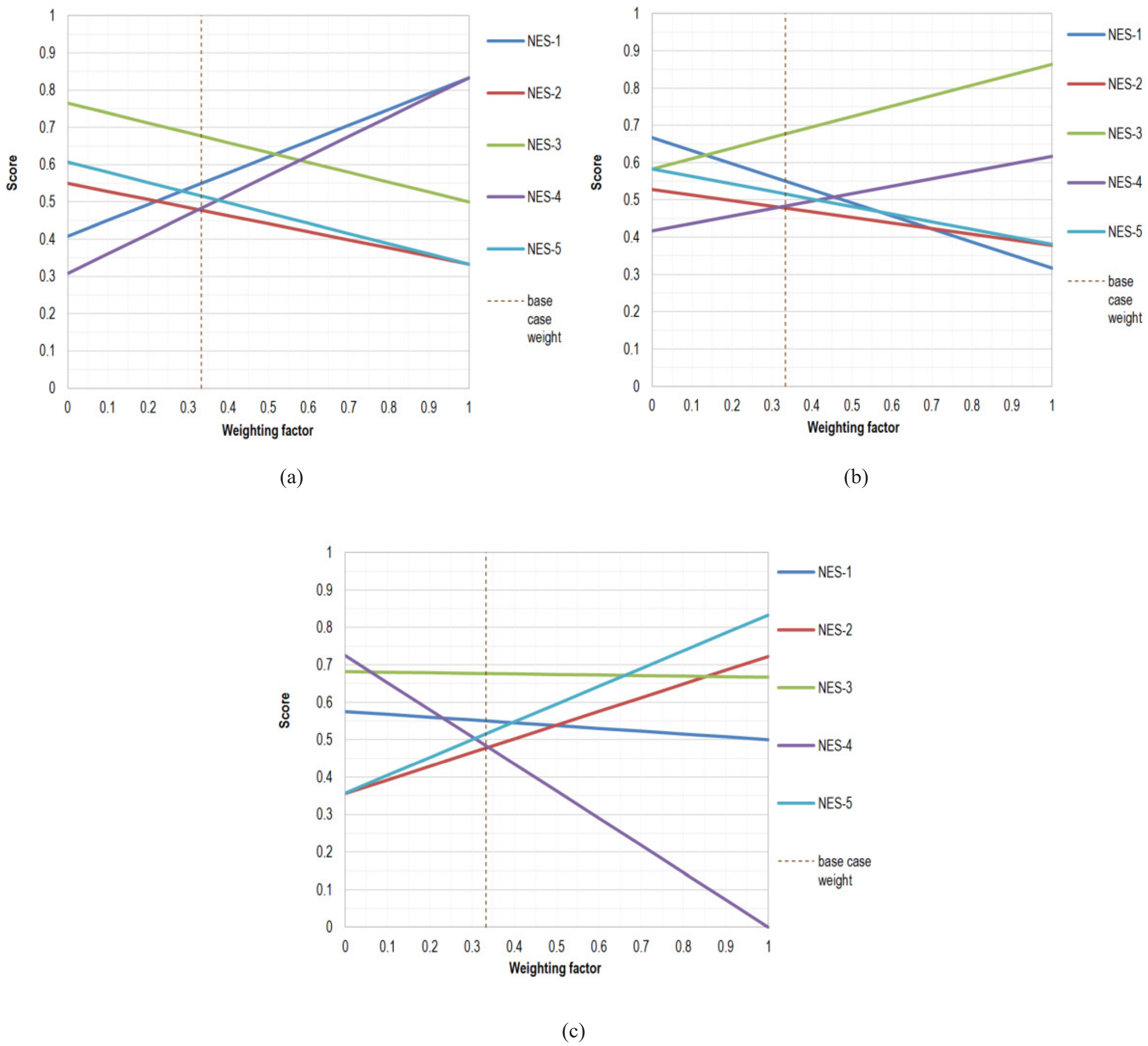


FIG. 5.5. Linear weights approach to weight sensitivity analysis. (a) Cost weighting factor; (b) performance weighting factor; (c) acceptability weighting factor.

(c) Differentiation of undistinguished alternatives

This section illustrates the second stage in the implementation of the two tier comparative evaluation procedure, when alternatives that are indistinguishable using a set of KIs are differentiated using a set of SIs. It was shown above that NES-2 and NES-4 are indistinguishable alternatives. In this situation, further differentiation seems necessary and can be performed by using a set of SIs. A comparison of these two options was performed in accordance with the recommendations made in the previous section: the 15 SIs were involved in the procedure, with each indicator being evaluated on a 10 point scoring scale, and linearly decreasing functions defined on local domains were chosen as single-attribute value functions. A broader scoring scale was used to compare the two alternatives because it provides a subtler differentiation of the alternatives, reducing the likelihood of obtaining similar values for indicators, which would lead to the elimination of corresponding information from the evaluation. Table 5.4 corresponds to the performance table for this problem.

The ranking results based on the above mentioned assumptions are presented in Table 5.5. Alternative NES-2 is the most attractive one, while alternative NES-4 is less attractive. The scores of the multi-attribute value functions are 0.522 (NES-2) and 0.367 (NES-4), which allows one to consider these alternatives as distinguishable ones. As

TABLE 5.4. PERFORMANCE TABLE

High level objectives	Evaluation areas	SIs	Weights	NES performance	
				NES-2	NES-4
Cost	Economics	SI-1	0.167	3	9
		SI-2	0.167	6	1
Performance	Waste management	SI-3	0.083	6	6
	Proliferation resistance	SI-4	0.028	9	7
		SI-5	0.028	9	2
		SI-6	0.028	4	4
	Environment	SI-7	0.083	2	9
	Country specifics	SI-8	0.017	6	3
		SI-9	0.017	1	8
		SI-10	0.017	3	6
		SI-11	0.017	2	8
		SI-12	0.017	6	5
Acceptability	Maturity of technology	SI-13	0.111	7	5
		SI-14	0.111	6	7
		SI-15	0.111	6	7

shown in Table 5.5, the scores on the aggregated high level objective cost are identical for both systems. At the same time, the scores for NES-2 on the aggregated high level objectives performance and acceptability are superior to the corresponding scores for NES-4. This indicates that the former alternative is the most attractive option.

A comparison of the aggregated scores shown in Table 5.6 for all evaluation areas provides an opportunity to understand the contribution of these areas to the values for the high level objectives. Since the high level objectives cost and acceptability only include one evaluation area (‘economics’ and ‘maturity of technology’, respectively), the corresponding values of the aggregated scores for the high level objectives and evaluation area levels of the objectives tree are the same. Regarding the corresponding areas’ contribution to the high level objective performance, it should be noted that the first alternative is a less attractive option in terms of ‘proliferation resistance’, while this alternative prevails over its competitor in terms of ‘environment’ and ‘country specifics’. For the ‘waste management’ area, the scores are equal to zero for both alternatives because they have the same scores for all of the indicators included in this evaluation area.

A sensitivity analysis for the case of the two compared alternatives usually demonstrates the stability of the ranking results over a wide range of possible model parameters. The sensitivity analysis performed for the example considered confirms this thesis. In the case where two alternatives with domains for single-attribute value functions specified from the performance table are compared, the ranking results are not sensitive to the form of the single-attribute value functions.

The results for the application of the linear weights approach for high level objective weights are shown in Fig. 5.6. For all possible values of the weighting factors, the first alternative looks more attractive than the second one. Thus, it may be concluded that the ranking results are stable and robust to possible changes in weighting factor values.

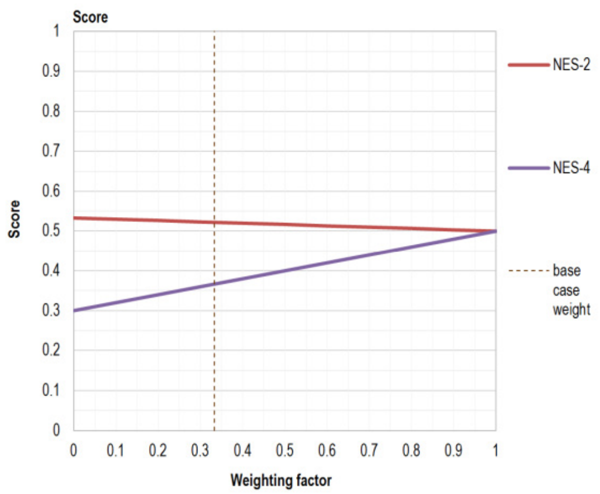
The performed study showed that in cases where the MAVT method is correctly used (i.e. taking into account major requirements for the NES comparative evaluation procedure), it will provide an identification of the merits and demerits of the nuclear technological options being compared and their performance rankings based on the judgements and preferences of experts and decision makers. These case studies have also demonstrated the basic

TABLE 5.5. HIGH LEVEL AGGREGATED OBJECTIVE SCORES

	Cost score	Performance score	Acceptability score	Overall score
NES-2	0.167	0.133	0.222	0.522
NES-4	0.167	0.089	0.111	0.367

TABLE 5.6. SECOND LEVEL SCORES

	Economics	Waste management	Proliferation resistance	Environment	Country specifics	Maturity of technology
NES-2	0.167	0	0	0.083	0.05	0.222
NES-4	0.167	0	0.056	0	0.033	0.111



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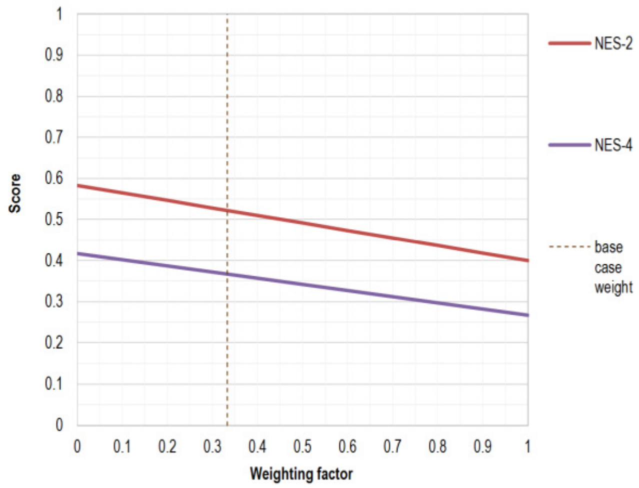

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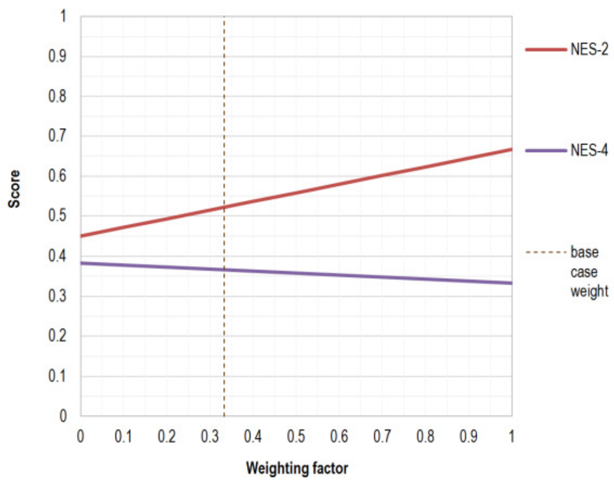


(c)

FIG. 5.6. Linear weights approach to weight sensitivity analysis. (a) Cost weighting factor; (b) performance weighting factor; (c) acceptability weighting factor.

steps to be completed within the NES comparative evaluation procedure in the framework of the KIND project, which may be considered as a possible template for the representation and interpretation of calculation results that may be implemented in the comparison of real systems.

5.2.3. Comparison of two hypothetical NESs

The comparison of two NESs is extremely important; it can find wide application for solving practical problems, because the number of competing options offered by the decision maker for the final selection usually does not exceed two. At the same time, consideration of this case is characterized by significant risks regarding the indistinguishability of alternatives as well as the relatively low sensitivity of the ranking results to the model parameters.

The particulars of this case are that a comparison of two NESs using single-attribute value functions with local domains specified by means of the performance table will not depend on the forms of the single-attribute value functions. In this case, the values of an alternative multi-attribute value function may be evaluated by the following simple equation:

$$\text{NES score} = \sum_{i=1}^{N_{KI}} w_i \cdot \delta_i, \text{ where } w_i - i \text{ weighting factor, } \delta_i = \begin{cases} 1 \text{ if the NES is better then competitor on } i \text{ KI} \\ 0 \text{ if the NES is worse then competitor on } i \text{ KI} \end{cases} \quad (5.1)$$

This formula implies that in order to estimate the overall scores of alternatives (values of multi-attribute value functions), it is simply required to sum up the weighting factors for those indicators that, for a certain alternative, have scores superior to those of their competitors. This sum is the final value of a multi-attribute value function for the corresponding alternative.

Another specific feature of this case is that it is reasonable to use wider scoring scales for indicator evaluations because this provides a chance for more substantial differentiation of alternatives than it is possible to reach by using a narrow scale. This hypothetical case study is focused on the evaluation of the impact of the different scoring scales used for indicator evaluations and the single-attribute value function domains on the overall scores of the alternatives and the ranking results.

5.2.3.1. Description of considered NESs and assumptions

A comparative evaluation of two hypothetical NESs was performed in accordance with the recommendations given in the previous sections. A set of 19 unspecified KIs was involved in the comparative evaluation procedure. Each indicator was evaluated on 2 and 10 point scoring scales. It was assumed that the two point scoring scale is the base option.

Linearly increasing functions defined on the local and global domains were chosen as single-attribute value functions for the base case option. A sensitivity analysis regarding the form of the single-attribute value function was carried out using exponential forms of single-attribute value functions.

5.2.3.2. Performance table

The values of all KIs for the considered NESs are presented in Table 5.7 (qualitative evaluation, and on 2 and 10 point scoring scales). In accordance with the assumptions made regarding the goals that are to be achieved by each indicator, a score value of 1 is the best possible indicator value, while a score value of 0 is the worst one, if a two point scoring scale is used. Accordingly, for a 10 point scoring scale, a score value of 10 is the best possible indicator value, while a score value of 1 is the worst one.

The performance table is also presented in the form of a value path for the case of the utilization of a two point scoring scale (Fig. 5.7). This figure shows variations in the values of KIs for the considered NESs demonstrating the merits and demerits of the options considered. It should be noted that this graph depends on the scoring scale selected for evaluation of the indicators, and in the case of a 10 point scoring scale, it will have a different representation for some indicators.

In devising Table 5.7, it was assumed that if the evaluation of a certain indicator for two alternatives in the relevant scale is the same, this indicator will be assigned a value of 0. According to the assumptions made about the form of the single-attribute value functions, this will not lead to a contribution of the corresponding indicators to the values of the multi-attribute value functions for the considered alternatives. Note that a 10 point scoring scale provides more subtle opportunities for evaluating the alternatives. For example, on a two point scoring scale, alternatives may have the same evaluation, while on a broader scale they may be awarded various scores.

5.2.3.3. Weighting factors

In order to evaluate the weights, it is assumed that at each level of the objectives tree, the importance of all high level objectives, the areas of evaluation and the KIs are identical. This option suggests that the experts and the decision maker need to agree that high level objectives characterized by the cost, performance and acceptability of the aggregated goals are equally important. Since evaluation of the weights is to be done based on consideration of the ranges over which the indicators may vary, it may be possible to achieve this goal of equal weights by adjusting the ranges over which the single-attribute value functions are defined. Expanding a range will typically increase the corresponding weight of an indicator, and vice versa.

TABLE 5.7. PERFORMANCE TABLE

High level objectives	Areas	KIs abbr.	Qualitative evaluation		Two point scoring scale		10 point scoring scale	
			NES-1	NES-2	NES-1	NES-2	NES-1	NES-2
Cost	Economics	E.1	x[a]		1	0	9	1
		E.2	~[b]	~	0	0	4	2
Performance	Waste management	WM.1		x	0	1	2	9
		WM.2		x	0	1	1	10
		WM.3		x	0	1	2	10
	Proliferation resistance	PR.1	x		1	0	10	2
		PR.2		x	0	1	1	10
		PR.3	~	~	0	0	2	3
		PR.4	~	~	0	0	4	3
	Environment	ENV.1		x	0	1	1	9
	Country specifics	S.1	~	~	0	0	3	1
		S.2	~	~	0	0	2	2
		S.3	x		1	0	10	1
		S.4		x	0	1	1	10
		S.5		x	0	1	2	9
Acceptability	Maturity of technology	M.1	~	~	0	0	4	1
		M.2	~	~	0	0	1	1
		M.3	~	~	0	0	2	3
		M.4	x		1	0	9	2

[a] x indicates that the NES provides the best performance for a corresponding KI.

[b] ~ indicates a KI for which both NESs show comparable performance, and which may be differentiated by using different scoring scales.

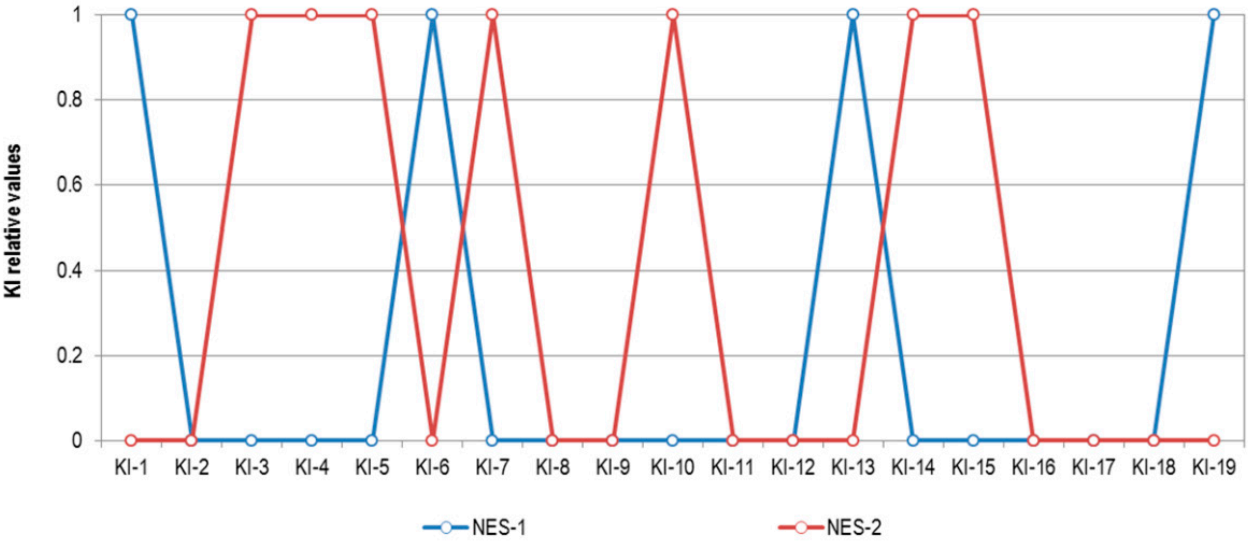


FIG. 5.7. Value path.

At the evaluation area level, in accordance with the high level objectives (cost (economics), performance (waste management, proliferation resistance, environment, country specifics), and acceptability (maturity of technology)), equal weighting factors were assigned to each evaluation area. These factors were determined based on the requirement that the sum of all the weighting factors for each area be equal to unity. As the table shows, the sum of weighting factors in one branch of the objectives tree is equal to unity.

At the final level (the level of the KIs), the weighting factors for each indicator included in the corresponding evaluation area were assumed to be equal as well. The weighting factors calculated in accordance with the above mentioned assumptions for each indicator are shown in Table 5.8. The table illustrates the procedure for hierarchical weighting. It can be seen that the final weighting factors obtained satisfy the condition that their sum be equal to unity. These values were used for a comparative evaluation in both the 2 and 10 point scoring scales.

5.2.3.4. Ranking results and their interpretation

The ranking results based on the above mentioned assumptions are presented in Fig. 5.8 for a two point scoring scale. The results from utilizing a 10 point scoring scale are discussed in the sensitivity analysis section. The alternative NES-1 is the preferred one, while alternative NES-2 is less attractive. The values of the multi-attribute value functions are 0.288 (NES-1) and 0.221 (NES-2); therefore, these alternatives can be considered with a certain degree of confidence as being distinguishable.

The results for decomposition of the analysis into individual components in accordance with the objectives tree structure are shown in Table 5.9, which makes it possible to interpret the ranking results. As shown in Table 5.9, the score for the aggregated high level objective performance is greater for the NES-2 than for the NES-1, but the scores for the aggregated high level objectives cost and acceptability are higher for the first alternative than for the second alternative. These advantages ensure that the first alternative is the preferred one.

A comparison of aggregated scores for all the evaluation areas provides an opportunity to examine the contribution of these areas to the values for the high level objectives. The corresponding evaluations are shown in Table 5.10 and Fig. 5.9.

The high level objectives cost and acceptability only include one evaluation area (economics and maturity of technology, respectively), while the corresponding values of the aggregated scores for the high and intermediate levels of the objectives tree are the same. In terms of the economics and maturity of technology areas, NES-1 is preferable to NES-2.

Regarding the corresponding area contribution to the high level objective performance, it should be noted that the first alternative is a less attractive option in terms of waste management, environment and country specifics, while these alternatives are identical in terms of proliferation resistance.

TABLE 5.8. WEIGHTING FACTORS

High level objectives	High level objective weights	Areas	Area weights	Indicators	Indicator weights	Final weighting factors
Cost	0.333	Economics	1	E.1	0.5	0.167
				E.2	0.5	0.167
Performance	0.333	Waste management	0.25	WM.1	0.333	0.028
				WM.2	0.333	0.028
				WM.3	0.333	0.028
		Proliferation resistance	0.25	PR.1	0.25	0.021
				PR.2	0.25	0.021
				PR.3	0.25	0.021
				PR.4	0.25	0.021
		Environment	0.25	ENV.1	1	0.083
		Country specifics	0.25	S.1	0.2	0.017
				S.2	0.2	0.017
				S.3	0.2	0.017
				S.4	0.2	0.017
				S.5	0.2	0.017
Acceptability	0.333	Maturity of technology	1	M.1	0.25	0.083
				M.2	0.25	0.083
				M.3	0.25	0.083
				M.4	0.25	0.083

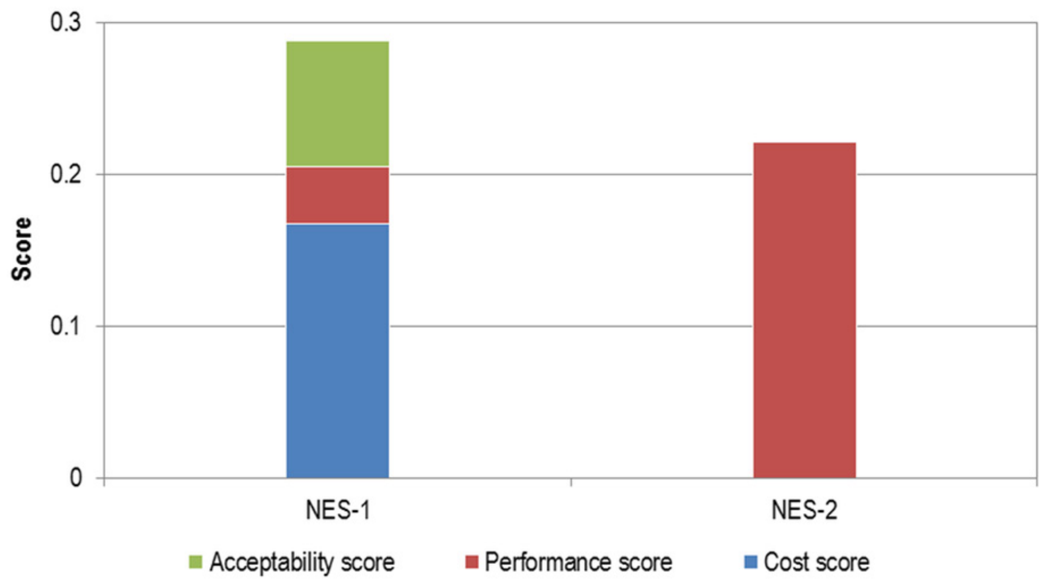


FIG. 5.8. Ranking results.

TABLE 5.9. HIGH LEVEL AGGREGATED OBJECTIVE SCORES

	Cost score	Performance score	Acceptability score	Overall score
NES-1	0.167	0.038	0.083	0.288
NES-2	0	0.221	0	0.221

TABLE 5.10. SECOND LEVEL SCORES

	Economics	Waste management	Proliferation resistance	Environment	Country specifics	Maturity of technology
NES-1	0.167	0	0.021	0	0.017	0.083
NES-2	0	0.083	0.021	0.083	0.033	0

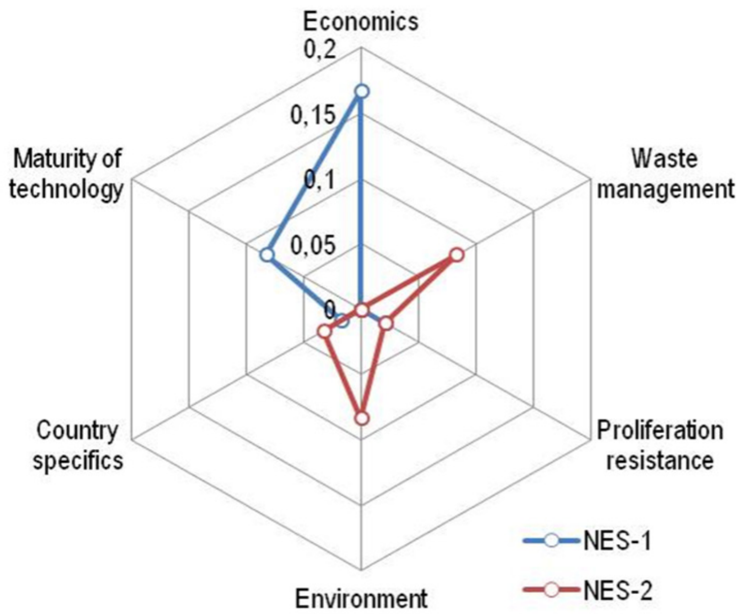


FIG. 5.9. Evaluation area scores.

TABLE 5.11. OVERALL SCORES FOR SCORING SCALES AND DOMAINS

	Two point scoring scale		10 point scoring scale	
	Local domain	Global domain	Local domain	Global domain
NES-1	0.288	0.288	0.575	0.375
NES-2	0.221	0.221	0.325	0.266

5.2.3.5. Sensitivity analysis

(a) Impact of single-attribute value function forms

The overall scores for different assumptions regarding the scoring scales and domains are given in Table 5.11. For a two point scoring scale, both the global and local domains provide the same ranks for the alternatives.

Utilization of a 10 point scoring scale provides more significant differences between the overall scores because this scale offers more precise indicator evaluation (for the local domain, these differences are 0.250 for a 10 point scoring scale and 0.067 for a 2 point scoring scale). When comparing two alternatives with a local domain of single-attribute value functions, the ranking results are not sensitive to the form of the single-attribute value functions: both alternatives have the same ranks for any form of single-attribute value function with a local domain. The same is true for global domains of single-attribute value functions within a two point scoring scale.

If global domains have been chosen for all single-attribute value functions and if a 10 point scoring scale is used, the probability that the first alternative will have the first and second ranks will be equal to 93% and 7%, respectively. This also leads to a decrease in the difference between the values of the multi-attribute value functions: the overall scores for the NESs are equal to 0.375 and 0.266 for the first and second alternatives, respectively. Obviously, this situation makes the alternatives less distinguishable. This example demonstrates how the distinguishability of the alternatives is improved as a result of the utilization of local domains for single-attribute value functions and a wider scoring scale for indicator evaluations.

(b) Weight sensitivity

The results of the sensitivity analysis carried out based on the linear weights method are presented in Fig. 5.10. These results correspond to the weighting factors for the high level objectives of the objectives tree for a two point scoring scale. The values of the weighting factors, at which the lines corresponding to different alternatives are crossed, divide the range of the weighting factors into areas where the alternatives being considered have different ranks. NES-1 looks more attractive than NES-2 owing to the lower values (less than 0.4) of the weighting factors for the performance objective. Such an analysis can be performed for both the intermediate level of the objectives tree (evaluation area level) and the KI level.

The analysis of the impact of the indicators' weighting factor values on the ranking results makes it possible to identify indicators that could ultimately provide a change in the ranks of the alternatives. These are the indicators numbered 3, 4, 5, 7, 10, 14 and 15. However, in order to realize this rank reversal, it is necessary to increase the weighting factor values for the corresponding indicators at least twice.

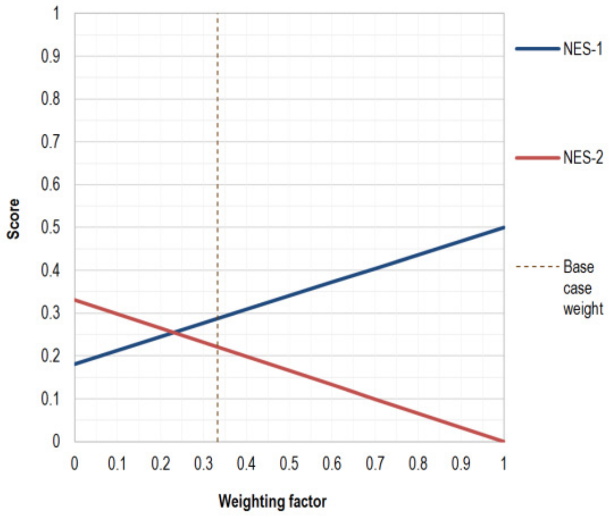
In conclusion, the results of an expanded sensitivity analysis regarding the weighting factors for the high level objectives are presented. The analysis implied simultaneous variation of weighting factors for the high level objectives over a wide range and identification of the most preferred NES for corresponding weight combinations. The NES attractiveness for different weight combinations is shown in Fig. 5.11. Based on this information, the preference probabilities for NES-1 and NES-2 (the relative square of corresponding areas) may be evaluated, and these are 63% and 37%, respectively.

The case studies presented, describing the comparison of five or two hypothetical NESs, have demonstrated the basic steps to be completed for a multi-criteria comparative evaluation of NESs based on the MAVT method within the framework of the KIND approach and represent a possible template for presenting and interpreting calculation results that may be implemented in the comparison of real systems.

5.3. INNOVATIVE VERSUS INNOVATIVE NUCLEAR ENERGY SYSTEMS

5.3.1. Russian case studies

Two Russian case studies were performed under the KIND project, Russian Case Study on the Innovative versus Innovative Nuclear Energy Systems and Application of the KIND Approach for Comparison of Innovative NESs Based on Closed NFC. These trial applications of the KIND approach and the KIND-ET tool (an evaluation toolkit based on MAVT) show how to evaluate and formulate the existing features of alternatives being compared. Further, the approach and the tool make it possible to compare the selected NESs even if they are not unified and not matured. The case studies have different KIs and compared alternatives, but provide very similar conclusions regarding the further application and improvement of the KIND approach.



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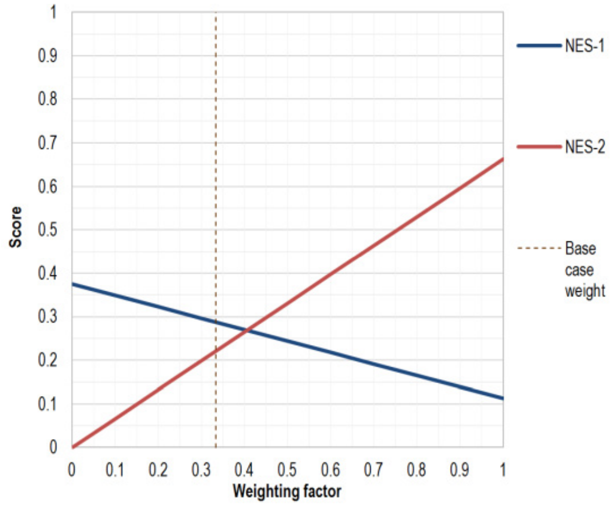

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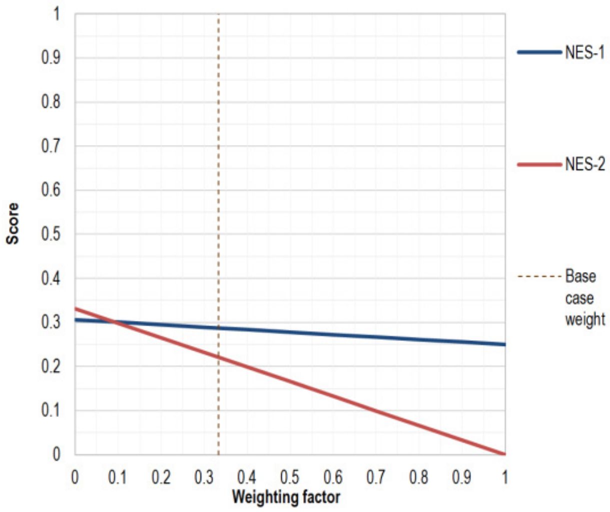

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FIG. 5.10. Linear weights approach to weight sensitivity analysis. (a) Cost weighting factor; (b) performance weighting factor; (c) acceptability weighting factor.

5.3.1.1. Russian Case Study on the Innovative versus Innovative Nuclear Energy Systems

(a) Introduction

The potential of a fast reactor (FR) with a closed fuel cycle for breeding was realized from the very inception of nuclear energy. However, to date, FR technology has not matured sufficiently to be economically competitive with thermal reactors (TRs). In some countries, the main motivation for the FR fuel cycle is recycling plutonium in combination with ^{238}U for the breeding of additional plutonium fuel. In other countries, advanced partitioning techniques are being developed for the separation of plutonium and minor actinides (MAs) (neptunium, curium, americium) so that they can be burned in FRs in order to reduce the long term radiotoxicity of SNF. The Russian Federation has also identified the importance of sodium cooled fast reactors (SFRs) and related fuel cycles for multiple recycling of plutonium.

The Russian Federation (previously as part of the former Soviet Union) is very experienced (~50 years) in the area of SFRs, including R&D and successful operation.

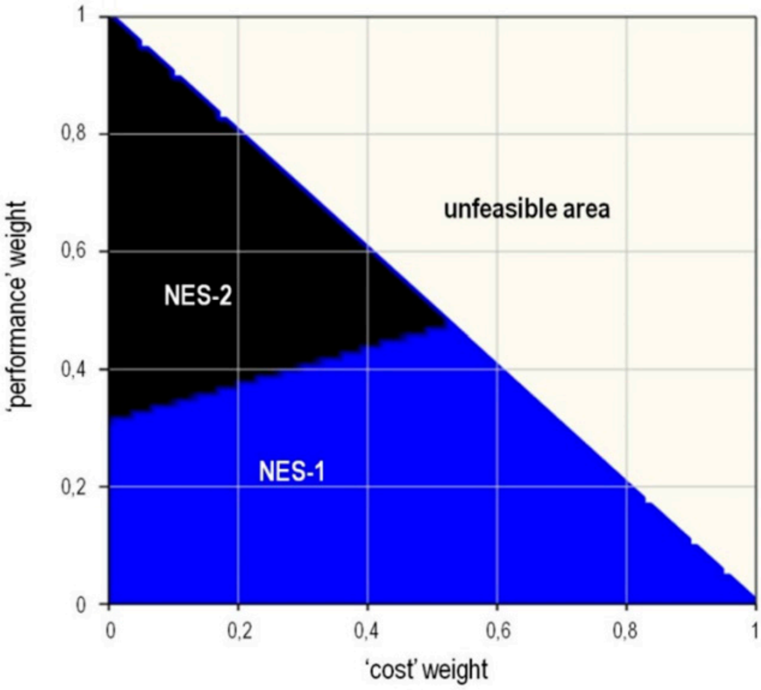


FIG. 5.11. Attractiveness of NESs for different weights.

The KIND approach and the KIND-ET tool for the comparative evaluation of NESs aimed to help the leaders of industry, decision makers and experts conducting research to support decision making in selecting the direction of technological NES development.

(b) Objective and problem formulation

The present case study is of a methodological nature and does not show any possible direction of the country's nuclear energy development. However, it reflects the country's experience in the field of FR technology extension.

The main objective of this case study is to test the KIND approach and the KIND-ET tool for the comparative evaluation of NESs. Each NES may include innovative FR technologies in addition to evolutionary FR technologies. The comparative evaluation of NESs assigns weight coefficients to performance features. To achieve the objective, the following tasks were set:

(i) Develop a limited number of KIs for FRs and TRs, encompassing the peculiarities of the corresponding NESs;
(ii) Carry out calculations and make evaluations of relevant KIs according to the KIND approach;
(iii) Use the KIND-ET Excel tool and KI batch and prepare a preliminary comparative evaluation of the NESs;
(iv) Realize a weight sensitivity study for selected KIs.

(c) Formulation of alternatives (NES options)

Each reactor technology may establish a relevant NES, as shown in Table 5.12. In such circumstances, the LUEC of the NES will coincide exactly with the LUEC of the technology. Therefore, if the initial alternatives are one component systems based on technologies, then the electricity cost for the system will match the electricity cost of the technology, as shown in Fig. 5.12. The study suggests a market price of US $45/MW(e)·h for simplicity.

Figure 5.12 shows that the NES based on FR1 (Sys(FR1)) is not economically attractive in the market. The electricity generation cost is beyond the bounds of the market price. Therefore, the system Sys(FR1) will not be considered in the current study because it does not fit into an economically profitable investment process. The estimated electricity costs generated for the four other systems are very close to each other. In addition, the

TABLE 5.12. TECHNICAL AND ECONOMIC DATA FOR REACTORS AND ASSOCIATED NFCs

Item	Units	TR based NESs			FR based NESs	
		TR1	TR2	TR3	FR1	FR2
Capacity	MW(e)	1000	1000	1000	800	1200
Nat. U consumption	t/year	178	178	178	0	0
LUEC	US $/MW(e) h	39[a]	42[b]	41[c]	50	42[d]
Radioactive waste generation	t HM/year	23	23	23	1	1

Note: FR — fast reactor, HM — heavy metal, LUEC — levelized unit electricity cost, nat. U — natural uranium, TR — thermal reactor.

[a] With a natural uranium cost of US $100/kg U and a disposal cost of US $850/kg HM.

[b] With a natural uranium cost of US $100/kg U and a disposal cost of US $1580/kg HM.

[c] Disposal cost of US $850/kg HM and escalation of uranium base price of US $100/kg at 2%/year.

[d] Construction time of 5 years for each unit and serial units.

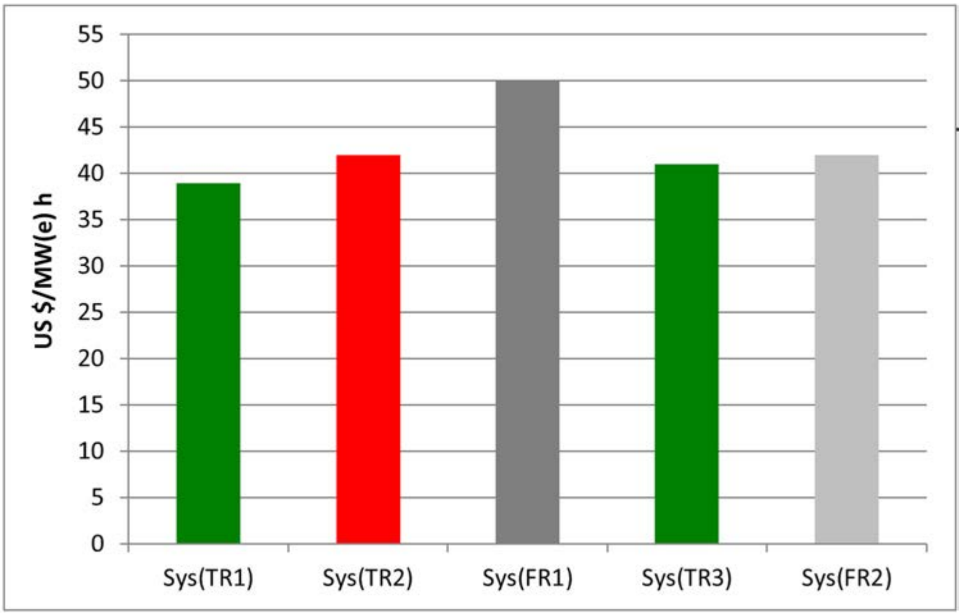


FIG. 5.12. Interim formulation of alternatives (energy systems) based on the ratio of costs and the market price.

NES based on FR2 (Sys(FR2)) is an innovative system that has not yet been implemented on an industrial scale and requires time and significant investment in R&D (see Table 5.13). Moreover, one cannot exclude the risks associated with the R&D costs and maturity period.

Apart from the initial one component systems, FRs and TRs could form a joint closed NFC (two component) based NES. Such a system would be economically attractive, since the 'dilution' cost of electricity from FRs makes it cheaper than the electricity from TRs, as shown in Table 5.13. It will receive the benefits of a closed NFC in terms of natural uranium savings and reduction of spent fuel and radioactive waste.

The current methodological study considers four alternatives for 20 GW(e) electrical system capacity and three alternatives for 100 GW(e) electrical capacity (see Fig. 5.13). The study does not consider the dynamic case of nuclear energy development. Each system corresponds to a theoretical country with certain fixed level of nuclear energy demand. As already mentioned, the study includes an additional parameter for the total capacity of the NESs, with values of 20 GW(e) and 100 GW(e) selected for evaluation.

A country with 20 GW(e) capacity has the following four alternatives and represents a country with low electrical capacity:

(i) Once through NFC based on TR1 TRs (OFC1 (TR1));
(ii) Once through NFC based on TR2 TRs (OFC2 (TR2));
(iii) Joint closed NFC based on 50% TR1 TRs and 50% FR1 FRs (joint CNFC1 (FR1, TR1));
(iv) Joint closed NFC based on 50% TR3 TRs and 50% FR2 FRs (joint CNFC2 (FR2, TR3)).

A country with 100 GW(e) capacity has three alternatives and represents a country with high electrical capacity:

(a) Once through NFC based on TR3 TRs (OFC3 (TR3));
(b) Joint closed NFC based on 50% TR3 TRs and 50% FR2 FRs (joint CNFC2 (FR2, TR3));
(c) Closed NFC based on FR2 FRs (CNFC3 (FR2)).

The CNFC3 (FR2) alternative has an additional feature in that it relies solely on FRs without any TRs. This system does not contain plutonium at the moment of deployment. Therefore, CNFC3 (FR2) requires natural uranium for startup and part of the FR2 fleet works on enriched uranium. The characteristics of the KIs for the above mentioned alternatives are presented in Table 5.13.

TABLE 5.13. PERFORMANCE TABLE

System KI \ System		20 GW(e)				100 GW(e)		
		OFC1 (TR1)	OFC2 (TR2)	Joint CNFC1 (FR1, TR1)	Joint CNFC2 (FR2, TR3)	OFC3 (TR3)	Joint CNFC2 (FR2, TR3)	CNFC3 (FR2)
1	Nat. U (GW(e)·h/t)	43	43	86	88	43	88	210
2	LUEC (US $/MW(e)·h)	39	42	44.5	41.5	41	41.5	42
3	Wastes (t/TW(e)·h)	3.0	3.0	0.1	0.1	3.0	0.1	0.1
4	TtMature (years)	0	0	8	18	0	18	18
5	R&D refund (billion US $)	0	0	12	17	0	17	17

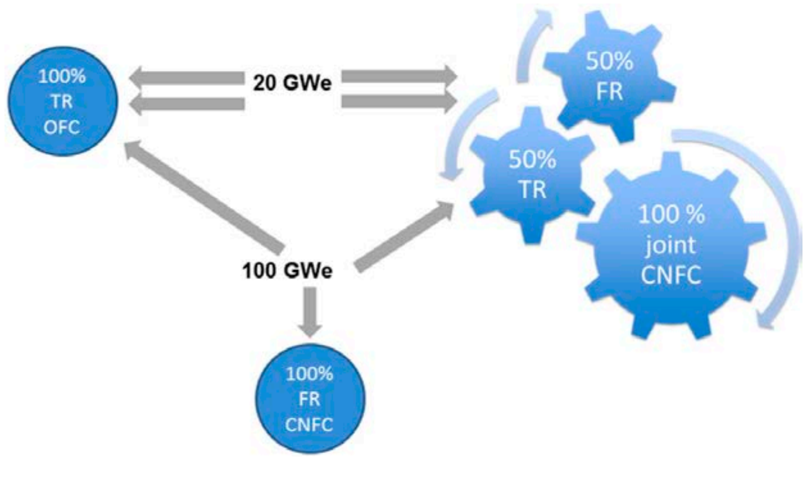


FIG. 5.13. Formulation of alternatives (energy systems).

(d) Identification of indicators

The INPRO methodology has developed over a hundred indicators related to the areas of evaluation for the sustainable development of NESs. Many of these indicators can only be estimated in the presence of detailed data for an NES, which only become available at the final stages of technical projects. Such an approach is not feasible for INESs, because many factors cannot currently be evaluated on the basis of available data. Many indicators related to INESs are characterized by considerable uncertainty and cannot be evaluated based on statistical data, as they involve unique events that have never happened before. The objective of INES evaluation at the early design stages and the large uncertainty of the original data require that an appropriate set of KIs be sought. Therefore, a set of KIs developed by the GAINS project [5.1] was taken as the starting point for the KIND project.

KIs could be defined for selected areas or for all areas of the INPRO methodology, depending on the objective. The main idea is that KIs need to reflect the most essential features of an issue and signpost the technical and infrastructural characteristics of the nuclear energy system. Moreover, the KIs need to be as independent as possible from each other in order to avoid assigning erroneous weighting factors. The minimization of the KI set facilitates the evaluation process, but overlooking KIs that are essential to evaluate the systems needs to be avoided.

The GAINS project identified a set of 10 KIs and several related evaluation parameters [5.1]. These can be used to estimate NES global/regional architectures, develop transition scenarios from current to advanced systems based on innovative technologies and meet the more stringent requirements for the basic features.

The current composition of KIs comes from the INPRO methodology [5.2], the GAINS project and the discussions of the KIND project participants regarding specific KIs for the comparative evaluation of NESs that are in the early stages of development in terms of their innovative elements. The comparative evaluation is restricted to the evaluation areas of economics, waste management, environment and maturity of technology. It is assumed that the facilities at the time of the introduction of the technology would meet the national regulatory requirements of the country.

The study investigates a single level objectives tree and five KIs. A short description of the KIs for the above mentioned areas is as follows:

(i) The amount of useful energy produced by the system from a unit of mined natural uranium/thorium — this KI is taken from GAINS, where it appears as KI-2. Hereinafter, this KI is referred to as ‘Nat. U’, with units of GW(e) h/t.

(ii) LUEC (levelized unit electricity cost) — this represents a cumulative economic KI. In accordance with classical economic theory, it shows the specific value of the final useful product cost (secondary electricity), taking into account the return of interest on capital investments, operation and maintenance, and fuel costs.

Levelized cost of energy product and services is selected as a KI from GAINS, where it is represented as KI-9. Hereinafter, this KI is referred to as ‘LUEC’, with units of US \$/MW(e)·h.

According to the results of the BN-800 (FR, Russian design) reactor deployment, one of the main requirements imposed on the first of a kind BN-1200 (FR, Russian design) project is the reduction of the cost of electricity generated. The main difference required between an existing BN-800 and the BN-1200 project is the demonstration of significant progress in terms of increased safety level and better system economics.

(iii) Radioactive waste inventories per unit energy generated — the cumulative annual quantity of this parameter is selected as a KI from GAINS, where it is presented as KI-5. Hereinafter, this KI is referred to as ‘Wastes’, with units of t/TW(e)·h. The Wastes KI shows the annual generation of HLW produced by the system. It might be one of the main drivers in the transition from TR technology and an open NFC system to a two component NES with FR technology in a closed fuel cycle.

(iv) Time needed to mature the technology — this KI shows the timescale over which the technology will be matured. Hereinafter, this KI is referred to as ‘TtMature’, with units of years. Technology maturity requires a series of deployments and a proven technological scheme. For example, at the moment, the TR technology and the open NFC system are mature.

(v) Research and development (R&D) cost — this indicator is also taken from GAINS, where it is referred to as KI-10. Hereinafter, this KI is referred to as ‘R&D refund’, with units of billion US \$. The development of FRs became a long term goal for many countries. Billions of dollars were spent on R&D

for nuclear energy around the world. The governments of the Organisation for Economic Co-operation and Development (OECD) countries have spent about US $50 billion (2007) on R&D in the area of FRs. The Russian Federation (including the former Soviet Union), which is not an OECD member, has spent an estimated US $12 billion on R&D in the area of FRs [5.3]. Today, these expenditures will be even higher. In the Russian Federation, a high growth rate for nuclear energy is an unlikely scenario in the short term. The R&D refund can most likely be expected with the implementation of an integrated proposal from Rosatom for user countries, including the reprocessing of SNF.

(e) Evaluation of indicators, including uncertainties

There is no focus on specific reactor technologies under the current trial consideration, while the general features of TR and FR units are studied. The characteristics correspond to steady state reactor operation (see Table 5.12).

The following types of reactors were considered in the case study:

(i) TR technologies TR1, TR2 and TR3 have the same technical features regarding natural uranium consumption and spent fuel generation. The main difference between TR1 and TR2 lies in the levelized unit fuel cost in the fuel cycle back end. As shown in Table 5.12, TR1 and TR2 have the same costs, excluding the disposal cost. For TR1, the disposal cost is US $850/kg HM (average value for the disposal), and for TR2, the disposal cost is US $1580/kg HM (top value for the disposal range). Thermal reactor TR3 has a disposal cost of US $850/kg HM, and the escalation rate for the uranium base price of US $100/kg is 2%/year. All of the TRs consume uranium oxide (UOX) fuel, as depicted in Table 5.12.

(ii) Two types of FR technologies are under consideration in the current study. The first FR, FR1, is considered to be a near term deployable reactor. As a new technology, its LUEC is higher than that for the TR, as shown in Table 5.12. The FR FR2 is a concept project with improved design safety and a more attractive LUEC. FR1 consumes MOX fuel; FR2, depending on the system under consideration, consumes MOX or enriched uranium fuel.

The ^{235}U content in natural uranium is 0.007114. It is assumed that the plutonium extracted from the fuel of TRs and FRs will be reused. The input data for the reactors and associated fuel cycles, and the technical characteristics necessary for the case simulation were taken from the databases provided in Ref. [5.4].

The discount rate for the case study is considered to be 5%. The LUEC was calculated using the NESA Economic Support Tool (NEST) [5.5].

In the case of a two component system (CNFC), the LUEC is calculated as the sum of the LUEC values of the FR and the TR multiplied by the corresponding weight, which is proportional to the installed capacity of the particular reactor type in the system.

The TtMature KI was evaluated according to subjective probabilities of the occurrence of the event ‘maturing of technology’, as determined by experts, and the R&D refund indicator was evaluated based on international and domestic publications and expert opinions.

(f) Selection of an MCDA method

The most suitable MCDA method for the Russian case study is MAVT. The transition from the actual specifications for KIs to their values/estimates (the transition from Table 5.13 to Table 5.14) requires specifying an objective for each KI. For example, the first KI, Nat. U, is responsible for the efficient use of natural uranium resources. Therefore, a system that generates more electricity per tonne of uranium, among other considered NES alternatives, would have a rating of 1. Therefore, the target for the indicator Nat. U is to maximize the production of electricity per tonne of natural uranium. On the same principle, the objectives for the remaining KIs were set.

The form of the single-attribute value functions for Table 5.13 is linear and the objective for KI No. 1 (Nat. U) is maximum and for KI Nos 2–5 (LUEC, Wastes, TtMature and R&D refund) it is minimum. Table 5.14 shows the KIs from Table 5.13 in unified form.

TABLE 5.14. SINGLE-ATTRIBUTE VALUE FUNCTION PARAMETERS

System KI \ System		20 GW(e)				100 GW(e)		
		OFC1 (TR1)	OFC2 (TR2)	Joint CNFC1 (FR1, TR1)	Joint CNFC2 (FR2, TR3)	OFC3 (TR3)	Joint CNFC2 (FR2, TR3)	CNFC3 (FR2)
1	Nat. U	0	0	0.96	1	0	0.263	1
2	LUEC	1	0.455	0	0.545	1	0.5	0
3	Wastes	0	0	1	1	0	1	1
4	TtMature	1	1	0.33	0	1	0	0
5	R&D refund	1	1	0.2	0	1	0	0

(g) Determination of weights, including uncertainties

The weights quantitatively reflect the preferences of the experts regarding the importance of a particular KI. Changing weights means changing the strategy, and each vector of numerical weights shows a specific variant of the development of the NES. The determination of weight values as a way of formalizing the preferences of experts has the most fundamental place in the formal application of multi-criteria methods, requiring accuracy in their assignment.

In the case study, the grading of weights is carried out as follows: ‘0’ is the lowest priority and ‘1’ is the highest priority. Table 5.15 shows the following options for weight determination for 20 GW(e) and 100 GW(e) electrical system capacities:[1]

— For 20 GW(e) and option I, the weight of the LUEC KI is 0.25 and the weight of the Wastes KI is 0.3. The relatively low LUEC weight and the high Wastes weight means that there are some acute problems of spent fuel and radioactive waste at the final stage of the fuel cycle, requiring considerable effort and expenditure in a relatively short time. This means that the indicator TtMature also requires a weight of 0.25.
— For 20 GW(e) and option II, the weight of the LUEC KI is 0.5 and the weight of the Wastes KI is 0.2. This option represents the situation where the spent fuel and radioactive waste issue is less acute than in option I, and allows the decision to be postponed.
— For 100 GW(e) and option I, the weight of the LUEC and Wastes KIs is 0.35, while the weight of the Nat. U KI is 0.2, and that of the TtMature and R&D refund KIs is 0.05. This shows the considerable difficulties in natural uranium supply arising from a large electricity system and limited natural uranium resources. The enlargement of the NES to 100 GW(e) creates the conditions for the R&D refund and the development of the technology. Therefore, the TtMature and R&D refund KIs could be assigned a small weight (i.e. 0.05).
— For 100 GW(e) and option II, the weight of the KIs LUEC and Wastes is 0.4. This value is increased in comparison to option I. The weight of the Nat. U KI is 0.2. The increase in the economic importance of the region and the final stage of the NFC is driven by the TtMature and R&D refund KIs, which are assigned a weight of 0.

(h) Ranking alternatives (NES options) with the selected MCDA method and interpretation of results with relevance to objectives at different levels

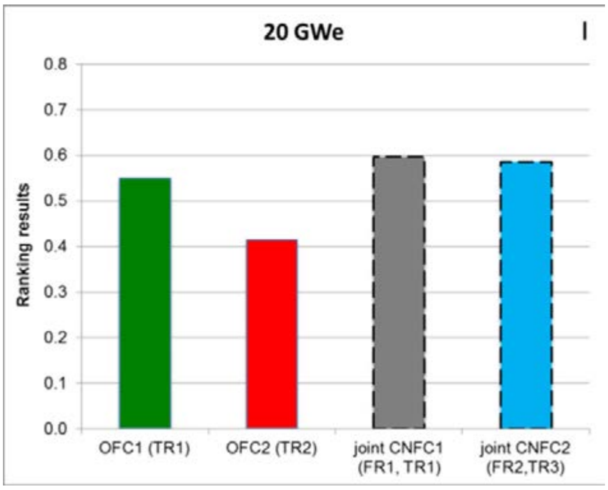
Based on above mentioned modelling conditions, Figs 5.14 and 5.15 show the main results for the compared alternatives. Figs 5.14(a) and (b) provide the results for the 20 GW(e) country case, whereas Figs 5.15(a) and (b) illustrate the results for the 100 GW(e) country case.

Option I shows that the problems at the final stage of the fuel cycle are not resolved and are perceived by society and the Government to be a very serious issue; the Wastes KI has substantial weight. In this case, as shown

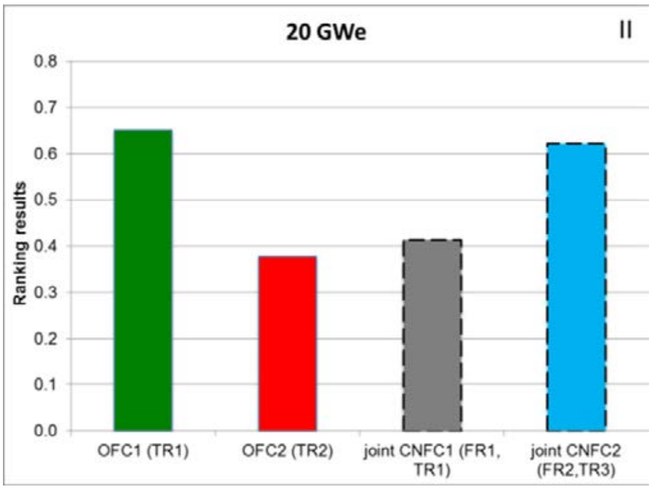
[1] In addition, it is assumed in options I and II that the reactor technology is sufficiently mature and investments in their creation are mostly returned (the R&D refund KI is equal to 0.05).

TABLE 5.15. BASIC WEIGHTING FACTORS

Final weight \ KI		1 Nat. U	2 LUEC	3 Wastes	4 TtMature	5 R&D refund
20 GW(e)	Option I	0.15	0.25	0.3	0.25	0.05
	Option II	0.15	0.5	0.2	0.1	0.05
100 GW(e)	Option I	0.2	0.35	0.35	0.05	0.05
	Option II	0.2	0.4	0.4	0	0



(a)



(b)

FIG. 5.14. NES comparative evaluation results for the 20 GW(e) case. (a) Option I; (b) option II.

by Fig. 5.14(a), the potential of OFC1(TR1) will be lower than that for the joint CNFC1 (FR1, TR1). This result shows that an acceptable solution to the problem can be found in the fuel cycle back end if there is cooperation between the technology holder and the technology user countries. Option II allows the decisions regarding the final stages of the NFC, such as long term interim storage of SNF, to be postponed. An open NFC 1 based on the TR TR1 (OFC1(TR1)) obtains the highest score/potential, with a value of 0.65 (see Fig. 5.14(b)). This is an option where the best cost makes the best alternative.

Figure 5.15 shows that a larger scale of nuclear energy development gives preference to systems with innovative technologies. Joint CNFC2 is the best of the alternatives considered (among options I and II). In option I, joint CNFC2 (FR2, TR3) has a score of 0.58, whereas in option II it has a score of 0.65 (option II has increased LUEC and Wastes KI weights in comparison to option I). In general, large demand for nuclear energy offers the possibility to develop innovative systems by creating the conditions for a full R&D refund.

The above mentioned examples demonstrate several capabilities of the model developed. Countries may choose their own path, setting their preferences using the set of weights (see Table 5.15). For some countries with high expected rates of nuclear energy development, the weight of the Nat. U KI could be increased, which will increase the potential of FRs and closed NFCs. In countries where the demand for electricity is low and environmental issues are of significant concern owing to public opinion, a large impact on the choice of strategy could result from choices such as giving increased weight to the Wastes KI.

(i) Sensitivity and uncertainty analysis

Figures 5.16–5.20 show the sensitivity for 20 GW(e) capacity, for basic weighting factors (see Table 5.15) and for option I. The linear final weight sensitivity for 20 GW(e) show the trends of the alternatives. Figures 5.16–5.20 also indicate the overall score for the linear KI sensitivity. A sensitivity study employing iteration modelling was conducted to determine the potential scope of the technologies under variation of weights.

The reference weight vectors are presented in Table 5.15. The starting point for iteration modelling was provided by the weights from expert evaluation. Then, the value of each indicator was consistently changed from 0 to 1, with a step of 0.05. The values of the remaining four indicators were varied proportionally, keeping the total value of all weights equal to unity under each step. This procedure was carried out for each of the five KIs, hence the number of options amounted to 105 for each parameter. Based on the opinions of experts, the study determined the frames for each of the KI weights (see Table 5.16).

The most interesting aspect of the sensitivity analysis is that there is an intersection of the potential of the systems (lines and areas on Figs 5.16–5.20). The figures also show the fluctuation areas for the KIs separately. The yellow vertical lines on these figures show the reference weights from Table 5.15.

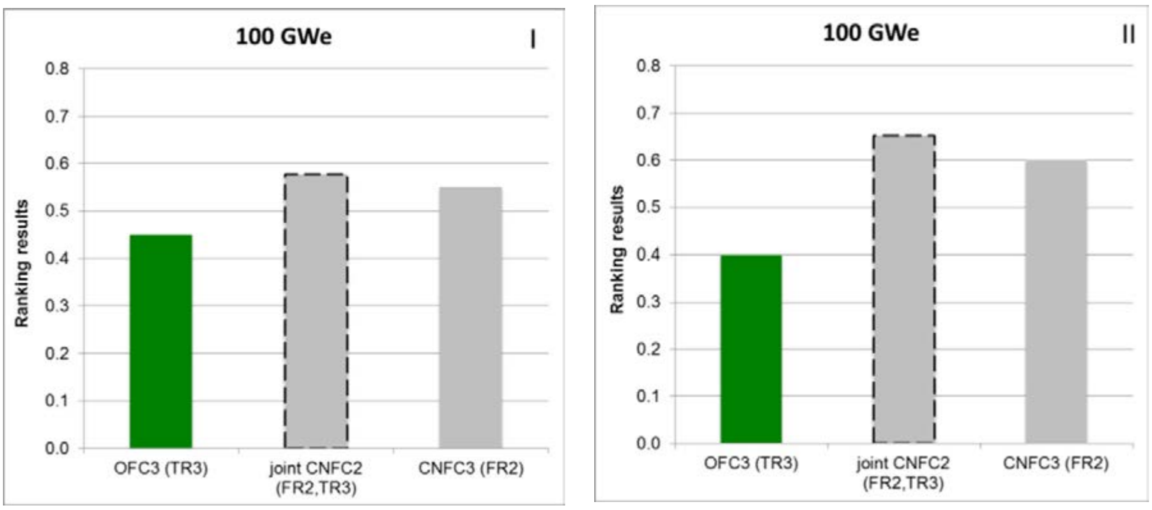
The grey dashed line defines the potential of the joint CNFC1 (FR1, TR1) system. The blue line defines the potential of the joint CNFC2 (FR2, TR3) system. The green line shows the potential of the open OFC1 (TR1) system based on TR1 reactors, whereas the red line shows the potential of the open OFC2 (TR2) system based on TR2 reactors. The shaded grey area in Figs 5.16–5.20 shows the differences between the potentials of a CNFC based on different types of FR.

Figure 5.16 shows that for 20 GW(e) electrical system capacity, the potential of OFC1 remains larger than the potential of joint CNFC2 for the Nat. U KI weight from 0.05 to 0.12. However, as the natural uranium KI weight exceeds 0.12, the joint CNFC2 potential starts to surpass the potential of the OFC1 system.

Figure 5.17 shows that for 20 GW(e) electrical system capacity, for the LUEC KI weight values from 0.2 to 0.3, the potential of CNFC2 remains larger than the potential of OFC1 and OFC2. However, as the LUEC KI weight exceeds 0.3, the OFC1 potential starts to surpass the potential of the CNFC2 and other systems.

Figure 5.18 shows that for 20 GW(e) electrical system capacity, as the Wastes KI weight rises from 0.05 to 0.27, the potential of OFC1 is higher than the potential of CNFC2. However, as the Wastes KI weight exceeds 0.27, the potential of CNFC2 starts to surpass that of OFC1 and the other systems.

Figure 5.19 shows that for 20 GW(e) electrical system capacity, as the TtMature KI weight rises from 0 to 0.24, the potential of CNFC2 stays larger than the potential of CNFC1 and OFC1. In the weight range 0.24–0.33 for the TtMature KI, CNFC1 has the greatest potential; as the weight exceeds 0.33, the potential of OFC1 starts to surpass that of CNFC1 and the other systems.



(a) (b)

FIG. 5.15. Comparative evaluation results for the 100 GW(e) case. (a) Option I; (b) option II.

TABLE 5.16. VARIATION RANGE FOR THE WEIGHTING FACTORS

KI	1 Nat. U	2 LUEC	3 Wastes	4 TtMature	5 R&D refund
Final weight	0.05–0.5	0.2–0.8	0.05–0.5	0–0.4	0–0.4

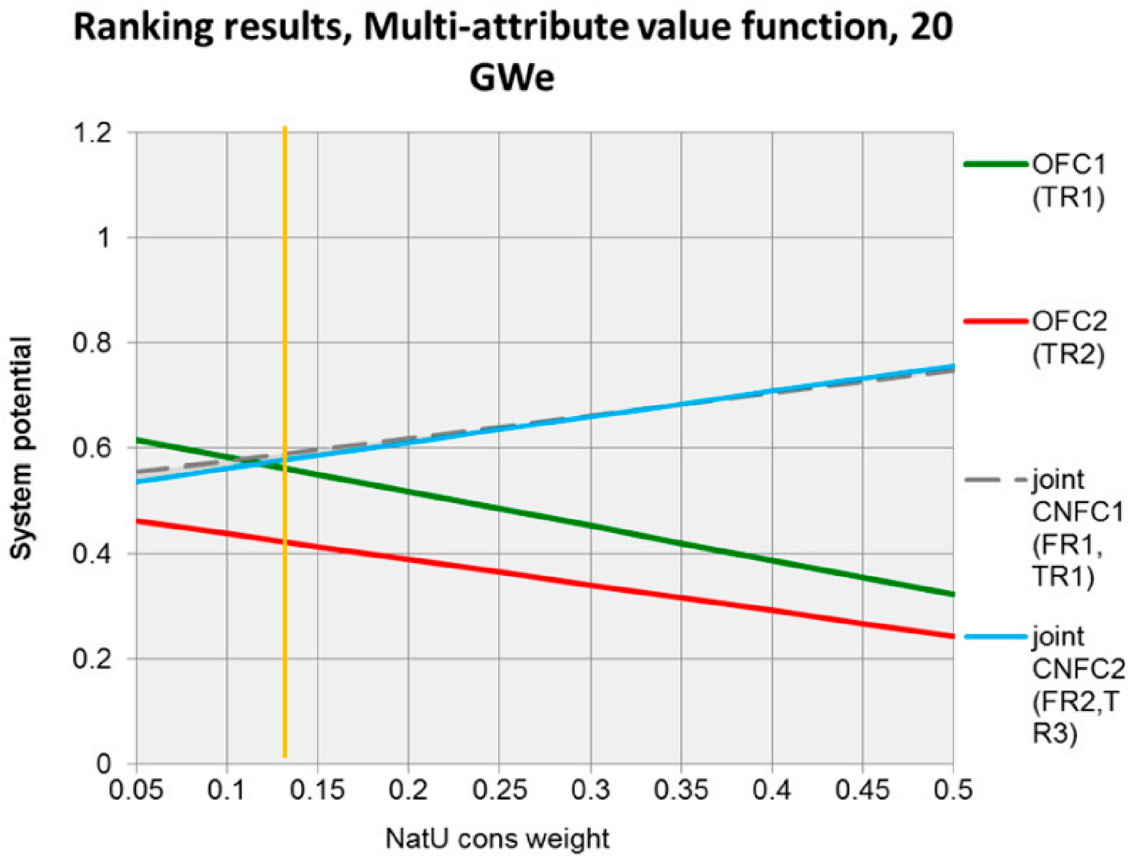


FIG. 5.16. Linear weight approach to weight sensitivity of Nat. U consumption, option I.

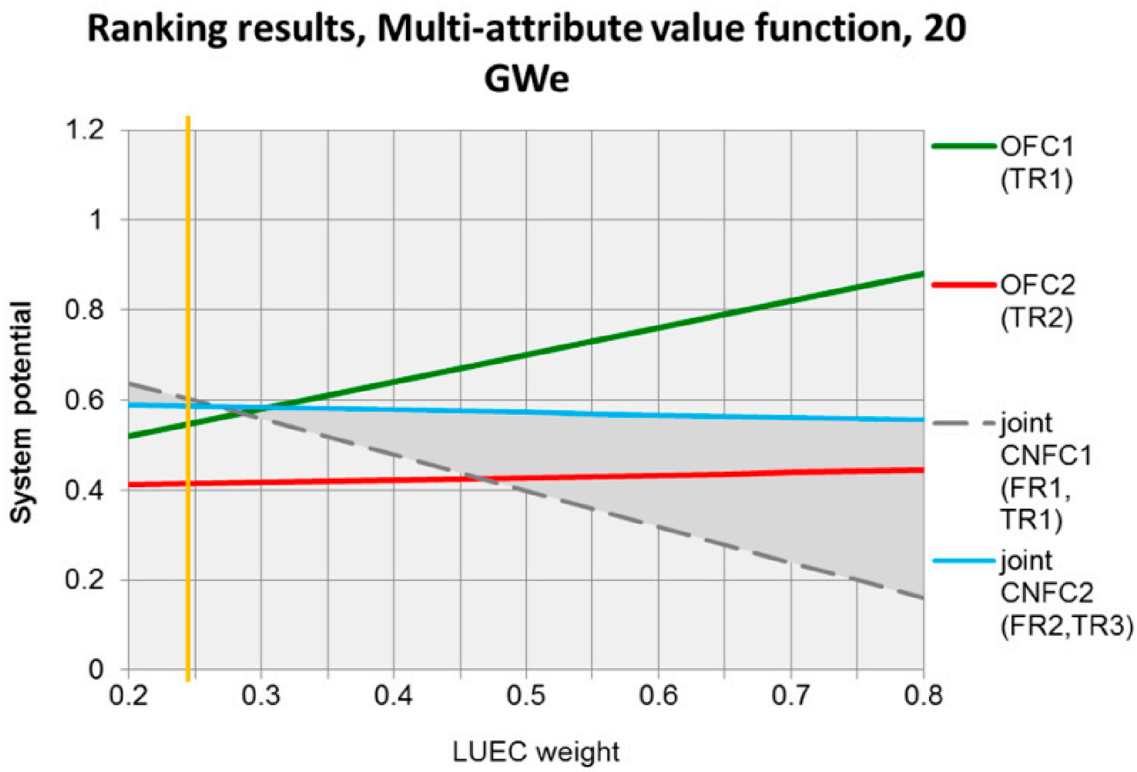


FIG. 5.17. Linear weight approach to weight sensitivity of LUEC, option I.

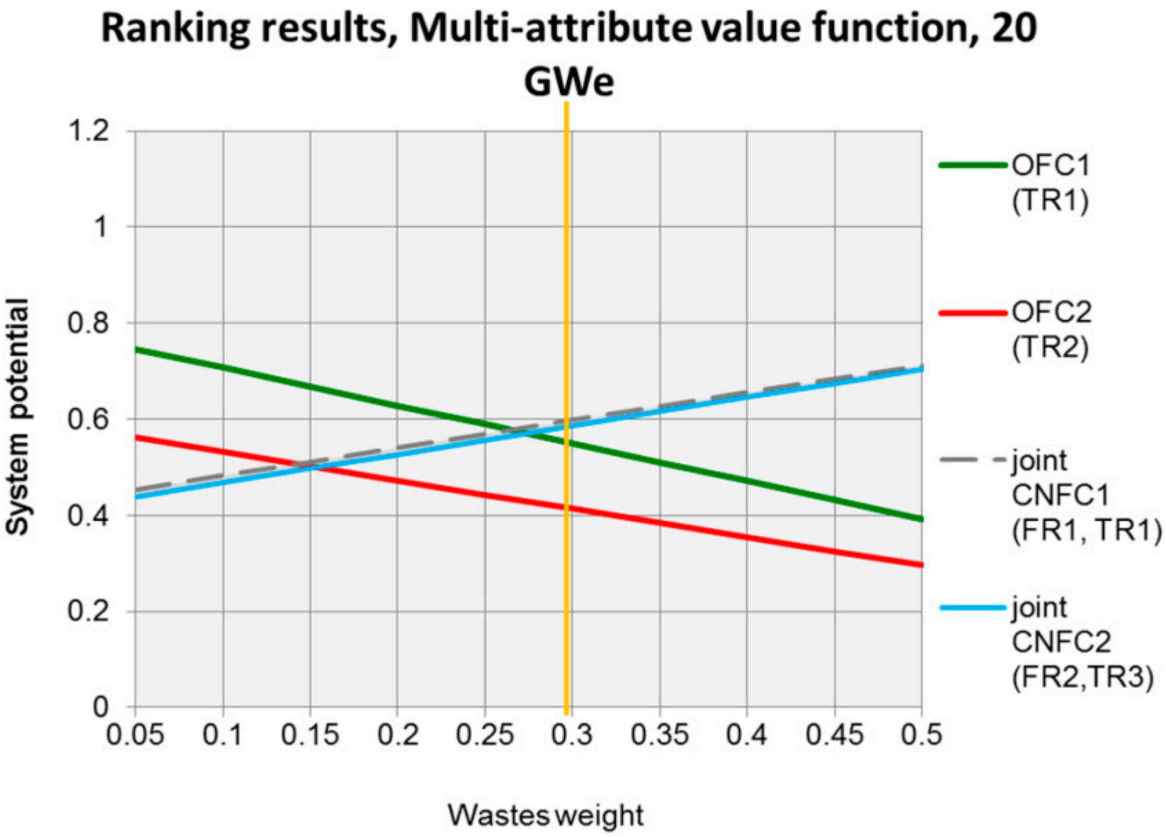


FIG. 5.18. Linear weight approach to weight sensitivity of Wastes, option I.

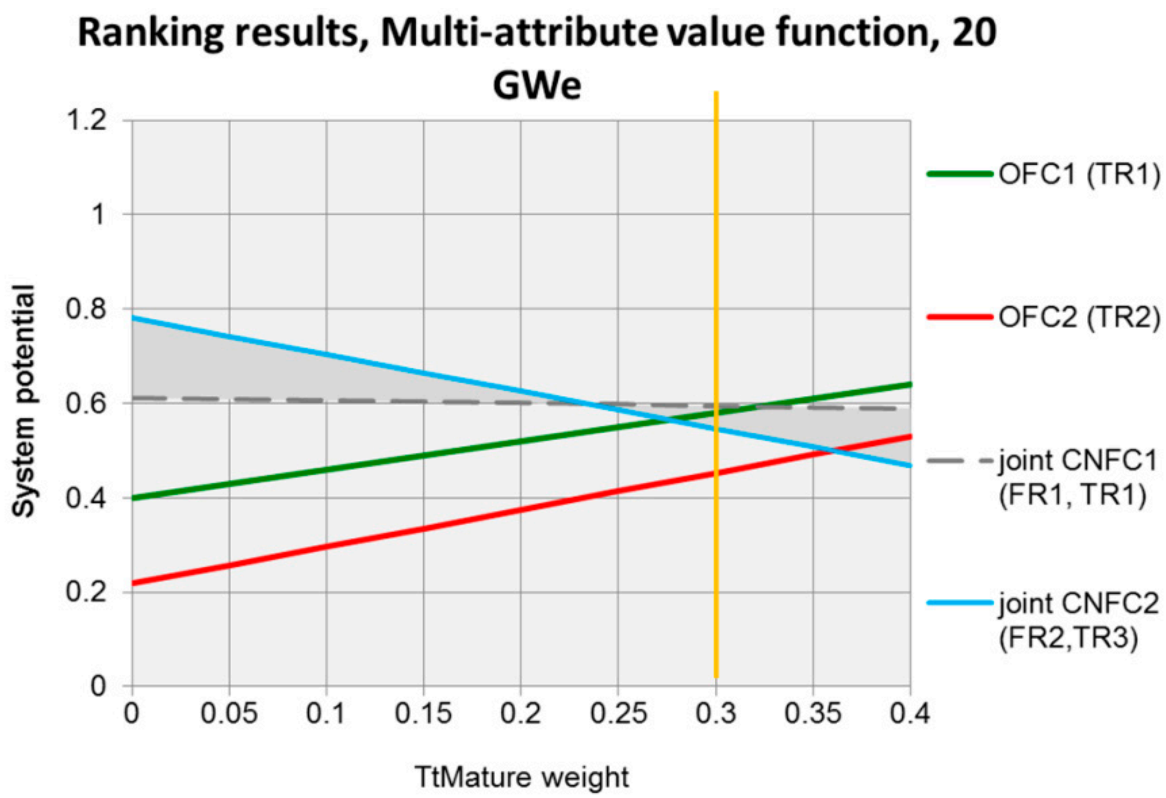


FIG. 5.19. Linear weight approach to weight sensitivity of TtMature, option I.

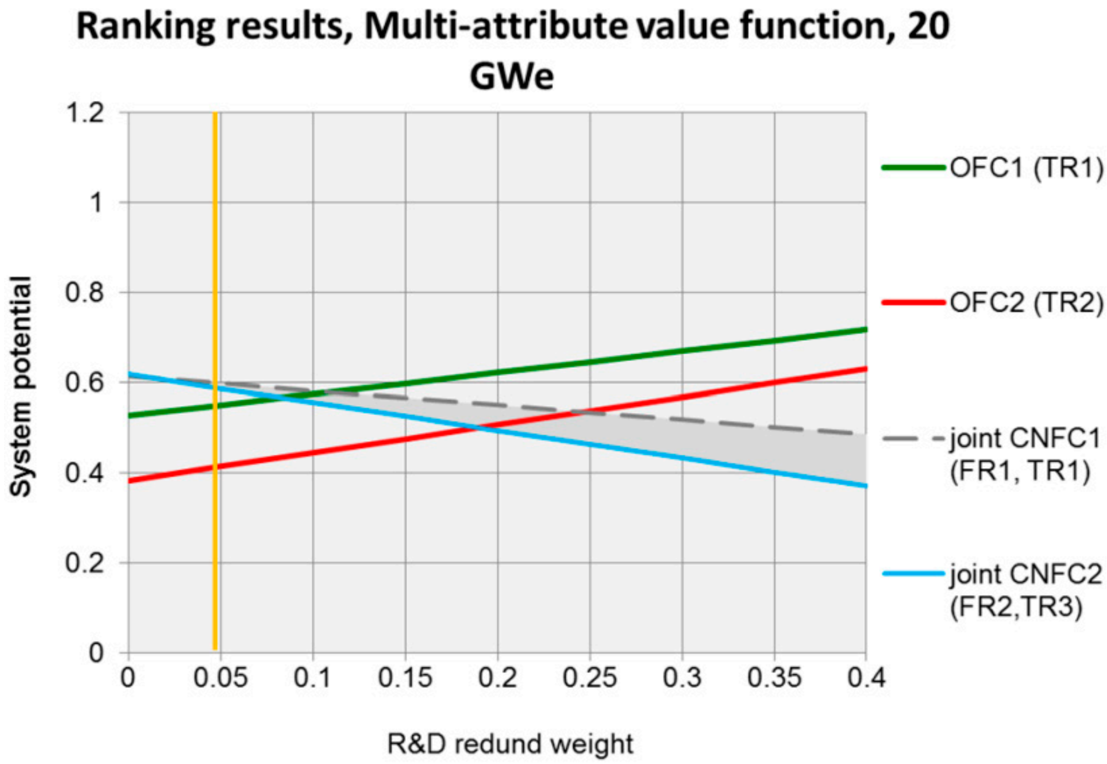


FIG. 5.20. Linear weight approach to weight sensitivity of R&D refund, option I.

Figure 5.20 shows similar behaviour to that in the previous figures; at 20 GW(e) electrical system capacity, as the R&D refund KI weight rises from 0 to 0.1, the potential of CNFC1 and CNFC2 remains larger than that of the once through NFC system, but as the R&D refund KI weight exceeds 0.1, the potential of OFC1 starts to surpass that of the joint closed NFC systems. Hence, Figs 5.16–5.20 show that the results for the comparison of the system potentials are highly dependent on the values of the indicator weights. Such uncertainty may alter the ranks of the compared alternatives.

(j) Conclusion

Comparative evaluation of INESs within the scope of the KIND approach was conducted for two deployment scales of nuclear energy: low power (20 GW(e)) and high power (100 GW(e)). Five KIs from different areas of the INPRO methodology were considered for analysis. A small number of KIs from the comparative evaluation of NESs were selected to visualize the most significant trends and to ensure their maximum independence from one another. The current mathematical model has shown that:

(i) The priorities and preferences in the selection of KIs, which are assumed at the stage of NES strategy development and taken into account in the generated model via weighting factors, define the system architecture and its specific characteristics in comparison with other systems.
(ii) Application of the generated mathematical model has demonstrated that for newcomer countries not planning to develop nuclear energy on a very large scale, it is advisable to develop NESs based on a once through NFC with TRs. At the same time, if the problems at the back end of a fuel cycle are perceived as challenging by the society and the Government, the potential of once through NFC systems becomes lower than that of joint closed NFCs based on TRs and FRs. This conclusion shows that an acceptable solution to the problems of the NFC back end could be found through cooperation with countries holding the technologies for FRs, TRs and CNFCs, as well as possessing the developed infrastructure necessary for a two component system.
(iii) For countries planning a large scale nuclear energy development, the calculations performed have demonstrated that the model gives preference to systems based on FRs. For countries seeking high

rates of nuclear energy development and expecting nuclear fuel shortages (e.g. India and China) the best of the aforementioned alternatives is a joint system containing FRs with short doubling time and lying closer to technological maturity. For the conditions of stabilization of electricity consumption in the country in the long term, a multi-tier closed NFC based on TRs and FRs and focused on the best economic indicators is a priority option.

Sensitivity analysis of the systems under consideration shows that the rating of alternatives under the same KI values would essentially depend on the priorities set by the decision makers and taken into account in the model through selection of the weights.

In principle, the dependences obtained offer the possibility of controlling the construction of NESs with predefined characteristics.

5.3.1.2. Application of the KIND approach to the comparison of INESs based on closed NFC

(a) Introduction

Many countries all over the world are involved in R&D for innovative technologies, which could become a basis for NESs for sustainable development. Under rapidly changing conditions it is necessary to estimate the status, prospects, benefits and risks related to the development of one or another technology in order to the arrange the timeline of priorities for the development of innovative nuclear technologies in the framework of national programmes.

In contrast to the technologies available today or those that will be deployed in the near future, detailed technical data and a full regulatory framework may not be available for innovative technologies that are deployable in the long term. Moreover, the comparative evaluation of innovative systems is more important, as it cannot be completed by means of previously available evaluation tools.

All these conditions make the effective implementation of the tools available for the evaluation of INESs, such as the INPRO methodology, barely possible. For this reason, evaluators often have to rely on expert judgement in areas where design information and other data are incomplete or not yet available.

Expert opinion may differ between different groups of experts, and therefore the effective application of information received from experts requires that the approach and tools for data and evaluation be viewed with high confidence.

(b) Objective and problem formulation

The objective of this study is to apply the KIND approach for the comparative evaluation of INESs, including both reactor facilities and the related NFC in the long term, in order to evaluate the advantages and drawbacks of the approach. According to the objective, the following two tasks were formulated: (1) the definition of a set of KIs suitable for use in the case of a lack of technical, regulatory and legal information about INESs, especially those at a conceptual design development stage, and (2) consideration of different options for weighting factor evaluation.

(c) Formulation of alternatives (NES options)

This case study considers three NES options: a TR system, an FR system and a mixed, two component system consisting of TRs and FRs (TR+FR). All systems are considered to be closed NFC systems with recycling of all heavy nuclides (including uranium, plutonium and MA).

The TR system consists of MOX fuelled light water reactor (LWR) type reactors with a closed NFC. The reactor core is characterized by 1.47×10^{14} n/cm^2·s neutron flux averaged through the entire fuel cycle and spectrum averaged neutron cross-sections. Other parameters include thermal efficiency of 37 %, fuel residence time of 4 years and average discharge burnup of 51 MW·d/kg. The length of the external fuel cycle (cooling, reprocessing and refabrication of irradiated fuel) is 5 years, during which 0.1% (by mass) of annually reprocessed heavy metal is assumed to be lost. Since the TR system cannot consume ^{238}U only, it is fed with a mixture of ^{238}U and ^{235}U nuclides. The fraction of the latter nuclide is high enough to provide minimal neutron gain of the system to compensate for the neutron losses occurring from neutron capture in structural materials and fission products and neutron leakage.

The FR system consists of metal fuelled sodium cooled fast breeder reactors with a closed NFC. These reactors meet the system requirements for initial plutonium loading of 3–4 t/GW(e) and excess plutonium production of over 300 kg/GW(e)·year [5.6]. NESs based on such reactors can achieve 5000 GW(e) of installed capacity with integrated natural uranium consumption within 20 million metric tonnes by 2100. The reactor is characterized by 1.05×10^{15} n/cm^2·s neutron flux averaged over the entire fuel cycle with the spectrum averaged neutron cross-sections. Other parameters of interest include thermal efficiency of 43%, fuel irradiation time of 2 years and average burnup of 76 MW·d/kg. The length of the external fuel cycle (cooling, reprocessing and refabrication of irradiated fuel) is 3 years, during which 0.1% (by mass) of the annually reprocessed heavy metal is lost. In this case, the FR system only consumes fertile isotopes of ^{238}U (or ^{232}Th in the U–Th NFC, which is not considered here).

The two component INES consists of TRs and FRs with a closed NFC. The length of the external fuel cycle for the TR is 5 years, and for the FR it is 3 years. SNF from the TR and the FR is reprocessed separately after 4 and 2 years of cooling, respectively. After 1 year of reprocessing, all recovered heavy nuclides, including uranium, plutonium and MA, are mixed and the TR and FR fuel is fabricated. Therefore, the total TR and FR external fuel cycle lengths stay the same as in the other two NES options (5 and 3 years, respectively). This simple NFC scheme is only used for the present trial application. Generally, MAs should be recycled in fast or even molten salt reactors, rather than TRs. The system is fed solely by ^{238}U: annually, the TR consumes 223 kg and the FR consumes 779 kg. In this case, the TR installed capacity fraction is 508 MW(e) and the FR installed capacity fraction is 492 MW(e) (for a total system installed capacity of 1000 MW(e)).

(d) Identification of indicators

All KIs are grouped under three high level objectives: cost, performance and acceptability. It is difficult to imagine an NES that is mature on the one hand and innovative on the other, especially in the case of technology for a long term prospect. Since this case study deals with INESs for the long term, it is difficult to define all of the KIs described in the project. Therefore, a limited set of KIs will be chosen and the sustainability potential of an INES will be examined on the basis of this KI set. Moreover, this case study considers INESs with both reactor facilities and related fuel cycles (closed). In this case, the KIs from the waste management area are to be defined carefully.

Economics is a complicated issue. Until now, the comparison of even existing reactors' (LWRs) economics has been disputed. The KI set considered for economic evaluation only includes LUEC. The acceptability and appropriateness of such an approach is beyond the subject of the study. It should be noted that in the Russian Federation, the closed NFC has not been widely deployed at a commercial scale and the fuel service market has not been established yet. The relevant data on closed fuel cycle services provided by foreign vendors, such as AREVA, are confidential and not openly available. Therefore, one can only provide a very approximate evaluation of LUEC rather than its real value. The second KI of the cost group, R&D cost, was not considered in this study.

In the case of a once through NFC, SNF is not designated for further use and is considered to be waste. In this case, different systems can be compared by means of the amount of SNF produced per 1 GW(e)·year of energy generated. From this viewpoint, high burnup facilities seem to be more attractive. However, in a properly organized INES with a closed NFC, all SNF undergoes reprocessing. Assuming zero losses of all heavy nuclides, they are all recycled until they undergo fission. In real life, however, losses are not equal to zero. Under such conditions, the amount of waste removed from the NES does not depend on the energy produced and is determined by NFC losses. This quantity of heavy nuclides is proportional to the installed capacity of a system rather than the energy produced. This fact has great importance for the acceptability of an INES in terms of economy.

For the reasons mentioned above, in this study, the specific annual losses of heavy nuclides (kg/(GW(e)·year)) are used as the waste management KI instead of the specific radioactive waste inventory. One can evaluate this value by means of equilibrium quantities of heavy nuclides in the NES and the fraction of losses. In the case of a once through NFC, one can assume 100% losses and calculate the equilibrium quantities of nuclides and the absolute quantity of the related losses. In a mixed, two component NES, the equilibrium nuclide quantities depend on the strategy of nuclide mass flow between the TR and the FR. However, here this dependence is not considered, because only one of the two component INESs with fixed nuclide exchange parameters is taken into account.

The amount of useful energy produced by the system from a unit of mined natural uranium/thorium is also considered as an environmental KI. As shown above, the TR system is fed with both ^{235}U and ^{238}U. Therefore, ^{235}U consumption defines the total quantity of heavy nuclides used. All evaluations are normalized per 1 GW(e) of the system installed capacity. In order to calculate this KI, the electric energy produced is transformed into a thermal energy equivalent, taking into account thermal efficiency (37% for the TR). The quantity of mined natural uranium (the ^{235}U fraction is assumed to be 0.72%) is to contain the quantity of ^{235}U that is sufficient to feed the system. Thus, the KI value is defined as the thermal energy produced by the system over 1 year divided by the amount of natural uranium consumed. If the system consumes ^{238}U (the FR and TR+FR cases), the thermal energy produced is divided by the mass of ^{238}U consumed, which is nearly 1000 kg (depending on thermal efficiency) — a value required to generate 1 GW(e)·year of electricity.

The next parameter considered as a KI in this study is neutron gain, which is equal to the number of excess neutrons produced by the system per one fission reaction. The neutron gain, in fact, will describe the excess of neutrons in an NES produced owing to the transformation of one heavy nucleus and its reaction products into fission products. These excesses of neutrons can be spent on loss compensation, on involving additional heavy nuclei in the NES to increase its power capacity or on transmutation. The main difference between neutron gain and breeding ratio is that the first indicator takes into account neutrons that were spent to transform all the heavy nuclides produced by means of neutron capture into fission products. That is why neutron gain can be less than unity even for an FR system. In a simple way, neutron gain can be defined as the ratio of the generation rate for surplus neutrons to the fission rate (e.g. $NG = (R_p - \mathrm{R}_d)/R_f$, where R_p is the neutron production rate, R_d is the neutron disappearance rate and R_f is the neutron fission rate.

The general (necessary but not sufficient) principle of nuclear power existence can be formulated in terms of neutron gain as follows: the total (time integrated) quantity of surplus neutrons generated by nuclear energy system should exceed the quantity of neutrons required to sustain the nuclear energy generation process. These excess neutrons can be spent on loss compensation or involving additional heavy nuclei in the NES to increase its power capacity.

It should be observed that a similar approach applied to a particular reactor (rather than NES) was introduced in Ref. [5.7]. In the case of the TR system, the ^{235}U feed is high enough to provide minimal neutron gain (0.3), which makes it possible to sustain a chain reaction in the system. Excess neutrons are spent to compensate losses resulting from structural materials and fission products capture and neutron leakage. The FR system has the highest neutron gain (among the three options discussed) and could be considered as a boundary case. In the system consisting of FRs and TRs and consuming ^{238}U only, minimal neutron gain is provided by the FRs (the FR fraction in this case is 49.2%).

Safety is an essential part of nuclear energy. Therefore, safety indicators describing the reactor safety are included in the KI set. Many KIs have been proposed for the safety area because reactor safety issues have been dealt with from the very beginning of nuclear energy and many general approaches and methods have been developed for reactor safety evaluation. However, NESs consist not only of the reactors themselves, but also aspects such as fuel reprocessing and fabrication facilities, and nuclear materials transportation systems. Therefore, the evaluation of safety for INESs requires consideration of the entire NFC, including all its stages and processes. It is difficult to find a general indicator that is well known and describes the whole NFC rather than a particular reactor or NPP and, at the same time, has clear quantitative measures. Such an indicator could probably be derived by following general suggestions. Generally, all safety measures for NFC facilities have the same main objective — to prevent the release of radioactivity into the environment beyond specified limits. Release of radioactivity could occur during nuclear reactor operation incidents, or as a consequence of severe accidents. Safety measures include actions to prevent incidents and arrangements put in place to mitigate their consequences if they occur. The other NFC facilities could also become a source of radioactivity release under unfavourable conditions. It is then reasonable to assume that the lower the inventory of radioactive materials in the NES (a core factor affecting the source term), the lower the risk of large scale release of radioactivity into the environment.

This study considers the potential to prevent release — a KI from the safety area. However, this indicator implies an equilibrium amount of heavy nuclides in the system. The suggestions mentioned above that lower the inventory of radioactive materials in the NES will lead to reduced risk of large scale release of radioactivity into the environment. Hence, the goal is to keep this indicator as minimal as possible.

The last KI considered in the study belongs to the acceptability group. Since this case study deals with INESs as a long term prospect, it is difficult to characterize these facilities in terms of degree of standardization and licensing adaptability. Most facilities are at the conceptual design stage. For these reasons, 'time needed to mature the technology' is chosen as a KI. However, this indicator is measured in dimensionless units or scores, rather than years. These scores represent KI evaluation based on expert judgement. This indicator needs to be maximized, which assumes that the highest score is assigned to the most mature system. The maturity of these systems is evaluated within a five score scale that takes the following into account. FR and TR+FR systems contain metal fuelled SFRs. The Russian Federation has great experience in the operation of FRs including sodium cooled facilities, as well as having undertaken very substantial R&D. There are ongoing studies on pyro-chemical fuel reprocessing. For these reasons, the INES option based on FRs has the highest (compared to other options) score. Plutonium recycling and remix technology applications are in the scope of the current studies related to TRs. However, this study considers the recycling of all heavy nuclides in the TR system. This option is not well developed and the question arises as to whether this technology will be developed or not. Hence, this option is assumed to be less mature than the previous one. The least mature option is the two component system, because of its complicated structure and organization.

(e) Evaluation of indicators, including uncertainties

All of the indicators considered can be divided into three groups: indicators evaluated on the basis of general principles without any tool or code (for example, environmental KIs), indicators evaluated on the basis of expert judgement (maturity KIs) and indicators evaluated by means of special codes, namely, the NEST (for LUEC evaluation) and ISTAR (for the evaluation of other indicators). As a result, Table 5.17 contains the characteristics of the INESs considered in this study: INES-1 (TR), INES-2 (FR) and INES-3 (TR+FR). The text below describes the quantitative evaluation of these indicators.

The E.1 indicator ‘levelized energy product or service cost’ is measured in mills/kW(e)·h and evaluated by means of NEST. In the case of a mixed, two component system, the E.1 indicator is calculated as the sum of LUEC of FRs and TRs multiplied by the corresponding weight, which is proportional to the capacity of the particular reactor type installed in the system. As in this case the TR and FR fractions are 50.8% and 49.2%, respectively, the LUEC for this system is close to the average of the separate LUECs for TRs and FRs.

The WM.1, NG.1 and S.1 indicators are evaluated on the basis of an equilibrium state calculation of the considered systems by means of the ISTAR code. As a result of these evaluations, the neutron gain, the equilibrium quantities of uranium, plutonium, minor actinides and all heavy nuclides, and the annual nuclide losses are calculated. In addition, the external feed of ^{238}U and ^{235}U (if necessary) is estimated to sustain the required power level (1 GW(e)) of the system. Table 5.18 shows the results of these evaluations.

The ENV.1 indicator ‘the amount of useful energy produced by the system from a unit of mined natural uranium/thorium’ is calculated on the basis of the external feed that is required to provide 1 GW(e) of installed capacity.

Finally, the M.2 indicator ‘time needed to mature the technology’ is scored as a result of expert judgement.

TABLE 5.17. PERFORMANCE TABLE

High level objectives	Areas	Indicators	Indicators abbr.	INES-1 (TR)	INES-2 (FR)	INES-3 (TR+FR)
Cost	Economics	Levelized energy product or service cost (mills/kW(e)·h)	E.1	33.5	44	38.3
Performance	Waste management	Specific radioactive waste inventory (kg)	WM.1	31	62	45
	Neutron gain	Neutron gain	NG.1	0.301	0.806	0.301
	Environment	The amount of useful energy produced by the system from a unit of mined natural uranium/thorium (MW·d/kg U)	ENV.1	5.1	390.9	364.2
	Safety	The potential to prevent release — equilibrium amount of heavy nuclides in the system (kg)	S.1	275 518	312 380	356 345
Acceptability	Maturity of technology	Time needed to mature the technology	M.2	3	4	2

TABLE 5.18. EQUILIBRIUM STATE EVALUATION RESULTS FOR INES-1, INES-2 AND INES-3 WITH A CLOSED NFC WITH 0.1 % LOSSES

INES type		TR	FR	TR+FR
Neutron gain		0.301	0.806	0.301
Equilibrium nuclide quantity (kg)	U	264 225	268 546	330 450
	Pu	7 278	41 593	21 987
	MA	4 011	2 241	3 906
	All heavy nuclides	275 518	312 380	356 345
Losses (kg/year)	U	29	53	41
	Pu	1	8	3
	MA	0.4	0.4	0.5
	All heavy nuclides	31	62	45
Energy produced (MW·d/kg U)		5.1	390.9	364.2
Feed (kg/year)	^{235}U	515	0	0
	^{238}U	535	934	223(TR)+779(FR)
Installed capacity (MW(e))	TR	1 000	0	508
	FR	0	1 000	492

Note: FR — fast reactor, MA — minor actinide, TR — thermal reactor.

(f) Selection of an MCDA method

The MAVT method was applied to the performance table for comparison of the systems considered. The KIND-ET Excel template was modified to process six KIs.

(g) Determination of weights, including uncertainties

According to the performance table, all KIs are included in the three level objectives tree. High level objectives include cost, performance and acceptability. On the second level, each objective can be split into several areas. In this study, performance is split into four areas: waste management, neutron gain, environment and safety. Each area can contain several indicators, which form the final (third) level of the objectives tree.

Table 5.19 shows that, in the case of a single indicator within a high level objective group, its final weight is equal to the weight of high level objectives (for example, cost and acceptability high level objectives). If a high level objective contains multiple indicators, each of these indicators is diluted with the other indicators of this area and it has low final weight (the performance high level objective in Table 5.19). As a result, the final score is less sensitive to improvement in this particular indicator. In this case, the significant improvement of a performance indicator can be suppressed by a slight deterioration of a cost or acceptability indicator.

Therefore, in this study, the second option for the definition of weights was considered, which assumes equal final weights for all indicators (see Table 5.20). This approach makes it possible to pay equal attention to all areas of interest, and this corresponds to the weak link principle assumed in the INPRO methodology.

(h) Ranking alternatives (NES options) with the selected MCDA method and interpretation of results with relevance to objectives at different levels

The KI set considered in this study, weighting factors, single-attribute value functions and indicator goals (see Table 5.21) were put into the KIND-ET Excel template and ranking results were obtained for three INES options.

TABLE 5.19. OPTION 1 FOR WEIGHT DEFINITION WITH EQUAL WEIGHTS OF HIGH LEVEL OBJECTIVES

High level objectives	High level objective weights	Areas	Area weights	Indicators abbr.	Indicator weights	Final weights
Cost	0.333	Economics	1	E.1	1	0.333
Performance	0.333	Waste management	0.25	WM.1	1	0.083
		Neutron gain	0.25	NG.1	1	0.083
		Environment	0.25	ENV.1	1	0.083
		Safety	0.25	S.1	1	0.083
Acceptability	0.333	Maturity of technology	1	M.2	1	0.333

TABLE 5.20. OPTION 2 FOR WEIGHTS WITH EQUAL FINAL WEIGHTS

High level objectives	High level objective weights	Areas	Area weights	Indicators abbr.	Indicator weights	Final weights
Cost	0.167	Economics	1	E.1	1	0.167
Performance	0.666	Waste management	1	WM.1	1	0.167
		Neutron gain	1	NG.1	1	0.167
		Environment	1	ENV.1	1	0.167
		Safety	1	S.1	1	0.167
Acceptability	0.167	Maturity of technology	1	M.2	1	0.167

TABLE 5.21. SINGLE-ATTRIBUTE VALUE FUNCTION PARAMETERS

High level objectives	Areas	Goal	Form	Exponent power	INES-1 (TR)	INES-2 (FR)	INES-3 (TR+FR)
Cost	Economics (E.1)	Min.	Linear	1	0.239	0.000	0.130
Performance	Waste management (WM.1)	Min.	Linear	1	0.500	0.000	0.274
	Neutron gain (NG.1)	Max.	Linear	1	0.373	1.000	0.373
	Environment (ENV.1)	Max.	Linear	1	0.013	1.000	0.932
	Safety (S.1)	Min.	Linear	1	0.227	0.123	0.000
Acceptability	Maturity of technology (M.2)	Max.	Linear	1	0.750	1.000	0.500

This hierarchical structure was proposed as a result of the discussion of the indicator weight assigning procedure and reflects the user priorities to be able to choose any nuclear (or non-nuclear) technology. Since many users consider INESs to be an alternative to conventional technologies based on organic fuels, the high level objectives include cost, consisting of LUEC, capital cost and R&D cost. Since many countries will use the KIND approach to provide sufficient grounds for the construction of their first NPP, public and government acceptance is very important. Important features of an INES include safety, resource availability, waste minimization, and others. All these features shape the performance of an INES.

This case study considers two options of weight definition, which are shown in Tables 5.19 and 5.20. The first weight definition option assumes equal high level weights (0.333). On the second level, all indicator areas within one high level group have equal weights. In this study, according to the objectives tree and selected indicators, the economy and acceptability areas have weights equal to 1. The performance group contains four areas (safety, waste management, neutron gain and environment), therefore each area weight is 0.25. Since each second level area only includes one indicator, their weights within that area equal unity. The final columns in Tables 5.19 and 5.20 show the final weights. The ranking results for the INES options considered are shown in Fig. 5.21. In the option 1 case, the final weights for the cost and acceptability groups exceed the final weights for performance. Option 2 uses equal final weights for all KIs.

The two component system only consumes ^{238}U, including the MOX fuelled TRs which use uranium mixed with plutonium produced by FRs. This results in increased equilibrium of nuclide quantities, the growth of losses (absolute value, rather than relative, which is the same — 0.1%) and LUEC increment. This system inherits the disadvantages of the TR system and the FR system. Nevertheless, the advantages are also inherited because the natural uranium utilization efficiency (ENV.1) is comparable with the same indicator for FR systems.

If the final weights are assumed to be equal in accordance with the weak link principle (see Table 5.21), the FR system demonstrates the highest score, which slightly exceeds the one for a TR system with a closed NFC. The reason for this is better natural uranium utilization efficiency, sufficient quantities of neutrons and higher maturity. Moreover, high neutron gain enables this system to develop with a high rate (i.e. to increase its installed capacity rapidly). The TR system can only increase its installed capacity with increased ^{235}U consumption.

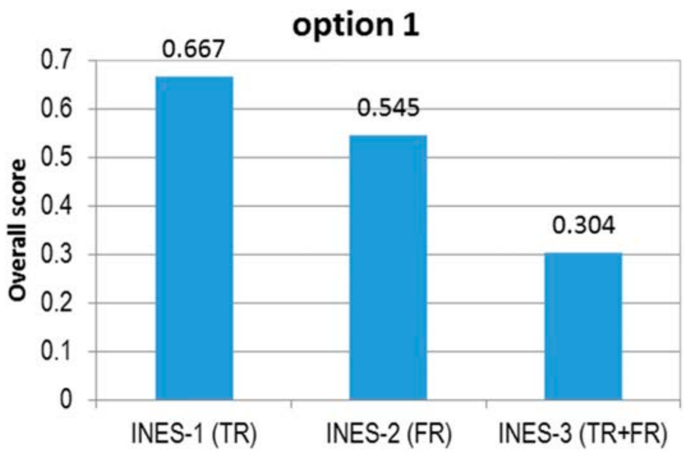
The two component system of FRs and TRs looks less attractive than the FR system, but points to possible transient period issues, because TRs cannot be shut down instantaneously. Moreover, before doing this, one needs to investigate all possible fuel cycle options, for instance, a thorium based NFC for TRs and a Th–U–Pu NFC for a two component system of FRs and TRs.

According to the KI set and weights considered, the main advantages are achieved in the neutron gain, environment and maturity areas. The evaluation of maturity can be disputed, because expert judgement was used to characterize this parameter. However, the first two indicators (neutron gain and environment) demonstrate the advantages of this system compared to the other INES options. It should be noted that the FR option for INESs is regarded as an ultimate case because this system produces more neutrons than are required to sustain a chain reaction in the reactors of this system.

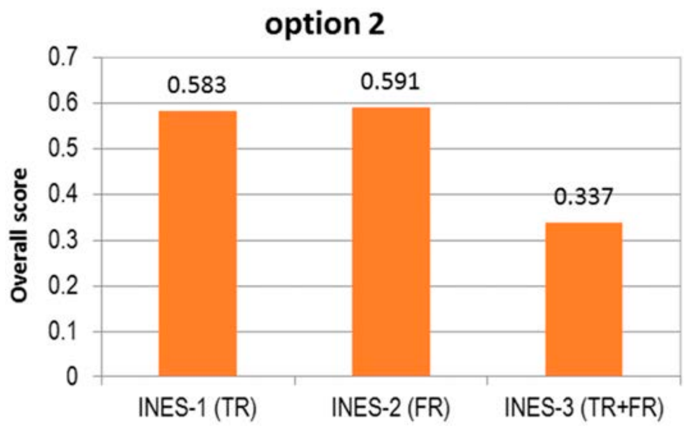
There are two interpretations of this result. First, the installed capacity of the system stays the same and all excess neutrons are considered to be a commodity, such as electricity, or could be used for applications such as the production of radioisotopes for medicine. Second, all these neutrons could be used for the production of excess fuel to load new reactors (FRs). In this case, the system installed capacity grows at the maximum rate possible. If the system installed capacity is constant or increases at a rate that is lower than the highest rate provided with FRs, the excess neutrons are irretrievably lost or need to be used for the breeding of plutonium (or ^{233}U). This excess plutonium needs to be stored, which impacts economic characteristics (because of the storage cost) and security, since the equilibrium quantity in the system will rise in this case. The neutron gain indicator can be useful to estimate the maximum quantity of plutonium that could be put to the storage while maintaining fuel self-supply.

(i) Sensitivity and uncertainty analysis

Sensitivity and uncertainty analysis was not considered in this study.



(a)



(b)

FIG. 5.21. Ranking results for compared systems. (a) Option 1 — different final weights; (b) option 2 — equal final weights.

(j) Conclusion

In this study, the KIND approach was applied to compare INESs as a long term prospect. Three INES options with a closed NFC for all heavy nuclides were considered: a TR system, an FR system and a two component system with TRs and FRs.

In the comparative evaluations performed, the following features were found for the KIND approach:

(i) Using different techniques for the final weight definition has a significant impact on the ranking results and could result in qualitative changes to the final comparative scores for the alternatives considered; the preference for one or another alternative depends on the definition of weights provided by experts or users.

(ii) Evaluations of INESs with closed NFCs need to use KIs related to the entire NES rather than to a particular reactor (as was done in this study).

It should be noted that the evaluation method for INESs developed in the KIND project could be useful in comparative evaluations of such NESs to explain their enhanced sustainability in the long term. To achieve this, however, one would need to take the indicators describing features of the entire INES into account, rather than those of its single constituents, such as, for example, a particular reactor.

5.4. EVOLUTIONARY VERSUS INNOVATIVE NESs

5.4.1. Romanian case study

5.4.1.1. Introduction

Existing NESs, which are mainly based on TRs operating in a once through cycle, will continue to represent the main contribution to nuclear energy production for at least several decades. As many national and international studies have shown, major innovations in reactor and NFC technologies are needed in order to achieve sustainable nuclear energy development. New reactors, nuclear fuels and fuel cycle technologies are under development and are being demonstrated worldwide. In these conditions, the evaluation of the status, prospects, benefits and risks associated with innovative technologies is very important. The results of such an evaluation could be useful not only for countries engaged in nuclear power development, but also for newcomer countries evaluating their potential to start a nuclear programme.

This case study, performed by the team of Romanian experts from RATEN ICN Pitesti, proposes to apply the KIND approach to evaluate evolutionary and INES technologies comparatively, based on specific KIs. The analyses performed address the status, prospects, benefits and risks related to the development of these technologies, taking into consideration country specifics. The general and specific goals of the case study are in agreement with the KIND objectives.

5.4.1.2. Objective and problem formulation

The Romanian nuclear programme started in 1950. Two research reactors were commissioned, namely WWR-S in 1957 (decommissioning started in 1997) and TRIGA (14 MW(e)) in 1979. The current Romanian policy is based on a once through NFC based on indigenous facilities, without enrichment or reprocessing [5.8]. Nuclear generation is assured by the Cernavoda NPP with two pressurized heavy water (PHWR) reactors of the Canada deuterium–uranium (CANDU) 6 type (700 MW(e) each) currently in operation (Unit 1 since December 1996 and Unit 2 since 2007).

The electricity generated by the Cernavoda NPP represents about 20% of national electricity production. “In 2025–2050, Romanian NPPs must contribute about 40% of the total national electricity production in cost competitive conditions and assuring nuclear safety at the international standard requirements,” according to Ref. [5.9].

The Romanian Government’s long term commitment to nuclear power development is clearly demonstrated by several major undertakings. The existing nuclear capacities will be maintained in operation and are expected to undergo refurbishment with a lifetime extension to 50 years (the lifetime of a CANDU reactor is 30 years), according to the official plans. Two further CANDU 6 units (720 MW(e) each) are officially planned for completion before 2025, in cooperation with the China General Nuclear Power Corporation (in November 2015, a memorandum of understanding for the development, construction, operation and decommissioning of Units 3 and 4 of the Cernavoda NPP was signed) [5.10, 5.11].

Romania enrolled at the early stages (2006) in the European Consortium working to develop the European Lead Fast Reactor, a Generation IV project. Official support for R&D activities in this direction came in 2011, when the Romanian Government signed a memorandum defining national availability to host ALFRED, a lead cooled fast reactor (LFR) demonstrator. The FALCON Consortium is developing support activities for ALFRED construction in Romania [5.12].

The main goal of this case study was to apply the KIND-ET evaluation template developed under the framework of the KIND collaborative project (KIND CP) to multi-criteria comparative evaluation of two types of NES technologies, namely evolutionary and innovative NESs.

The study performed by the Romanian team addressed the following specific objectives:

(i) To evaluate the considered NES together with the already existing/operating NES technology (CANDU 6), based on specific KIs (KIs developed under the framework of the KIND CP) and taking into consideration the country specifics;
(ii) To sustain the obtained results by performing sensitivity analysis.

Given Romania's potential interest in the nuclear technologies considered, the case study looks to offer expert technical support for decision making based on reasonable answers to several questions of interest:

(a) What is the status of the analysed NES technologies for different weights assigned to the high level objectives considered?
(b) How do the analysed NES technologies perform for different weights assigned to specific areas of evaluation for the high level objectives considered?
(c) How much could the country specifics affect the results of the analyses?

5.4.1.3. Formulation of alternatives (NES options)

The case study considers three NES technologies, which will be evaluated using the KIND approach, as follows: CANDU NES technology (two CANDU 6 reactors are actually operating at the Cernavoda NPP and the electricity generated comprises approximately 20% of Romania's total electricity production) — CANDU; an evolutionary NES, the Generation III+ enhanced CANDU technology — ENES; and an INES, the Generation IV lead cooled fast reactor technology — INES. Table 5.22 presents the main technical parameters of the NES technologies.

5.4.1.4. Identification of indicators

For the comparative analysis of the CANDU, ENES and INES technologies, the following three high level objectives have been considered:

(a) Cost;
(b) Performance;
(c) Acceptability.

Specific areas of interest have been selected for each of the high level objectives considered:

(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.

The evaluation of the NES technologies considered has been performed based on a set of 18 KIs; 16 KIs have been developed under the framework of the KIND CP and 2 KIs have been defined by considering country

TABLE 5.22 MAIN TECHNICAL PARAMETERS OF CONSIDERED NESs

Parameter	CANDU	ENES	INES
Reactor type	PHWR	PHWR	LFR
Fuel type	Natural UO_2	Slight enriched UO_2	MOX
Capacity (MW(e))	700	700	700
Plant factor (%)	95	85	85
Efficiency (%)	33	33	33
Average burnup (MW d/t·HM)	7 500	15 000	60 000
Lifetime (years)	50	60	60

specifics. In the following, the KIs considered are listed (together with their abbreviations), along with short explanations. Economics represents one of the main factors to be taken into consideration when evaluating the development of a technology, either conventional, nuclear or renewable. Two KIs were selected for the evaluation of the economics area, as follows:

(a) Levelized energy product or service cost (E1);
(b) R&D cost (E2).

LUEC is equivalent to the average price that would have to be paid by consumers to repay exactly all costs incurred by the owner/operator of a plant, at the selected discount rate, in a defined timeframe (the lifetime of the plant), and without profits. LUEC includes the capital costs, the operation and maintenance costs and the fuel costs.

R&D cost includes costs associated with the technology research and development. It also includes costs corresponding to infrastructure development and human resource training and development (the availability of adequate human resources to operate the NES is targeted).

According to the INPRO methodology, Waste Management Basic Principle 1 states that “Generation of radioactive waste in an INES shall be kept to the minimum practicable” [5.13]. It is very important to minimize the generation of waste at all stages, in order to avoid the transfer of undue burdens to future generations. The evaluation in the waste management area has been performed by considering the following two KIs:

(a) Specific radioactive waste inventory (WM1);
(b) SNF costs (WM2).

The WM2 KI takes into account the costs associated with all the operations related to spent fuel management; these costs have not been included in the LUEC calculation. According to the INPRO methodology, the attractiveness of nuclear material needs to be low for sustainable NESs [5.14]. Two intrinsic features, namely conversion time and significant quantity, can illustrate this KI; the attractiveness of nuclear material increases with shorter conversion time and smaller significant quantity. In addition, the overall technical difficulties of building a nuclear weapon with the type and quality of material available might be considered.

The comparison of different NESs with respect to attractiveness is a complex process [5.14]. Certain proliferation sensitive components of an NES (such as an enrichment facility or a reprocessing facility) have a higher attractiveness for proliferation compared to the rest of the components. While comparing the proliferation resistance of NESs with closed and open fuel cycles, the attractiveness of the latter might be lower, but in this case we have to deal with the accumulation of spent fuel containing direct use material (plutonium and/or ^{233}U) with high attractiveness, which is avoided in a closed fuel cycle.

Another important aspect related to proliferation resistance is the identification and availability of safeguards for the NES considered, addressing legal agreements between the party having authority over the NES and a verification or control authority, binding obligations on both parties and verification using, inter alia, on-site inspections. The evaluation of NESs in the area of proliferation resistance has been performed by means of the following three KIs:

(a) Attractiveness of nuclear material (PR1);
(b) Attractiveness of technology (PR2);
(c) Safeguards approach identified (PR3).

Nuclear power can support sustainable development by providing much needed energy with a relatively low burden on the atmosphere, water and land use. The efficient use of materials can be considered as a contributing factor to increased NES performance. In this respect, 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).

Following the recommendations of Ref. [5.2], five KIs were chosen for the evaluation of considered NESs in the safety area, namely:

(a) Potential to prevent release (S1);
(b) Design concept specific inherent and passive safety features and systems (S2);
(c) Core damage and large early release frequencies (S3);
(d) Source term (S4);
(e) Short term and long term accident management (S5).

An important step in the NES evaluation concerns the maturity of the technology, an aspect that is also included in the INPRO methodology [5.2]. The assessment of an NES's ability to fulfil the criteria, user requirements and basic principles needs to be completed by a judgement concerning the level of maturity of the INES. The higher the uncertainty, the greater the risk that development objectives will not be fully met and that the costs of development will exceed the estimated costs. The effort required to advance an innovation from the pre-conceptual stage to the commercially proven stage is addressed.

For the evaluation of considered NESs in the maturity of technology area, three KIs have been selected in a comprehensive approach:

(a) Design stage (M1);
(b) Time needed to mature the technology (M2);
(c) Degree of standardization and licensing adaptability (M3) (higher value is better for evaluation).

The nuclear technology could contribute to the development of the country on multiple levels (economy, society, infrastructure, R&D, human resources, education, culture, etc.) based on the following aspects:

(a) Stimulation of national research through the active involvement of R&D organizations and industry in programmes of international interest.
(b) Reinforcement of the R&D groups by adding relevant experimental facilities, together with specific methods and tools.
(c) Reduction of the loss of highly qualified human resources and young talent (in Romania, the effect of the migration of talented researchers to Western research organizations is relatively strong).
(d) Implementation of a high level technology and consolidation of the position of the country in the nuclear sector, including aspects derived from intellectual property and the quality of the R&D.
(e) Increasing the spirit of innovation and the quality of research.
(f) Improvement of experimental and testing infrastructure leading to the deep involvement of the country in nuclear technology development.
(g) Better sustainability of the use of natural resources (for example, Romania currently uses the natural uranium option with a low efficiency in the use of resources — less than 0.5%; the implementation of LFRs as a strategy will increase the efficiency of the use of resources to as close to 100% as the technological limits of the reprocessing techniques allow).
(h) Stimulation of national, regional and local development by creating new direct and indirect jobs, and keeping high expertise personnel such as senior researchers, researchers and technicians with large experience of complex technologies.
(i) Stimulation of the education and training sector (general quality of education and training, and also higher education in technical areas being more attractive through the perception of future jobs being available and access to valuable laboratories and experimental facilities).
(j) Stimulation for stakeholders to get involved and invest in the community in terms of education, health or infrastructure development.
(k) Strengthening of the local economy through investment and the stimulation of commercial activities (tourism, services such as education, health, transport, recreation, etc.).
(l) Improvement of human and social capital — the social capital relates to research facilities being a magnet for the best researchers, influencing the mobility of students and scientists (a major mechanism through which knowledge flows) and contributing to capacity building through training and learning effects. The human capital that is built through meaningful interactions between people in turn facilitates learning and the use of skills and knowledge.

The present case study included the country specifics area in the high level objective acceptability in order to address the importance of local considerations in the evaluation. Two KIs were chosen to introduce the country specifics in the evaluation of the selected NESs, namely:

(a) Socioeconomic impact (CS1), quantified by:
   (i) Number of new jobs created by implementation of the technology and number of jobs maintained;
   (ii) Stimulation of the national and local economy (number of spin-offs, newly created small and medium enterprises, new products, improvements to the quality of products and services, budgetary impact from local taxes, contribution to GDP);
   (iii) Impact on consolidation of the nuclear sector of the country;
   (iv) Keeping young talent in the country and the nuclear sector through the attractiveness of the field.

(b) Technological impact on national R&D (CS2), evaluated using the following elements:
   (i) Number of newly generated research themes, projects or national programmes;
   (ii) Number of publications and generated patents;
   (iii) Number of newly generated international collaborations;
   (iv) Capacity to stimulate the expansion of new R&D infrastructure;
   (v) Impact on the quality of human resources (including education and training aspects) and knowledge capital.

The objectives tree structure for the case study, including the high level objectives (cost, performance and acceptability), the evaluation areas (safety, economics, waste management, environment, proliferation resistance, maturity of technology and country specifics) and the corresponding KIs, is illustrated in Fig. 5.22.

5.4.1.5. Evaluation of indicators, including uncertainties

The multi-criteria comparison performed for evolutionary and innovative NES technologies included several steps, according to the KIND-ET evaluation template:

(a) Preparation of performance table by scoring considered NES technologies for each KI;
(b) Evaluation of the weighting factors according to the weights chosen for high level objectives, evaluation areas and KIs specific for each evaluation area;
(c) Determination of the single-attribute value functions for each KI, according to the corresponding goals to be achieved;
(d) Selection of the value function form and domain (local or global);
(e) Obtaining the ranking results, including the multi-attribute value function and corresponding scores for high level objectives and evaluation areas;
(f) Performance of the sensitivity analysis;
(g) Elaboration of the obtained results.

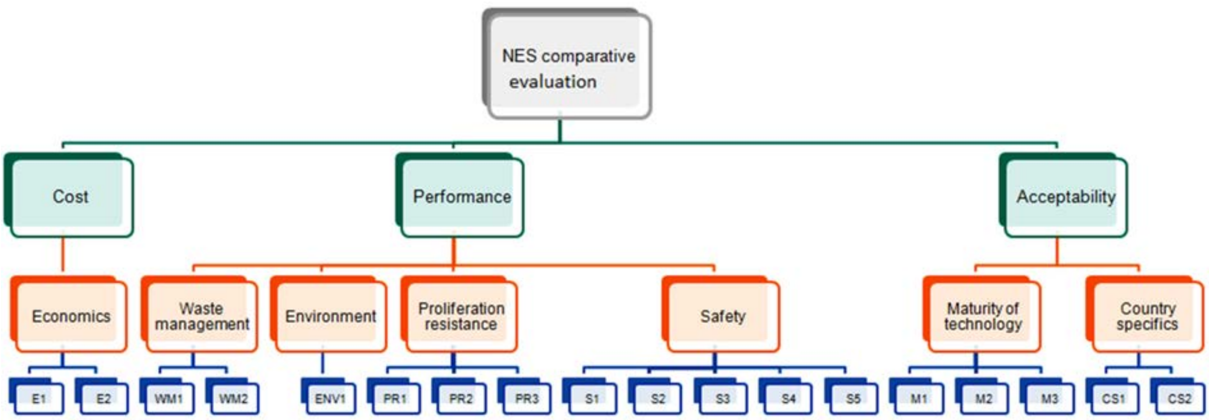


FIG. 5.22. Objectives tree structure for the case study.

The values for each KI corresponding to the NES technologies considered have been established using a 10 point scoring scale, in accordance with the assumptions regarding the goals to be achieved for each KI. Therefore, as a general rule, if the goal defined for a KI is to be maximum (=10), then 6 is better than 2 (because 6 is closer to 10 than 2); consequently, the technology with KI = 6 is better than the one with KI = 2 for that specific KI. If the goal defined for a KI is to be minimum (=1), then 3 is better than 8 (because 3 is closer to 1 than 8); for this specific KI, the technology with KI = 3 is better than the one with KI = 8.

Table 5.23 presents the performance table prepared by the Romanian experts for the case study. For better understanding, in addition to the performance table provided in the KIND-ET evaluation tool, the goals for each KI were included. It is worth mentioning that the scores for the NES technologies considered represent the experts' opinions, without involving any official plans or documents. As previously mentioned, the following acronyms were used for NES technologies: CANDU (existing CANDU NES), ENES (evolutionary NES) and INES (innovative NES).

In the preliminary phase of the case study, the analyses were performed by considering initially equal weights for high level objectives, evaluation areas and KIs, and screening for realistic solutions to be further considered in the elements weighting by means of the sensitivity analyses. The scores for KIs have been selected considering both a 2 point scoring scale and a 10 point scoring scale, with the use of local or global ranges being another critical issue. A couple of uncertainty analyses were also performed in order to support the consistency and robustness of the obtained results.

5.4.1.6. Selection of an MCDA method

Many MCDA techniques have been developed to deal with different kinds of problems. Depending on the problem context analysis and the quality of the initial information provided by the experts, the most appropriate method for a particular problem can be chosen. The MAVT technique has been applied to a wide range of decision making problems in the area of multi-criteria evaluation of nuclear reactors with respect to NFCs and NESs.

The NES evaluation proposed in the case study has been performed by applying the KIND-ET evaluation template. KIND-ET uses the MAVT technique, combining different measures of costs, risks and benefits along with expert and decision maker preferences into a high level aggregated performance index — the multi-attribute value function.

5.4.1.7. Determination of weights, including uncertainties

The results obtained in the preliminary analyses of the case study recommended several weighting solutions for the objectives tree levels (high level objectives, evaluation areas and KIs) and the case study applied them in various combinations to develop the proposed comparative evaluation. The working cases (different ratings for objectives tree levels) were as follows:

(a) Case 1 — Ratings for high level objectives: cost 50%, performance 30%, acceptability 20%; the ratings for elements of the objectives tree are presented in detail in Table 5.24 (final weights calculated with KIND-ET are also shown).
    (i) Case 1a — Ratings for high level objectives and KIs are the same as for case 1; different ratings for evaluation areas in the performance high level objective: waste management 25%, proliferation resistance 23%, environment 6%, safety 46%;
    (ii) Case 1b — Ratings for high level objectives and KIs are the same as for case 1; different ratings for evaluation areas in the performance high level objective: waste management 25%, proliferation resistance 20%, environment 5%, safety 50%;
    (iii) Case 1c — Ratings for high level objectives and evaluation areas are the same as for case 1; different ratings for KIs in the cost high level objective: E1 50%, E2 50%.
(b) Case 2 — Ratings for high level objectives: cost 30%, performance 50%, acceptability 20%; the ratings for the evaluation areas and KIs are as in Table 5.24.
    (i) Case 2a — Ratings for high level objectives and KIs are the same as for case 2; different ratings for evaluation areas in the performance high level objective: waste management 25%, proliferation resistance 23%, environment 6%, safety 46%;

TABLE 5.23. PERFORMANCE TABLE PREPARED FOR THE CASE STUDY

High level objectives	Evaluation areas	KIs	KIs abbr.	Goals	ENES	INES	CANDU
Cost	Economics	Levelized energy product or service cost	E1	Min	5	3	6
		R&D cost	E2	Min.	3	7	1
Performance	Waste management	Specific radioactive waste inventory	WM1	Min.	6	2	7
		SNF cost	WM2	Min.	6	2	5
	Proliferation resistance	Attractiveness of nuclear material	PR1	Min.	3	4	2
		Attractiveness of technology	PR2	Min.	3	4	2
		Safeguards approach identified	PR3	Max.	7	4	9
	Environment	Amount of useful energy produced by the system from a unit of mined natural uranium	ENV1	Max.	4	7	2
	Safety	Potential to prevent release	S1	Max.	5	7	4
		Design concept specific inherent and passive safety features and systems	S2	Max.	4	8	2
		Core damage and large early release frequencies	S3	Min.	4	2	5
		Source term	S4	Min.	4	2	4
		Short term and long term accident management	S5	Max.	5	7	5
Acceptability	Maturity of technology	Design stage	M1	Max.	8	4	9
		Time needed to mature the technology	M2	Min.	3	6	1
		Degree of standardization and licensing adaptability	M3	Max.	6	3	8
	Country specifics	Socioeconomic impact	CS1	Max.	6	8	3
		Technological impact on national R&D	CS2	Max.	4	8	2

Note: SNF — spent nuclear fuel.

(ii) Case 2b — Ratings for high level objectives and KIs are the same as for case 2; different ratings for evaluation areas in the performance high level objective: waste management 25%, proliferation resistance 20%, environment 5%, safety 50%;

(iii) Case 2c — Ratings for high level objectives and evaluation areas are the same as for case 2; different ratings for KIs in the cost high level objective: E1 50%, E2 50%.

(c) Case 3 — Ratings for high level objectives: cost 40%, performance 40%, acceptability 20%; the ratings for the evaluation areas and KIs are as in Table 5.24.

(i) Case 3a — Ratings for high level objectives and KIs are the same as for case 3; different ratings for evaluation areas in the performance high level objective: waste management 25%, proliferation resistance 23%, environment 6%, safety 46%;
(ii) Case 3b — Ratings for high level objectives and KIs are the same as for case 3; different ratings for evaluation areas in the performance high level objective: waste management 25%, proliferation resistance 20%, environment 5%, safety 50%;
(iii) Case 3c — Ratings for high level objectives and evaluation areas are the same as for case 3; different ratings for KIs in the cost high level objective: E1 50%, E2 50%.

It is worth mentioning that the working cases 1a, 1b, 1c, 2a, 2b, 2c, 3a, 3b and 3c were in fact treated as sensitivity analyses for case 1, case 2 and case 3. The final weights calculated using the KIND-ET for the cases mentioned above are shown in Tables 5.25–5.27.

5.4.1.8. Ranking alternatives (NES options) with the selected MCDA method and interpretation of results with relevance to objectives at different levels

The results obtained in the comparative evaluation of evolutionary and innovative NES technologies are presented in this section for the three level objectives tree considered.

The ranking results for the NES technologies for the multi-attribute value function are presented in Table 5.28 with respect to the three main working cases.

As can be seen from the results, the INES technology seems to be more attractive than the ENES technology, with the ENES multi-attribute value function values being lower than those for INES by 8.5% in case 1, by 16.3% in case 2 and by 12.3% in case 3. The CANDU NES technology has the lowest overall scores, with these being lower than the INES overall scores by 9.4% in case 1, by 18.0% in case 2 and by 13.6% in case 3.

Figures 5.23 and 5.24 illustrate the scores obtained for the high level objectives and evaluation areas, respectively, with respect to the three main working cases. The evaluation area scores are also presented in Table 5.29 to show their contribution to the high level objective scores.

TABLE 5.24. WEIGHTS FOR THE OBJECTIVES TREE ELEMENTS (CASE 1)

High level objectives	High level objective weights	Evaluation areas	Area weights	KIs abbr.	KI weights	Final weights
Cost	0.500	Economics	1.000	E1	0.700	0.350
				E2	0.300	0.150
Performance	0.300	Waste management	0.300	WM1	0.500	0.045
				WM2	0.500	0.045
		Proliferation resistance	0.200	PR1	0.333	0.020
				PR2	0.333	0.020
				PR3	0.333	0.020
		Environment	0.100	ENV1	1.000	0.030
		Safety	0.400	S1	0.200	0.024
				S2	0.200	0.024
				S3	0.200	0.024
				S4	0.200	0.024
				S5	0.200	0.024
Acceptability	0.200	Maturity of technology	0.700	M1	0.333	0.047
				M2	0.333	0.047
				M3	0.333	0.047
		Country specifics	0.300	CS1	0.500	0.030
				CS2	0.500	0.030

TABLE 5.25. FINAL WEIGHTS FOR CASE 1 AND RELATED SENSITIVITY CASES

High level objectives	Evaluation areas	KIs abbr.	Final weights			
			Case 1	Case 1a	Case 1b	Case 1c
Cost	Economics	E1	0.350	0.350	0.350	0.250
		E2	0.150	0.150	0.150	0.250
Performance	Waste management	WM1	0.045	0.038	0.038	0.045
		WM2	0.045	0.038	0.038	0.045
	Proliferation resistance	PR1	0.020	0.023	0.020	0.020
		PR2	0.020	0.023	0.020	0.020
		PR3	0.020	0.023	0.020	0.020
	Environment	ENV1	0.030	0.018	0.015	0.030
	Safety	S1	0.024	0.028	0.030	0.024
		S2	0.024	0.028	0.030	0.024
		S3	0.024	0.028	0.030	0.024
		S4	0.024	0.028	0.030	0.024
		S5	0.024	0.028	0.030	0.024
Acceptability	Maturity of technology	M1	0.047	0.047	0.047	0.047
		M2	0.047	0.047	0.047	0.047
		M3	0.047	0.047	0.047	0.047
	Country specifics	CS1	0.030	0.030	0.030	0.030
		CS2	0.030	0.030	0.030	0.030

TABLE 5.26. FINAL WEIGHTS FOR CASE 2 AND RELATED SENSITIVITY CASES

High level objectives	Evaluation areas	KIs abbr.	Final weights			
			Case 2	Case 2a	Case 2b	Case 2c
Cost	Economics	E1	0.210	0.210	0.210	0.150
		E2	0.090	0.090	0.090	0.150
Performance	Waste management	WM1	0.075	0.063	0.063	0.075
		WM2	0.075	0.063	0.063	0.075
	Proliferation resistance	PR1	0.033	0.038	0.033	0.033
		PR2	0.033	0.038	0.033	0.033
		PR3	0.033	0.038	0.033	0.033
	Environment	ENV1	0.050	0.030	0.025	0.050
	Safety	S1	0.040	0.046	0.050	0.040
		S2	0.040	0.046	0.050	0.040
		S3	0.040	0.046	0.050	0.040
		S4	0.040	0.046	0.050	0.040
		S5	0.040	0.046	0.050	0.040
Acceptability	Maturity of technology	M1	0.047	0.047	0.047	0.047
		M2	0.047	0.047	0.047	0.047
		M3	0.047	0.047	0.047	0.047
	Country specifics	CS1	0.030	0.030	0.030	0.030
		CS2	0.030	0.030	0.030	0.030

TABLE 5.27. FINAL WEIGHTS FOR CASE 3 AND RELATED SENSITIVITY CASES

High level objectives	Evaluation areas	KIs abbr.	Final weights			
			Case 3	Case 3a	Case 3b	Case 3c
Cost	Economics	E1	0.280	0.280	0.280	0.200
		E2	0.120	0.120	0.120	0.200
Performance	Waste management	WM1	0.060	0.050	0.050	0.060
		WM2	0.060	0.050	0.050	0.060
	Proliferation resistance	PR1	0.027	0.031	0.027	0.027
		PR2	0.027	0.031	0.027	0.027
		PR3	0.027	0.031	0.027	0.027
	Environment	ENV1	0.040	0.024	0.020	0.040
	Safety	S1	0.032	0.037	0.040	0.032
		S2	0.032	0.037	0.040	0.032
		S3	0.032	0.037	0.040	0.032
		S4	0.032	0.037	0.040	0.032
		S5	0.032	0.037	0.050	0.032
Acceptability	Maturity of technology	M1	0.047	0.047	0.047	0.047
		M2	0.047	0.047	0.047	0.047
		M3	0.047	0.047	0.047	0.047
	Country specifics	CS1	0.030	0.030	0.030	0.030
		CS2	0.030	0.030	0.030	0.030

TABLE 5.28. OVERALL SCORES FOR CONSIDERED NES

Working case	ENES	INES	CANDU
Case 1	0.592	0.642	0.587
Case 2	0.571	0.664	0.563
Case 3	0.582	0.653	0.575

Different high level objective ratings lead to an increase in the overall scores obtained by NES technologies that receive a more favourable evaluation for a particular high level objective whose rating has been increased. For example, when modifying the ratings for the high level objectives cost (reducing it from 50% to 30%) and performance (increasing it from 30% to 50%), the multi-attribute value function for the INES increases by 3.5%; meanwhile, the multi-attribute value function for the ENES and CANDU decreases by 16.3% and 18%, respectively.

INES receives a more favourable evaluation for the high level objective performance, which is a realistic result, taking into account the improvements that the INES technology makes in the evaluation areas of safety, waste management and environment. As shown in Fig. 5.23, the INES values for the high level objective performance are 46% higher than those for the ENES and 54% higher than those for CANDU (the ENES values are 5.8% higher than the CANDU ones). The ENES and CANDU receive a more favourable evaluation for the high level objective acceptability, which is a realistic result given the good scores for the maturity of technology evaluation area as compared to those for the INES. As can be observed in Fig. 5.23, the INES values for the high level objective acceptability are 34% lower than those for the ENES and 44% lower than those for CANDU.

With regard to the scores for the high level objective cost, INES obtained slightly higher values than the ENES (3.6% lower than the INES values) and CANDU (5.4% lower than the INES values). The small differences in the evaluation of NES technologies for the high level objective cost can be explained through the ratings of KIs

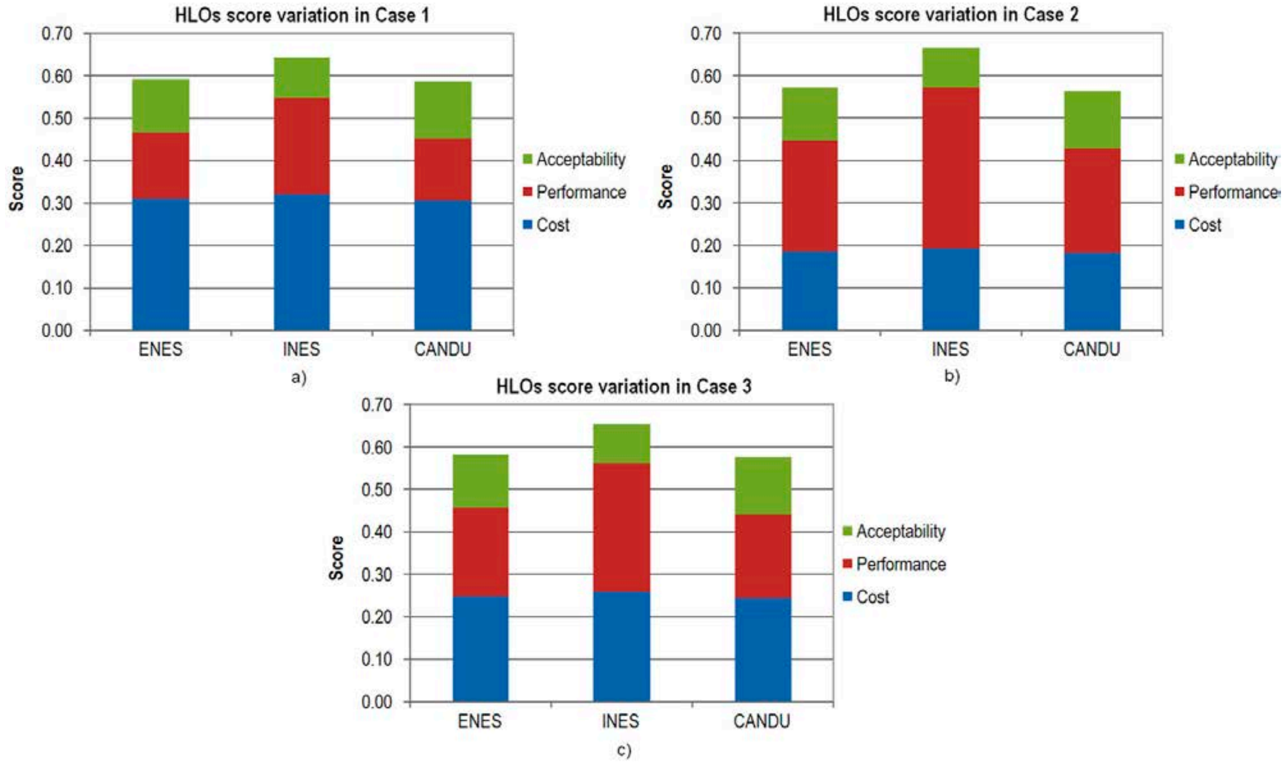


FIG. 5.23. High level objective scores for the main working cases. (a) Case 1; (b) case 2; (c) case 3.

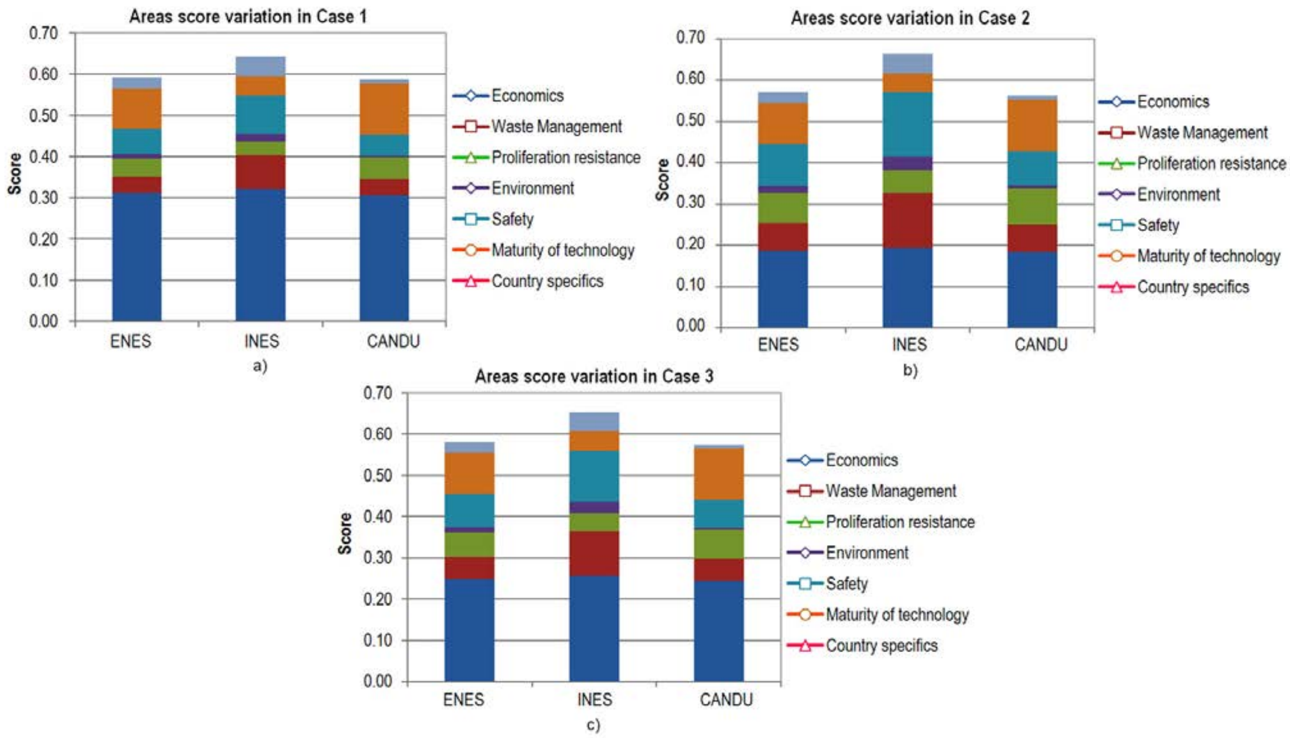


FIG. 5.24. Evaluation of area scores for the main working cases. (a) Case 1; (b) case 2; (c) case 3.

TABLE 5.29. EVALUATION AREA SCORES FOR CONSIDERED NESs

Evaluation area	Case 1			Case 2			Case 3		
	ENES	INES	CANDU	ENES	INES	CANDU	ENES	INES	CANDU
Economics	0.311	0.322	0.306	0.187	0.193	0.183	0.249	0.258	0.244
Waste management	0.040	0.080	0.040	0.067	0.133	0.067	0.053	0.107	0.053
Proliferation resistance	0.044	0.033	0.053	0.074	0.056	0.089	0.059	0.044	0.071
Environment	0.010	0.020	0.003	0.017	0.033	0.006	0.013	0.027	0.004
Safety	0.061	0.093	0.051	0.102	0.156	0.084	0.082	0.124	0.068
Maturity of technology	0.098	0.047	0.124	0.098	0.047	0.124	0.098	0.047	0.124
Country specifics	0.027	0.047	0.010	0.027	0.047	0.010	0.027	0.047	0.010

in the economics area. In the performance table, INES has a more favourable score than the ENES and CANDU for E1 (LUEC — 70% rating), but it was pulled back by the poor score for E2 (R&D costs — 30% rating), so the differences between the INES and the ENES and CANDU have reduced.

5.4.1.9. Sensitivity and uncertainty analysis

The results for the sensitivity analysis are presented below. As previously mentioned, these results were obtained for the working cases for which the ratings were changed for the evaluation areas or the economics KIs (cases 1a, 1b, 1c, 2a, 2b, 2c, 3a, 3b and 3c).

The ratings for the evaluation areas of the performance high level objective were changed in working cases 1a, 2a, 3a, and 1b, 2b and 3b, as presented in Table 5.30 (shown for case 1, but applies also to cases 2 and 3). The interest in these sensitivity analyses was dictated by the fact that the INES technology is promoted by the high level objective performance (the safety and waste management areas, in particular).

The overall scores were modified slightly for the ENES and CANDU (increased by less than 2.5%) and not modified for the INES (for the second choice of weights), as can be seen in Table 5.31. The overall scores for the base cases (main working cases) were also included in the table as a reference. The INES maintains its leading position in the comparative evaluation, even if its corresponding overall scores decrease or remain the same as in the base case.

For the second sensitivity analysis case, the ratings changed for the economics area KIs. Equal ratings were considered for both KIs, increasing the importance and consideration of the R&D costs in the high level objective cost (the R&D costs KI pulls back the cost scores for the INES). The multi-attribute value function values for the considered NES technologies are given in Table 5.32. The multi-attribute value function values for the reference cases (main working cases) are also included.

Using equal ratings for both economics area KIs led to a reduction of the overall scores for the INES (which is natural, as long as the R&D costs for INESs are much higher than for the other two NES technologies, so the score in the performance table is very low). The multi-attribute value function values for the INES decreased by 7% in case 1c, by 4% in case 2c and by 5.4% in case 3c. The INES still attracted the best score for case 2c, while for case 3c its score was only 0.3% lower than that for CANDU, which received the highest score. In fact, equal ratings for the economics area KIs place the CANDU technology on top, with the overall scores obtained by CANDU placing it first in cases 1c (the multi-attribute value function value increased by 9.5% compared to the reference value from case 1) and 3c (the multi-attribute value function value increased by 7.7% compared to the reference value from case 3).

The comparative evaluation was performed while employing a linear form for the single-attribute function. To study the effect of the value function form on the multi-attribute value function, the exponential form was employed, with the exponent power equal to unity. The results are presented in Table 5.33, together with the reference multi-attribute value function values for the main working cases.

TABLE 5.30. MODIFIED RATINGS FOR EVALUATION AREAS FROM THE HIGH LEVEL OBJECTIVE PERFORMANCE

High level objectives	Evaluation areas	Areas weights (%)		
		Case 1	Case 1a	Case 1b
Cost	Economics	100	100	100
Performance	Waste management	30	25	25
	Proliferation resistance	20	23	20
	Environment	10	6	5
	Safety	40	46	50
Acceptability	Maturity of technology	70	70	70
	Country specifics	30	30	30

TABLE 5.31. OVERALL SCORE VARIATION FOR MODIFIED EVALUATION AREA RATINGS

Working case	ENES	INES	CANDU
Case 1 (reference)	0.592	0.642	0.587
Case 1a	0.597	0.640	0.595
Case 1b	0.596	0.642	0.591
Case 2 (reference)	0.571	0.664	0.563
Case 2a	0.580	0.660	0.576
Case 2b	0.577	0.664	0.570
Case 3 (reference)	0.582	0.653	0.575
Case 3a	0.589	0.650	0.585
Case 3b	0.587	0.653	0.581

TABLE 5.32. OVERALL SCORES FOR MODIFIED ECONOMICS KI RATINGS

Working case	ENES	INES	CANDU
Case 1 (reference)	0.592	0.642	0.587
Case 1c	0.614	0.598	0.643
Case 2 (reference)	0.571	0.664	0.563
Case 2c	0.585	0.638	0.596
Case 3 (reference)	0.582	0.653	0.575
Case 3c	0.599	0.618	0.620

The exponential form for the single-attribute function leads to a decrease in the multi-attribute value function values; for the working cases considered, the values obtained were lower by 24% for the ENES, 16% for the INES and 15% for CANDU. Given that the exponential form for the single-attribute function does not affect the INES's leading position, this technology obtains the best ranking.

TABLE 5.33. MULTI-ATTRIBUTE VALUE FUNCTION SENSITIVITY TO VALUE FUNCTION FORM

Working case	Value function form	ENES	INES	CANDU
Case 1	Linear	0.592	0.642	0.587
	Exponential	0.480	0.549	0.508
Case 2	Linear	0.571	0.664	0.563
	Exponential	0.460	0.574	0.483
Case 3	Linear	0.582	0.653	0.575
	Exponential	0.470	0.561	0.496

5.4.1.10. Conclusion

The KIND approach has been applied to perform a comparative evaluation for different NES technologies (evolutionary, innovative and CANDU (well proven) technologies) by means of the KIND-ET evaluation tool.

The KIND approach helps to communicate the positive potential of innovative technologies by providing a correct picture of them, if the approach is applied properly.

For the main working cases considered (cases 1, 2 and 3, with different ratings for high level objectives), the overall scores obtained by 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).

The case study analyses could obtain more weight by including a two level tree analysis based on benefits versus risks for the NES technologies considered, as long as these important elements are always associated with strategic importance, especially on the decision making level.

The sensitivity analyses were performed for two situations, namely considering different ratings for the evaluation areas in the high level objective performance (where the INES has a better ranking) and selecting equal ratings for the economics area KIs in the high level objective cost (therefore increasing the importance of R&D costs and affecting the ranking of the INES with unfavourable scores for this KI). The ranking results proved the reliability and robustness of the evaluation.

KIND-ET is a flexible evaluation tool that uses the MAVT technique. It allows the implementation of different approaches for comparative evaluation, offers the possibility of performing sensitivity analyses and enables graphical representation of the ranking results. One of the critical issues is related to the selection of local versus global domains. KIND-ET proved very useful and could be recommended to be further applied for NES evaluation.

The KIND approach appears to be sound, but in each case, country specific conditions need to be taken into account, as they can significantly impact the ranking of the considered technologies.

Romanian energy policy in the near term (2015–2035) is strategically directed towards security of energy, sustainable development and economic competitiveness, with respect to the European Union Energy Policy. Nuclear power is a reliable source of energy in the national energy mix for assuring Romania’s energy needs through a balanced portfolio of energy sources, including fossil fuel (coal and natural gas) power plants and renewables (hydropower plants, wind farms and photovoltaic power stations).

The comparative evaluations of energy systems by means of the KIND approach can offer reliable support for decision making, taking into consideration the possibility of defining alternatives by using various objectives tree options according to the interests or aspects required by the decision makers. The flexibility of the KIND evaluation tool means that a variety of options for defining and ranking the high level objectives, corresponding evaluation areas and appropriate KIs are available to accomplish the targeted goals of the comparative evaluation.

The 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.

5.5. EVOLUTIONARY VERSUS EVOLUTIONARY NESs

5.5.1. Armenian case study

5.5.1.1. Introduction

The most important issue for the Republic of Armenia is to choose a new nuclear option, which will replace the existing unit after its decommissioning in 2026. The latest strategies for the development of the Armenian energy system are formulated in a Republic of Armenia governmental decree that was adopted in December 2015 and contained a long term (up to 2036) energy sector development strategy (referred to as 'Strategy' hereafter). This Strategy provides various possible expansion plans for the Armenian energy system, including different nuclear options. The future development of the Armenian energy system is expected to be mainly based upon nuclear energy and modern gas fired power generation plants, the development and expansion of economically viable and technically available renewable energy sources, and the diversification of fuel supply chains. At the same time, the Strategy document has not provided a final decision about the technologies expected to be implemented in the system.

The main goal of the present study is to clarify and select the most attractive nuclear option for Armenia reflected in the Strategy by carrying out some additional evaluations and comparative analyses. For this purpose, the KIND approach and KIND-ET evaluation tool have been used. This report summarizes the main findings of the study.

5.5.1.2. Objective and problem formulation

This evaluation was based on the data and outcomes for the development pathways of the Armenian energy system. More than 40 scenarios with different energy generation technologies were considered, including thermal and renewable options. From these scenarios, the main nuclear (i.e. the WWER-1000, the CANDU 6, a small modular reactor (SMR) with a capacity of 360 MW(e) and the ACP-600) and thermal expansion plans have been selected for this study. Table 5.34 presents the main economic data for these scenarios, which were extracted from calculations completed during the preparation of the Strategy.

The results show that the parameters for the selected scenarios' outcomes are close to each other. The existence of such small differences creates problems for making the final decision on technology selection. Thus, the objective of this study was formulated as follows: "to identify the best solution for NES development in Armenia by making comparative evaluation of nuclear technologies using the KIND approach".

According to this approach, to perform a multi-criteria comparison using the MAVT method, it is necessary:

(1) To prepare a performance table;
(2) To evaluate weighting factors;
(3) To determine single-attribute value functions for each indicator;
(4) To interpret ranking results;

TABLE 5.34. MAIN ECONOMIC INDICATORS BY SCENARIOS

Scenario	Levelized long term average NPP production cost (US \$/MW(e)·h)	Power system long term average generation cost (US \$/MW(e)·h)	New generation investment cost[a] (billion US \$)	Whole energy system cost[b] (billion US \$)
WWER-1000	91	75.9	8.6	44.6
CANDU 6	73	69.2	7.0	44.0
SMR (360 MW(e))	97	77.1	6.9	44.7
ACP-600	71	73.2	5.0	44.3
No nuclear	0	78.3	2.4	44.9

[a] Comprising investments in all new generation facilities (NPP, thermal power plant, renewables).

[b] Includes investments in new generation and new demand facilities, fixed, operation and maintenance costs, and fuel costs for the whole planning period (20 years) and all types of energy carriers.

(5) To perform sensitivity analysis;
(6) To formulate recommendations.

5.5.1.3. Formulation of alternatives (NES options)

An important point for officials to be aware of is the economic burden of energy system developments. Thus, the key system costs have been included in this comparative evaluation study. It is important to present both nuclear and non-nuclear scenarios to decision makers, in addition to the comparison of nuclear options. These topics are included in this study. All of the selected nuclear options, as well the 'no nuclear' case, have been identified as NES alternatives described in the KIND approach. Possible utilization of these alternatives is based on their acceptability for the country's energy system. The country's environmental issues have also been considered as one of the main selection criteria.

Some of the main characteristics of the selected NPPs (presented in Table 5.35) were also taken into account in this evaluation.

The next sections present the study results obtained by following the steps defined above.

5.5.1.4. Identification of indicators

Comparative evaluation was performed by considering the four above mentioned NES options, namely the WWER-1000, the CANDU 6, the SMR and the ACP-600, in addition to the no nuclear case (development without a nuclear option). For this purpose, 11 KIs have been identified in accordance with the requirements of the KIND approach. It was decided not to use SIs. The selected KIs and their abbreviations were as follows:

(1) E.1 — Levelized long term average NPP production cost;
(2) E.2 — Power system long term average generation cost;
(3) E.3 — New generation investment cost;
(4) E.4 — Whole energy system cost;

TABLE 5.35. TECHNICAL AND ECONOMIC DATA FOR SELECTED NPPS

Indicator	Units	WWER-1000	CANDU 6	SMR	ACP-600[a]
Unit capacity	MW(e)	1028	670	360	610
Maximum annual production	GW(e)·h/year	8105	5282	2838	4809
Efficiency	%	34.2	33.2	34	34.2
Investment[b]	Million US $	5377	2141	2156	2440
Spent fuel cost	US $/MW(e)·h	1.77	5.35	1.03	1.77
Variable costs	US $/MW(e)·h	0.67	0.73	0.87	0.67
Total variable costs	US $/MW(e)·h	2.44	6.07	1.90	2.44
Fresh fuel cost	US $/MW(e)·h	6.90	2.92	7.76	6.90
Specific investment	US $/kW(e)	5230	3196	5988	4000
Specific fixed costs	US $/kW(e) /year	70.24	75.78	91.04	70.24
Fixed costs[c]	Million US $/year	72.20	50.77	32.78	42.85
Construction period	Years	6	6	4	6

[a] All costs are estimated because of the lack of exact economic indicators for the ACP-600 reactor.
[b] Construction cost of the plant.
[c] Decommissioning costs have been included in the fixed costs.

(5) WM.1 — Specific radioactive waste inventory;
(6) CS.1 — Energy independence level;
(7) ENV.1 — Amount of useful energy produced by the system from a unit of mined natural uranium/thorium;
(8) M.1 — Design stage;
(9) M.2 — Time needed to mature the technology for Armenia;
(10) M.3 — Degree of standardization and licensing adaptability for Armenia;
(11) PA.1 — Public acceptability to use nuclear energy.

These performance indicators were grouped into six evaluation areas:

(1) Economics;
(2) Waste management;
(3) Country specifics;
(4) Environment;
(5) Maturity of technology;
(6) Public acceptance.

Based on the requirements of the KIND approach, three high level objectives characterized by the aggregated goals ‘cost’, ‘performance’ and ‘acceptability’ were chosen and grouped as follows:

(1) Economics — for cost;
(2) Waste management, country specifics and environment — for performance;
(3) Maturity of technology and public acceptance — for acceptability.

Figure 5.25 shows the indicators arranged in an objectives tree.

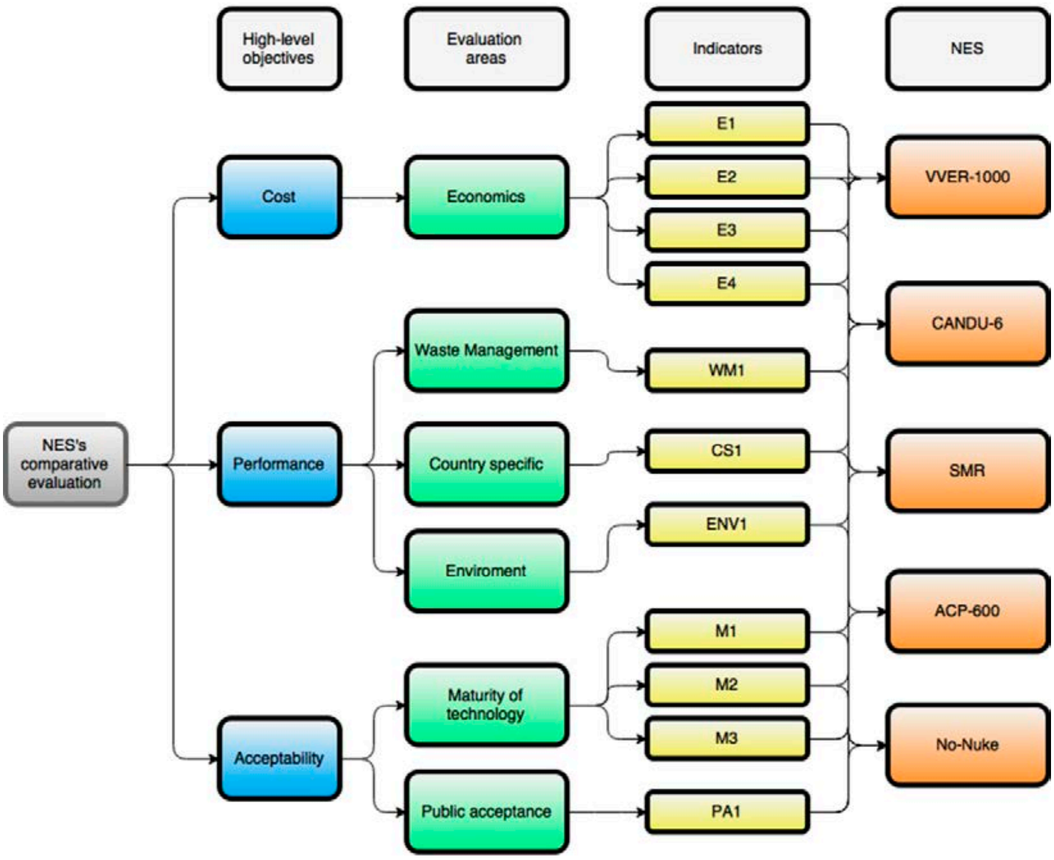


FIG. 5.25. The objectives tree.

5.5.1.5. Evaluation of indicators, including uncertainties

The values of all KIs for the NESs considered are presented in the performance table (Table 5.36) for the problem. This was prepared in accordance with the assumptions regarding the goals to be achieved for each KI. The assumptions are given below, in addition to explanations of the numerical values of the scores and weighting factors:

(1) E.1 — Real numerical values from Table 5.34 with the same column name were used. It should be noted that this indicator for the no nuclear case is presented via the levelized long term average production cost for the thermal power plant. They need to be minimized.
(2) E.2 — Real numerical values from Table 5.34 with the same column name were used. They need to be minimized.
(3) E.3 — Real numerical values from Table 5.34 with the same column name were used. They need to be minimized.
(4) E.4 — Real numerical values from Table 5.34 with the same column name were used. They need to be minimized.
(5) WM.1 — Real numerical values for SNF costs were used (Table 5.35). A CO_2 emission cost of US $8/MW(e)·h was used for the no nuclear case. Values need to be minimized.
(6) CS.1 — Real numerical values for generation share in the total generation mix for domestic energy sources were used. The numbers were obtained from a series of calculations performed during the preparation of the Strategy. Generation from all NPPs was considered to be generation from a domestic energy source, with the exception of CANDU 6, which requires continuous fuel supply. Values need to be maximized.
(7) ENV.1 — Real numerical values (in tonnes per million MW(e)·h) were used. The quantity of natural gas required to produce one million kW(e)·h in a closed cycle gas turbine type thermal power plant was considered for the no nuclear case. Values need to be minimized.
(8) M.1 — A five point scoring scale was used for the evaluation of indicators, where an indicator score value of 1 is the best value, and an indicator score value of 5 is the worst one. For the WWER-1000 and CANDU 6 reactors, as well as for the no nuclear case (closed cycle gas turbine), scores equal to 1 are assigned because the designs already exist. It is assumed that the design of the ACP-600 has progressed further than that for the SMR based on the following quotations. For the ACP-600: "Construction of units is scheduled to begin by 2018" [5.15]. For SMRs: "NuScale was recently awarded funding from the US DOE's SMR development program. The program goal is to promote the deployment of SMRs in the US by 2025" [5.16]. Therefore, the ACP-600 receives a score of 4, while the SMR receives a score of 5. Values need to be minimized.
(9) M.2 — A five point scoring scale was used for the evaluation of indicators, where an indicator score value of 1 is the best value, and an indicator score value of 5 is the worst one. The best score was assigned to the no nuclear option (score is 1) because of the widespread use of thermal power plant technologies in Armenia. It is assumed that the WWER-1000 is more mature in Armenia because its technology is similar to that of the already existing WWER-440 reactor. However, as a new reactor, it will take time for local specialists to become fully familiar with it. As a result, it received a score of 2. The next most suitable reactor is the ACP-600 (score is 3), which is also close to the WWER-440 technology, but still does not exist. The SMR received a score of 4 based on the assumption that its technology is similar to that of the existing reactor (pressurized water reactor (PWR)), but its details are not yet known. The worst score was assigned to the CANDU 6 because it uses completely different technology that has never been used in Armenia before, with it requiring the longest time to become mature. Values need to be minimized.
(10) M.3 — The same five point scoring scale was used for the evaluation of indicators, where an indicator score value of 1 is the best value, and an indicator score value of 5 is the worst one. It is assumed that the highest degree of standardization and licensing adaptability for Armenia is offered by the no nuclear case (score of 1), followed by the WWER-1000 (score of 2), and then by the ACP-600, which requires much greater effort for adaptability (score of 4), and finally, by both the CANDU 6 and the SMR (scores of 5). Values need to be minimized.
(11) PA.1 — A two point scoring scale was used for the evaluation of indicators, where an indicator score value of 1 is the worst value, and an indicator score value of 2 is the best one. Covering electricity demand without nuclear energy may be acceptable for the public. However, it is understood that the development

scenario without a nuclear option is a high risk case for Armenia due to a lack of domestic energy sources. Consequently, it creates substantial dependence on imported fuels. Therefore, the use of nuclear technologies is still acceptable for the country's public. Thus, all nuclear technologies are assigned a score of 2, while no nuclear receives a score of 1. This corresponds to the case of a YES (2)/NO (1) decision. Values need to be maximized.

In accordance with the above descriptions, a performance table was prepared for further evaluation (Table 5.36).

5.5.1.6. Selection of an MCDA method

The foundation of the MAVT method is the use of single-attribute value functions, which can be used when quantitative information is available for each alternative. Every attribute has a value function created for it. These functions transform diverse attributes evaluated on a 'natural' scale to one common, dimensionless scale or score (from 0 to 1), known as a single-attribute value function, in accordance with experts' and decision makers' judgements. These scores are used in further calculations. It should be noted that the MAVT method is quite flexible; it allows the implementation of different approaches to the comparison and differentiation of alternatives, as well as the interpretation of the ranking results. In this study, the proposed MAVT method has been used.

TABLE 5.36. PERFORMANCE TABLE

High level objectives	Areas	Indicators	Indicators abbr.	WWER-1000	CANDU-6	SMR	ACP-600	No nuclear
Cost	Economics	Levelized long term average NPP production cost	E.1	91	73	97	71	103
		Power system long term average generation cost	E.2	75.9	69.2	77.1	73.2	78.3
		New generation investment cost	E.3	8 566	6 986	6 896	5 022	2 431
		Whole energy system cost	E.4	44 555	43 954	44 701	44 347	44 868
Performance	Waste management	Specific radioactive waste inventory	WM.1	1.768 8	5.346	1.029 6	1.768 8	8
	Country specifics	Energy independence level	CS.1	0.585	0.331	0.511	0.500	0.349
	Environment	The amount of useful energy produced by the system from a unit of mined natural uranium/thorium	ENV.1	22.4	18.1	21	21	137 000
Acceptability	Maturity of technology	Design stage	M.1	1	1	5	4	1
		Time needed to mature the technology for Armenia	M.2	2	5	4	3	1
		Degree of standardization and licensing adaptability for Armenia	M.3	2	5	5	4	1
	Public acceptance	Public acceptability of using nuclear energy	PA.1	2	2	2	2	1

5.5.1.7. Determination of weights, including uncertainties

According to the requirements of the KIND approach, each high level objective, area and indicator have been assigned weights, which indicate their level of importance. For Armenia, the most important issue is the cost of energy sector development, and so the weight for the high level objective cost is assigned a value of 0.5, followed by performance with a weight of 0.3 and finally by acceptability with a weight of 0.2.

Of the economics indicators, E.2 (power system long term average generation cost) has the greatest weight (0.4), and is the main indicator for analysing the power system development issues. The next most important indicator is E.4 (whole energy system cost), which has a weight of 0.35. This cost indicates the burden on the whole economy of the country (0.35). The other two indicators in this category (E.3 and E.1) are less significant and have weights of 0.15 and 0.1, respectively.

It should be noted that that for the performance high level objectives, the highest weight is assigned to the country specifics indicator (energy independence level). Historically, Armenia overcame a severe energy and economic crisis resulting from the loss of its energy independence (1991–1995). Therefore, this is assigned a weight of 0.5. Another important issue is radioactive waste management, due to the uncertainty of waste utilization in the future (weight of 0.4). The third area (environment) is not important for the country because it relates to the mining of energy carriers, which is not available in Armenia. Therefore, this is a global environmental problem, which to a large degree does not depend on the country (weight of 0.1).

In the acceptability area, the maturity of technologies (weight of 0.7) is much more important than public acceptance of nuclear energy use (weight of 0.3), because of the above mentioned crisis, which arose due to the closure of an Armenian NPP after an earthquake in December 1988. Hence, the public approves of the use of nuclear energy.

Finally, it should be noted that the time necessary to mature the nuclear technology in the country is a very important issue. It requires a great deal of effort from different bodies and specialists. Hence, this has been assigned a weight of 0.6, while the degree of standardization and licensing adaptability has been assigned a weight of 0.3 and public acceptance has been assigned a weight of 0.1.

Single-attribute linear value functions have been chosen for each indicator according to their meanings as presented in Table 5.37. For most of the indicators, the single-attribute value function is targeted for minimization, whereas only two indicators have this function targeted for maximization (CS.1 and PA.1).

The weights for the evaluation areas and indicators are summarized in Table 5.38.

5.5.1.8. Ranking alternatives (NES options) with the selected MCDA method and interpretation of results with relevance to objectives at different levels

After forming all of the required input data tables, the necessary calculations were performed. The ranking results for the alternatives are presented in Table 5.39. In the subsequent sections, the main results and findings are presented in detail.

(a) Multi-attribute value function

The ranking results for the alternatives are presented in Fig. 5.26. The outcomes show that the most desirable alternative for implementation in Armenia is a medium sized reactor, the ACP-600, with an overall score of 0.658. The CANDU 6 and the WWER-1000 alternatives can be considered as indistinguishable according to the scores of the multi-attribute value functions and take the second and third places, respectively. The worst case for energy system development is the no nuclear scenario, which has a significantly lower ranking value (0.225), and it may not be considered in future investigations.

(b) High level objective scores

For interpretation of the ranking results, it is necessary to decompose the multi-attribute value functions into individual components (Fig. 5.27) in accordance with the specified structure of the objectives tree.

As can be seen from the chart, the CANDU 6 has the best rank for cost (0.441), followed by the ACP-600 (0.305). The ranks of the other three alternatives are very close to each other and significantly lower than the

TABLE 5.37. WEIGHTING FACTORS

High level objectives	High level objective weights	Areas	Area weights	Indicators abbr.	Indicator weights	Final weights
Cost	0.500	Economics	1	E.1	0.10	0.050
				E.2	0.40	0.200
				E.3	0.15	0.075
				E.4	0.35	0.175
Performance	0.300	Waste management	0.4	WM.1	1.00	0.120
		Country specifics	0.5	CS.1	1.00	0.150
		Environment	0.1	ENV.1	1.00	0.030
Acceptability	0.200	Maturity of technology	0.7	M.1	0.10	0.014
				M.2	0.60	0.084
				M.3	0.30	0.042
		Public acceptance	0.3	PA.1	1.00	0.060

TABLE 5.38. SINGLE-ATTRIBUTE VALUE FUNCTIONS

High level objectives	Areas	Indicators abbr.	Goal	Form	WWER-1000	CANDU 6	SMR	ACP-600	No nuclear
Cost	Economics	E.1	Min.	Linear	0.375	0.938	0.188	1.000	0.000
		E.2	Min.	Linear	0.264	1.000	0.132	0.560	0.000
		E.3	Min.	Linear	0.000	0.258	0.272	0.578	1.000
		E.4	Min.	Linear	0.342	1.000	0.183	0.570	0.000
Performance	Waste management	WM.1	Min.	Linear	0.894	0.381	1.000	0.894	0.000
	Country specifics	CS.1	Max.	Linear	1.000	0.000	0.708	0.665	0.070
	Environment	ENV.1	Min.	Linear	1.000	1.000	1.000	1.000	0.000
Acceptability	Maturity of technology	M.1	Min.	Linear	1.000	1.000	0.000	0.250	1.000
		M.2	Min.	Linear	0.750	0.000	0.250	0.500	1.000
		M.3	Min.	Linear	0.750	0.000	0.000	0.250	1.000
	Public acceptance	PA.1	Max	Linear	1.000	1.000	1.000	1.000	0.000

TABLE 5.39. NUMERICAL VALUES OF RANKING RESULTS

Levels	WWER-1000	CANDU 6	SMR	ACP-600	No nuclear
Multi-attribute value function	0.587	0.591	0.425	0.658	0.225
			High level objective scores		
Cost	0.131	0.441	0.088	0.305	0.075
Performance	0.287	0.076	0.256	0.237	0.010
Acceptability	0.169	0.074	0.081	0.116	0.140
			Area scores		
Economics	0.131	0.441	0.088	0.305	0.075
Waste management	0.107	0.046	0.120	0.107	0.000
Country specifics	0.150	0.000	0.106	0.100	0.010
Environment	0.030	0.030	0.030	0.030	0.000
Maturity of technology	0.109	0.014	0.021	0.056	0.140
Public acceptance	0.060	0.060	0.060	0.060	0.000

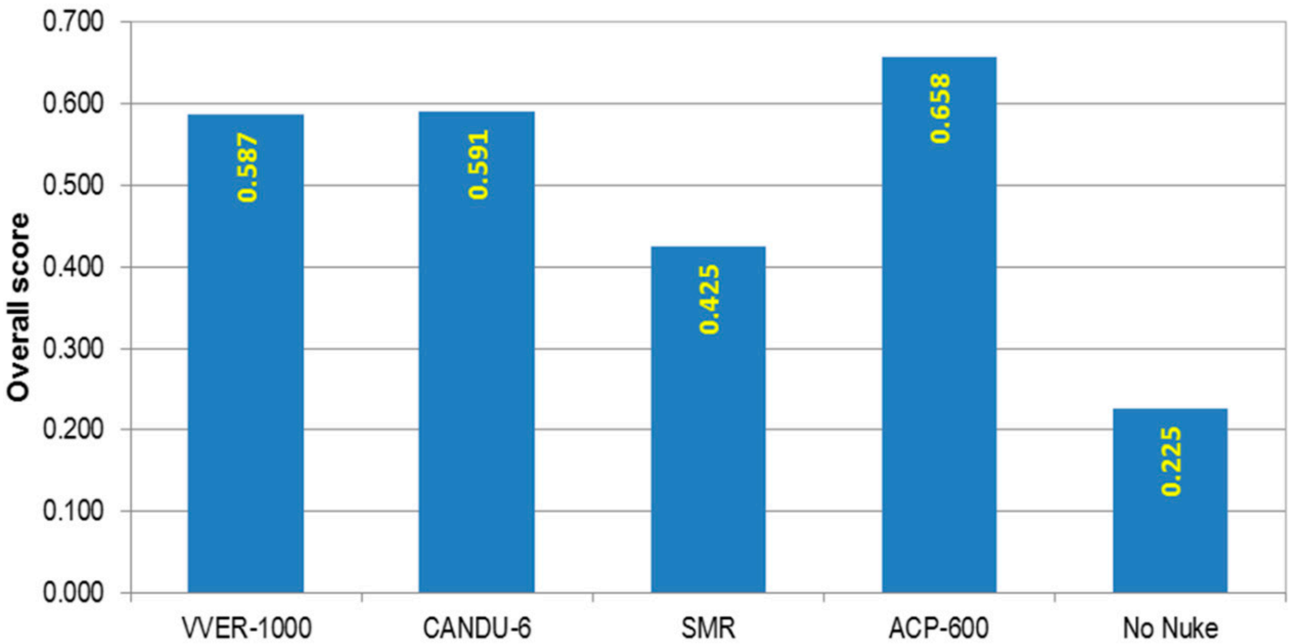


FIG. 5.26. Multi-attribute value function results for the selected alternatives.

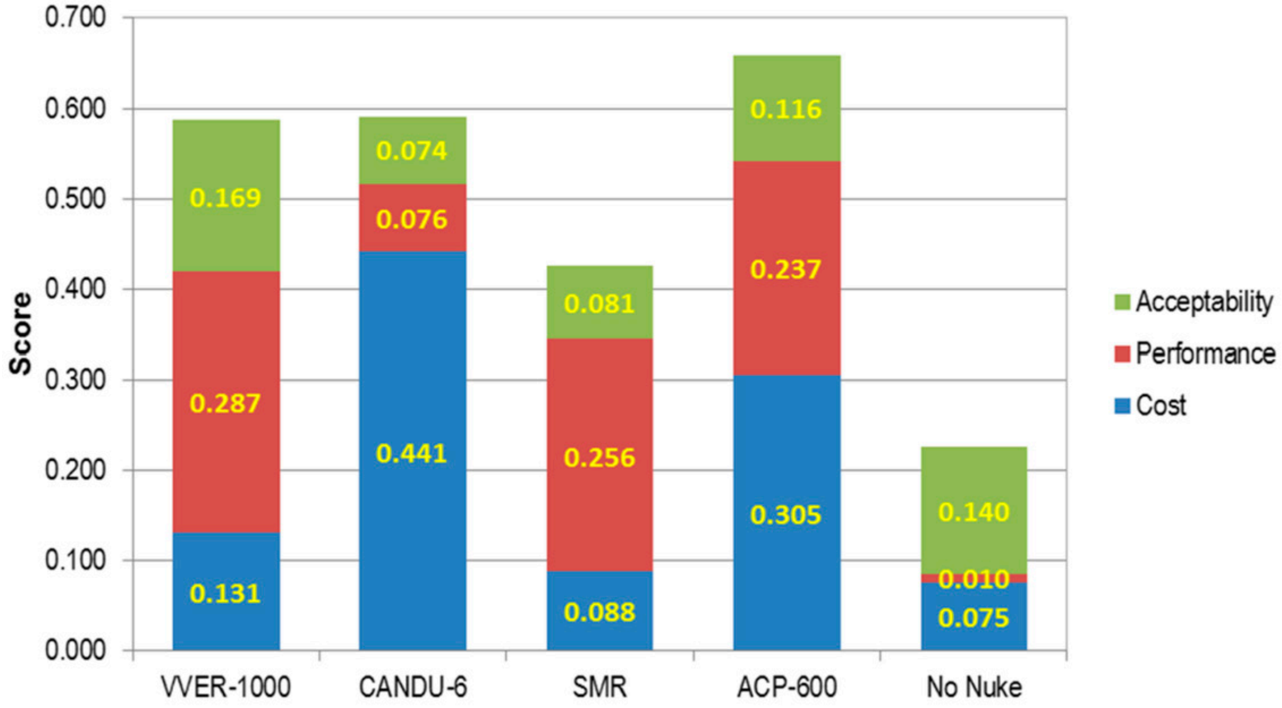


FIG. 5.27. High level objective scores for the selected alternatives.

best case value. At the same time, the CANDU 6 is the lowest ranked of the nuclear options for performance and acceptability, whereas the WWER-1000 has the best rank.

(c) Area scores

For a further explanation of why one alternative was dominant over another, the multi-attribute value function is decomposed into components corresponding to each evaluation area. Table 5.39 shows the scores for the alternatives for each of the evaluation areas. They are also presented in Fig. 5.28.

Analysis shows that, compared to the other NES options, the CANDU 6 is the best choice in the area of economics, as a result of low costs for both investment and fresh nuclear fuel. The next most attractive alternative in terms of economics is the ACP-600 (0.305). All the remaining alternatives have significantly lower ranking values in terms of economics.

The CANDU 6 is the worst in the waste management area (0.046) because it creates too much radioactive waste in comparison with the other nuclear alternatives considered. The best nuclear reactor in this category is the alternative that uses the SMR technology (0.120). The highest level of country independence (country specific indicator) is provided by the WWER-1000 (0.150), which also has the highest electricity production capability. As mentioned previously, this generated electricity is considered to be the country's internal source of energy, and in comparison with the other alternatives, it has the highest share in the total energy mix alongside other domestic sources. The lowest ranked alternatives in this area were the CANDU 6 (0.0) and the no nuclear option (0.010). It is obvious that the environment issue (in view of the given definitions) favours all of the nuclear technologies to a significant degree because they need considerably less mining for each MW(e)·h of electricity produced than thermal technologies (natural gas). With regard to the maturity of technology, the highest score for the nuclear reactors was shown by the WWER-1000 (0.109), followed by the no nuclear alternative (0.140). Finally, it is noticeable that public acceptance favours any nuclear option over thermal development, but the score for this only has a small influence on the total scoring.

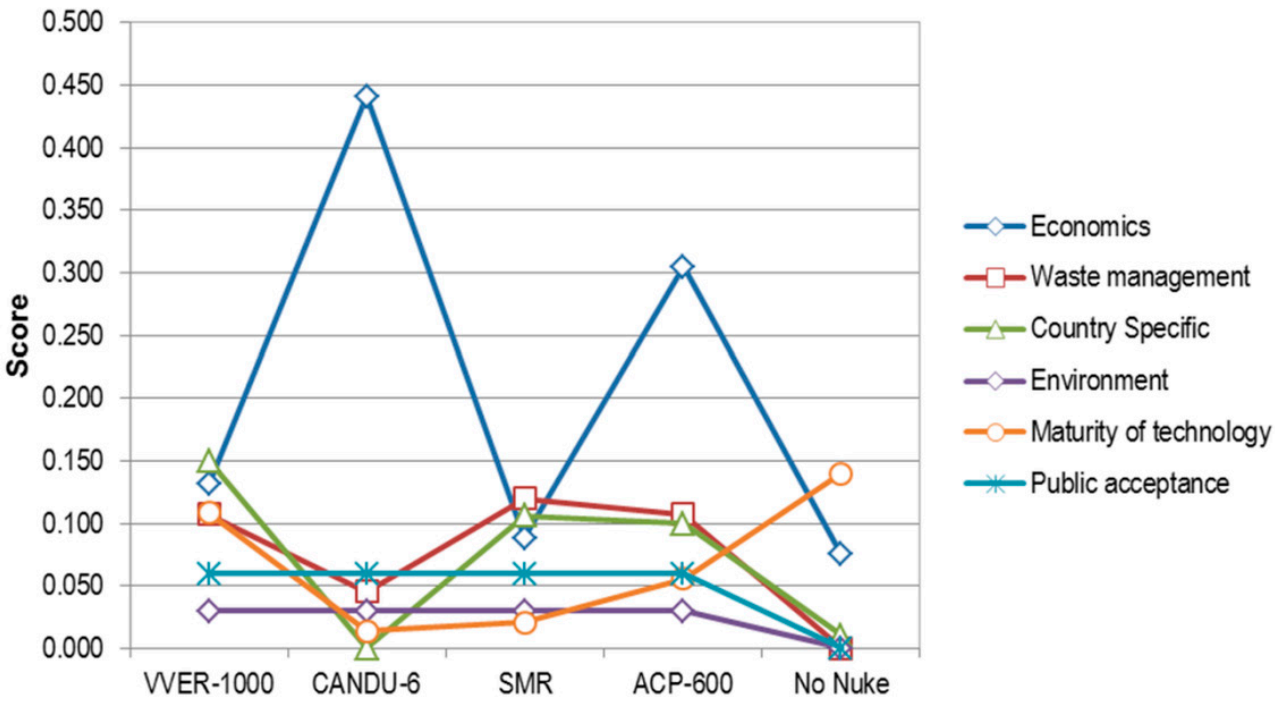


FIG. 5.28. Area scores for the selected alternatives.

5.5.1.9. Sensitivity and uncertainty analysis

Sensitivity analysis has been performed for the indicators' final weights to analyse the stability and robustness of the ranking results. For this purpose, a special Excel worksheet was prepared in the KIND evaluation tool and linked to the calculating parameters. Based on the given percentage of the final weight change, it determines an impact of each indicator on ranking results with respect to the base/modified case in the steps described below:

(1) Assignment of a new value to the first indicator based on the given percentage;
(2) Recalculation of the numerical values of the final weights for the remaining indicators by relevant distribution of this percentage to their final weights;
(3) Repetition of the two steps mentioned above for all the indicators;
(4) Recalculation of the multi-attribute value function for each case;
(5) Summarization of the results in the form of charts.

Based on the aforementioned procedure, the calculation of the objective function variation for a change of the final weights of ±20% has been considered. The results are summarized in Figs 5.29–5.34 and in Table 5.40. Analysis show that the most sensitive (critical) criteria are: E.2 and CS.1 for WWER-1000; E.2, E.4 and CS.1 for CANDU 6; E.2 and WM.1 for SMR; WM.1 for ACP-600; and E.3 and M.2 for the no nuclear case. It should be noted that relative to the base case, the percentage of changes is no greater than 6.3%, which is fully acceptable for such studies. This indicates the stability and robustness of the ranking results.

5.5.1.10. Conclusion

The following conclusions can be drawn from the case study:

(1) The MAVT method is quite flexible. It allows different approaches for the comparison and differentiation of alternatives to be implemented, in addition to facilitating the interpretation of the ranking results. It can be recommended for use in KIND evaluations.

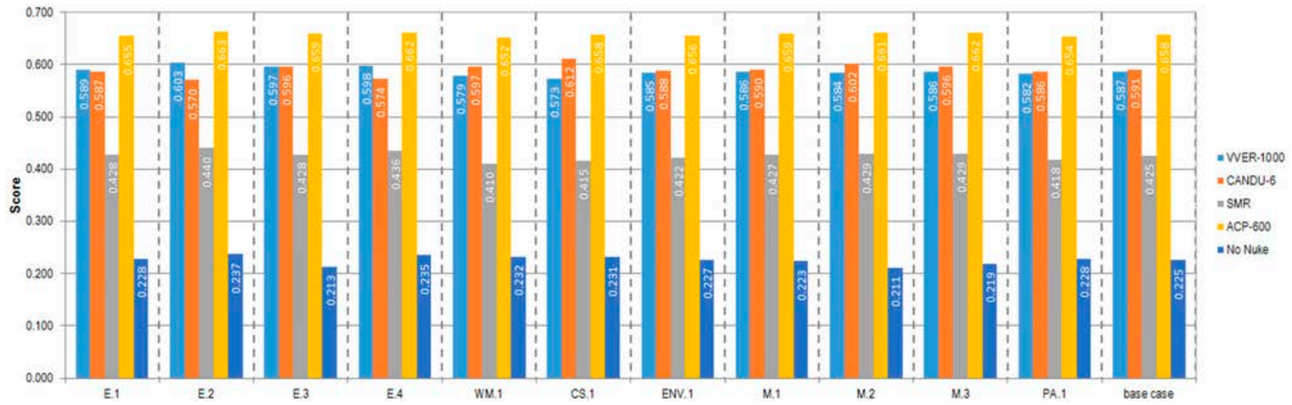


FIG. 5.29. Impact on ranking results from −20% change to KI final weights (grouped by indicators).

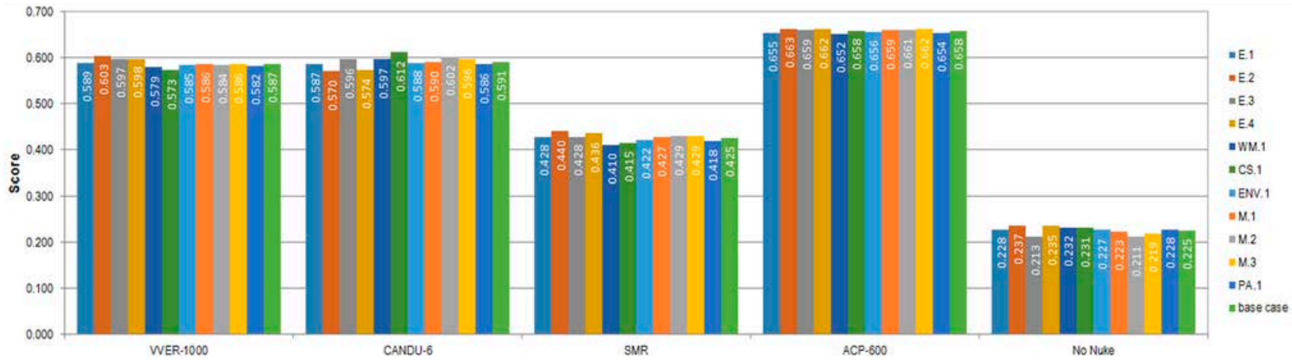


FIG. 5.30. Impact on ranking results from −20% change to KI final weights (grouped by alternatives).

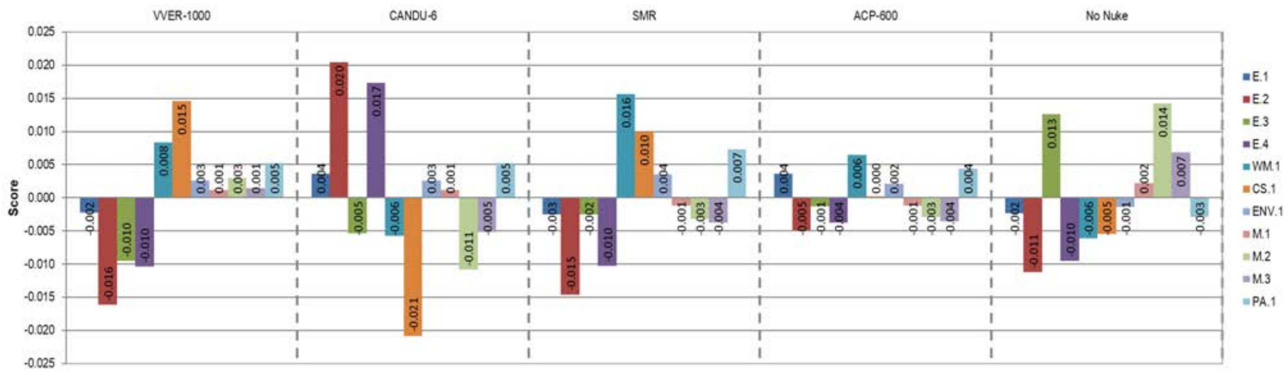


FIG. 5.31. Differences between values in the ranking results in the case of a −20% final weight change to each KI compared to the base case (grouped by alternatives).

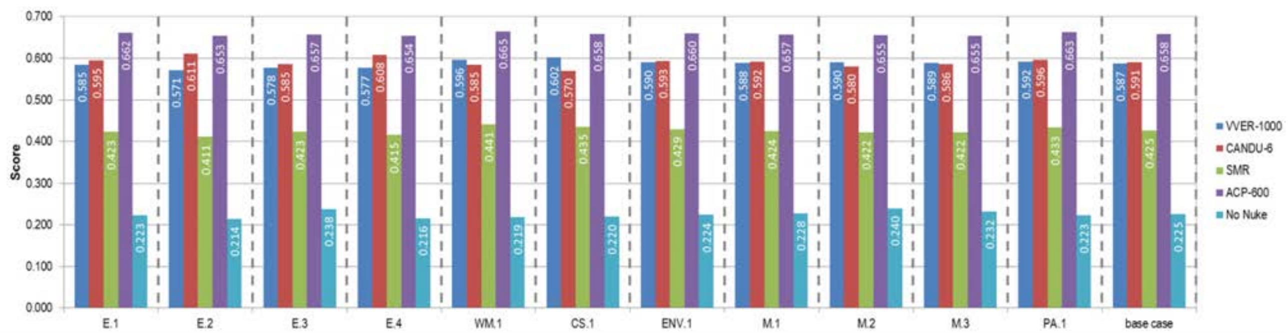


FIG. 5.32. Impact on ranking results from +20% change to KI final weights (grouped by indicators).

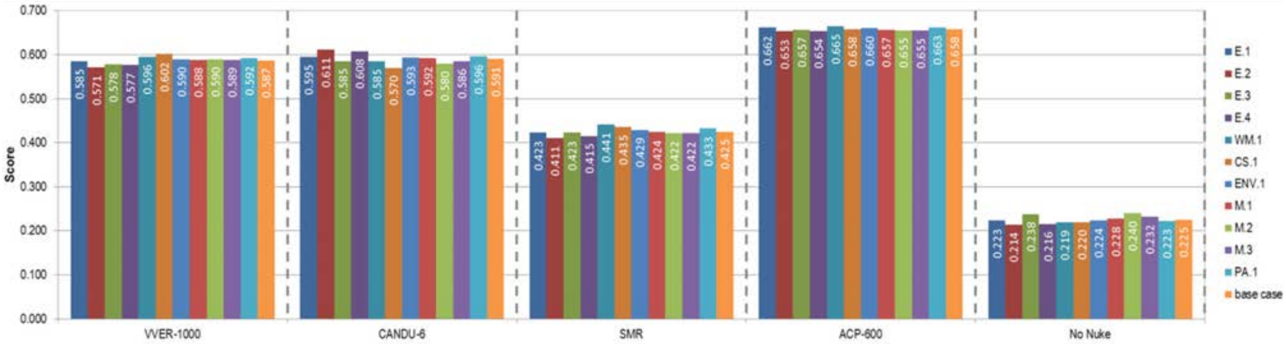


FIG. 5.33. Impact on ranking results from +20% change to KI final weights (grouped by alternatives).

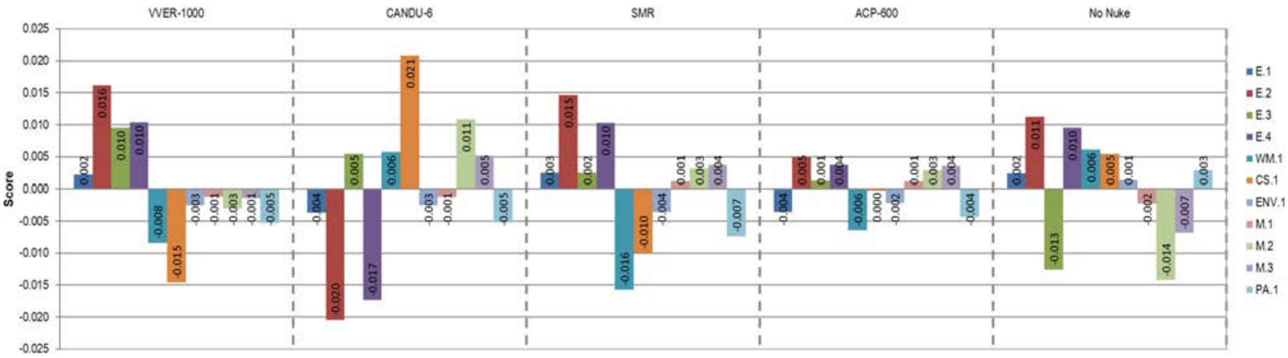


FIG. 5.34. Differences between values in the ranking results in the case of a +20% final weight change to each KI compared to the base case (grouped by alternatives).

TABLE 5.40. THE MOST CRITICAL INDICATORS FOR EACH ALTERNATIVE

Indicator definition	Abbr.	WWER-1000	CANDU 6	SMR	ACP-600	No nuclear
Power system long term average generation cost	E.2	2.75%	3.46%	3.45%		
New generation investment cost	E.3					5.57%
Whole energy system cost	E.4		2.94%			
Specific radioactive waste inventory	WM.1			3.68%	0.98%	
Energy independence level	CS.1	2.48%	3.53%			
Time needed to mature the technology for Armenia	M.2					6.30%

(2) As the most suitable nuclear option for implementation, a medium sized reactor such as the ACP-600 can be recommended for Armenia.
(3) Sensitivity analysis indicated that the selected model parameters provide stability and robustness for the ranking results.
(4) Decisions based on the evaluation outcomes can be considered to be a reasonable basis for future development of strategies.
(5) Use of the KIND approach together with the KIND-ET in future comparative energy system evaluations will allow due aggregation of the results of these comprehensive assessments and presentation of them to the decision makers involved in establishing energy system expansion policies.

5.6. NUCLEAR VERSUS NON-NUCLEAR ENERGY SYSTEMS

5.6.1. Thailand case study

5.6.1.1. Introduction

The latest strategy for an energy system in Thailand was revised in 2015 and is provided in the Thailand Power Development Plan 2015–2036 [5.17], which proposes the deployment of NPPs. However, Thailand is a newcomer country regarding the deployment of nuclear technology, whereas coal power plants (CPPs) have been widely used in the country. Therefore, coal power technology is considered to be a potential energy source in Thailand. According to the Electricity Generating Authority of Thailand, coal technology currently accounts for approximately 20% of total electricity production, and the authority itself has planned to install a few more CPPs across the country in the near future. For this reason, a CPP was chosen as a non-NES alternative for the comparative evaluation in this study. The supporting data for the study have been taken from relevant national or international organizations in the form of articles, reports, presentations and expert judgements.

5.6.1.2. Objective and problem formulation

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 between an NES and a non-NES. This KI set belongs to four areas: economics, energy security, public acceptance and infrastructure. There are two KIs in the area of economics: 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 most 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.

5.6.1.3. Formulation of alternatives (NES options)

The options under consideration include an NES (evaluated using data for the Generation III+ light water cooled reactors of interest (i.e. the AP-1000, APR1400, ACPR and VVER)) and a CPP. The main characteristics of the selected NPPs and CPPs are presented in Table 5.41.

5.6.1.4. Identification of indicators

Eleven KIs from 4 different areas were used in this study. The details of the KIs, including their scoring, are explained in Section 2.4.3. The list of KIs and their abbreviations are:

(1) KI-1 — LUEC;
(2) KI-2 — Cash flow;
(3) KI-3 — Degree of dependence on supplier(s);
(4) KI-4 — Survey of public acceptance;
(5) KI-5 — External cost;
(6) KI-6 — Risk of accidents;
(7) KI-7 — Status of legal framework;
(8) KI-8 — Status of state organizations;
(9) KI-9 — Availability of infrastructure to support owner/operator;
(10) KI-10 — Government policy;
(11) KI-11 — Availability of human resources.

TABLE 5.41. PARAMETERS FOR COMPARATIVE EVALUATION OF THE LUEC AND CASH FLOW FOR NESs AND CPPs

No.	Parameters	Units	Nuclear[a]	Coal[a]
1	Net electric power	MW(e)	1000–1400	600
2	Construction period	Years	4–6	3.5–4.5
3	Lifetime of plant	Years	60	40
4	Average load factor	—	0.9	0.75
5	Decommissioning cost	mills/kW(e)·h	0–0.14	0.03–0.12
6	Overnight cost	US $/kW(e)	2577–4983	3784–4400
7	Contingency cost	%	10–20	5
8	Capital investment schedule	—	Uniform	Uniform
9	Real discount rate	%	7–11	7–11
10	PUES	mills/kW(e)·h	85.71	85.71
11	Market income	million US $	15 919	15 919
12	Market share	—	1	1
13	Profit margin	%	7	7
14	Time of growth	Years	3.09–4.33	1.85
15	Adjusting coefficient	—	0.5–1.5	1
16	Variable operation and maintenance cost	mills/kW(e)·h	9.88–18.70	7.22
17	Fuel price	US $/GJ		0.86–1.85
18	Real fuel price escalation rate	%/year		1
19	Nuclear fuel backend cost	US $/kg	379–2449	
20	Unloaded fuel average burnup	MW d/kg	48.4–60	
21	Net thermal efficiency	%	34–37	38–43.1
22	Reactor first core average power density	kW/kg	25–40.2	
23	Natural U purchase cost	US $/kg	135	
24	U conversion cost	US $/kg	9	
25	U enrichment cost	US $/kg	146	
26	Nuclear fuel fabrication cost	US $/kg	312	
27	First core lowest ^{235}U concentration	%	3.95	
28	First core medium ^{235}U concentration	%	4.95	
29	Refuelling fuel ^{235}U concentration	%	4.95	29
30	Enrichment tails' ^{235}U concentration	%	0.25	30

Note: PUES — price per unit of electricity sold.

[a] All values are determined based on articles or reports published by national or international organizations, reports or presentations of the Electricity Generating Authority of Thailand, or expert judgements.

5.6.1.5. Evaluation of indicators, including uncertainties

The scores for each KI corresponding to the NES and non-NES alternatives were established using a 10 point scoring scale. The scores assigned for each KI are explained below:

(a) Economics

There are two important KIs to be evaluated in the area of economics, namely LUEC and cash flow. For this case study, the NEST was used to perform the comparative evaluation of these two indicators for the NES and the CPP.

(i) LUEC

The parameters presented in Table 5.41, which are based on the present situation in Thailand (as of September 2015) and expert judgements, have been adopted in this evaluation. In order to be able to take the ranges of some uncertain parameters into account, the NEST was modified to make iterative calculations with the values of each uncertain parameter being randomized within the range shown in Table 5.41.

The LUEC values for the NES and the CPP are shown in Fig. 5.35. It can be seen from the figure that the LUEC values for both energy systems are in the same range. This is because the integrated gasification combined cycle is selected as the representative CPP, and its overnight cost is relatively high compared to that for other CPP technologies. Therefore, even though the coal price is relatively low in this region, the LUEC of the CPP is not different from that of the NES. Here, the 50th percentile values of the LUEC of the NES and the CPP are 86 and 88 mills/kW(e)·h, respectively. Since the CPP value is the higher one, its score is equal to 10, while the NES score equals (86/88) × 10 = 9.8, which is rounded to 10. Note that, if other technologies (e.g. pulverized coal combustion), were selected as the representative CPP, the LUEC of the CPP would be significantly lower than that of the NES.

(ii) Cash flow

Figure 5.36 shows the total investment (solid lines) and the investment limit (dashed lines) for the NES and the CPP. The investment is over the investment limit for both energy systems. However, the calculation is based on the assumption that the investment will be based solely on the equity (no loan from banks taken into account), which is unrealistic. For example, if the ratio of equity to debt is set as 50% to 50%, the investment in the CPP would definitely be covered by the investment limit, and the investment in the NES would have a good chance of being below the investment limit. Therefore, it is too soon to reject the NES in this KI.

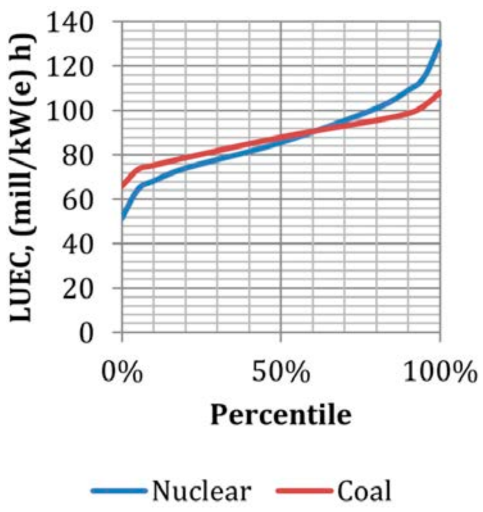


FIG. 5.35. LUEC for the NES and CPP.

The next step is to evaluate the differences between the WACC and the IRR, and between the WACC and the ROI. The WACC can be calculated as:

$$\text{WACC} = s_e \times r_e + (1 - s_e) \times r_d \times (1 - t) \tag{5.2}$$

Most of the values are taken from Ref. [5.18], as there is no NES in Thailand at the moment. The inflation rate is not taken into account in order to simplify the evaluation. The equity share, debt share and required rate of return on equity are 50%, 50% and 15%, respectively, for the NES, and 40%, 60% and 12%, respectively, for the CPP. The required rate of return on the debt is set to 9%, based on the value of the real discount rate given in Table 5.41. The tax rate is not taken into account. The calculated WACC for the NES and the CPP is 12% and 10.2%, respectively. Furthermore, the IRR and ROI of the NES and the CPP are shown in Figs 5.37 and 5.38, respectively. As the influence of time was not taken into account in the calculation of the WACC (the inflation rate was not considered), the WACC is compared with the ROI. The 50th percentile values of the ROI of the NES and the CPP is 11.2% and 9.8%, respectively. Therefore, the difference between the WACC and the ROI will be 0.8% and 0.4%, respectively, which means that investment in either energy system is not attractive.

One way to deal with this issue is to increase the price per unit of electricity sold (PUES). The IRR and ROI of the NES and the CPP when the PUES is increased by 10% are shown in Figs 5.39 and 5.40, respectively. The 50th percentile values of the ROI of the NES and the CPP is 13.1% and 11.1%, respectively, hence the difference between the WACC and the ROI will be 1.1% and 0.9%, respectively. The cash flow scores for the NES and CPP are 10 and 8, respectively.

(b) Energy security

The degree of dependence on supplier(s) (overseas versus domestic) is used as the KI for comparative evaluation between an NES and a CPP in Thailand. The results will indicate the degree of dependence on overseas suppliers, implying a certain level of energy security if that energy system is selected.

(i) Degree of dependence on supplier(s)

In order to evaluate the degree of dependence on supplier(s), as mentioned previously in Section 2.4.3, the following areas are taken into consideration:

— Technology;
— Construction;
— Fuel supply;
— Operation;
— Maintenance;
— Waste management;
— Decommissioning.

An appropriate weighting factor will be assigned to each area of interest based on priority. The scoring scale and criteria are shown in Table 5.42.

The evaluation results are reported in Table 5.43. The degree of dependence on supplier(s) (DDS) of each energy system is calculated by the summation of the products of the weighting factor and corresponding score(s) in each area, as demonstrated in the following equation:

$$DDS = \sum (wf \times s) \tag{5.3}$$

This calculation method yields values of 9 and 5 (out of 10) for DDS_{NPP} and DDS_{CPP}, respectively. In summary, based on this calculation method, the NPP value for the degree of dependence on supplier(s) is almost twice that for the CPP. The results indicate that in order to launch a nuclear energy project in a newcomer country (Thailand in this case), the country has to be highly dependent on external sources (up to 90%). Thus, from the viewpoint of energy security, it is almost impossible for an NPP to compete with the currently deployed technology (i.e. a CPP in this case).

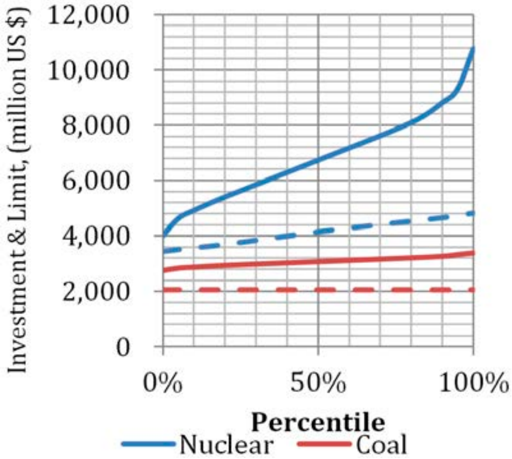


FIG. 5.36. Total investment and investment limit for the NES and CPP.

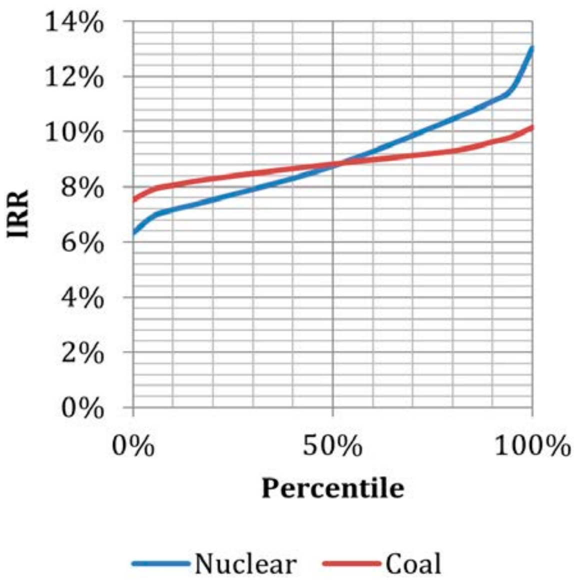


FIG. 5.37. Internal rate of return (IRR) for the NES and CPP.

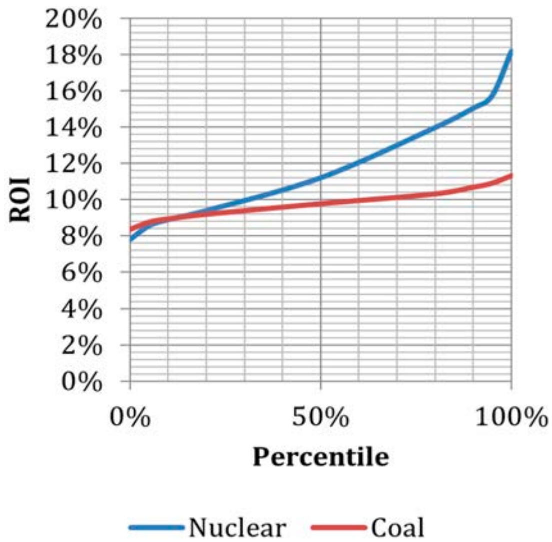


FIG. 5.38. Return on investment (ROI) for the NES and CPP.

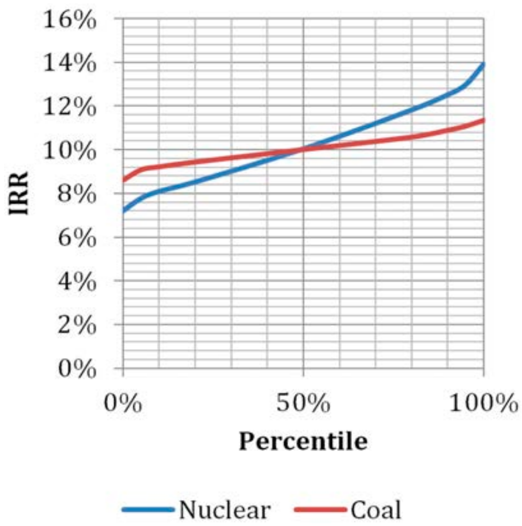


FIG. 5.39. Internal rate of return (IRR) for the NES and CPP (PUES +10%).

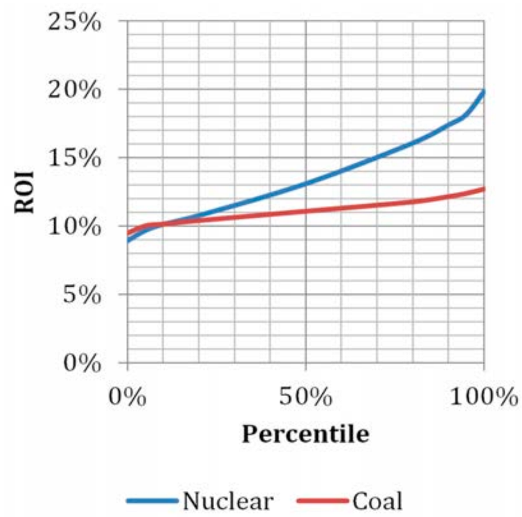


FIG. 5.40. Return on investment (ROI) for the NES and CPP (PUES +10%).

TABLE 5.42. SCORING SCALE CRITERIA

Scoring scale	Criteria
10	Entirely imported
8	Partially imported, with up to 40% of products, labour, expertise or services available in the country
6	Partially imported, with 41–60% of products, labour, expertise or services available in the country
4	Partially imported, with 61–80% of products, labour, expertise or services available in the country
2	Partially imported, with 81–99% of products, labour, expertise or services available in the country
0	100% of the products, labour, expertise or services available in the country

TABLE 5.43. EVALUATION RESULTS

Area	Weighting factor	NPP	CPP	Rationale
		Score		
Technology	0.25	10	10	It is particularly obvious that for newcomer countries, the technologies for an NPP project will be provided by the technology holders, such as China, Japan, the Russian Federation and the United States of America. Similarly, the CPP technologies used in Thailand are also imported from France (ALSTOM) and Japan (Marubeni) [5.19].
Construction	0.15	8	4	The main parts of the NES will be constructed under the supervision of the technology holder(s). However, labour and certain services are expected to be available domestically. With over 40 years of CPP experience, the local labour and services need to be able to contribute more than 60% of the required effort to construction.
Fuel supply	0.15	10	10	Since Thailand has no plans for uranium mining, milling and fuel fabrication, 100% of nuclear fuel must be supplied by an external source. Similar to the NES case, high quality coal for coal power generation has been wholly imported (mainly from Australia and Indonesia).
Operation	0.125	8	2	For the first nuclear power project, it is necessary that the majority of experts and services for operation be assured by the technology holder(s). Eventually, this external support is expected to decrease almost to zero after the completion of technology transfer. In the case of the Mae Moh CPP project (Thailand's first CPP, launched in 1972), the technology has been transferred completely and the power plant is currently operated by Thai personnel with an occasional requirement for international consultation.
Maintenance	0.125	8	2	It is of particular importance that the maintenance of the NES will initially rely on the technology holder(s). However, this reliance would eventually decrease. The maintenance of a CPP requires very little external support, with only occasional consultation required.
Waste management	0.1	10	0	The scenario taken into consideration in the area of waste management for an NES is that SNF from Thailand will be sent back to the country of origin. In the case of a CPP, international support is not necessary for waste management.
Decommissioning	0.1	8	2	NES decommissioning includes the removal of spent fuel, decontamination of the entire facility, demolition of the buildings and other structures, transportation and storage of the radioactive wastes. Therefore, it is highly likely that this process will require both international and domestic services. Decommissioning of a CPP will be very similar to that for an NES, except fewer international services will be required.

(c) Public acceptance

(i) Survey of public acceptance

The survey of public acceptance could be evaluated by compilation of the results of surveys on public opinion regarding the introduction of energy systems in the country. Priority could be given to surveys conducted throughout the country or to surveys conducted in local areas or with specific groups of people, depending on the influence of local opinion on the energy system project.

The survey of public acceptance presented in this study is a compilation of data reflecting public attitudes toward the installation of an NES and a selected non-NES (CPP) in Thailand. The data were taken from a number of research articles and questionnaires. All available data are shown here. However, only the latest survey data, collected after public turning points for the energy systems (i.e. the Fukushima Daiichi accident[2] for NPPs and the Mae Moh sulphur dioxide emissions incident[3] for CPPs) have been used in the evaluation [5.20]. This is because the survey data before these public turning points do not reflect the current situation in the country, and the results of the evaluation may be unrepresentative if these data are included.

The percentages of agreement and disagreement from each dataset concerning NES and CPP installations have been normalized. Subsequently, the results obtained were multiplied by the number of samples. Finally, the sum of the products from the previous step was divided by the sample size. The results were then converted back into a percentage, which was scored on a scale of 1–10. The data and evaluation results are shown in Table 5.44.

In summary, the results obtained from the public survey for the NES, which was completed in 2011 after the Fukushima Daiichi accident, revealed over 80% public disagreement due to concerns regarding radioactivity release, government corruption, nuclear waste management and work culture in Thailand. Similarly, the evaluation results based on the public survey regarding the installation of a CPP (taken after the turning point of toxic emissions at Mae Moh CPP) showed that up to 40% of the respondents were opposed to CPP installation in the country.

(ii) External cost

The external cost is adopted as an indicator for a comparative evaluation of the unneeded products of different energy systems, including health effects from toxic emissions, water pollution, radioactive waste and climate change from greenhouse gas emissions. This indicator aims to measure the impacts of the unneeded products of the energy system, which is different from the LUEC, which evaluates the internal cost of an energy system. External cost can better reflect the real cost of the societal and environment effects of the energy systems via monetary units.

As mentioned in Section 2.4.3, some countries, such as Thailand, may not have sufficient resources to evaluate the external cost for their own countries, since this requires extensive data acquisition and compilation. Therefore, reliable reports or papers could be referred to, which estimate the external cost based on non-OECD data.

Shrestha et al. [5.21] estimated the external cost of two CPPs at two different locations in Thailand. The first one was the Thapsake plant, a 1000 MW(e) thermal power plant using imported coal, located in Thapsake district, in the southern part of Thailand. The second plant was the Mae Moh plant, a 300 MW(e) lignite fired plant equipped with an electrostatic precipitator and flue gas desulphurization, which was installed in the Mae Moh area in the northern part of the country. The study in Ref. [5.21] estimated the external cost using a simplified method. Emissions of only two types of pollutants, namely PM10 (particulate matter of size less than 10 μm) and SO_2 (not including CO_2 emission), were taken into consideration. The results were reported as monetary unit cost by converting the unit cost into US dollars in 1995. The monetary damage cost for all affected areas was US $1 767 442/year for the Thapsake (imported) CPP and US $2 600 613/year for the Mae Moh lignite power plant. In order to make an easy comparison with the other creditable reports or papers, the external costs have been calculated per unit energy output. In this calculation, the average annual energy output of each plant is estimated from a load factor of 80%. Therefore, the external cost in units of US $/MW(e)·h of the Thapsake and Mae Moh

TABLE 5.44. DATA AND EVALUATION RESULTS FOR SURVEY OF PUBLIC ACCEPTANCE IN THAILAND

Type	Sampling size	Agree	Disagree
NES	5.222	2	8
Non-NES	1.153	6	4

2 Turning point for NESs: in 2011, an earthquake scoring 9.0 on the Richter scale caused a 14 meter high tsunami that struck the Fukushima Daiichi NPPs. The initial events led to a malfunction of the emergency cooling systems of the power plants, resulting in consecutive explosions in the containment buildings. Inevitably, radioactivity was released into the environment [5.22].

3 Turning point for non-NESs: in 1992, the Mae Moh CPP released a high concentration of sulphur dioxide with a maximum value of 3.418 μg/m^3 in 1 hour and 567 μg/m^3 (average) in 24 hours. The highly contaminated environment has had a severe health impact on the local population. A very similar situation took place in 1998, when a concentration of sulphur dioxide that exceeded the limit value (1.3 μg/m^3) was detected.

plants is US \$0.25/MW(e)·h and US \$1.24/MW(e)·h (in 1995), respectively. However, only the health impact from two types of pollutants was addressed in the study of Shrestha et al. Therefore, several data sources corrected by Grausz [5.22] have been taken into consideration in addition to the study by Shrestha et al., as shown in Table 5.45.

It should be noted that the results for external cost obtained from various sources are distinctive and also wide ranging; therefore, the mean values are used to calculate the average external cost of the CPP and the NPP. The results show that the average external cost of the CPP is US \$57/MW(e)·h and that of the NPP is US \$4.4/MW(e)·h. Thus, the scores for the CPP and the NES will be 10 and 1, respectively, with the target score of external cost to be minimized.

TABLE 5.45. EXTERNAL COST OF ELECTRICITY GENERATION PER MW(e)·h [5.21, 5.22]
(unit: US \$ in 2010)

Data source	Coal		Nuclear
	Pulverized coal-fired boiler	Integrated coal gasification combined cycle	
RFF/ORNL (1995)	2.3	—	0.5
Rowe et al. (1995)	1.3–1.4	—	0.2
ExternE (2005)	27–202	—	3.4–9.4
NRC (2010)	2–126	—	—
Epstein et al. (2011)	180.7	—	—
Rafaj and Kypreos (2007)	58.0	57	10.5
Shrestha et al. (2003)[a]	0.37[b]–1.79[c]	—	—

[a] The calculation is based on an inflation rate of 2.5% for conversion into US \$ at 2010 value.
[b] Thapsake plant.
[c] Mae Moh plant.

(iii) Risk of accidents

As mentioned in Section 2.4.3, the embarking countries may not have adequate resources to perform the evaluation, and other reliable reports or papers could be referred to in such cases. Since Burgherr et al. [5.23] gathered a large quantity of information before analysing the risks posed by both NESs and CPPs to the publics of both OECD and non-OECD countries, the results obtained for non-OECD countries seem appropriate for the evaluation.

— Accident rate (per GW(e)·year)

The average number of accidents per GW(e)·year for CPPs in non-OECD countries was 1.46×10^{-1}. As for the NESs, there have been three severe accidents in the past: Three Mile Island NPP (United States of America, 1979), Chernobyl NPP (Ukraine, 1986) and Fukushima Daiichi NPP (Japan, 2011). Since the sum of all the electricity supplied from nuclear reactors connected to the grid during 1995–2014 was approximately 5600 GW(e)·year [5.24], it could be said that the total generated power was 10 000 GW(e)·year. Therefore, the average number of accidents per GW(e)·year for NESs would be 3×10^{-4}. The reciprocal of the absolute values of the log of the accident rate can be used to do the scoring: $1/|\log_{10}1.46 \times 10^{-1}| = 1.196$ and $1/|\log_{10}3.00 \times 10^{-4}| = 0.284$, thus the scores for the NES and the CPP will be 2 and 10, respectively.

— Fatality rate (per GW(e)·year)

The fatality rate for CPPs in non-OECD countries was 2.31 per GW(e)·year, while the fatality rate estimated from the experience in the Chernobyl NPP was 3.02×10^{-2} per GW(e)·year. Thus, $\log_{10}2.31 = 0.36$ and

$\log_{10}3.02 \times 10^{-2} = -1.52$. As the fatality rate for the CPP was so large that it gives a positive log value, the scores for the NES and the CPP are 0 and 10, respectively.

— Maximum fatalities for a single accident

The maximum fatalities from a single accident for CPPs in non-OECD countries was 434, while the maximum fatalities estimated from the experience in the Chernobyl NPP was between 9000 and 33 000[4]. The median value, 21 000, was taken as the maximum number of fatalities for a single accident in an NES. Thus, $\log_{10}434 = 2.64$ and $\log_{10}21\,000 = 4.32$, and the scores for the NES and the CPP will be 10 and 6, respectively.

— Accident cost rate (euro cent per kW(e)·h)

The accident cost rate for CPPs in non-OECD countries was 3.44×10^{-3} euro cent/kW(e)·h, while the accident cost rate for NESs, as estimated in the level 3 probabilistic risk analysis by Burgherr et al. [5.23], was 1.02×10^{-3} euro cent/kW(e)·h. Thus, $1/|\log_{10}3.44 \times 10^{-3}| = 0.334$ and $1/|\log_{10}3.00 \times 10^{-4}| = 0.407$, and the scores for the NES and the CPP will be 8 and 10, respectively.

— Maximum cost of a single accident

The maximum cost of a single accident in an NES, as estimated by the ExternE project [5.25], was €83 252 million, while the maximum accident cost of a single accident in a coal mine, as estimated by Sovakool [5.26], was US $162 million (€147 million, as of 27 October 2015). Hence, $|\log_{10}83\,252| = 4.92$ and $|\log_{10}147| = 2.17$, and the scores for the NES and the CPP will be 10 and 4, respectively. A summary of the weighting factors and the scores for each sub-indicator for the risk of accidents is given in Table 5.46.

(d) Infrastructure

The weighting factors and scores for the KIs in the infrastructure area are shown in Tables 5.47–5.51. The scores and weighting factors have been determined based on the available information, relevant previous studies and the opinions of evaluators who are Thai experts in the various fields of nuclear power. The scoring criteria for each section have been classified into three levels, as described in the Table 5.52. The scoring scales for the 11 KIs in 4 different areas are summarized in Table 5.53.

5.6.1.6. Selection of an MCDA method

The set of KIs developed for newcomer countries has been selected to perform a multi-criteria comparison using the MAVT method and to identify the structure of the objectives tree.

The KIND-ET Excel based tool, developed in the framework of the KIND collaborative project and based on MAVT, accompanied by a set of KIs, was used for the comparative evaluation. Therefore, for a small number of comparative evaluations between an NES and non-NES pair, the indicators could be evaluated based on a 10 point scoring scale. In addition, linear functions have been used as single-attribute value functions defined on problem oriented domains.

5.6.1.7. Determination of weights, including uncertainties

Two high level objectives, namely economics and acceptability, have been classified for the comparative evaluation. Acceptability is further divided into three areas: energy security, public acceptance and infrastructure, as presented in Table 5.54. The minimum score is the best possible value for KI-1, KI-3, KI-5 and KI-6, while the maximum value is the best value for KI-2, KI-4 and KI-7 to KI-11.

[4] The maximum values have been selected to take a conservative approach to the comparative evaluation of NESs against CPPs.

TABLE 5.46. SUB-INDICATORS FOR RISK OF ACCIDENTS AND THEIR SCORES

No.	Sub-indicators	Weighting factor	NES	CPP
1	Accident rate (per GW(e)·y)	0.2	2	10
2	Fatality rate (per GW(e)·y)	0.2	0	10
3	Maximum fatalities for a single accident	0.2	10	6
4	Accident cost rate (euro cent/kW(e)·h)	0.2	8	10
5	Maximum cost of a single accident	0.2	10	4
	Risk of accidents		6	8

TABLE 5.47. WEIGHTING FACTORS AND SCORES FOR LEGAL FRAMEWORK

Items	Weighting factors	Score		Rationale
		NES	CPP	
Operational safety	0.33	5	10	Because of the lengthy experience of CPP deployment (more than 30 years) in Thailand, the legal framework for CPP installation and operation is well developed. Regarding NESs, the legal framework is currently being developed to cover all aspects related to NES installation, operation and decommissioning. This corresponds to the recommendations of the IAEA experts during the Integrated Nuclear Infrastructure Review mission in Thailand 13–18 December 2010 [5.27].
Environmental protection	0.33	5	10	
Waste management	0.33	5	10	
Weighted score		5	10	

TABLE 5.48. WEIGHTING FACTORS AND SCORES FOR STATE ORGANIZATIONS

Items	Weighting factors	Score		Rationale
		CPP	NES	
Operational safety	0.33	5	10	Similar reasons to those in the rationale given for the status of the legal framework [5.27].
Environmental protection	0.33	5	10	
Waste management	0.33	5	10	
Weighted score		5	10	

TABLE 5.49. WEIGHTING FACTORS FOR AVAILABILITY OF INFRASTRUCTURE TO SUPPORT OWNER/OPERATOR

Items	Weighting factors	Score		Rationale
		NES	CPP	
Domestic industry	0.5	5	5	According to [5.28], which was prepared by Chulalongkorn University in Thailand, the infrastructure to support the owner/operator of an NES is considered to be partially available. Several areas of infrastructure for NES construction, installation and operation are unavailable and must be developed domestically or imported from other international organizations if needed. By contrast, the infrastructure to support the owner/operator of a CPP is available because of the lengthy CPP deployment in Thailand.
Government	0.5	5	10	
Weighted score		5	8	

TABLE 5.50. WEIGHTING FACTORS FOR GOVERNMENT POLICY

Items	Weighting factors	Score		Rationale
		NES	CPP	
Existing	0.7	0	10	According to the Thailand Power Development Plan 2015–2036 [5.17], Thailand has clearly stated that it will promote the deployment of clean coal technology in the country for the next 20 years, while the attitude towards NESs is not clearly defined.
Accessible and understandable	0.3	0	5	The government policies on both CPPs and NESs are considered to be not sufficiently reachable and understandable for the public.
Weighted score		0	8	

TABLE 5.51. WEIGHTING FACTORS FOR AVAILABILITY OF HUMAN RESOURCES

Items	Weighting factors	Score		Rationale
		NES	CPP	
Establishment and operation	0.33	5	10	IAEA experts recommended that Thailand take significant action for human resource development during the Integrated Nuclear Infrastructure Review mission in Thailand 13–18 December 2010 [5.27].
Regulatory agency	0.33	5	10	
Research and academics	0.33	5	5	
Weighted score		5	8	

TABLE 5.52. SCORING CRITERIA FOR EACH SECTION

Level	Score	Description
1	0	Not available at this moment
2	5	Partially available but may not be sufficient in terms of performance and numbers at this moment
3	10	Sufficient at this moment

TABLE 5.53. SUMMARY OF SCORING SCALE

Area title	Key indicator	NPP	CPP
Economics	LUEC	10	10
	Cash flow	10	8
Energy security	Degree of dependence on supplier(s)	9	5
Public acceptance	Survey of public acceptance	2	6
	External cost	1	10
	Risk of accidents	6	8
Infrastructure	Status of legal framework	5	10
	Status of state organizations	5	10
	Availability of infrastructure to support owner/operator	5	8
	Government policy	0	8
	Availability of human resources	5	8

For a newcomer country considering its first NES, acceptability is more important than economics. Therefore, the weighting factor of economics/acceptability has been defined as 0.3:0.7. The weighting factors were evaluated by following expert opinions, as shown in Table 5.55. All KIs have been determined as linear functions and use the global domains of single-attribute value functions rather than using the local domains (Table 5.56).

TABLE 5.54. PERFORMANCE TABLE

High level objectives	Areas	Indicators	Abbr.	NES	CPP
Economics	Economics	LUEC	KI-1	10	10
		Cash flow	KI-2	10	8
Acceptability	Energy security	Degree of dependence on supplier(s)	KI-3	9	5
	Public acceptance	Survey of public acceptance	KI-4	2	6
		External cost	KI-5	1	10
		Risk of accidents	KI-6	6	8
	Infrastructure	Status of legal framework	KI-7	5	10
		Status of state organizations	KI-8	5	8
		Availability of infrastructure to support owner/ operator	KI-9	5	8
		Government policy	KI-10	0	8
		Availability of human resources	KI-11	5	8

TABLE 5.55. WEIGHTING FACTORS

High level objectives	High level weights	Areas	Area weights	Abbr.	Indicator weights	Final weights
Economics	0.3	Economics	1	KI-1	0.5	0.150
				KI-2	0.5	0.150
Acceptability	0.7	Energy security	0.2	KI-3	1	0.140
		Public acceptance	0.5	KI-4	0.333	0.117
				KI-5	0.333	0.117
				KI-6	0.333	0.117
		Infrastructure	0.3	KI-7	0.2	0.042
				KI-8	0.2	0.042
				KI-9	0.1	0.021
				KI-10	0.3	0.063
				KI-11	0.2	0.042

TABLE 5.56. SINGLE-ATTRIBUTE VALUE FUNCTION

Areas	Abbr.	Goal	Form	Exponent power	VF type domain	NES	CPP
Economics	KI-1	Min.	Linear	1	Global	0.0	0.0
Economics	KI-2	Max.	Linear	1	Global	1.0	0.8
Energy security	KI-3	Min.	Linear	1	Global	0.1	0.5
Public acceptance	KI-4	Max.	Linear	1	Global	0.2	0.6
Public acceptance	KI-5	Min.	Linear	1	Global	0.9	0.0
Public acceptance	KI-6	Min.	Linear	1	Global	0.4	0.2
Infrastructure	KI-7	Max.	Linear	1	Global	0.5	1.0
Infrastructure	KI-8	Max.	Linear	1	Global	0.5	1.0
Infrastructure	KI-9	Max.	Linear	1	Global	0.5	0.8
Infrastructure	KI-10	Max.	Linear	1	Global	0.0	0.8
Infrastructure	KI-11	Max.	Linear	1	Global	0.5	0.8

5.6.1.8. Ranking alternatives (NES options) with the selected MCDA method and interpretation of results with relevance to objectives at different levels

The ranking results for the comparative evaluation show that the CPP is more attractive than the NPP for Thailand, with them receiving scores of 0.468 and 0.412, respectively, as illustrated in Table 5.57. The contribution of each indicator value to the multi-attribute value functions and the structure of the area scores are shown in Fig. 5.41 to identify the areas and indicators that could significantly improve the attractiveness of the NES and cause a re-evaluation of the corresponding contributions. The results show 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 results of the base case analysis show that, in view of the existing national peculiarities and preferences, as well as the degree of national infrastructure development, the NES is a less attractive option than the CPP. The NES is behind the CPP in the energy security and infrastructure evaluation areas for the basic set of weighting factors that reflect national preferences in relation to the importance of the considered indicators.

5.6.1.9. Sensitivity and uncertainty analysis

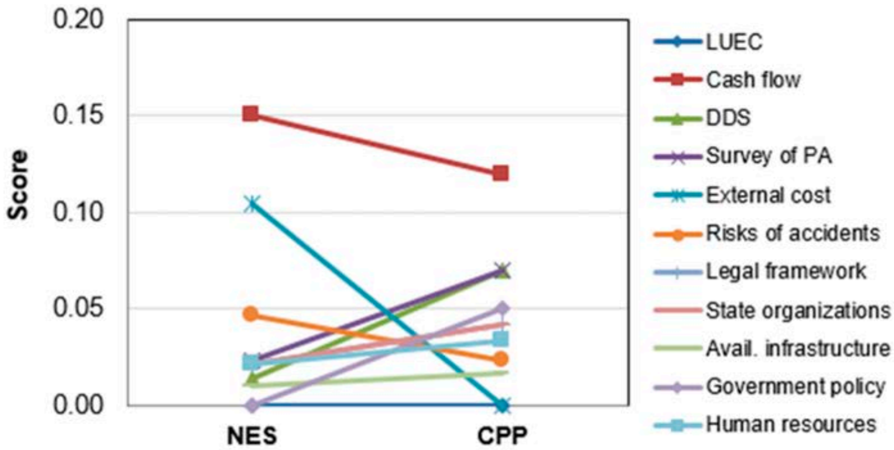
(a) Weighting sensitivity analysis option 1: Vary weighting factor of high level objective

For the case where the NES is less attractive than the CPP when the high level objective weighting factors for economics and acceptability are considered as 0.3/0.7, the sensitivity analysis has to be performed by varying the ratio of the high level objective weighting factor and fixing the weighting factor of the evaluation area and indicator. Figure 5.42 shows the results of the comparative evaluation between the NES and the CPP when the high level objective weighting factors are varied.

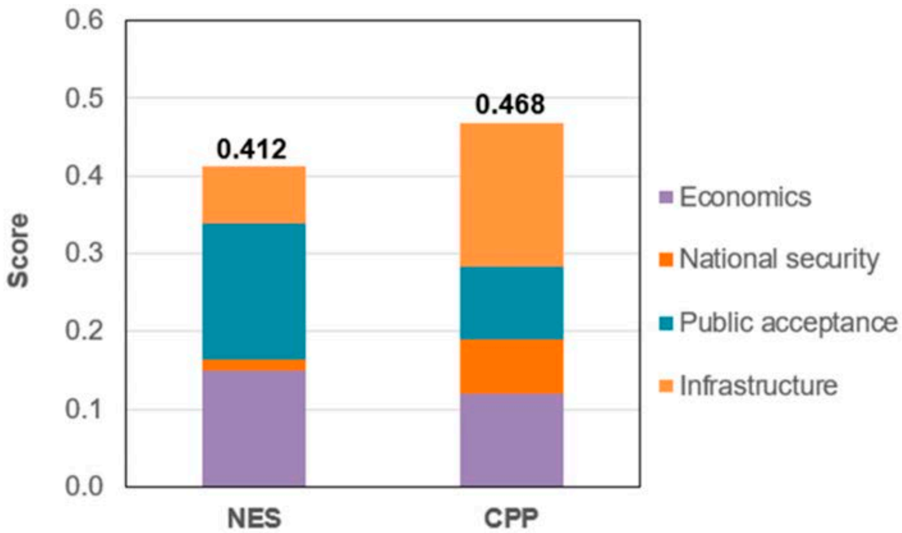
In Fig. 5.42, the results for an expanded sensitivity analysis regarding the weighting factors for the high level objectives economics and acceptability are presented. For fixed area weighting factors and indicator weighting, increasing the weight of economics while decreasing the weight of acceptability down to 0.4 (approximately) could result in the NES appearing to be more attractive than the CPP. The results show that the attractiveness of the NES surpasses that of the CPP when the weighting factor of acceptability is lower than 0.4.

TABLE 5.57. RANKING RESULT FOR THE COMPARATIVE EVALUATION OF AN NES AND A CPP (BASE CASE)

Levels	NES	CPP
Multi-attribute value function	0.412	0.468
High level objective scores		
Economics	0.150	0.120
Acceptability	0.262	0.348
Area scores		
Economics	0.150	0.120
Energy security	0.014	0.070
Public acceptance	0.175	0.093
Infrastructure	0.074	0.185



(a)



(b)

FIG. 5.41. Contribution of each indicator value. (a) KI scores; (b) area scores.

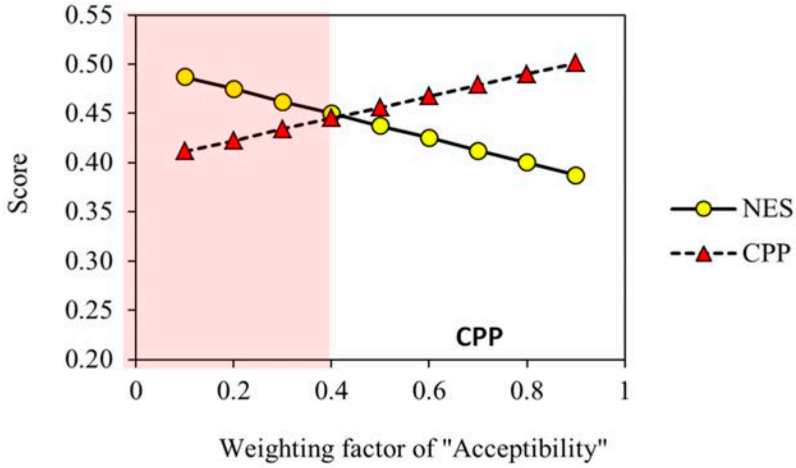


FIG. 5.42. Sensitivity analysis for the NES and CPP performed by varying the acceptability weighting factors.

(b) Weighting sensitivity analysis option 2: ignore the energy security and infrastructure areas

According to the results shown in Section 5.6.1.8, the energy security and infrastructure evaluation areas have a profound impact on the overall score for the NES (making it a less attractive option than the CPP). Therefore, the option to ignore both evaluation areas is adopted such that only the area of public acceptance remains in the high level objective acceptability. The basic set of high level objective weighting factors for economics: acceptability is fixed at 0.3:0.7, as presented in Table 5.58.

The results show that without the energy security and infrastructure evaluation areas, the NES could become a more attractive option than the CPP, as shown in Table 5.59 and Fig. 5.43.

5.6.1.10. Conclusion

The improvement of one indicator is not sufficient for the system of interest to become attractive compared to its competitors. It also needs to be understood that an unlimited increase in values for one indicator of the set being considered, as a rule, is costly or even infeasible. In this context, it seems reasonable to select indicators that, if improved, would enhance the efficiency of the alternative of interest at minimum cost. For this purpose, it is advisable to use the global domains of single-attribute value functions, which will reflect improvements in the system performance more informatively by gradually improving the values of the indicators used in evaluations.

5.7. DEVELOPMENT SCENARIOS

5.7.1. GAINS scenarios

This study applied the KIND framework to the comparative evaluation of NES deployment scenarios developed in the INPRO collaborative project Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS).

5.7.1.1. MCDA methods applied in the study

The comparative evaluations of NES deployment scenarios presented in this study were carried out using the following well known and widely used classical deterministic MCDA methods: MAVT, MAUT, TOPSIS, PROMETHEE, AHP and a simple scoring model [5.29–5.35]. The approach to comparison implemented in the study consisted of using several diverse MCDA methods to help recognize and examine the problem more thoroughly, achieve consistency in judgements and examine the stability and robustness of the ranking results

TABLE 5.58. WEIGHTING FACTORS WHEN THE ENERGY SECURITY AND INFRASTRUCTURE EVALUATION AREAS ARE IGNORED

High level objectives	High level objective weights	Areas	Area weights	Indicators abbr.	Indicator weights	Final weights
Economics	0.3	Economics	1	KI-1	0.5	0.150
				KI-2	0.5	0.150
Acceptability	0.7	Energy security	0	KI-3	1	0.000
		Public acceptance	1	KI-4	0.333	0.233
				KI-5	0.333	0.233
				KI-6	0.333	0.233
		Infrastructure	0	KI-7	0.2	0.000
				KI-8	0.2	0.000
				KI-9	0.1	0.000
				KI-10	0.3	0.000
				KI-11	0.2	0.000

TABLE 5.59. RANKING RESULTS FOR THE COMPARATIVE EVALUATION OF THE NES AND THE CPP (OPTION 2)

Levels	NES	CPP
Multi-attribute value function	0.500	0.306
	High level objective scores	
Economics	0.150	0.120
Acceptability	0.350	0.186
	Area scores	
Economics	0.150	0.120
Energy security	0.000	0.000
Public acceptance	0.350	0.186
Infrastructure	0.000	0.000

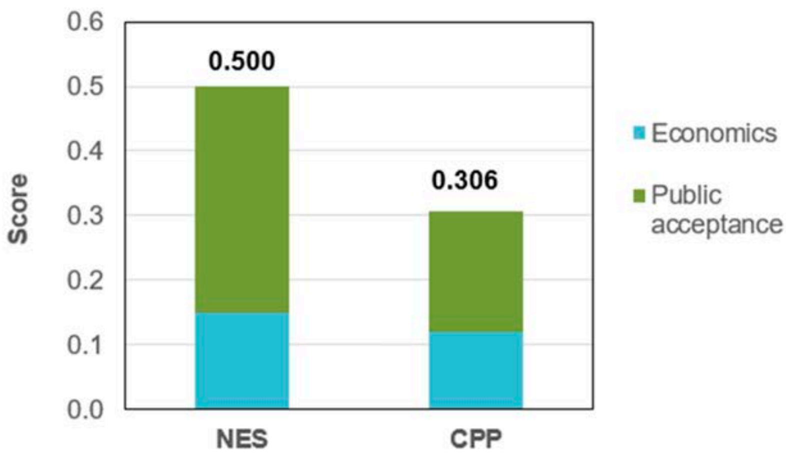


FIG. 5.43. The structure of the area scores for the NES and CPP for option 2.

from different perspectives. It also demonstrates that the application of different MCDA methods for comparative evaluation of the NES deployment scenarios may provide non-contradictory results [5.36].

5.7.1.2. The GAINS analytical framework

The 11 NES deployment scenarios obtained in the GAINS collaborative project considered in Ref. [5.1] were compared by the aforementioned MCDA methods to demonstrate the value added to the examination of NES performance and sustainability by the application of MCDA. The GAINS analytical framework offers a tool for the evaluation of NES deployment scenario KIs, but without any guidance on how to apply these data to formulate aggregated judgements regarding preferable NES deployment scenarios and their sustainability potential. The GAINS performance indicators, in combination with the MCDA methods, may be used for sorting, ranking and comparatively evaluating NES deployment scenarios, providing an opportunity to make definite judgements about the preferred NESs. The GAINS analytical framework consists of the following components:

(a) Long term nuclear energy demand scenarios based on the IAEA Member States' high and low estimations for nuclear power deployment until 2030 and expected trends until 2050, including forecasts of competent international energy organizations;
(b) Heterogeneous world model comprising groups of non-personified and non-geographical countries with different policies regarding the NFC back end;
(c) Architectures of NESs;
(d) A toolkit for the evaluation of NES deployment scenarios regarding sustainability, including KIs and evaluation parameters;
(e) An internationally verified database containing the characteristics of existing and advanced nuclear reactors and related NFCs for material flow analysis, extending the IAEA databases and taking into account the preferences of different countries;
(f) The results of trial analyses for scenarios involving a transition from the current nuclear reactor fleets and NFCs to future sustainable INES architectures.

5.7.1.3. NES evolution scenarios

Among more than 55 GAINS NES deployment scenarios, the following 11 scenarios were considered in the study[5] (Table 5.60):

(a) L1H1 — The business as usual (BAU) scenario based on pressurized LWRs (L1) (94% of power generation) and HWRs (H1) (6% of power generation) operated in a once through NFC.
(b) L1L2H1 — The BAU+ scenario based on HWRs and LWRs being replaced by high burnup advanced light water reactors (ALWRs) (L2) from 2015.
(c) L1L2H1F1 — A scenario involving the introduction of the break even (breeding ratio ~1.0 (BR~1.0)) FR (F1) into BAU+. The FRs are being introduced starting from 2021. The objective is to have a total generation rate of 10 GW(e)·year from FRs in 2030 for both growth cases and a total of 400 GW(e)·year in 2050 for the high case.
(d) L1L2H1F2 — A scenario involving the introduction of the breeder (BR~1.2) FR (F2) into BAU+.
(e) L1L2H1F3 — A scenario involving the introduction of the high burnup breeder (BR~1.2) FR (F2) into BAU+. The fuel for the high burnup FR breeder contains MAs and, hence, this reactor contributes to MA burning.
(f) L1L2H1F1A1 — Scenario L1L2H1F1 with the introduction of accelerator driven systems (ADSs) (A1) for the transmutation of MAs to eliminate the need for the transmutation of MAs in a critical FR (the total installed capacity of ADSs is about 148 GW(e) — approximately 3% of the total installed capacity). The ADSs are being introduced between 2075 and 2100, and only when a look ahead identifies sufficient MAs and plutonium feeds for their 60 year lifetime.

[5] L1 — light water reactor (LWR) with low burnup (45 GW·d/t); L2 — LWR with high burnup (60 GW·d/t); H1 — heavy water reactor (HWR; typical current prototype); F1 — break even fast reactor (FR) with breeding ratio (BR)~1.0; F2 — FR with medium BR (BR~1.2), medium burnup (~31 GW·d/t); F3 — FR with medium BR (BR~1.2), high burnup (~54 GW·d/t); A1 — accelerator driven system (ADS) for minor actinide (MA) burning; M1 — molten salt reactor (MSR) for MA burning.

(g) L1L2H1F2A1 — The L1L2H1F2 scenario with the introduction of the ADS (A1).
(h) L1L2H1F3A1 — The L1L2H1F3 scenario with the introduction of the ADS (A1).
(i) L1L2H1F1M1 — The L1L2H1F1 scenario with the introduction of the molten salt reactor (MSR) (M1) for MA burning (the total installed capacity of MSRs is about 160 GW(e) — around 3% of total installed capacity).
(j) L1L2H1F2M1 — The L1L2H1F2 scenario with the MSR (M1) for MA burning.
(k) L1L2H1F3M1 — The L1L2H1F3 scenario with the MSR (M1) for MA burning.

In all scenarios, it is assumed that global nuclear energy generation will be about 1500 GW(e)·year by 2050 and 5000 GW(e)·year by 2100. According to the GAINS assumptions, a restriction on power production by FRs is expected between 2030 and 2050 through the specification of a maximum deployment rate, depending on the overall nuclear energy growth scenario. The objective is to have a total generation rate of 10 GW(e)/year from FRs in 2030 and a total of 400 GW(e)/year in 2050 for the high scenario case. After 2050, the deployment rate for FRs will be maximized and limited only by the amount of plutonium available and the overall nuclear growth rate. The plutonium inventory in the storage was kept close to zero. The calculations were carried out using the Nuclear Fuel Cycle Simulation System software tool [5.37]. The power production for all of the considered scenarios is shown in Fig. 5.44 by each reactor type.

TABLE 5.60. NES DEPLOYMENT SCENARIOS

No.	NES deployment scenario	Scenario denotation	Colour code
1	BAU	L1H1	
2	BAU+	L1L2H1	
3	BAU+, FR break even	L1L2H1F1	
4	BAU+, FR medium BR, medium burnup	L1L2H1F2	
5	BAU+, FR medium BR, high burnup	L1L2H1F3	
6	BAU+, FR break even and ADS	L1L2H1F1A1	
7	BAU+, FR medium BR, medium burnup and ADS	L1L2H1F2A1	
8	BAU+, FR medium BR, high burnup and ADS	L1L2H1F3A1	
9	BAU+, FR break even and MSR	L1L2H1F1M1	
10	BAU+, FR medium BR, medium burnup and MSR	L1L2H1F2M1	
11	BAU+, FR medium BR, high burnup and MSR	L1L2H1F3M1	

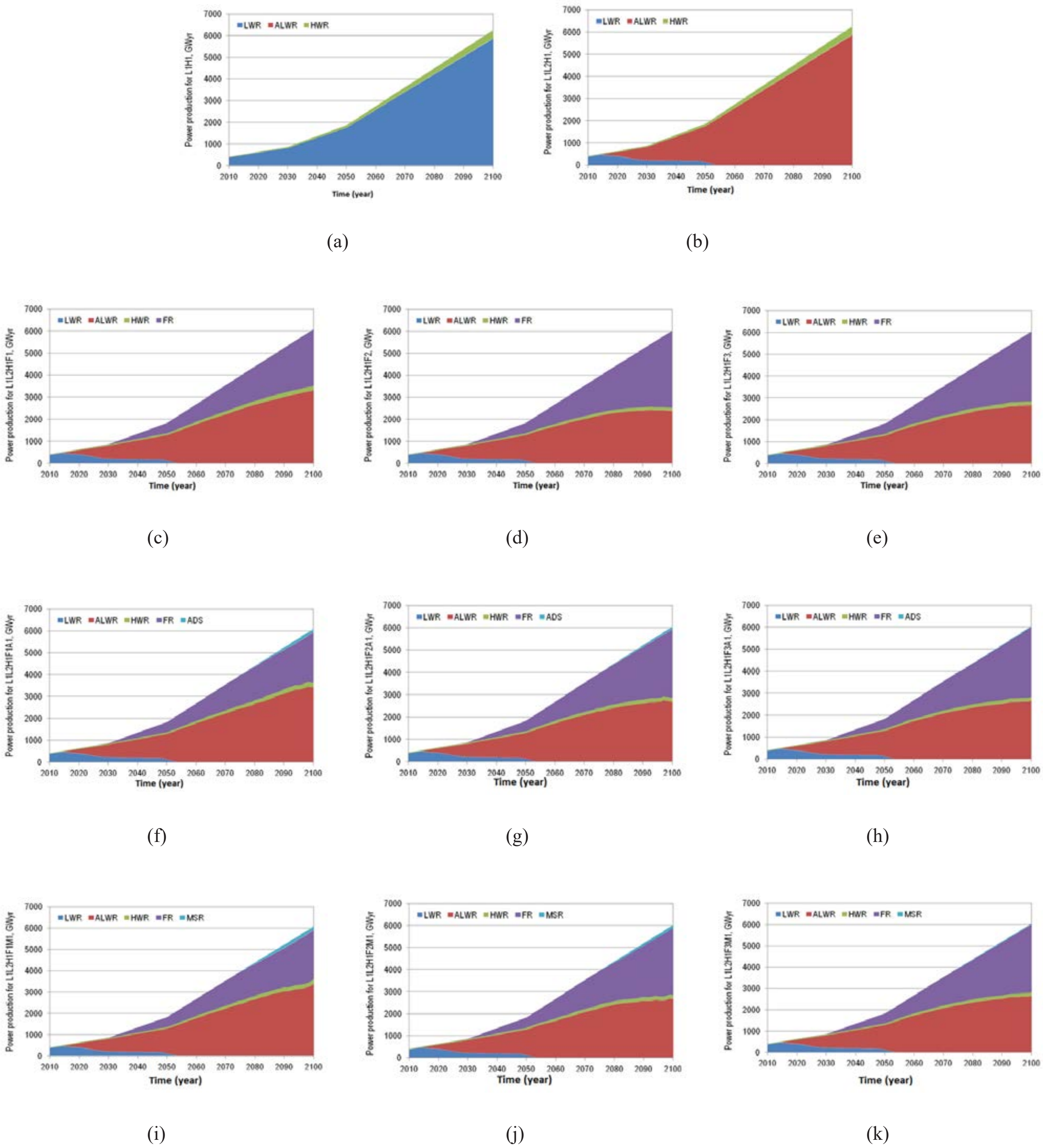


FIG. 5.44. Energy production by NESs in the deployment scenarios considered in the study.

5.7.1.4. KIs

Nine KIs were selected for the performance of the comparative evaluation (see Table 5.61). This selection was made while considering the following: the indicators need to provide information regarding all areas related to the NES deployment (resources, waste management, proliferation resistance and economics) and they are to be evaluated based on data available in the GAINS project report [5.1]. A short explanation of the KIs considered is presented below (all KIs need to be minimized).

(a) Total natural uranium consumption (KI 1) is a measure of natural uranium consumption (a measure of resource sustainability) representing the total consumed uranium in the 1970–2100 timeframe by all nuclear reactors.
(b) Annual SNF generation (KI 2) serves as a measure for SNF management performance and represents annual SNF discharge shipped to at reactor storage facilities in 2100 from all nuclear reactors.
(c) Total SNF in long term storage (KI 3) characterizes another measure for SNF management performance and represents an integral SNF quantity from all nuclear reactors accumulated in away from reactor storage by 2100.
(d) MA in NFC (KI 4) is a measure for waste management performance that represents total MA inventories at all NFC steps produced by all nuclear reactors in 2100.
(e) Plutonium in NFC (KI 5) serves as one more measure of proliferation resistance, representing the total quantity of plutonium produced by nuclear reactors that was circulated and accumulated at all NFC steps in 2100.
(f) Total enrichment capacity (KI 6) is an additional proliferation resistance measure representing the cumulative enrichment service requirements to produce nuclear fuel for nuclear reactors in the 2008–2100 timeframe.
(g) Total reprocessing capacity (KI 7) serves as a measure of the cumulative reprocessing capacity requirement to reprocess SNF from nuclear reactors in the 2008–2100 timeframe and specifies another proliferation resistance measure.
(h) Total uranium cost (KI 8) is a measure of the economic performance of limited natural uranium consumption representing the total uranium recovery cost needed to produce nuclear fuel for deployment scenarios by 2100. This KI was evaluated by taking the following into account:
    — The evaluation was performed for the lower estimation of uranium recovery cost according to [5.38].
    — All uranium reserves with the estimated recovery cost were consumed (13 800 kt) for all NES deployment scenarios.
    — The remainder of the uranium reserves (the majority of consumed uranium reserves) were recovered at US $260 per kg.
    — The discount rate was taken as 5%.
(i) Total investments in NPPs (KI 9) characterizes the total discounted investment cost in NPP construction until 2100 and represents a possible measure of the economic performance for NES deployment scenarios. The following assumptions were made to evaluate the investments required for the deployment of nuclear reactors for the scenarios considered:

TABLE 5.61. KEY INDICATORS CONSIDERED

KI	Abbreviation	Unit	Goal
Total natural uranium consumption	KI 1	kt HM	Min.
Annual SNF generation	KI 2	kt HM + FPs	Min.
Total SNF in long term storage	KI 3	kt HM + FPs	Min.
MAs in NFC	KI 4	t HM	Min.
Pu in NFC	KI 5	t HM	Min.
Total enrichment capacity	KI 6	kt SWU	Min.
Total reprocessing capacity	KI 7	kt HM + FPs	Min.
Total uranium cost	KI 8	billion US $	Min.
Total investments in NPPs	KI 9	billion US $	Min.

Note: FPs — fission products, HM — heay metal, SWU — separative work unit.

— The overnight capital construction costs of existing nuclear reactor types (LWR and HWR) were assumed to be equal to US $4000/kW(e).
— For the construction of the new nuclear reactor types ALWR, FR1, FR2, FR3, ADS and MSR, the overnight capital costs were assumed to be more than those of existing nuclear reactor types by 10%, 20%, 25%, 30%, 40% and 40%, respectively.
— The discount rate was assumed to be 5%.

The performance table (Table 5.62) for the evaluated KIs for all of the NES deployment scenarios was formed based on the aforementioned assumptions and data available in Excel tables from the supplementary material from the GAINS collaborative project report [5.1]. The performance table is visualized in the form of a value path and a radar chart (Fig. 5.45):

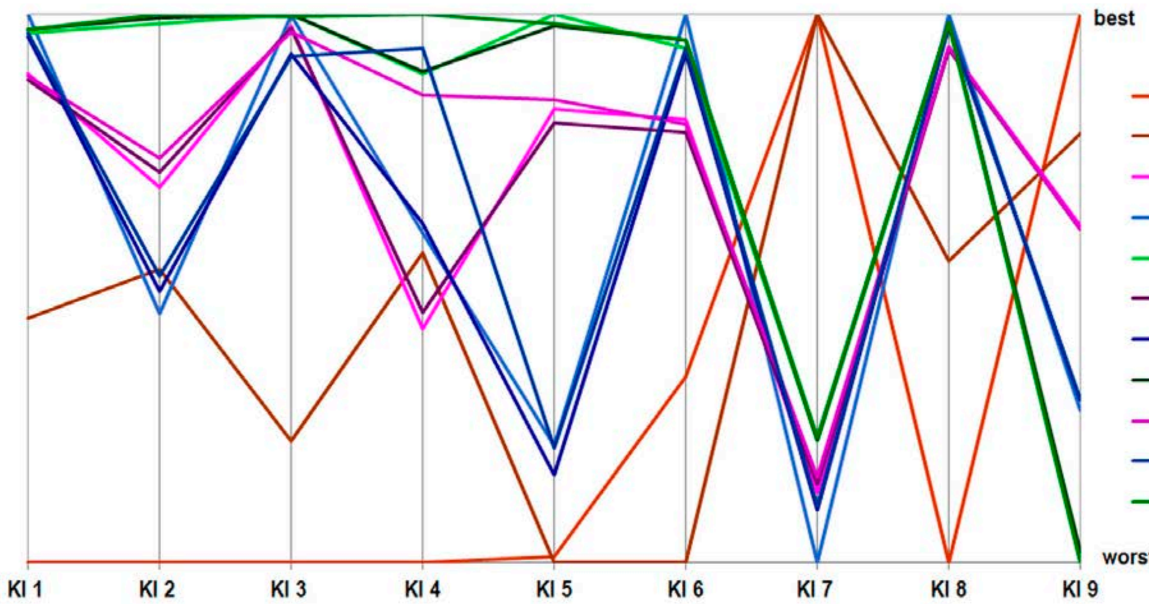
(i) A value path diagram demonstrates in relative terms (1 is the best value, 0 is the worst value) the KI values for the entire set of NESs, showing how much improvement in the value of one KI reduces the values of other KIs due to the transition from one NES to another;
(ii) A radar chart (web chart, spider chart, etc.) is a method of displaying multivariate data in the form of a two dimensional chart of three or more quantitative variables represented on axes starting from the same point.

It should be mentioned that in this case study, all alternatives are non-dominated (e.g. Pareto optimal, Pareto efficient or non-inferior). This means that each alternative has some advantages over the others. The non-dominated alternative is an alternative for which none of the KIs can be improved without degrading some of the other KIs. Without additional subjective preference information, all non-dominated alternatives are considered to be equally suitable (compromised or trade-off options). The identification of non-dominated alternatives and the information about domination may be used for excluding dominated alternatives from the consideration.

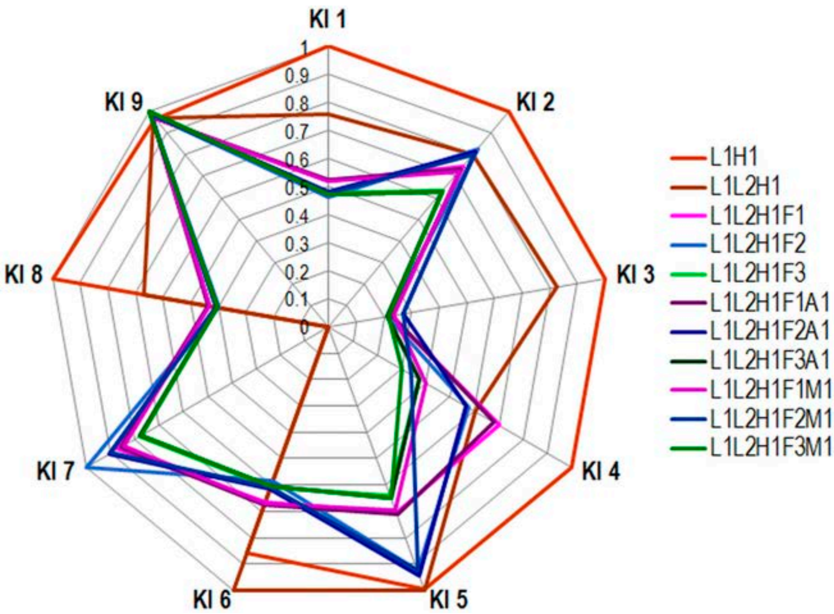
TABLE 5.62. PERFORMANCE TABLE

KI	Unit	L1H1	L1L2H1	L1L2H1F1	L1L2H1F2	L1L2H1F3	L1L2H1F1A1	L1L2H1F2A1	L1L2H1F3A1	L1L2H1F1M1	L1L2H1F2M1	L1L2H1F3M1
KI 1	10^3 kt HM	49.8	37.8	25.8	22.9	23.8	26.1	24.0	23.6	25.9	23.8	23.6
KI 2	kt HM + FPs	172	138	128	143	109	126	140	108	125	139	108
KI 3	10^3 kt HM + FPs	6.06	5.00	1.38	1.29	1.28	1.40	1.62	1.28	1.43	1.64	1.30
KI 4	10^3 kt HM	11.7	7.07	8.21	6.76	4.37	7.95	6.62	4.34	4.70	4.00	3.49
KI 5	10^3 kt HM	52.0	52.2	36.7	48.2	33.5	37.2	49.2	33.9	36.4	48.3	33.8
KI 6	10^3 kt SWU	26.9	31.3	20.8	18.3	19.1	21.1	19.2	18.9	20.9	19.1	18.9
KI 7	10^3 kt HM + FPs	0.00	0.00	3.55	4.07	3.17	3.49	3.68	3.16	3.44	3.65	3.14
KI 8	billion US $	567	379	245	225	231	247	232	230	245	231	230
KI 9	billion US $	4106	4138	4163	4213	4253	4164	4210	4251	4164	4210	4254

Note: FPs — fission products, HM — heay metal, SWU — separative work unit.



(a)



(b)

FIG. 5.45. Presentation of results. (a) Value path, (b) radar chart.

5.7.1.5. Weighting factors

The sets of the weights (Table 5.63) were discussed with and agreed by the subject matter experts. Within the study, the same weights were used for all MCDA methods. The following weight options were considered with regard to desirable objectives that NES deployment scenarios need to achieve:

(a) Equal significance of all KIs (variant 1);
(b) Expert preferences based on questionnaires from the INPRO meetings[6] (variants 2a, 2b);

[6] Two groups of experts: (a) INPRO Dialogue Forum 4 participants and (b) SYNERGIES participants.

(c) Preference for investment minimization (variant 3);
(d) Preference to waste minimization (variant 4).

TABLE 5.63. SUMMARY TABLE FOR WEIGHTS

KIs	Variants				
	1	2a	2b	3	4
Total natural uranium consumption	0.11	0.11	0.12	0.03	0.02
Annual SNF generation	0.11	0.13	0.12	0.03	0.6
Total SNF in long term storage	0.11	0.13	0.12	0.03	0.18
MAs in NFC	0.11	0.10	0.11	0.03	0.1
Pu in NFC	0.11	0.10	0.11	0.03	0.02
Total enrichment capacity	0.11	0.10	0.10	0.03	0.02
Total reprocessing capacity	0.11	0.10	0.10	0.03	0.02
Total uranium cost	0.11	0.13	0.10	0.11	0.02
Total investments in NPPs	0.11	0.11	0.12	0.68	0.02

5.7.1.6. Ranking results and sensitivity analysis

The NES deployment scenarios could be combined in three groups:

(a) The first group consists of the scenarios with the F3 type FR.
(b) The second group contains the scenarios with F2 and F1 type FRs.
(c) The third group includes the scenarios based on the once through NFC.

The combination of the alternatives in such groups seems reasonable because the ranks of alternatives in each applied MCDA method are close for the corresponding scenario families and this provides a clearer interpretation of the ranking results. Figure 5.46 shows the ranking results for the MAVT method with weights variant 1.

The applied MCDA methods and simple scoring model have demonstrated that, despite some differences in the ranks of scenarios, the results obtained by using different methods are quite consistent. Because of this, it is possible to differentiate the performance of the NES deployment scenarios and reach general conclusions regarding the efficiency of the associated reactor technologies and NESs (Table 5.64).

The results indicate that the NES deployment scenarios based on the F3 type FR are the most preferable options and the scenarios based on the once through NFC are the least preferable ones. The scenarios with the F1 and F2 FRs demonstrate some variation in ranks for different methods that does not allow one to make a final judgement regarding their performance. The same is true for the MA burners (MSR and ADS).

All of the considered MCDA methods used for variants 1, 3 and 4 demonstrate the dominance of the first and second groups of NES deployment scenarios over the third one (Table 5.64). The ranking results for variants 1, 2a and 2b identified by using all of the MCDA methods are the same and correlate to a considerable degree with the ranking results for variant 4. The result for weights variant 3 differs significantly from those for the other weights variants (Table 5.65).

This numerical example has revealed that five methods (MAVT, MAUT, PROMETHEE, AHP and the simple scoring model) provide similar ranking results for all weights variants. TOPSIS generally gives similar results too, although not for weights variant 3, because of the specifics of the decision rule (ranking approach) realized in it.

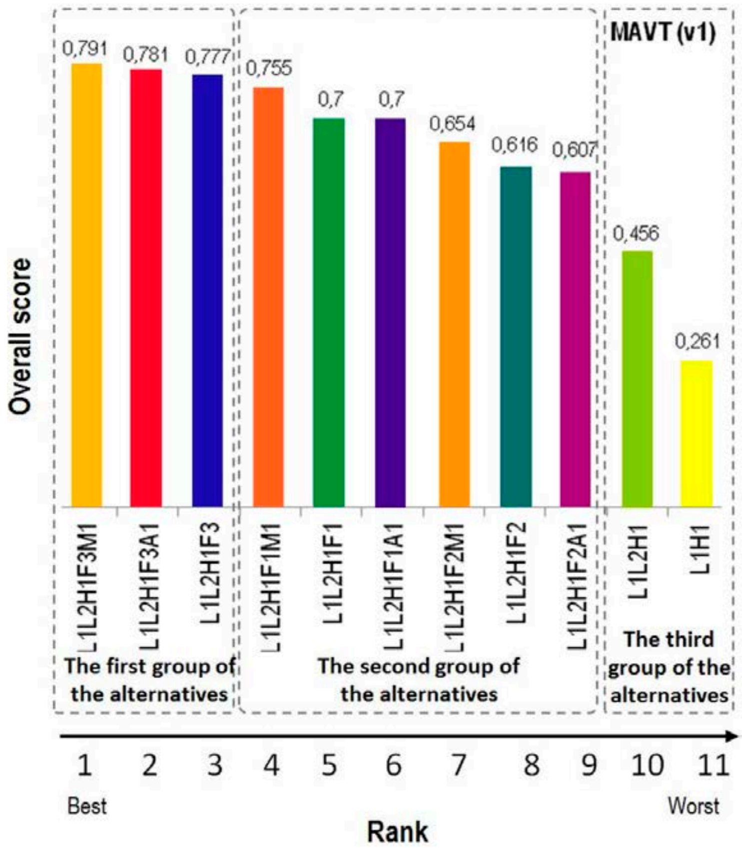


FIG. 5.46. Ranking results for the MAVT method with weights variant 1.

TABLE 5.64. RANKING RESULTS BY METHOD USED (WEIGHTS VARIANT 1)

Rank	Simple scoring model	MAVT	MAUT	TOPSIS	PROMETHEE	AHP
1	L1L2H1F3A1	L1L2H1F3M1	L1L2H1F3M1	L1L2H1F3M1	L1L2H1F3M1	L1L2H1F3M1
2	L1L2H1F3M1	L1L2H1F3A1	L1L2H1F3A1	L1L2H1F3A1	L1L2H1F3A1	L1L2H1F3
3	L1L2H1F3	L1L2H1F3	L1L2H1F3	L1L2H1F3	L1L2H1F3	L1L2H1F3A1
4	L1L2H1F2	L1L2H1F1M1	L1L2H1F1M1	L1L2H1F1M1	L1L2H1F1M1	L1L2H1F1M1
5	L1L2H1F1M1	L1L2H1F1A1	L1L2H1F1A1	L1L2H1F2M1	L1L2H1F1A1	L1L2H1F2M1
6	L1L2H1F1	L1L2H1F1	L1L2H1F1	L1L2H1F1A1	L1L2H1F1	L1L2H1F2
7	L1L2H1F2M1	L1L2H1F2M1	L1L2H1F2M1	L1L2H1F2A1	L1L2H1F2M1	L1L2H1F1
8	L1L2H1F1A1	L1L2H1F2	L1L2H1F2	L1L2H1F1	L1L2H1F2A1	L1L2H1F1A1
9	L1L2H1F2A1	L1L2H1F2A1	L1L2H1F2A1	L1L2H1F2	L1L2H1F2	L1L2H1F2A1
10	L1L2H1	L1L2H1	L1L2H1	L1L2H1	L1L2H1	L1L2H1
11	L1H1	L1H1	L1H1	L1H1	L1H1	L1H1

TABLE 5.65. RANKING OF THE NES DEPLOYMENT SCENARIOS

Variants	The best NESs	→		→			The worst NESs
1, 2a, 2b, 4	L1L2H1F3 L1L2H1F3A1 L1L2H1F3M1	≻	L1L2H1F1 L1L2H1F2 L1L2H1F1A1 L1L2H1F2A1 L1L2H1F1M1 L1L2H1F2M1	≻	L1L2H1	≻	L1H1
3	L1H1 L1L2H1	≻	L1L2H1F1 L1L2H1F1A1 L1L2H1F1M1	≻	L1L2H1F2 L1L2H1F2A1 L1L2H1F2M1	≻	L1L2H1F3 L1L2H1F3A1 L1L2H1F3M1

The MCDA methods, which are a support tool for the comparative evaluation of NESs, are only a means of demonstrating ranking results in general terms. In this regard, a more important output for supporting decision makers is the clarification (in a clear and understandable manner) of the features of NESs that result in the costs, risks and benefits to be identified. Table 5.66 shows the ranks of the NES deployment scenarios ordered by individual KI, highlighting the merits and demerits associated with each NES deployment scenario (using the heat map[7] approach).

The MAVT ranking results may be clarified by means of the decomposition of the multi-attribute value functions for the specific components in accordance with the specified structure of the objectives tree. If a decision maker and experts want an explanation of the reasons behind the dominance of one scenario over another, the multi-attribute value function has to be decomposed into individual constituents. Figure 5.47 demonstrates scores for the high level objectives costs and risk (1 is the best value and 0 is the worst value) for the alternatives considered. This graph illustrates the high level performance associated with each NES deployment scenario, providing the opportunity to observe the merits and demerits associated with the scenarios considered. The high level objectives cost and risk were evaluated based on single-attribute value functions for KIs No. 1, 8 and 9, and No. 2, 3, 4, 5, 6 and 7, respectively.

TABLE 5.66. HIGHLIGHTING THE MERITS AND DEMERITS ASSOCIATED WITH NESs

Rank	KI 1	KI 2	KI 3	KI 4	KI 5	KI 6	KI 7	KI 8	KI 9
1	L1L2H1F2	L1L2H1F3M1	L1L2H1F3	L1L2H1F3M1	L1L2H1F3	L1L2H1F2	L1H1	L1L2H1F2	L1H1
2	L1L2H1F3A1	L1L2H1F3A1	L1L2H1F3A1	L1L2H1F2M1	L1L2H1F3M1	L1L2H1F3A1	L1L2H1	L1L2H1F3A1	L1L2H1
3	L1L2H1F3M1	L1L2H1F3	L1L2H1F2	L1L2H1F3A1	L1L2H1F3A1	L1L2H1F3M1	L1L2H1F3M1	L1L2H1F3M1	L1L2H1F1
4	L1L2H1F3	L1L2H1F1M1	L1L2H1F3M1	L1L2H1F3	L1L2H1F1M1	L1L2H1F3	L1L2H1F3A1	L1L2H1F3	L1L2H1F1A1
5	L1L2H1F2M1	L1L2H1F1A1	L1L2H1F1	L1L2H1F1M1	L1L2H1F1	L1L2H1F2M1	L1L2H1F3	L1L2H1F2M1	L1L2H1F1M1
6	L1L2H1F2A1	L1L2H1F1	L1L2H1F1A1	L1L2H1F2A1	L1L2H1F1A1	L1L2H1F2A1	L1L2H1F1M1	L1L2H1F2A1	L1L2H1F2A1
7	L1L2H1F1	L1L2H1	L1L2H1F1M1	L1L2H1F2	L1L2H1F2	L1L2H1F1	L1L2H1F1A1	L1L2H1F1	L1L2H1F2M1
8	L1L2H1F1M1	L1L2H1F2M1	L1L2H1F2A1	L1L2H1	L1L2H1F2M1	L1L2H1F1M1	L1L2H1F1	L1L2H1F1M1	L1L2H1F2
9	L1L2H1F1A1	L1L2H1F2A1	L1L2H1F2M1	L1L2H1F1A1	L1L2H1F2A1	L1L2H1F1A1	L1L2H1F2M1	L1L2H1F1A1	L1L2H1F3A1
10	L1L2H1	L1L2H1F2	L1L2H1	L1L2H1F1	L1H1	L1H1	L1L2H1F2A1	L1L2H1	L1L2H1F3
11	L1H1	L1H1	L1H1	L1H1	L1L2H1	L1L2H1	L1L2H1F2	L1H1	L1L2H1F3M1

[7] A heat map is a graphical representation of data where different values contained in the matrix are represented by different colours.

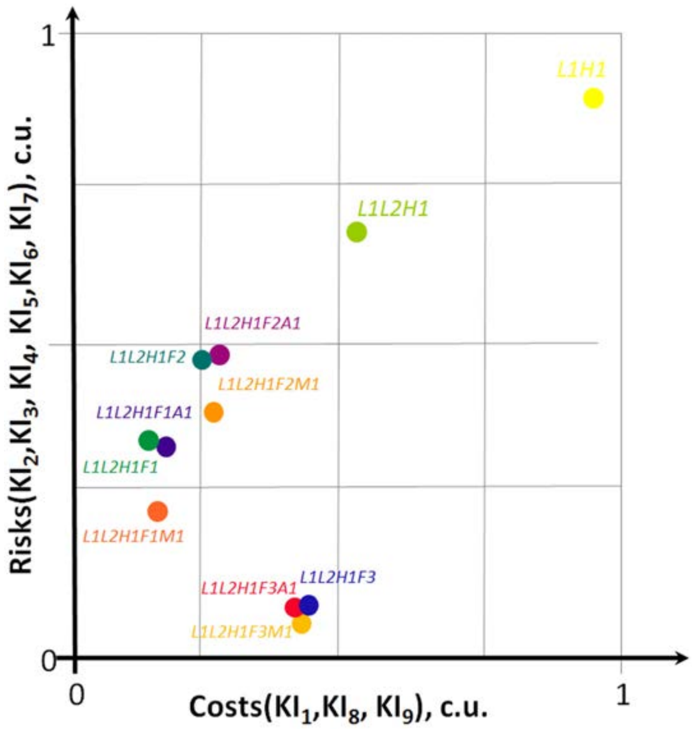


FIG. 5.47. The high level objectives for the NES deployment scenarios.

Within the study, uncertainties were examined through a sensitivity analysis, assuming sensitivity to variation in the weights and value, utility and preference functions. The sensitivity analysis confirmed that the ranks of the scenarios are generally stable against possible changes to the model assumptions for both the model parameters and the values of the weights. The sensitivity analysis for the weights demonstrated that the ranks of the scenarios are not very sensitive to the weighting factors and they may be considered to be stable since the ranks satisfy the following sensitivity test: the change of all weighting factors by 10% does not change the scenario ranks. Using a wide range of essentially different MCDA methods established the closeness of the scenario rankings obtained by different methods and confirmed in general that the results are robust and stable.

5.7.1.7. Discussion and conclusion

Taking into consideration the results of the sensitivity analysis, the examination of scenarios by the additional analytical methods and the entire set of graphical and attribute data, the most preferable option could be identified for different circumstances. Given below are recommendations regarding the most preferable reactor technologies and the associated NES deployment scenarios for different situations:

— If the requirement to minimize investment costs is not decisive, priority could be given to one of the scenarios with F3 fast reactors (L1L2H1F3, L1L2H1F3A1, L1L2H1F3M1). The most efficient material flow management (in terms of reduction of waste generation and proliferation risks) is provided by L1L2H1F3M1, which is 0.7% more expensive (relative increase in KI-9) compared to L1L2H1F3.
— If the requirement to minimize investment costs is dominant, the L1L2H1 scenario seems a better alternative than L1H1. The L1L2H1 scenario demonstrates superior NES performance without meaningfully raising the investment costs (0.8%) in comparison with the cheapest L1H1 option.
— The L1L2H1F1 scenario seems to be a trade-off alternative. This option involves an increase in the investment cost of 1.4% in comparison with the cheapest L1H1 option, but offers acceptable nuclear materials management performance.

It should be noted that from the system viewpoint, the F2 FR is less effective than its competitors, the F3 FR (more expensive but more efficient in the NES in terms of NFC material flow management) and the F1 FR (cheaper but provides performance comparable to F2 FR).

The MSR seems to some degree to be preferable to the ADS, but there is no meaningful difference between MSR and ADS performance for the given NES deployment scenarios because of the small share of these technologies in the corresponding NES structures. As a result, to make a final selection between these technologies it would be necessary to carry out a more detailed examination, assuming increasing shares of these technologies in the structures of the corresponding NESs.

The multi-criteria comparative evaluation of the performance of the NES deployment scenarios based on the MCDA methods considered demonstrates that the ranks obtained by means of different methods are well harmonized and reliable. In general, it may be concluded that in comparable circumstances, the ranking results obtained by different MCDA methods will be consistent and steady.

The MCDA methods that may be applied to perform comparative evaluation of NES deployment scenarios are not limited to those considered in the present study. However, it is desirable that other possible ranking/aggregation methods be verified for the consideration of a specific problem. This case study provides the following conclusions regarding the application of the MCDA methods for expert judgement aggregation for the comparison of NES deployment scenarios:

(a) All of the MCDA methods considered, including the simple scoring model, MAVT/MAUT, TOPSIS, PROMETHEE and AHP, can be used for the comparative evaluation of NES deployment scenarios, and the final choice of the most suitable method for a particular task needs to be based on consideration of the context for a problem and the quality of the initial information provided by subject matter experts.
(b) For the objectives of the KIND project, the use of transparent and uncomplicated methods can be recommended for comparative evaluations of NES deployment scenarios. Simple additive weighting and MAVT methods combined with uncertainty examination through a sensitivity analysis can be recommended for application as a primary option.
(c) To increase the confidence level of the study, it is reasonable to use several different MCDA methods that make it possible to obtain a better understanding of the problem and a more comprehensible analysis.

5.7.2. OECD/NEA scenarios: Evaluation and aggregation judgement approaches for comparing the performance of advanced NFCs

5.7.2.1. Background

NFC performance can be evaluated using a wide range of criteria. The categorization of the criteria can be considered from the perspective of such criteria as economics, sustainable security of resources, environmental aspects and proliferation resistance. On the other side, the broad range of advanced NFCs under development and their flexibility offer the possibility of designing and implementing safe and economical NESs in the future, addressing both natural resource consumption and waste management issues efficiently. Strategic choices will be based on the policy makers' priorities, which reflect country specific criteria such as access to uranium resources, the characteristics of the available waste repositories, the size of the nuclear power programme or social and economic considerations. Different countries tend to have different preferences regarding these issues, driven by national priorities. A similar characterization of criteria can be made from engineers' or scientists' points of view. A technically oriented study undertaken by the OECD Nuclear Energy Agency (OECD/NEA) and launched in 2004 was devoted to the evaluation of the impact of potential NFC strategies on the uranium consumption rate and radioactive waste management. The set of fuel cycle options analysed in this study includes once through, recycling in TRs, sustained recycle with a mix of TRs and FRs, and sustained recycle with FRs. Thus, among other technologies, the OECD/NEA study also addressed advanced NFCs that may arise in the future as a consequence of new developments in NFC technologies such as enrichment, advanced recycling processes, remote handling and fuel fabrication, reactor operations, advanced fuels and waste treatment.

5.7.2.2. Objective of the case study and fuel cycle evaluation criteria

The high level objective of the OECD/NEA study Advanced Nuclear Fuel Cycles and Radioactive Waste Management was to identify fuel cycles with the potential to provide benefits to the repository programme, to enhance the use of nuclear fuel resources and to improve the prospects for nuclear power. In order to compare the performance of the fuel cycle options, the OECD/NEA Expert Group developed a set of evaluation metrics. The data for each evaluation metric indicate how an NES performs in a particular area and, therefore, correspond directly to the KIs concept of the KIND project. KIs were evaluated for NESs in a 'steady state' of deployment, which was considered to be sufficient for the evaluation being done, mainly because the conditions for the transient phases of nuclear energy development vary widely among countries and are still subject to large uncertainties. Advanced fuel cycle options were evaluated in order to give OECD Member States an open perspective on the benefits and challenges of particular strategic choices and to support future decisions concerning national R&D programmes. The study was a generic one, but keeping in view the large diversity of NFC options evaluated, it can be adapted to permit the evaluation of country specific scenarios. The objectives of the case study were the following:

(a) To use the results of the OECD/NEA study as a basis for testing the concepts of the KIND approach;
(b) To apply the specific tools Visual PROMETHEE, developed at the University of Brussels for MCDA, and KIND-ET (dedicated evaluation tool) for comparison of the performance of NFCs;
(c) To demonstrate the application of both methods to rank NFCs/NESs;
(d) To provide guidance and evaluate applicability limitations.

The comparative evaluation of NFC options using MCDA techniques was out of the scope of the original OECD/NEA study. However, its results can be mapped onto the KIND approach using the bottom up approach. First, the KIs evaluated by the OECD/NEA Expert Group have to be assigned to INPRO categories. Then, the other inputs needed for the decision analysis must be customized according to the type of decision to be supported.

The metric data obtained by the experts can easily be adapted for the multi-criteria analysis type problem using the following evaluation criteria:

(i) Resource utilization;
(ii) Nuclear waste management;
(iii) Economics.

A full description and discussion of the KI set with respect to the environmental, technical and economic dimensions can be found in Refs [5.2, 5.39].

5.7.2.3. Discussion of INPRO performance categories and OECD/NEA evaluation metrics

The main objective of sustainable development is to maintain or even increase our overall available assets (natural, human-made and human or social) for future generations. The primary goal of advanced fuel cycle deployment is to improve the sustainability of nuclear energy through more effective natural resource utilization and by reducing the volume and long term radiotoxicity of HLW while keeping the costs of energy products, for example electricity production, economically viable.

Advanced fuel cycles address the problem of the long term radiotoxicity of HLW, reducing the mass of actinides to be disposed. Moreover, advanced separation techniques offer a greater degree of freedom for short and medium term waste management policies in which fission products are the main contributors to dose and decay heat. Thus, for instance, fission products could be immobilized in specially designed matrices for disposal, or placed in decay storage separately and disposed of after a suitable cooling down period. The potential reduction of short term heat load may have a direct impact on the footprint of current repository concepts [5.40]. However, the reduction of the short term heat load and long term dose per unit of generated electricity could drastically increase the mass and volume of intermediate and low level waste.

The results of the OCED/NEA study complement the analysis of the impact of advanced NESs on uranium resource utilization and transuranic (TRU) losses through the description of their impact on waste management policies, addressing the activity of HLW after 1000 years, decay heat after 50 and 200 years of cooling, and the volume of wastes produced. The activity of HLW after 1000 years characterizes the radioactive source term after the decay of heat generating isotopes. At this time horizon, the short lived fission products have decayed strongly and the removal of actinides from the waste stream efficiently decreases the ‘cold’ source term. The metrics quantifying the decay heat loading per energy generated after 50 and 200 years are thus representative of the time when waste goes to the final repository and the time when the majority of original fission products have already decayed, respectively.

The main purpose of the economic analysis carried out in the OECD/NEA study was to illustrate the impact of different cost elements and their uncertainties on NFC costs through parametric sensitivity cases. Therefore, the economic indicators are only indicative.

On the other hand, INPRO developed a set of basic principles, user requirements and criteria, together with an assessment method, which, taken together, comprise the INPRO methodology for the evaluation of NESs, including those with innovative components [5.2]. In order to achieve a sustainable NES, all basic principles need to be met in the areas of safety, economics, infrastructure, waste management, proliferation resistance, physical protection and environment. OECD/NEA evaluation metrics can be interrelated to the INPRO methodology. Table 5.67 indicates how the OECD/NEA evaluation metrics compare via evaluation criteria to INPRO objectives.

5.7.2.4. Evaluated fuel cycle options — selecting alternatives

The set of fuel cycle schemes considered in the OECD/NEA study covers a broad spectrum of NESs. While identifying alternatives, it is to be considered that both reactor design and fuel cycle characteristics have to be taken into account. Therefore, the questions which have to be addressed in a comprehensive NFC selection process refer to the choice of fuel cycle type: once through or recycle, and to the choice of NPPs involved in fuel cycle.

An overview of the reactor design and fuel cycle parameters used is given in Table 5.68 (see Ref. [5.39]).

When evaluating NFCs, it is convenient to subdivide the full set of options into groups or families that are distinguished from each other by the potential for waste reduction, the investment required in advanced technology, and the different timescales for development and implementation. Therefore, it was found to be appropriate to classify NFCs into three categories (called families):

(a) Schemes based on current technology and extensions (Figs 5.48 and 5.49);
(b) Schemes with a partially closed fuel cycle (Figs 5.50–5.52);
(c) Schemes involving a fully closed fuel cycle (Figs 5.53–5.55).

TABLE 5.67. INTERRELATIONSHIP OF OECD/NEA EVALUATION METRICS WITH INPRO STUDIES

Evaluation criteria/INPRO areas	Evaluation metrics	Units	Abbr.
Resource utilization	Natural uranium required per unit of energy generated	kg/TW(e)·h	KI-1
Nuclear waste management	Mass of TRU loss transferred to waste	kg/TW(e)·h	KI-2
	Activity of SNF + HLW at 1000 years	TBq/TW(e)·h	KI-3
	Decay heat loading of SNF + HLW at 50 years	W/TW(e)·h	KI-4
	Decay heat loading of SNF+HLW at 200 years	W/TW(e)·h	KI-5
	Volume of HLW + SNF (if it is declared a waste)	m^3/TW(e)·h	KI-6
	Maximum dose for repository in clay		X
	Maximum dose for repository in tuff		X
	Maximum dose for repository in granite		X
Economics	Fuel cycle costs	mills/kW(e)·h	KI-7
	Cost of electricity at equilibrium	mills/kW(e)·h	KI-8

Note: HLW — high level waste, SNF — spent nuclear fuel, TRU — transuranic.

TABLE 5.68. REACTOR DESIGN AND FUEL CYCLE PARAMETERS IN OECD/NEA STUDY (DETAILS IN Ref. [5.39])

Reactor	Thermal power (MW)	Net electric power (MW(e))	Electrical efficiency (%)	Fuel	Fuel burnup (GW·d/t HM)	Storage/ cooling time (years)
PWR-UOX	4250	1450	34.1	UOX	60[1]	2/5
PWR-MOX	4250	1450	34.1	MOX	60[2]	2/5
PWR MOX-EU	4250	1450	34.1	MOX-EU	60	2/5
FR-MOX	3600	1450	40.3	MOX	140	2/5
FR-HBU	3600	1450	40.3	MOX	185	2/5
FR-metal	1575	600	38.1	^{78}Ac-^{22}Zr	140	1/2
FR-carbide	2400	1158	48.3	(U,Pu)C-SiC	100	2/5
ADS-MA	377	119	31.6	^{29}AcN-^{71}ZrN	150	1/2
ADS-TRU	850	280	33.0	AcN-ZrN	150	1/2

Note: ADS — accelerator driven system, EU — enriched uranium, FR — fast reactor, HBU — high burnup, MA — minor actinide, MOX — mixed oxide, PWR — pressurized water reactor, TRU — transuranic, UOX — uranium oxide.

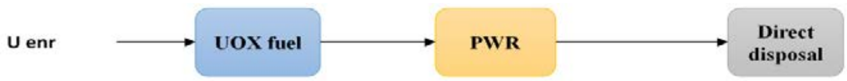


FIG. 5.48. Once through fuel cycle (reference fuel cycle).

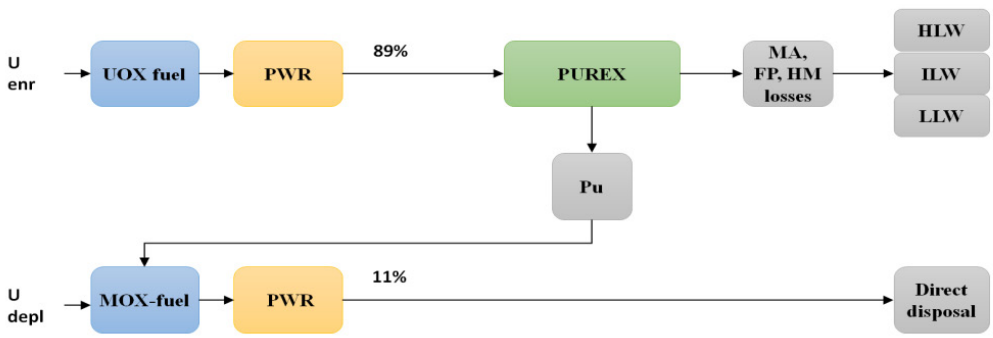


FIG. 5.49. Conventional reprocessing fuel cycle (plutonium is recycled once in the form of MOX fuel). Variant: the separation of pure plutonium is avoided by recycling neptunium together with the plutonium.

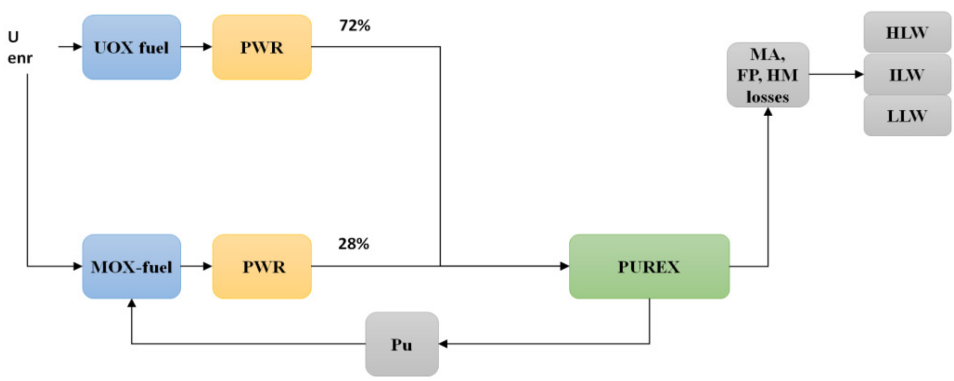


FIG. 5.50. Plutonium burning in LWR — only uses LWRs, requires MOX fuel with enriched uranium (MOX-EU).

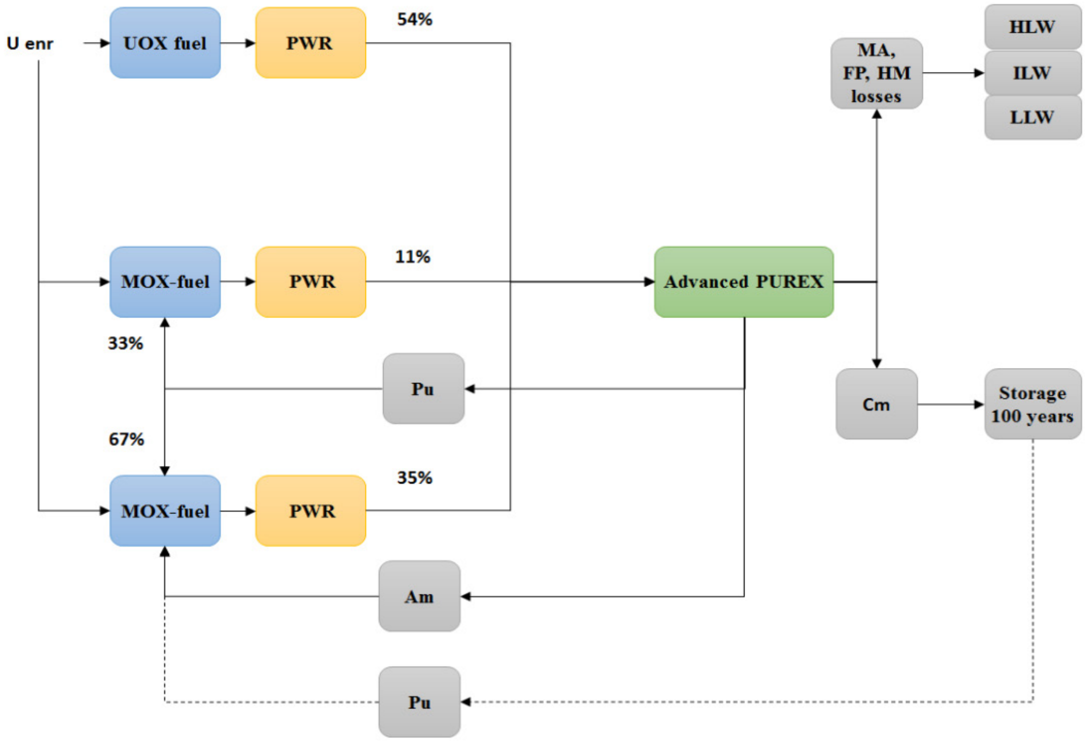


FIG. 5.51. Plutonium and americium burning in LWR — requires two types of MOX-EU fuel and americium–curium separation; the curium decay products (mostly plutonium) are either disposed of or recycled as MOX fuel.

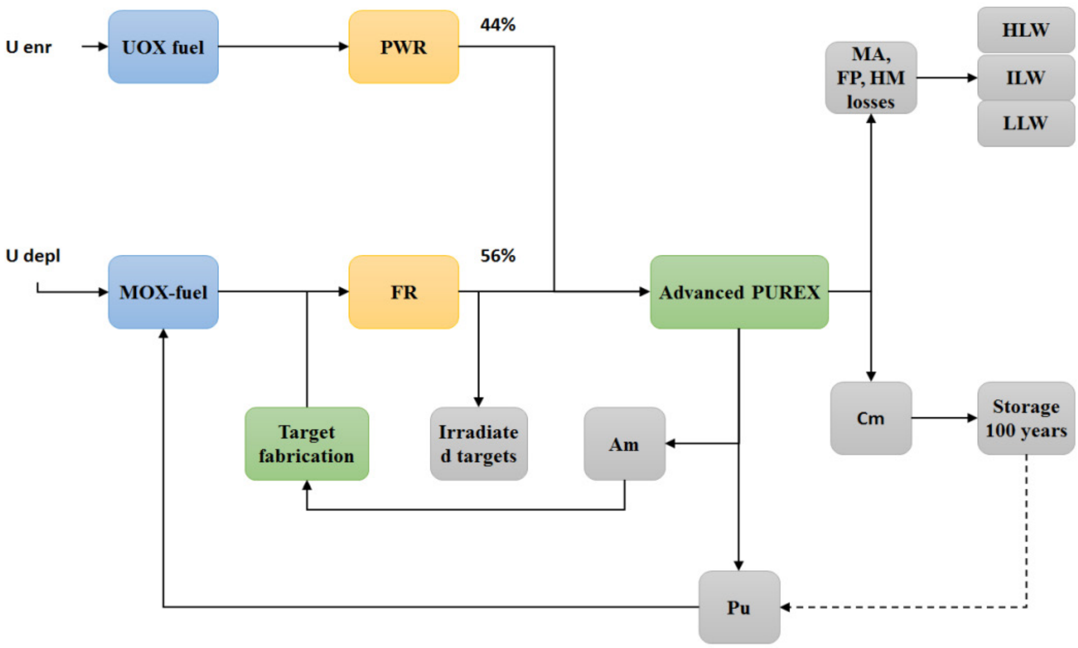


FIG. 5.52. Heterogeneous americium recycling — americium is recycled in targets that are disposed of after irradiation. Variant: americium goes to the storage facility together with the curium. The decay products are either disposed of or recycled as MOX fuel.

5.7.2.5. Performance table

The OECD/NEA report [5.39] contains the results of a comprehensive physics based quantitative evaluation of KIs for NFC families 1–3, applying well established codes and tools (such as DARWIN [5.40] and CESAR

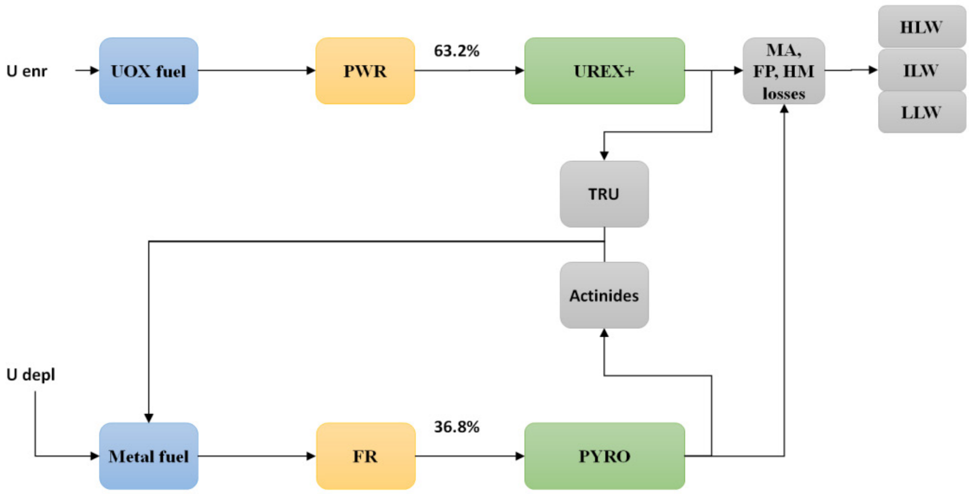


FIG. 5.53. TRU burning in an FR — based on the integral fast reactor concept. Avoids any separation of pure plutonium.

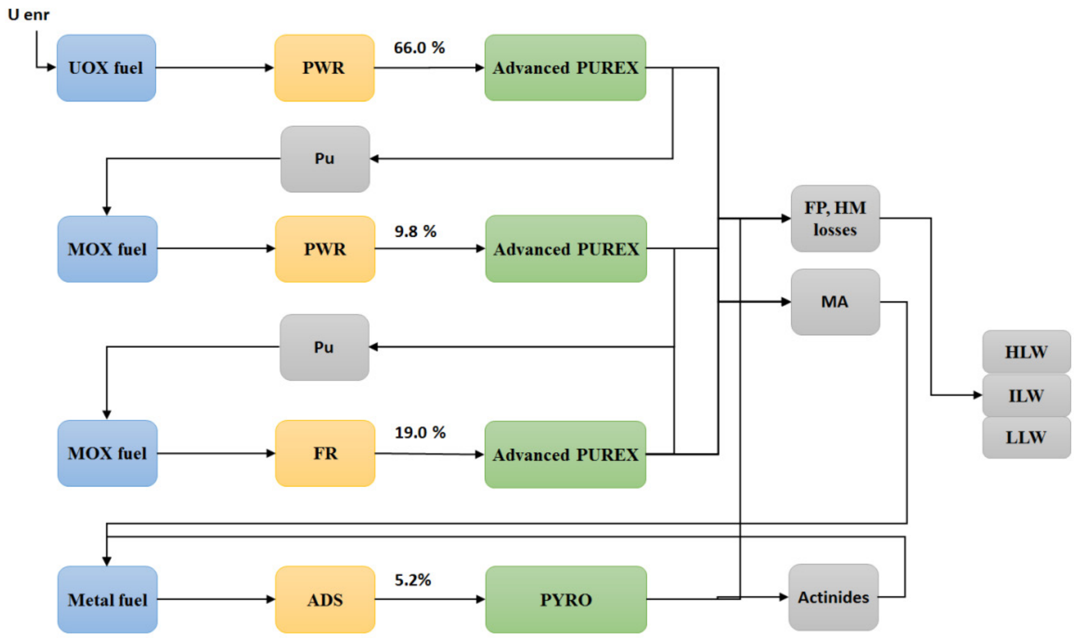


FIG. 5.54. Double strata fuel cycle: burns all plutonium in conventional LWRs and FRs. Variant: the FR stage is circumvented by transferring the plutonium from the PWR-MOX stage directly to the ADS fuel cycle.

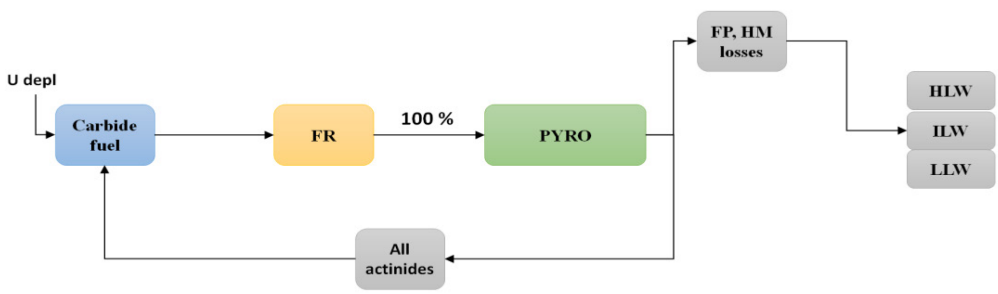


FIG. 5.55. All FR strategy — based on Gen IV gas cooled FR. Variant: based on EFR using MOX fuel reprocessed by UREX+; uranium is not recycled.

[5.41]). However, this study does not propose any multi-criteria method to compare the performance of NESs. The judgements are made by experts in a qualitative way. The final results (quantified metrics in the form of indicators) characterizing the NFC performance are combined in Ref. [5.39], as illustrated in Fig. 5.56.

The KIND approach, which applies MCDA methods, requires preparation of a performance table representing the whole set of selected KI metric values achieved for each criterion and specifying the 'performance' of each NFC option considered. Therefore, all of the necessary data for the case study discussed here had to be retrieved either directly from the OECD/NEA report or from Excel spreadsheets distributed among the OECD/NEA Expert Group members. The values for some KIs, such as KI-2, KI-3, KI-4, KI-5, KI-7 and KI-8, were available in their natural scale, while for other KIs, such as KI-1 and KI-6, they were only available in relative terms (with reference to NFC scheme 1a).

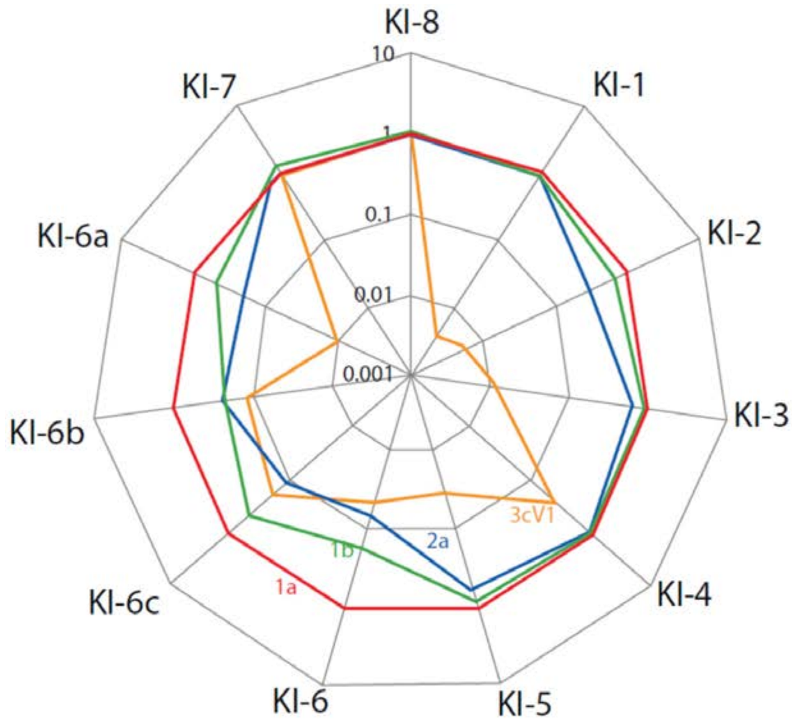
Table 5.69 summarizes the KI values in the form of a performance table. The full performance table contains 8 KI values (attributes) for 12 fuel cycle options, thus building a two dimensional matrix (12 × 8) with 96 elements. This table will be used in further analyses based on the KIND approach.

The visualization of the performance table in the form of a value path and a radar chart is shown in Figs 5.57 and 5.58. Both figures help in evaluating the performance of the NFCs qualitatively and in finding similar behaviour patterns that the KIs may follow. The value path may also be used to identify dominated alternatives. For example, it can be seen in Fig. 5.57 that alternative 1c is dominated by 1b, while the alternative 3bv is dominated by 3b.

5.7.2.6. Three level value tree for hierarchical aggregation of KI

For studies with large number of KIs (in general more than 10), the KIND approach recommends a procedure of hierarchical KI aggregation. The hierarchical aggregation approach is developed here using Tables 5.67 and 5.69 and applying a hierarchy tree as illustrated in Fig. 5.59. Composite values of KIs will be computed on each level of the three level model of the established hierarchy structure.

The lowest level of the tree is populated with eight single criteria/indicators. The second level contains three composite indicators (CIs) referring to INPRO evaluation areas. The aggregated indicators on the highest level measure, in relative terms, the 'performance' and the 'costs' associated with each investigated alternative (red framed on the righthand side in Fig. 5.59). An aggregation makes the perception of a problem simpler; however,



KI-1	Natural uranium required per energy generated
KI-2	Mass of TRU loss transferred to waste
KI-3	Activity of SNF+HLW at 1000 years
KI-4	Decay heat loading of SF+HLW at 50 years
KI-5	Decay heat loading of SF+HLW at 200 years
KI-6	Volume of HLW + SF (if it is declared a waste)
KI-6a	Maximum dose for repository in clay
KI-6b	Maximum dose for repository in tuff
KI-6c	Maximum dose for repository in granite
KI-7	Fuel cycle costs
KI-8	Costs of electricity at equilibrium

FIG. 5.56. Comparison of 11 representative indicator values for NFCs. 1a: once through NFC; 1b: full LWR park, SNF reprocessed and plutonium reused once; 2a: full LWR park, SNF reprocessed and multiple reuses of plutonium; 3cV1: full FR park and fully closed NFC.

TABLE 5.69. PERFORMANCE TABLE

NFC	KI-1	KI-2	KI-3	KI-4	KI-5	KI-6	KI-7	KI-8
1a	1	29.78	201	2110	591	1	3.55	36.42
1b	0.89	20.34	177	2030	506	0.234	4.53	37.1
1c	0.9	21.04	178	2380	619	0.235	4.66	37.22
2a	0.87	8.87	134	2000	337	0.262	5.13	37.69
2b	0.99	4.6	2.61	979	31.7	0.262	6.71	39.27
2c	0.44	1.63	3.91	888	32.1	0.166	3.84	40.69
2cV	0.44	3.93	2.24	852	26.7	0.166	4	40.85
3a	0.63	0.1	2.43	934	29.6	0.402	4.69	40.07
3b	0.65	0.11	2.8	963	31.9	0.26	5.25	40.37
3bV	0.76	0.14	2.98	1030	34.1	0.305	7.45	41.98
3cV1	0.004	0.17	2.28	572	19.3	0.178	4.41	51.06
3cV2	0.036	0.15	2.88	834	27.5	0.114	3.98	46.57

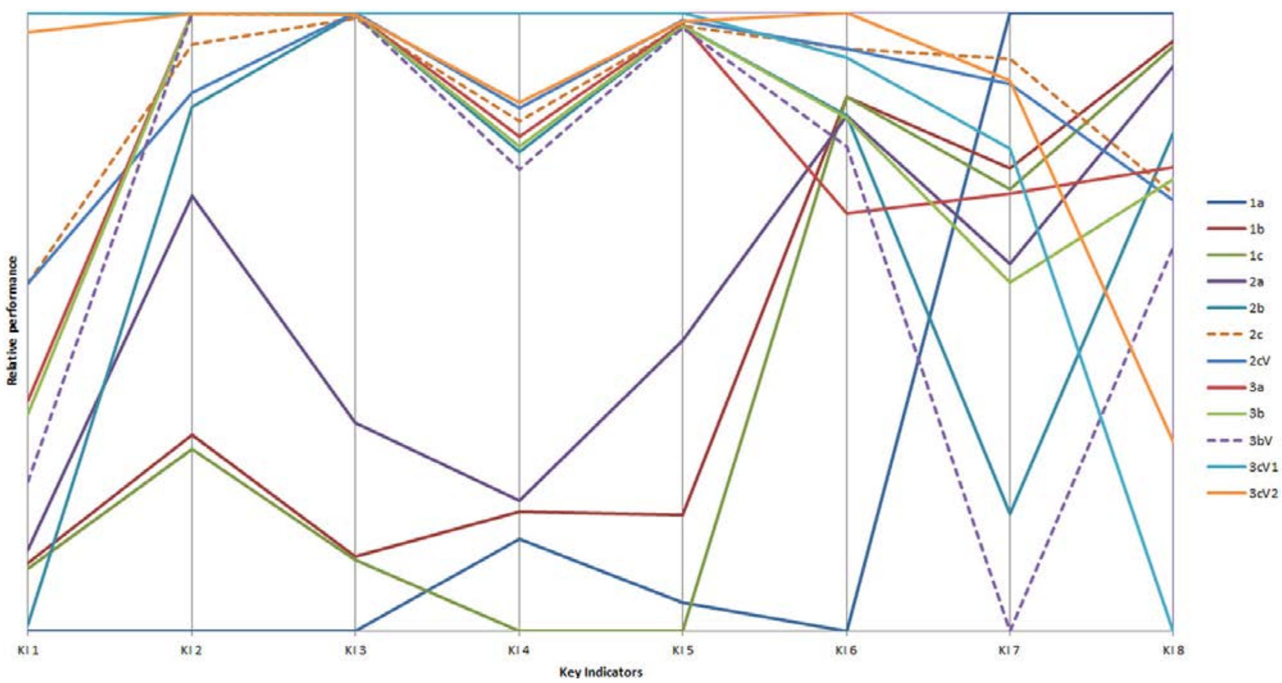


FIG. 5.57. Value path.

it requires an extra degree of effort devoted to the choice of appropriate sets of weights at each level. The weights express the expert preferences and acceptable trade-offs.

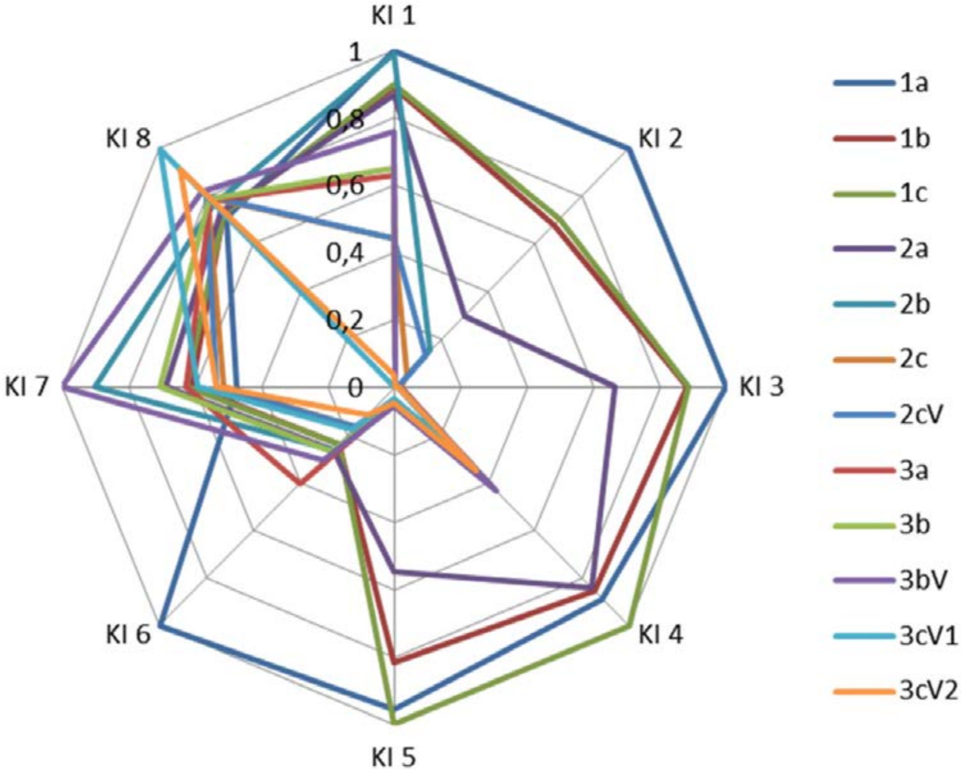


FIG. 5.58. Radar chart.

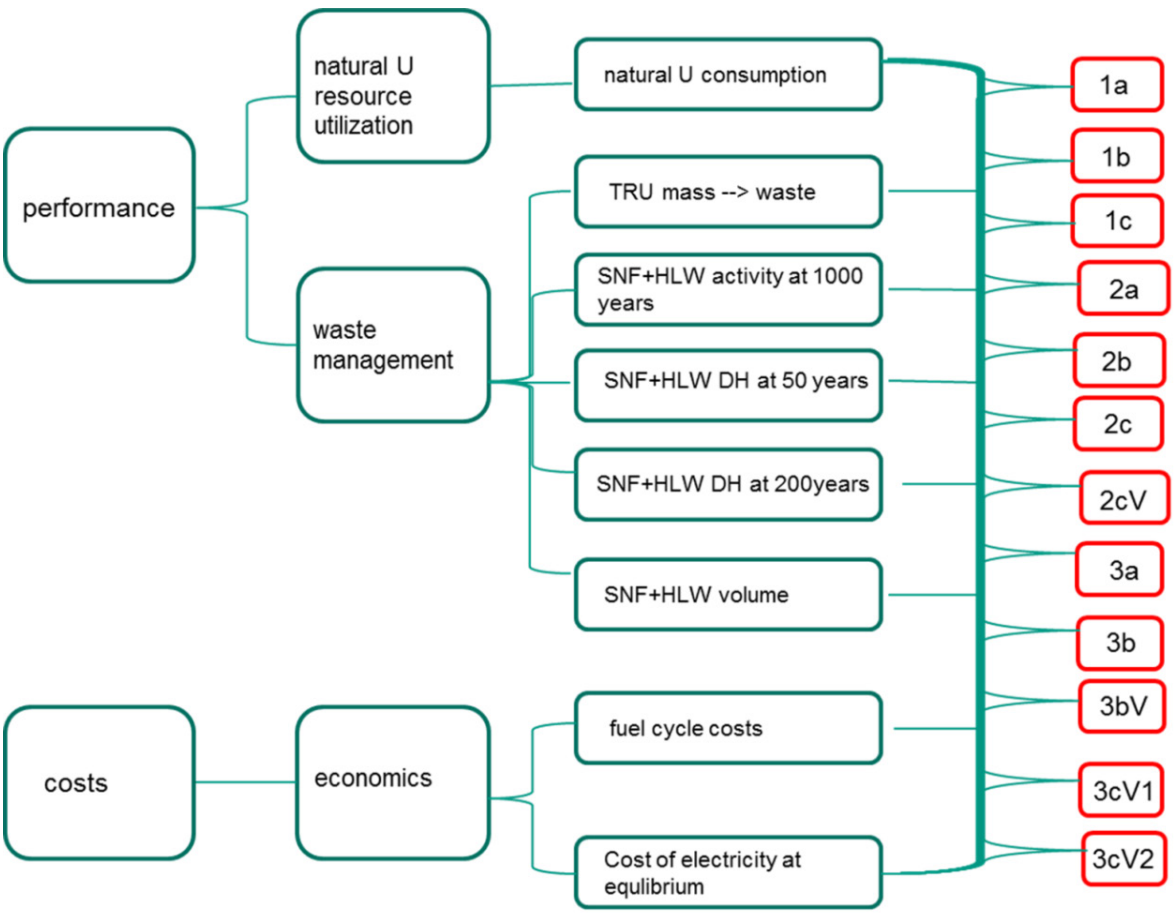


FIG. 5.59. Three level hierarchy structure.

5.7.2.7. Comparative evaluations using the PROMETHEE and KIND-ET evaluation tools

MCDA methods use various approaches that have been developed to compare specific alternatives. Among the most popular are MAUT/MAVT [5.29], AHP [5.29] and the analytic network process. Both AHP and the analytic network process use a kind of value function, which is derived by means of a nine point scale. The most essential assumption made in these approaches is that decision makers are aware of the utility/value of a single attribute for each criterion and are able to express the relative importance of different criteria in a univocal way. The objective of the decision making technique is then to disclose and interpret the preferences of the decision maker in transparent terms.

In contrast to other methods, methods based on outranking approaches such as ELECTRE [5.29] and PROMETHEE [5.29] assume that decision makers are not fully aware of their preferences and hence need support to structure the process, and that interactive help is required to demonstrate the impact of different criteria weightings.

Therefore, it will be interesting to apply at least two MCDA methods that are representative of both approaches in the same case study to demonstrate their similarities and limitations. In the present study, the simple additive weighting method (a very basic application of MAVT), which is a recommended technique in the KIND approach, and the outranking PROMETHEE approach have been used. The two methods will be compared. The MAVT method is described in Section 3. PROMETHEE will be described briefly here before its application is discussed.

PROMETHEE performs pairwise comparisons of alternatives for every criterion. For every couple of alternatives (a, b), the difference in KI values d for each criterion f is determined firstly as: $d(a, b) = f(a) - f(b)$; d depends on the units of criterion f and does not yet take into account the intra-criterion preference information for the expert/decision maker. Intra-criterion preference information is embedded in PROMETHEE through the generalized criterion concept. Next, the computation of the preference degrees $P(a, b)$ is performed as a mapping of $d(a, b)$ values into [0,1] $P{:}R \rightarrow [0,1]$: $d(a, b) \rightarrow P\,[d(a, b)] \cong P(a, b)$, where P is a positive non-decreasing function such that $P = 0$ for all $x < 0$. The degree of preference for alternative a over alternative b can vary from $P(d) = 0$, showing indifference through to weak preference, up to $P(d) = 1$, indicating strong preference. The shape of the generalized criterion preference function P can be chosen from among six types of generalized criteria (P, f) offered by the PROMETHEE toolkit developers: usual, U-shaped, V-shaped, level, V-shaped with indifference and finally S-shaped (see Ref. [5.29] for details). It is claimed that these shape value functions cover most of the decision problems. They may depend on the parameters specifying the indifference q and preference p thresholds. The indifference threshold q is the largest value of d that an expert considers to be negligible while comparing two alternatives, whereas the preference threshold p is the smallest value of d that an expert considers to be decisive. In contrast to MAVT, where a single-attribute value function is used, an outranking relation π is defined for every pair of alternatives; π is a weighted sum of the preference degree function values over all K criteria:

$$\pi : \pi(a,b) = \sum_{k=1}^{K} w_k \cdot P_k\left(f_k(a) - f_k(b)\right) \tag{5.4}$$

With the weights normalized to 1, π can be interpreted as an aggregated indicator (CI) that measures the intensity of the decision maker preferences for alternative a versus b if all criteria are considered simultaneously.

As an indicator of the strength of alternative a, the outgoing flow is calculated by measuring the outranking character of alternative a:

$$\varphi^{+}(a) = \frac{1}{N-1}\sum_{b \in A} \pi(a,b) \tag{5.5}$$

As an indicator of the weakness of the alternative a, the incoming flow is calculated by measuring the ‘outranked character’ of a:

$$\varphi^{-}(a) = \frac{1}{N-1}\sum_{b \in A} \pi(b,a) \tag{5.6}$$

where A denotes a full set of N discrete alternatives and obviously $b \neq a$.

PROMETHEE I determines the partial pre-orders induced by φ^+ and φ^-: a is preferred to b if $\varphi^+(a) \geq \varphi^+(b)$ and $\varphi^-(a) \leq \varphi^-(b)$ and at least one of the inequalities is strict (i.e. the higher the outgoing flow and the lower the incoming flow, the better the alternative). However, in some cases the positive and negative preference flows do not imply a consistent order. The PROMETHEE II complete pre-order eliminates these incompatibilities by using:

$$\varphi^{\text{net}}(a) = \varphi^+(a) - \varphi^-(a) \tag{5.7}$$

as a balance between the outgoing and the incoming flows, which aggregates the strengths and weaknesses of an alternative to a single score. Both the simple additive MAVT and PROMETHEE methods have been applied to analyse the OECD/NEA case study. In the first step, the reduced one level hierarchy tree was used, advocating equal weights (wk = 0.125) for each criterion attribute/indicator. It was also assumed that the performance of the alternatives has to be minimized for each criterion.

Further, linear single-attribute value functions on local domains were used in KIND-ET. Whereas in PROMETHEE I and II, the V-shaped (i.e. linear preference) functions were chosen with the indifference threshold parameter p being equal to the difference between the maximal and minimal KI values achieved for the given criterion k by all alternatives (p_k = max KI-$k(a)$ − min KI-$k(a)$ for all $a \in A$). In this particular case, the preference function can be defined in the following way:

$$P_k(d) = \begin{cases} 0 & d < 0 \\ \dfrac{d}{p_k} & 0 \leq d \leq p_k \\ 1 & d > p_k \end{cases} \tag{5.8}$$

The results obtained by means of the KIND-ET and PROMETHEE I and II toolkits, which were both applied to rank 12 NFC options (including 2 dominated alternatives), are shown in Figs 5.60 and 5.61.

(a) Comparison of ranking results

After the examination of the KIND-ET and PROMETHEE II ranking results for the 12 NFC alternatives investigated, it is apparent that both methods deliver the same ranking order. Moreover, the differences between the preference φ^{net} scores for two subsequent alternatives (higher scored and lower scored next to it) are equal to

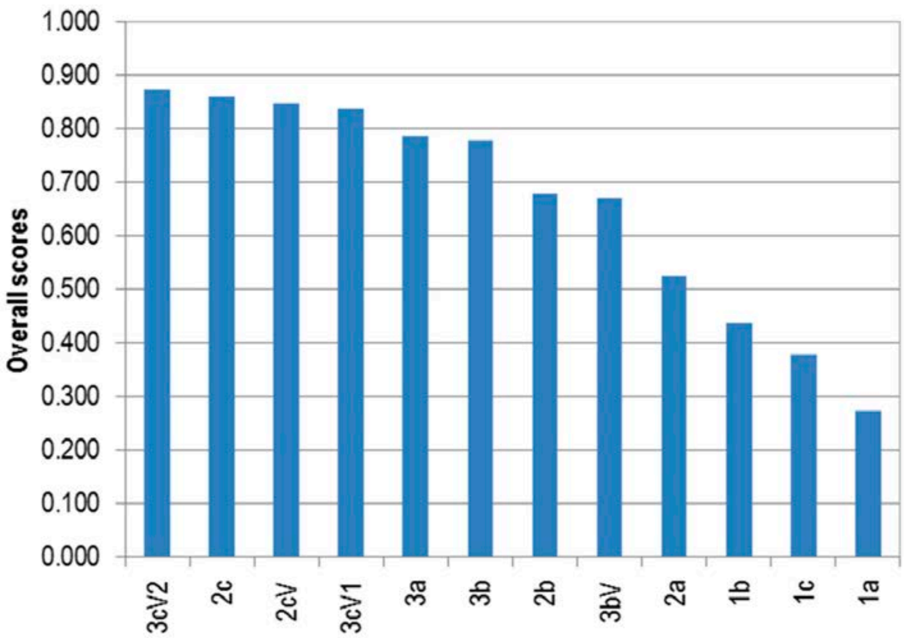


FIG. 5.60. Ranking for NFCs using the KIND-ET evaluation tool.

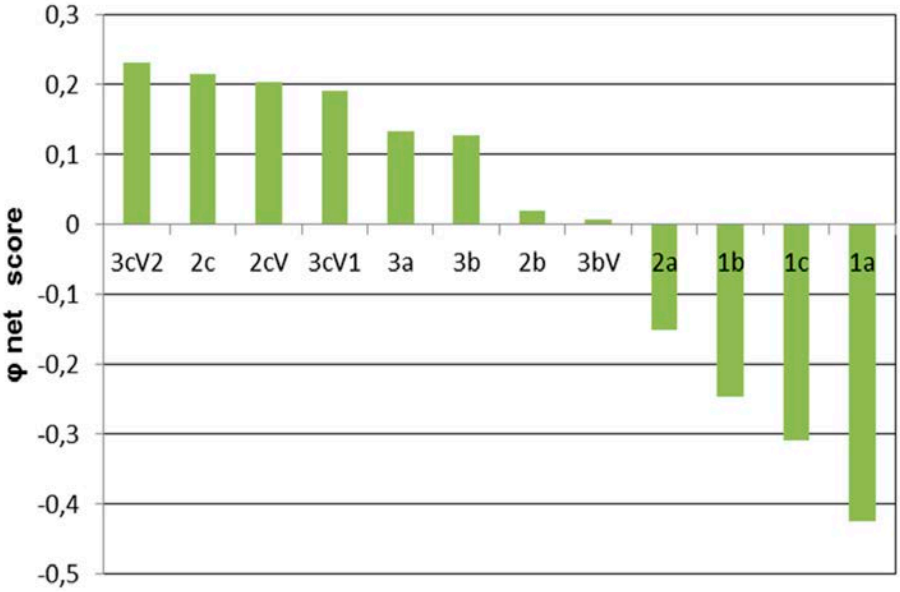


FIG. 5.61. Ranking for NFCs using the PROMETHEE I and II toolkits.

the differences between the two aggregated utility scores for the corresponding alternative pairs obtained with KIND-ET. This makes it possible to conclude that the outranking preference concept based on pairwise comparisons and the additive MAVT concept with linear single-attribute value functions are basically the same. The equivalence of both methods can be proven analytically by applying the formulas found in Ref. [5.42].

In view of this, the MCDA user could profit from using PROMETHEE as an 'add-in' to KIND-ET to increase the overall support capabilities of the applied MCDA tools. The additional benefit is obvious: PROMETHEE II can complete the ranking analysis, delivering more precise information on the weight stability intervals for each criterion, while PROMETHEE I can highlight incomparability problems between pairs of alternatives.

In general, for MCDA structures represented by two or three level hierarchy trees, the CIs (performance scores) calculated in PROMETHEE and KIND-ET cannot be compared directly owing to different weighted sum approaches. The reason behind this is the different purpose of the aggregation. MAVT carries out an aggregation for the transition from natural indicators to relative ones, whereas PROMETHEE uses aggregated scores for predefined groups and clusters of attributes (based on three level trees) for data envelopment analysis-like performance analysis [5.43], where two clusters of criteria (input and output) are compared to measure the relative efficiency of decision making units.

(b) Discussion

Ranking results that apply 'equal weights' demonstrate (compare Figs 5.57 and 5.58) the attractiveness of NFC families 2 and 3 with partial or full multi-recycling of TRUs in FRs and PWRs and the lower attractiveness of NFCs based on current technology and extensions (family 1). The fully closed fuel cycle 3cV2, multi-recycling plutonium in SFRs, seems to be the most attractive alternative, followed by NFCs 2c and 2cV, which, in turn, still perform well due to the high FR share (56%) in the reactor mix. Fuel cycle schemes 3cV1 (recycling all actinides in FRs) and 3b (recycling plutonium in PWRs and FRs while transferring MAs to an ADS fuel cycle) are more attractive than NFC 3bV, which transfers plutonium from the PWR-MOX stage directly to the ADS fuel cycle. NFC 2a has the lowest rank among other NFC schemes belonging to families 2 and 3 because it uses MOX fuel with enriched uranium and does not separate americium for recycling and/or curium for storage, as is the case in NFC 2b, and thus consumes more resources and produces more HLW. The conventional reprocessing fuel cycle 1b with a single plutonium recycle in PWRs is more attractive than 1c, in which the separation of pure plutonium is avoided by recycling plutonium together with neptunium. However, both 1b and 1c are still more attractive than an open PWR fuel cycle. The clear attractiveness of NFCs with FR types that has been demonstrated by the tools used here is restricted to both the criteria and the weights (decision maker preferences) chosen and thus needs to be, if FRs are pre-selected, further analysed in view of their effectiveness and performance in other country specific dimensions: economic, environmental, social and institutional.

Examples of the results obtained for the three level hierarchy structure of the objectives tree when using KIND-ET in order to rank NFCs and to evaluate the scores of composite indicators are illustrated in Figs 5.62–5.64. In this example, the corresponding criteria at each level were given equal criteria weights, that is:

$\mathbf{w}_{performance} = \mathbf{w}_{costs}=0.5$;
$\mathbf{w}_{waste\ man}=\mathbf{w}_{U\ util}=0.5, \mathbf{w}_{econ}=1$;
$\mathbf{w}_{KI\text{-}1}=1$, $\mathbf{w}_{KI\text{-}2}=\mathbf{w}_{KI\text{-}3}=\ldots=\mathbf{w}_{KI\text{-}6}=0.2$, $\mathbf{w}_{KI\text{-}7}=\mathbf{w}_{KI\text{-}8}=0.5$.

The CIs from the areas of economics, waste management and natural uranium resource utilization are presented in Fig. 5.63. The third level aggregation scores for the CIs performance and costs are given in Fig. 5.64.

As can be seen from Fig. 5.62, the ranking result order obtained while using the three level hierarchy structure corresponds to that achieved in the case of the one level structure on the first six positions. Then the ranking order changes owing to the different preferences of the decision maker, which are represented by different final KI weights, calculated as products of interrelated weights at each aggregation level. This way of proceeding leads to the final KI weight values: 0.25, 0.05, 0.05, 0.05, 0.05, 0.05, 0.25 and 0.25, respectively. Such a weight assignment implies a strong decision maker preference for the minimization of uranium consumption, fuel costs and total energy costs, with KI weight values that are five times higher than those for each single HLW minimization KI.

Figure 5.63 may further support decision maker judgement, providing additional information that, in this case for instance, indicates that the most attractive alternative, 3cV2, has well balanced scores (each equal to about 1/3 of the overall score) in the areas of economics, waste management and resource utilization (rank 4, similar to 3cV1). In addition to this, Fig. 5.63 shows that 2c only performs better than 2cV in the economics area; 3a consumes more uranium than 3V2, 2c, 2cV and 3cV1; 3cV2 has a more or less equal waste management score, but is economically more attractive than 3cV1, etc.

The cost and performance shares for each alternative can be extracted from Fig. 5.64. Obviously, open fuel cycle 1a seems to be the most economically attractive alternative, but on the other hand 1a consumes a large quantity of uranium and produces a large quantity of HLW to be disposed of.

Figure 5.65 indicates the potential for lower costs (represented by non-dimensional cost scores on the *y* axis) and the relative performance of fuel cycles providing such lower costs (represented by non-dimensional scores on the *x* axis).

The CI performance thresholds that might be considered as providing substantial or significant improvements can be added by the decision maker to this point spread graph by using straight lines.

5.7.2.8. Sensitivity analyses

To demonstrate the robustness of the results of the study, sensitivity analyses needed to be conducted, exploring the sensitivity to weights and preference/value function variation. Both PROMETHEE and KIND-ET supply the user with parametric analysis tools for sensitivity checking with regard to changes in weights and preference/value function shapes. Applying these tools shows that the ranks are quite sensitive to weights (see Figs 5.66 and 5.67).

This can be attributed to the KI metric values for the NES performance, which for many criteria are very close to each other and thus contribute to ‘poor’ resolution for NESs. It is worth noting that the weight stability intervals determined by the PROMETHEE method deliver significant support in a further, more detailed investigation of the impact of single-criterion weight variation on the complete ranking order. The sensitivity intervals give a range of values that the weight of one criterion can take without altering the ranking results obtained with the initial set of weights, with the relative weights of the other criteria being adequately renormalized. A narrow weight stability interval implies stronger sensitivity of the respective criterion and its weighting. Table 5.70 compares the stability intervals with regard to net flow for one level and three level objectives trees while ranking 12 alternatives.

For weight values beyond the lower and upper bound of the stability intervals, the rank order changes. It can be seen that for each single criterion the stability intervals obtained using the final KI weights computed for a three level objectives tree are narrower than those corresponding to one level with equal weights (equal to 12.5% for each indicator) due to lower weights being applied to the performance measures KI-2 to KI-6. Moreover, in the

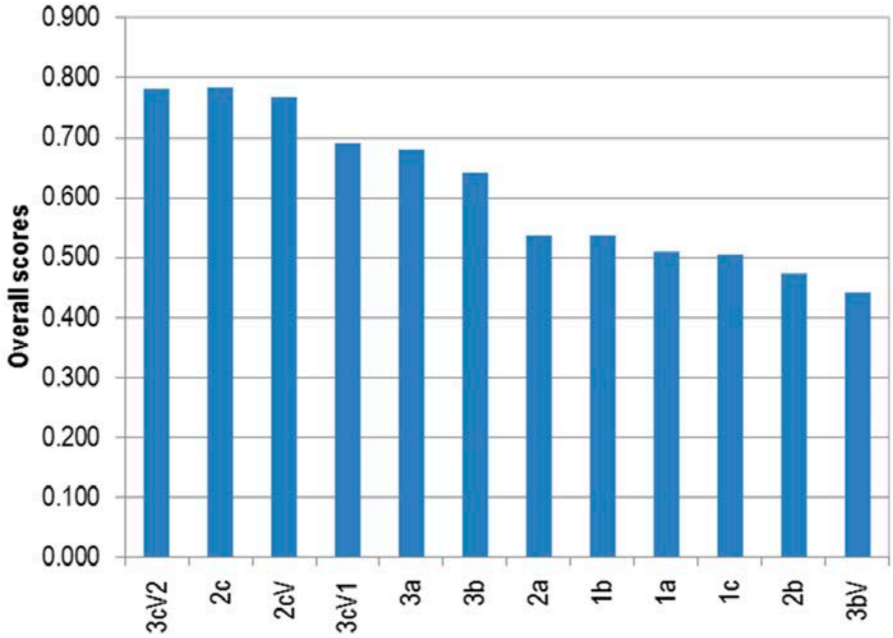
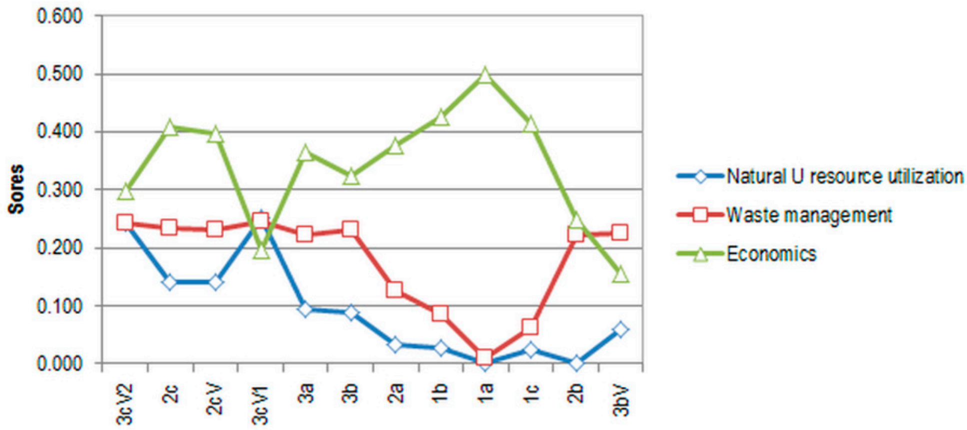
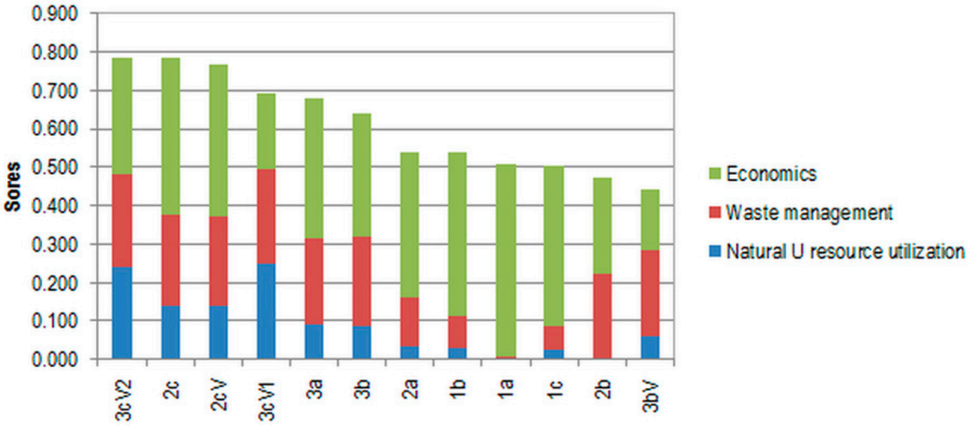


FIG. 5.62. Ranking results for three level tree with equal weights.

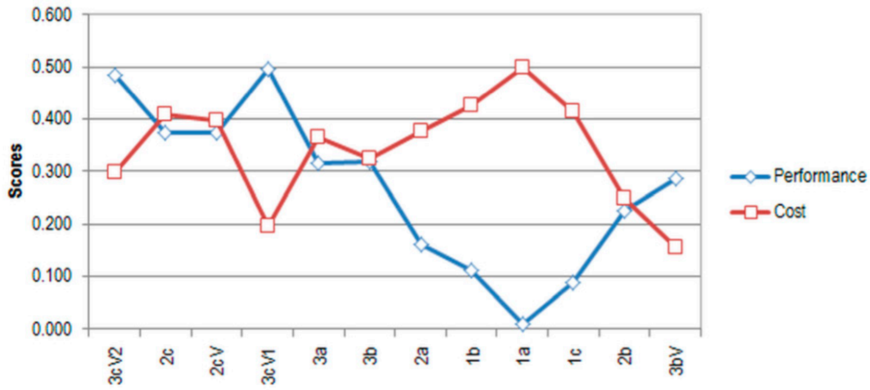


(a)

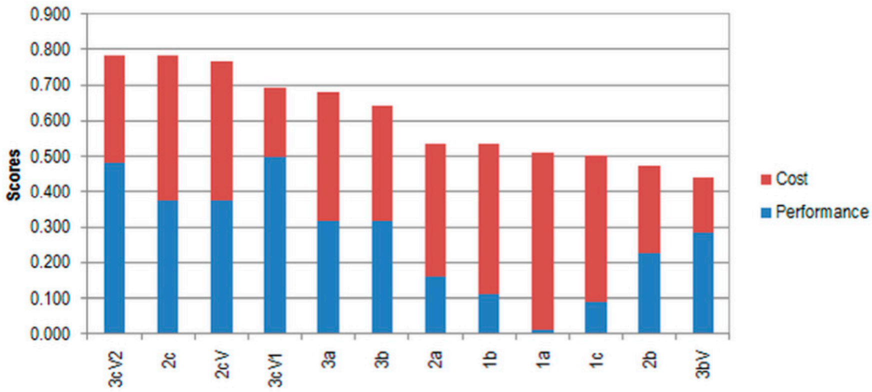


(b)

FIG. 5.63. Aggregated scores for CIs at the second level delivered by KIND-ET.



(a)



(b)

FIG. 5.64. Aggregated scores for CIs at the third level delivered by KIND-ET.

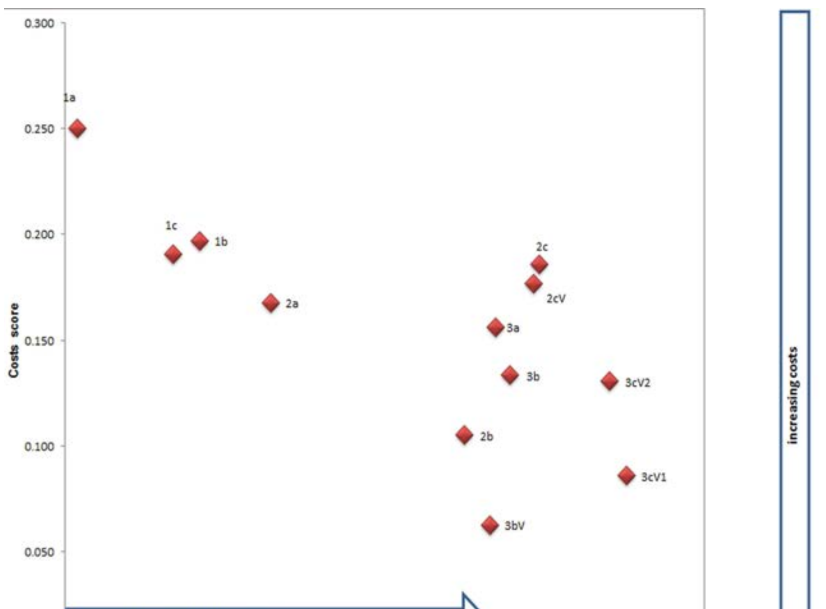


FIG. 5.65. Costs versus performance score for 12 evaluated NFCs.

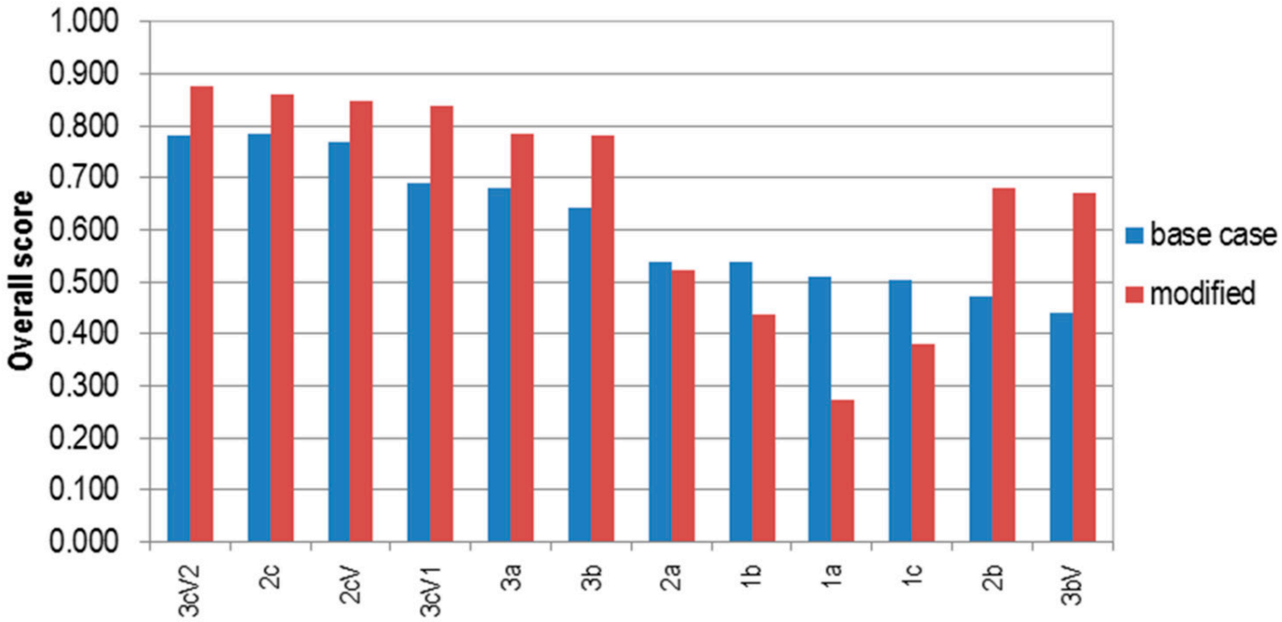


FIG. 5.66. KIND-ET: sensitivity of ranking results with regard to KI weight changes (base case refers to one level structure modified to three level structure).

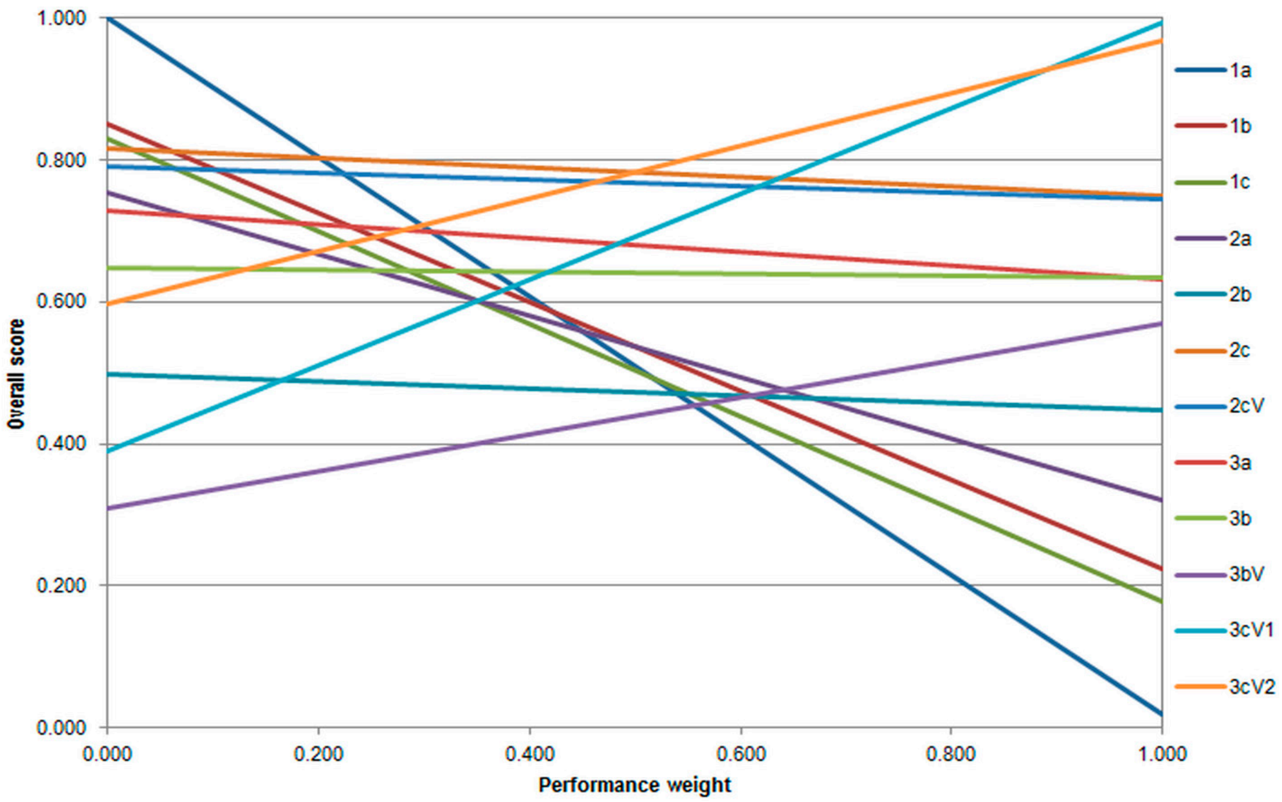


FIG. 5.67. KIND-ET: sensitivity of aggregated score with respect to weight changes for CI performance.

TABLE 5.70. STABILITY INTERVALS DETERMINED BY PROMETHEE WHEN APPLYING KI WEIGHTS FOR ONE LEVEL AND KI FINAL WEIGHTS COMPUTED IN KIND-ET FOR THREE LEVEL OBJECTIVES TREES

Criterion	One level objectives tree		Three level objectives tree	
	W_{min}(%)	W_{max}(%)	W_{min}(%)	W_{max}(%)
Nat. U required	9.13	14.52	23.62	25.03
TRU mass loss transferred to waste	0	17.69	1.12	5.0
Activity after 1000 years	0	63.08	0	5.0
Decay heat after 50 years	0	17.48	1.16	5.05
Decay heat after 200 years	0	52.40	0	5.0
HLW volume	0.4	15.52	4.97	5.23
Fuel cycle costs	8.86	29.78	25.00	29.79
Costs of electricity at equilibrium	11.18	15.67	24.98	26.12

case where the lower boundary for a criterion is zero, that single criterion may receive zero weight (i.e. vanish) without altering the ranking results. The one level objectives tree has four performance criteria stability intervals that have a lower boundary that is equal to null, while the three level objectives tree has two performance criteria stability intervals that have a lower boundary that is equal to null.

5.7.2.9. Overview and discussion of ranking results

Practical experience has been gained here from the application of the MAVT/KIND-ET and PROMETHEE methods for the comparative evaluation of NFC performance using evaluation metric data generated in the OECD/NEA study and a structured process of decision support developed in the KIND approach. Special emphasis was put on the concept of single-attribute value function in the MAVT approach and the preference function for generalized criteria in the outranking approach, which has been analysed thoroughly. It was demonstrated that both approaches basically lead to the same ranking results if the preference parameters for each criterion are applied consistently.

The strengths and the weaknesses of the considered NFC alternatives have been identified with the PROMETHEE and MAVT tools. However, an indispensable part of each application of any ranking method remains the interpretation of the results and the critical review of the underlying data and their aggregation. An especially sensitive issue in this process is weight selection, which is to be carried out in extensive discussions by experts.

The current study, which takes 12 fuel cycle schemes into account, produced ranking results that are very sensitive to criteria weights. Therefore, the experts recommend that the number of alternatives be reduced to, for instance, six NFC options that are ‘representative’ of each family. The representative fuel cycle scheme can be implemented by analysing the performance table and its graphical representations, the value path and radar chart. First, the dominated alternatives 1c and 3bV can be eliminated, and next, by examining Fig. 5.68, similar behavioural patterns can be identified for groups of NFCs, which make it possible to remove some alternatives. The selection of 1a and 1b from family 1, 2a and 2b from family 2, and 3a and 3cV2 from family 3, provides an example of how this elimination could be managed. The PROMETHEE ranking results obtained in this case are much more stable (for confirmation, see Fig. 5.68 and also Table 5.71, which contains the stability interval ranges for each criterion).

Another issue is the problem of double counting of KIs, which in general needs to be avoided. In principle, KI-7, as a component of KI-8, could be avoided in case the decision maker does not assign a ‘significant utility’ to the cost of nuclear fuel. KI-7 emphasizes the importance of fuel cycle costs versus other unit costs such as investment, decommissioning, maintenance and operation. The impact of such a decision on ranks is shown in Fig. 5.69, which depicts the PROMETHEE ranking results for an evaluation model with 10 non-dominated alternatives and 7 performance indicators for 7 criteria.

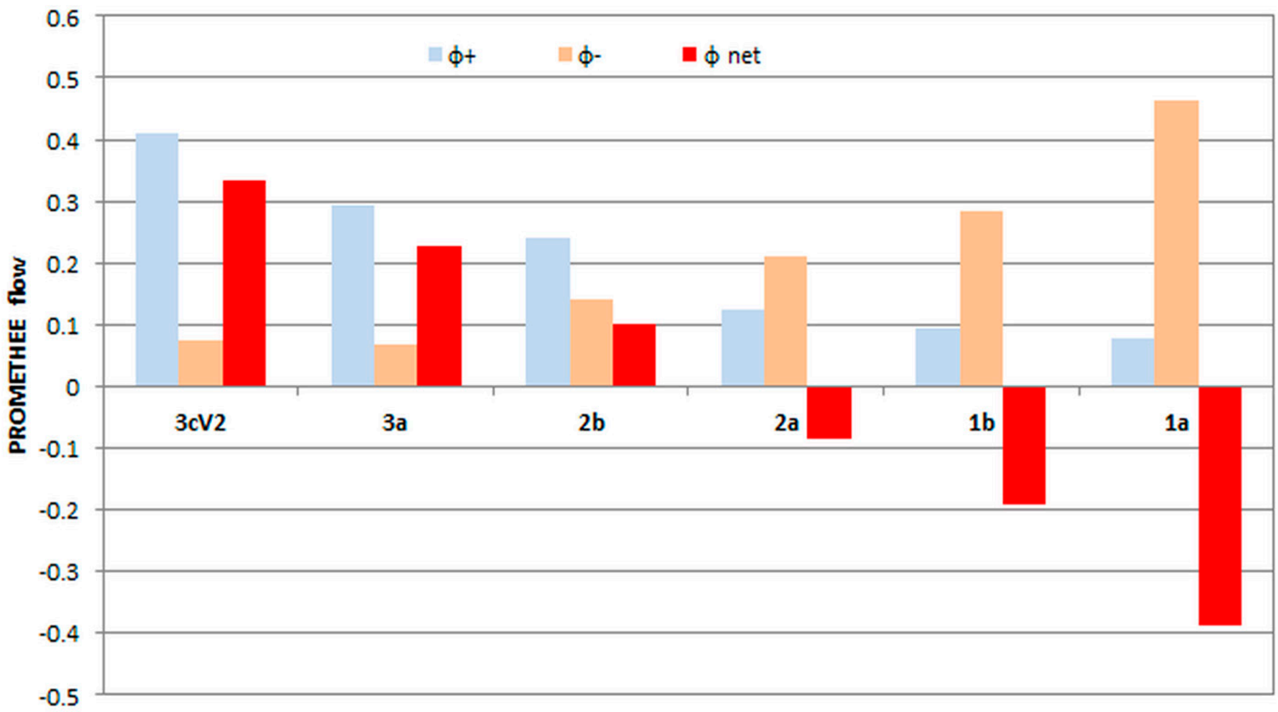


FIG. 5.68. PROMETHEE I and II ranking results for six NFC schemes.

TABLE 5.71. STABILITY INTERVALS DETERMINED BY PROMETHEE WHEN APPLYING KI WEIGHTS FOR ONE LEVEL AND KI FINAL WEIGHTS COMPUTED IN KIND-ET FOR THREE LEVEL OBJECTIVES TREES IN THE CASE OF SIX NFCs

Criterion	One level objectives tree		Three level objectives tree	
	W_{min}(%)	W_{max}(%)	W_{min}(%)	W_{max}(%)
Nat. U required	0	61.83	9.36	25.04
TRU mass loss transferred to waste	0	98.38	1.12	5.0
Activity after 1000 years	0	97.84	0	5.0
Decay heat after 50 years	0	100	0	5.05
Decay heat after 200 years	0	100	0	5.0
HKW volume	0	47.63	4.97	9.01
Fuel cycle costs	0	36.79	25.00	29.79
Cost of electricity at equilibrium	0	27.21	24.98	39.14

The sensitivity of the value/utility function form (linear versus exponential with $a = 1$) was analysed with KIND-ET in order to evaluate the impact on ranking results. The changes to the alternative ranks are shown in Fig. 5.70. Obviously, the metric data adopted for the present study are affected by the uncertainties that were partly quantified in Ref. [5.39]. The impact of those uncertainties on the ranking results obtained here is out of scope of this study, since it is more or less a generic study, but this problem could be investigated in national studies.

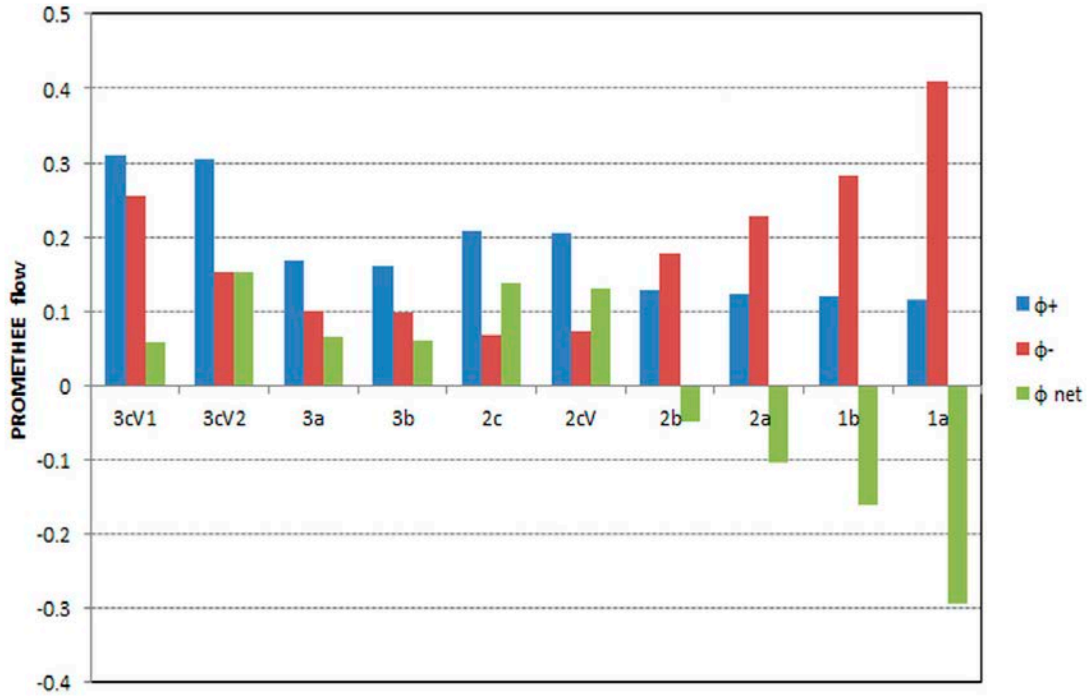


FIG. 5.69. PROMETHEE ranking results for 10 non-dominated alternatives and 7 criteria.

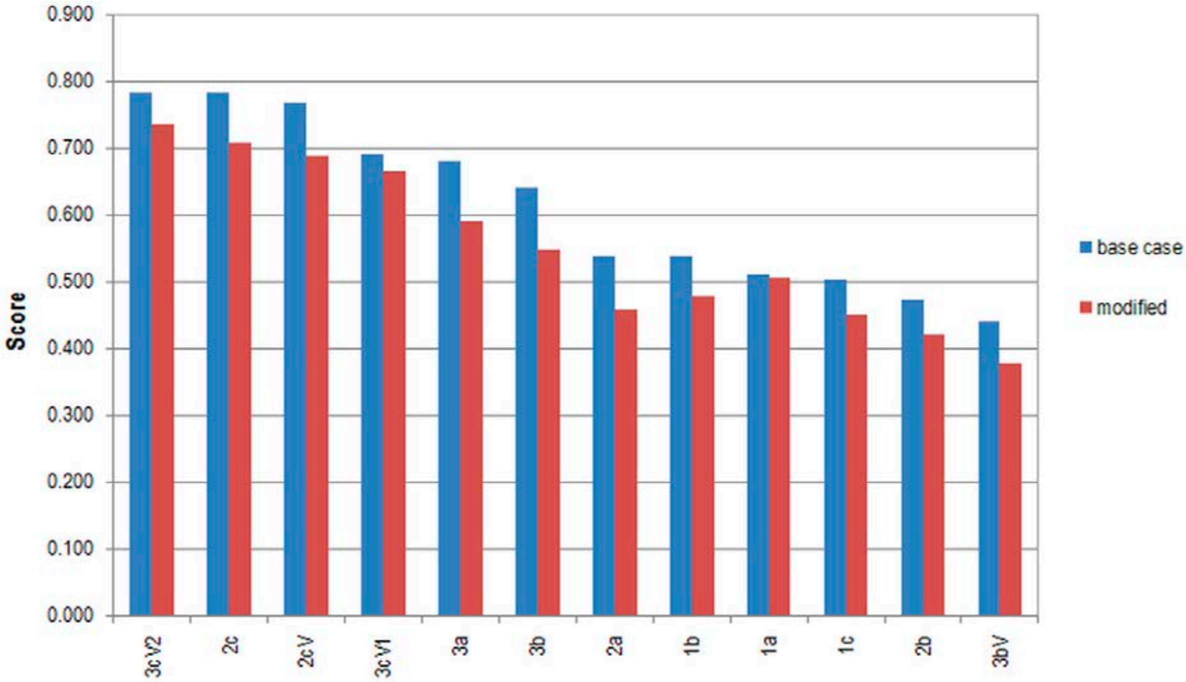


FIG. 5.70 Impact of value/utility function type on KIND-ET ranking results.

5.7.2.10. Conclusions

Comparative evaluations of advanced fuel cycles were performed by applying the KIND approach on the basis of the evaluation metrics and metric data retrieved from the OECD/NEA study. The set of indicators for each NFC option was evaluated in the original OECD/NEA study using relevant fuel cycle characteristics (radionuclide inventory, decay heat and spent fuel masses, HLW volume, material flows) obtained from physics based analyses.

Two MCDA methods — MAVT (evaluation tool: KIND-ET) and PROMETHEE (evaluation tool: Visual PROMETHEE [5.43]) — were used in the analyses to demonstrate their possible application limitations. In a base case, value/preference functions of linear type with equal significance for all low level criteria were assumed. It was shown that the outranking preference concept based on pairwise comparisons and the MAVT additive concept with linear single-attribute value functions are equivalent. The weight stability intervals for each criterion were determined.

Both evaluation methods identified fully closed fuel cycles deploying FRs as the best performing option with the potential to improve uranium resource utilization to bring benefits to the HLW repository programme.

The case study demonstrates that, similar to MAVT methods, PROMETHEE I and II can be applied efficiently for ranking NESs. The strengths and weaknesses of the compared technologies can be identified.

The ranking of PROMETHEE I can highlight incomparable alternatives indicating directions to modify model assumptions in order to improve differentiation between NFC options.

The question of what level of improvement is significant or substantial depends on the decision maker, whose real preferences can be combined with the estimated performance data (KIs) and introduced easily into PROMETHEE and KIND-ET using other weight settings and preference function types with different preference and indifference thresholds.

In any case, in order to properly rank alternatives using the KIND approach, the strict interrelation of decision makers and experts is indispensable to avoid ‘black box’ effects. The results of case studies thus only serve as an orientation, as they are strongly conditioned by the assumptions underlying the metric data evaluation and the MCDA model generation. Moreover, the subjective character of the weight setting and choice of preference/value functions (with associated parameters) adopted here needs to be kept in mind. As a general rule, it is not easy to find the ultimate ‘winners’ and ‘losers’ in a single generic study that abstracts away national peculiarities. At the same time, results are always conditional, as they depend on what stakeholders consider to be most important.

REFERENCES TO SECTION 5

[5.1] INTERNATIONAL ATOMIC ENERGY AGENCY, Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability: Final Report of the INPRO Collaborative Project GAINS, IAEA Nuclear Energy Series No. NP-T-1.14, IAEA, Vienna (2013).

[5.2] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems: INPRO Manual — Overview of the Methodology, IAEA-TECDOC-1575 Rev. 1, IAEA, Vienna (2008).

[5.3] COCHRAN, T.B., et al., Fast Breeder Reactor Programs: History and Status, Research Rep. 8, International Panel on Fissile Materials, Princeton, NJ (2010).

[5.4] PONOMAREV-STEPNOY, N.N., et al., Two-Component Nuclear Energy System with Thermal and Fast Reactors in Closed Nuclear Fuel Cycle, Tekhnosfera, Moscow (2016) (in Russian).

[5.5] INTERNATIONAL ATOMIC ENERGY AGENCY, INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Economics, IAEA Nuclear Energy Series No. NG-T-4.4, IAEA, Vienna (2014).

[5.6] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Energy Development in the 21st Century: Global Scenarios and Regional Trends, IAEA Nuclear Energy Series No. NP-T-1.8, IAEA, Vienna (2010).

[5.7] OECD NUCLEAR ENERGY AGENCY, Physics and Safety of Transmutation Systems: A Status Report, No. 6090, OECD/NEA, Paris (2006).

[5.8] INTERNATIONAL ATOMIC ENERGY AGENCY, Country Nuclear Power Profiles: 2015 Edition — Romania (2015), www-pub.iaea.org/books/IAEABooks/10971/Country-Nuclear-Power-Profiles-2015-Edition

[5.9] GOVERNMENT OF ROMANIA, National Strategy for the Development of the Nuclear Field in Romania and the Plan of Action for the Implementation of this Strategy, Official Bulletin No. 851/26.11.2002, Government of Romania, Sophia (2002).

[5.10] NUCLEARELECTRICA, The Signing of the Memorandum of Understanding for the Development, Construction, Operation and Decommissioning of Units 3 and 4 of Cernavoda NPP (2015), www.nuclearelectrica.ro/blog/2015/11/10/the-signing-of-the-memorandum-of-understanding-regarding-the-development-construction-operation-and-decommissioning-of-units-3-and-4-of-cernavoda-npp/?lang=en&print=pdf

[5.11] CHEN, Z., “Sustainable development based on clean nuclear energy: CGN’s story and prospect”, Proc. 9th Int. Conf. on Sustainable Development through Nuclear Research and Education (NUCLEAR 2016), Pitesti, Romania (2016).

[5.12] ALEMBERTI, A., “GIF Lead-cooled Fast Reactor Development Status”, paper presented at 12th INPRO Dialogue Forum on Generation IV Nuclear Energy Systems, Vienna, 2016.
[5.13] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems: INPRO Manual — Waste Management, IAEA-TECDOC-1575 (Rev. 1), IAEA, Vienna (2008).
[5.14] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems: INPRO Manual — Proliferation Resistance, IAEA-TECDOC-1575 (Rev. 1), IAEA, Vienna (2008).
[5.15] WORLD NUCLEAR NEWS, First Criticality for Two Chinese Reactors (2015), www.world-nuclear-news.org/NN-First-criticality-for-two-Chinese-reactors-1210154.html
[5.16] UNITED STATES AGENCY FOR INTERNATIONAL DEVELOPMENT, Workplan: Europe and Eurasia Low Emissions Strategies and Clean Energy Development, USAID, Washington, DC (2014).
[5.17] ELECTRICITY GENERATING AUTHORITY OF THAILAND, Thailand Power Development Plan 2015–2036, EGAT, Bangkok (2015).
[5.18] DEUTCH, J.M., et al., Update of the MIT 2003 Future of Nuclear Power, MIT, Cambridge, MA (2009).
[5.19] ELECTRICITY GENERATING AUTHORITY OF THAILAND, Contract for Mae Moh Units 4-7 Replacement Signed, to Help Strengthen Power System in the North (2015),
www.egat.co.th/en/news-announcement/news-release/
contract-for-mae-moh-units-4-7-replacement-signed-to-help-strengthen-power-system-in-the-north
[5.20] INTERNATIONAL ATOMIC ENERGY AGENCY, The Fukushima Daiichi Accident: Report by the Director General, IAEA, Vienna (2015).
[5.21] SHRESTHA, S., LEFEVRE, T., Estimation of External Cost Associated with Electricity Generating Options in Thailand using Simplified Methodologies, Asian Institute of Technology, Pathum Thani (2003).
[5.22] GRAUSZ, S., The Social Cost of Coal: Implications for the World Bank, Climate Advisers, Washington, DC (2011).
[5.23] BURGHERR, P., et al., Comparative risk assessment of severe accidents in the energy sector, Energy Policy **74** (2014).
[5.24] IAEA POWER REACTOR INFORMATION SYSTEM, Trend in Electricity Supplied, www.iaea.org/PRIS/WorldStatistics/WorldTrendinElectricalProduction.aspx
[5.25] EUROPEAN COMMISSION, ExternE: Externalities of Energy, EC, Luxembourg (2005).
[5.26] SOVACOOL, B.K., The costs of failure: A preliminary assessment of major energy accidents, 1907–2007, Energy Policy **36** 5 (2008) 1802–1820.
[5.27] PICHALAI, C., “NPPDP Self-assessment Process and IAEA INIR experience”, paper presented at Technical Meeting/ Workshop on the Introduction of Nuclear Power Programmes: Management and Evaluation of a National Nuclear Infrastructure, Vienna 2011.
[5.28] CHULA UNISEARCH, The Final Report of Study and Developing on Plan for Industrial Infrastructures and Relevant Standards for NPP Installation in Thailand, Chulalongkorn University, Bangkok (2010).
[5.29] FIGUEIRA, J., SALVATORE, G., MATTHIAS, E., Multiple Criteria Decision Analysis: State of the Art Surveys, Springer, Boston, MA (2005).
[5.30] BELTON, V., STEWART, T., Multiple Criteria Decision Analysis: An Integrated Approach, Kluwer Academic Publishers, Dordrecht (2002).
[5.31] KEENEY, R., RAIFFA, H., Decision with Multiple Objectives, John Wiley & Sons, New York (1976).
[5.32] VON WINTERFELDT, D., EDWARDS, W., Decision Analysis and Behavioral Research, Cambridge University Press, Cambridge (1986).
[5.33] HWANG, Ching-Lai, YOON, Kwangsun, Multiple Attribute Decision Making: Methods and Applications, Springer, Berlin (1981).
[5.34] BRANS, J., VINCKE, P., A preference ranking organization method: The PROMETHEE method for multiple criteria decision-making, Manage. Sci. **31** (1985) 647–656.
[5.35] SAATY, T.L., The Analytic Hierarchy Process, McGraw-Hill, New York (1980).
[5.36] KUZNETSOV, V., FESENKO, G., ANDRIANOV, A., KUPTSOV, I., INPRO activities on development of advanced tools to support judgment aggregation for comparative evaluation of nuclear energy systems, Sci. Technol. Nuclear Install. 2015 (2015).
[5.37] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Fuel Cycle Simulation System (VISTA), IAEA-TECDOC-1535, IAEA, Vienna (2007).
[5.38] OECD NUCLEAR ENERGY AGENCY, INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2011: Resources, Production and Demand, OECD, Paris (2012).
[5.39] OECD NUCLEAR ENERGY AGENCY, Advanced Nuclear Fuel Cycles and Radioactive Waste Management, NEA Report No. 5990, OECD, Paris (2006).

[5.40] FRENCH ALTERNATIVE ENERGIES AND ATOMIC ENERGY COMMISSION, Les codes de calcul de la neutronique et le calcul haute performance (2013),
www.cea.fr/Documents/monographies/La%20neutronique%20-%20Les%20codes.pdf.
[5.41] VIDAL, J.M., et al., “CESAR5.3: An Industrial Tool for Nuclear Fuel and Waste Characterization with Associated Qualification”, Proc. Conf. WM2012, Phoenix, 2012, WM Symposia, Tempe, AZ (2013).
[5.42] MARESCHAL, B., Some Properties of the PROMETHEE Net Flow (2015),
https://www.researchgate.net/publication/280598956_Some_properties_of_the_PROMETHEE_net_flow
[5.43] MARESCHAL, B., “Performance analysis using Visual PROMETHEE”, paper presented at EURO 2013, Rome, 2013.

6. FINDINGS AND CONCLUSIONS

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 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.
— Use one or several KIs for each main area to be considered in the evaluation (e.g. safety, cost), as appropriate. However, the total number of KIs must be limited, preferably to fewer than 20.
— 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.
— 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. Acknowledge which less important aspects are being left out to keep the evaluation focused.
— 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.
— Note that another approach to avoid an excessive number of KIs is to perform a multi-stage evaluation, where the first stage reduces the total number of options while the second stage goes into more detail in a couple of areas where it is difficult to separate the remaining options using the original KIs.
— Fully describe and document each KI, so that everyone involved can understand what is included, and how it is to be evaluated.
— Develop KIs that are as independent as possible from each other to avoid double counting the same aspects of the system.
— Put as much effort into developing the value/utility functions and weights as has gone into developing the KIs. These aspects of the KIND approach have just as much impact on evaluation results.
— Use sensitivity analyses to explore the robustness of the initial evaluation results. This acknowledges the uncertainty in the inputs and in the KIND approach and reveals where apparent differences between energy systems are tangible and not just within the margin of the uncertainty.

A key component of the KIND approach is the MCDA method, which is not a tool to suggest the 'best option' for all situations but a tool for finding a compromise or a trade-off among options for given circumstances (combining expert judgements on subject matter, as well as decision makers' preferences).

The selection and justification of an adequate MCDA method and the most appropriate method parameters are important points that depend on a decision support problem. Another important issue to be carefully examined within sensitivity studies is the possible impact of uncertainty in input data on the alternative ranks.

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. Thus, depending on whether a detailed evaluation of all indicators without uncertainty will be performed, or instead the consideration will be limited to qualitative judgements regarding indicator values, different methods need to be used. For example, the MAVT, TOPSIS and PROMETHEE methods are more appropriate in the former case, whereas the AHP method is more suitable in the latter. If it is necessary to consider the uncertainty in the indicator values, the MAUT method is more suitable than, for instance, MAVT or others.

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 analysed 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.

For KIs, it is only necessary to select those parameters or characteristics of an NES whose variation will result in tangible, well understood and interpreted changes of user oriented qualities. In this sense, comparative evaluation is complementary to the assessment, in which only full compliance with the defined set of criteria is required. Comparative evaluation is deemed to support the selection of an NES that is preferable for a particular user from a range of alternatives that otherwise meet (or are anticipated to meet) all regulatory and other assessment criteria.

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.

When correctly implemented, different theoretical frameworks applied in various MCDA methods yield similar ranking results. The KIND case studies demonstrated that, despite some differences in the ranks, the results are generally consistent and harmonized even when based on different methods. The numerical examples considered have identified that both elementary and more sophisticated judgement aggregation methods may be used effectively for the multi-criteria comparative evaluation of NESs in both technology and scenario based cases.

To avoid a black box effect, transparent and simplified MCDA methods (such as MAVT or simple additive weighting) are recommended for the objective of the KIND approach, given its application to less mature innovative technologies and proven nuclear and non-nuclear technologies, but this in no way restricts experts from applying other MCDA methods. Moreover, the scope of the MCDA methods does not need to be limited to those considered in this report. Experts may express their preference for other ranking/aggregation methods, but in this case it is essential to verify their applicability and results. It is also necessary to check whether under comparable conditions the results obtained using different methods are well coordinated and consistent.

If the evaluation is made based on only one method among all possible methods, questions may arise concerning the comprehensiveness of the study and the competence of the expert(s) who suggested that specific method. With this in mind, an approach that involves the application of several MCDA methods may be recommended, and this helps to ensure that the problem is recognized, understood and analysed more thoroughly. It also helps decision makers and subject matter experts to achieve consistency in their judgements and evaluations and obtain a stable and robust ranking of the results. In numerical studies, it is rational to move from the application of the simplest methods to more complicated ones. This provides an opportunity to examine the application of more sophisticated MCDA methods in comparison with simpler ones and identify the most suitable option.

If two different groups of experts examine the same comparative evaluation problem, the ranks of alternatives may be different in the general case, even when the same method is used. This is caused by different points of view regarding weights and model assumptions (value/utility functions, etc.). A similar situation could be expected if two expert groups perform their study under the supervision of different experts who are skilled in using different methods. In this case, the probability that the same ranking will result, even if these groups have similar judgements about the problem, is even smaller. Moreover, when evaluating weights using different procedures (for example, swing and pairwise methods), the results may vary significantly, even when they are implemented within the same

MCDA method. Therefore, the representation of the significance of different indicators (weighting factors) is the most sensitive issue in the formal application of MCDA methods, and it requires accuracy and reasonableness.

Differences in ranks may occur due to different performance table representations when experts apply different MCDA methods. Unfortunately, there are no specific rules for conversion of the different variants of the performance table into a universal form that is suitable for use with different methods: the automatic conversion of natural values to scores may result in scores that differ from the scores that experts give directly in the scoring scales.

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.

While MCDA methods can be recommended for use in support of comparative evaluations of NESs, they are only a means to an end, and the identification (in a clear and understandable manner) of the features of NESs that result in different costs, risks and benefits (i.e. ‘key indicators’) is a more important output for supporting decision making.

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-NES comparisons.

Trial applications have shown that the KIND approach provides sufficient flexibility and upgradability for users to choose, rank and sort different NES options at the technology and scenario levels. Such selection and ranking are achieved by searching for compromises among the conflicting indicators representing the performance and sustainability features of NESs and are based on both the judgements of subject matter experts and the preferences of decision makers. Several participants in the project have already examined the usefulness of the KIND approach in maintaining a dialogue with decision makers. What matters is not the final result of a comparative evaluation at the top aggregation level, but rather the option to go down to lower aggregation levels and, when necessary, to particular indicators, sensitivities and uncertainties. This kind of ‘down to the roots’ analysis and representation can make the dialogue with decision makers useful and productive.

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 will be accomplished within the 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.

Annex I

OVERVIEW OF PREVIOUS STUDIES

This annex reviews previous studies on the approach for the comparison of nuclear energy systems (NESs), including IAEA studies and projects [I–1 to I–8], several studies undertaken by the Nuclear Energy Agency of the Organisation for Economic Co-Operation and Development (OECD/NEA) on the evaluation of performance and the screening of advanced NESs [I–9 to I–15], Massachusetts Institute of Technology (MIT) studies on the future of nuclear power and nuclear fuel cycles (NFCs) [I–16 to I–18], and a related United States Department of Energy study [I–19]. A set of research articles give an overview of the experience gained in applying Multiple criteria decision making (MCDM) methods and tools in nuclear engineering [I–20 to I–27]. A preliminary analysis of the state of the art aggregation judgement measures applied to the performance comparison performed within the Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems (ROADMAPS) project is presented in Ref. [I–28].

I–1. IAEA RELATED STUDIES AND PROJECTS

I–1.1. INPRO methodology and GAINS framework for nuclear energy scenario assessment

I–1.1.1. The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) methodology

As part of INPRO, an NES performance assessment methodology was developed to meet national sustainability standards [I–1]. INPRO worked out a set of basic principles, user requirements, techniques and criteria to compare all NESs, including those with innovative components. The principles on which NES performance should be based to provide a sustainable energy supply were additionally proposed [I–2]. In order to become sustainable, each NES should meet all the basic principles in the areas of safety, economics, infrastructure, waste management, proliferation resistance, physical protection and environment.

Figures I–1 and I–2 show the INPRO hierarchy of requirements for Nuclear Energy System Assessment (NESA) that are applicable to the NES design. At the top level, 14 basic principles are established. The middle level ('user requirements') contains 52 user requirements specifying the conditions required to achieve compliance with the corresponding basic principle. Therefore, the user requirements contribute directly to the achievement of the top level goals. The third, bottom level presents a set of 125 criteria consisting of indicators and acceptance limits that help to make a judgement on the potential of the NES. These indicators may be based on a single parameter, an aggregated variable, or a status statement.

Two types of indicators, numerical and logical, are used to evaluate NES performance using the INPRO criteria. The numerical indicators reflect the measured or calculated values related to specific NES properties. An

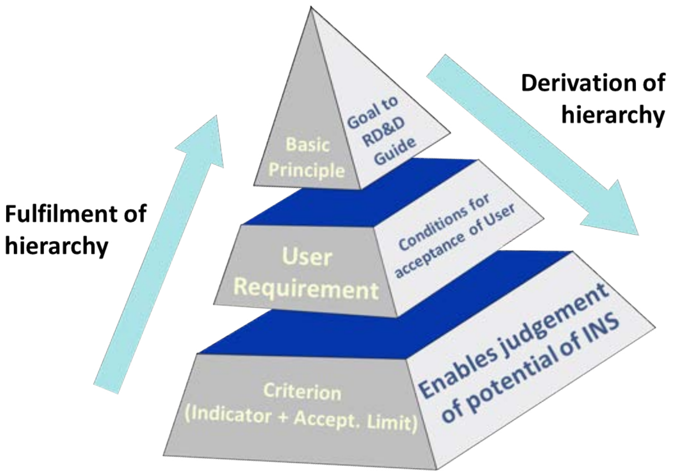


FIG. I–1. INPRO hierarchy.

example could be the estimated probability of a major release of radionuclides to the containment obtained from a probabilistic safety analysis or the number of intact safety barriers maintained after a severe accident. The logical indicators usually refer to specific NES features, and they represent the answers to questions.

In the INPRO assessment areas, some indicators may be applicable to the overall NES, whereas others are only valid for specific components (e.g. reactors). They may relate to the functionality of a whole system or its components, or set out measures to implement analytical methods. Some indicators may utilize evaluation parameters (EPs). These parameters may help the INPRO user to determine whether or not the acceptance limit for an indicator has been met. For example, the evaluation parameters can be applied to a combination of design simplifications, improved materials, increased operating margins and increased redundancy for increasing the robustness of an NES component relative to an existing design, enhancing the defence in depth. The above classification is supplemented by another type of indicator, the so called key indicator (KI), which may be defined in each specific area or in all INPRO areas and depends on the preferences of the technology developers and the Member States.

The acceptance limit of an INPRO criterion represents a qualitative or quantitative target against which the value of an indicator can be compared. It provides a judgement of acceptability (pass/fail, good/bad, better/worse). There are two types of acceptance limits — numerical (for quantitative targets) and logical (for qualitative targets). Typically, a logical acceptance limit is a go/no go (i.e. positive (yes) or negative (no)), answer to a question that the indicator addresses.

In the past, INPRO methodology has been applied for comparative assessments of NES sustainability. However, feedback from experts who attempted to compare different NES options with reference to sustainability using the full range of the INPRO methodology indicated that it is most suitable as an instrument for identifying gaps that prevent NES performance from being fully sustainable.

The INPRO methodology [I–2] has introduced the notions of KIs and 'desired target values' that can potentially be used as well. However, the number of KIs proposed in Ref. [I–2] is limited and significantly smaller than the overall number of indicators in the INPRO methodology. The extension of the concept of KIs with desired target values constitutes a 'relative benefit index' and a 'relative risk index' (to be defined for each KI). The risk may either include the uncertainty in the desired target value of the KI or reflect the required development effort and the level of concept maturity.

To elaborate the national and international recommendations for sustainable NES development, a structured and objective evaluation of the options is necessary. This process includes: (1) screening of one or more NESs selected by a Member State, which can be performed on a national, regional or global basis and aims at compatibility evaluation against objectives of sustainable energy development; (2) comparison of different NESs or their components (e.g. to find a preferred or optimum NES tailored to the needs of a Member State or to make a capability comparison on a global basis); (3) identification of necessary improvements that stimulate research and development to upgrade performance.

The above mentioned objectives can be achieved effectively through the thoughtful complementary application of the INPRO methodology (for sustainability assessment and gap analysis of each of the selected NES options) and the KIND approach (for comparative evaluation of NES options focused on benefits, risks and costs for a particular user). It should also be emphasized that both the INPRO methodology assessment and the comparative evaluation using the KIND approach are complementary; generically, they need to follow the assessments of safety and environmental impacts as defined according to national regulations and IAEA safety standards.

While performing an assessment based on the INPRO methodology [I–2], it is also indispensable to consider the development of nuclear energy in the future (i.e. to define the reference energy scenario (or scenarios) driven by a projected total time dependent demand for nuclear energy generation). This demand can be covered by different NESs; therefore, it is necessary to consider the deployment pace for each NES (power plants with related NFCs, NFC facilities) and the transition period from one NES type to the other. Comparative evaluation of different options for NES evolution scenarios can be analysed using the KIND approach (see Section 5.7).

I–1.1.2. The Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS) analytical framework

The scenario oriented evaluation in Section 5.7.1 was based on the results from the INPRO collaborative project GAINS [I–3]. GAINS created an analytical framework for assessing transition scenarios from existing to future NESs.

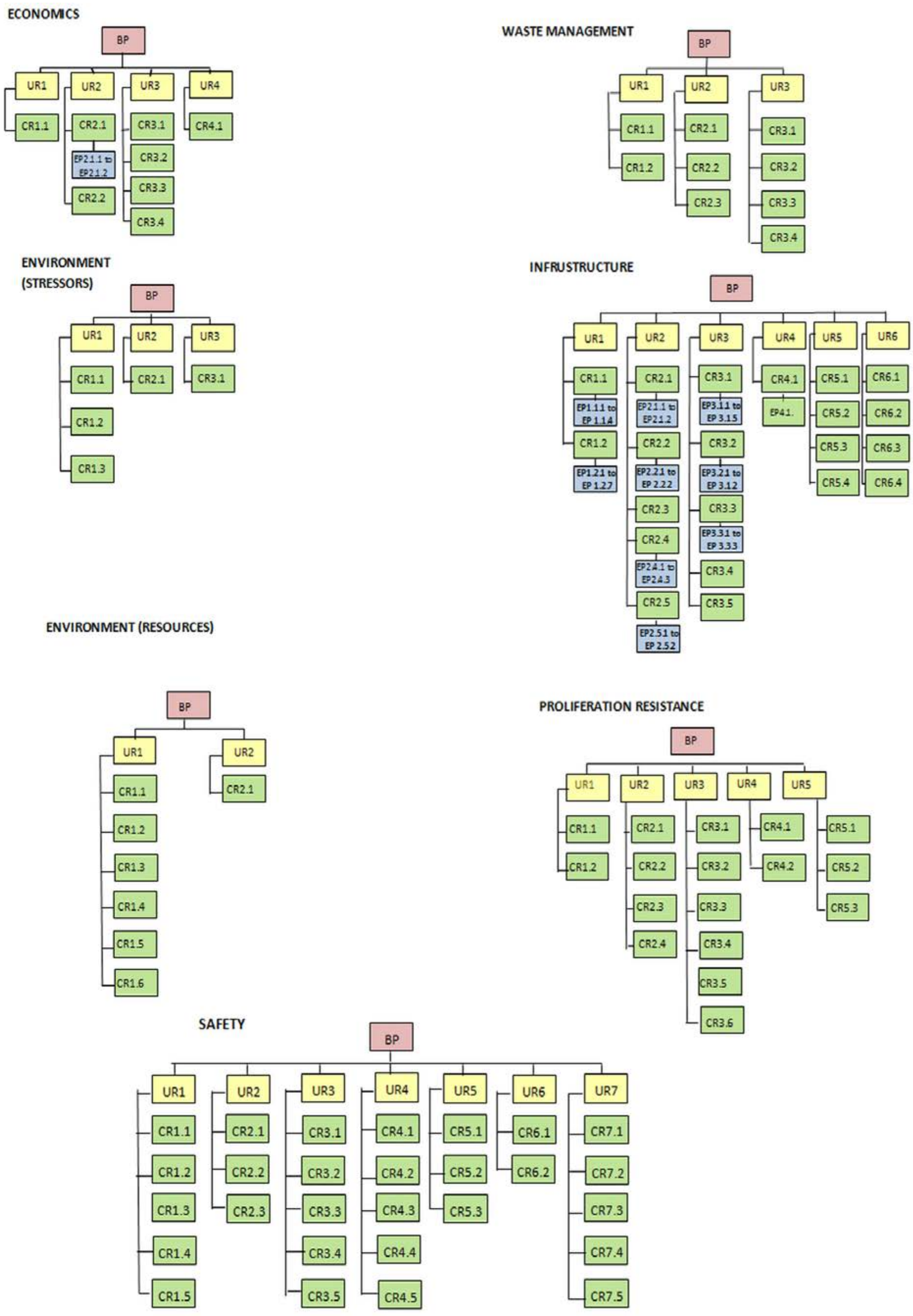


FIG. I–2. The INPRO hierarchical structure for each area.

The GAINS framework was a part of the integrated services provided by the IAEA to Member States — newcomer states considering embarking on nuclear energy generation in the near future and technology owner states pursuing R&D on the expansion of nuclear energy generation. The GAINS framework proposed a common methodological approach based on common assumptions and boundary conditions. The major components of the GAINS approach include the following:

(a) Long term nuclear power evolution scenarios;
(b) Energy demand estimation based on the IAEA Member States' high and low nuclear power utilization estimates up to 2050 and trend forecasts up to 2100 determined from the projections of international energy organizations;
(c) A so called 'heterogeneous' global model to capture countries' different policies regarding the NFC back end;
(d) Appropriate metrics and tools to assess the sustainability of NES dynamic deployment scenarios, including a set of KIs and EPs;
(e) An international database that includes the characteristics of existing and future innovative nuclear reactors with associated NFC material flow analysis and which expands the available IAEA databases and takes into account the different preferences of Member States;
(f) Lessons learned.

Whereas the INPRO methodology is designed to assess the ability of national NESs to meet sustainability requirements, the GAINS framework is intended to compare different options on the basis of development scenarios at the national, regional and global levels. Thereafter, the GAINS framework relates to the INPRO methodology primarily through the concept of KIs.

The GAINS framework assesses the transition from existing to future sustainable NESs, showing whether the selected targets (e.g. waste, quantity of direct use material in storage, or natural resource consumption minimization) are reached in particular nuclear power evolution scenarios. The KIs and EPs are compared to select the most promising options.

The set of KIs and EPs for the GAINS assessments was defined for global scenarios encompassing different NES architectures from a set of more than a hundred candidate indicators comprising all areas in the INPRO methodology. As shown in Table I–1, these KIs/EPs quantify nuclear power production according to reactor type, resource availability, discharged fuel mass, quantity of generated radioactive waste, NFC services, costs and investment for a 'global' NES. Although originally developed for global architectures, this set of KIs and EPs can be adapted for more specific application.

I–1.2. The IAEA's basic principles of nuclear technology

Any integrated analysis of NES and NFC options that relates to performance and sustainability assessments tends to be pluralistic by coherently accepting different priorities, intentions, values and norms, and simultaneously relying on a consensus about the established hierarchy of requirements and basic principles. A basic principle for nuclear technology is a statement of a general goal to be achieved by it, and it provides broad guidance for nuclear power deployment. The set of basic principles proposed by the IAEA may be broken down into three main categories: beneficial, sustainable and responsible use [I–4].

The 'beneficial use' category includes two basic principles: benefits and transparency. Nuclear energy should provide benefits that outweigh the associated costs and risks and should be based on open and transparent communication of all relevant information. The 'sustainable use' category includes two basic principles: resource efficiency and continuous improvement. Both of them should optimize the use of resources and advances in technology and engineering in order to improve safety, security, economics and proliferation resistance, and reduce environmental impact. The 'responsible use' category encompasses four basic principles: protection of people and the environment, security, non-proliferation and long term commitment in accordance with internationally recognized standards. Apart from this, the IAEA proposed general and specific objectives for nuclear power, NFCs, and radioactive waste management and decommissioning to be achieved at different implementation stages [I–5 to I–7]. The general basic principles in each specific area can be further used by experts to elaborate problem and practice oriented principles.

TABLE I–1. THE GAINS KIs AND EVALUATION PARAMETERS

No.	KIs and evaluation parameters Colour coding indicates relative uncertainty level of specific quantitative values estimated for future NESs (can vary based on a particular scenario): Low (blue); Medium/low (green); Medium/high (yellow); High (orange)	INPRO assessment areas: Resource sustainability	Waste management and environmental Stressors	Safety	Proliferation resistance and physical protection	Economics	Infrastructure
Power production							
KI-1	Nuclear power production capacity by reactor type						X
EP-1.1	(a) Commissioning and (b) decommissioning pace		X				X
Nuclear material resources							
KI-2	Average net energy produced per mass unit of natural uranium consumed	X	X				
EP-2.1	Cumulative demand for natural nuclear material, i.e. (a) natural uranium and (b) thorium	X	X				
KI-3	Direct use material inventories per unit energy generated	X			X		X
Discharged fuel							
KI-4	Discharged fuel inventories per unit of energy generated		X				X
Radioactive waste — minor actinides							
KI-5	Radioactive waste inventories per unit of energy generated		X				X
EP-5.1	(a) Radiotoxicity and (b) decay heat of waste, including discharged fuel for direct disposal		X				X
EP-5.2	Minor actinide inventories per unit of energy generated		X				X
Fuel cycle services							
KI-6	(a) Uranium enrichment and (b) fuel reprocessing plant capacity, both normalized per unit of nuclear power production				X		X
KI-7	Annual quantities of fuel and waste material transported between groups			X		X	X
EP-7.1	Category of nuclear material transported between groups				X		
System safety							
KI-8	Annual collective risk per unit of energy generation			X			
Cost and investment							
KI-9	Levelized unit of electricity cost					X	
EP-9.1	Overnight cost for *n*th of a kind reactor unit: (a) total and (b) specific (per capacity unit)					X	
KI-10	Estimated R&D investment in *n*th of a kind deployment					X	X
EP-10.1	Additional functions or benefits					X	

I–1.3. Nuclear reactor technology assessment for near term deployment

The IAEA's Nuclear Power Technology Development Section has developed an approach to nuclear reactor technology assessment for near term deployment. This approach, presented in detail in Ref. [I–8], is the basis of a service offered by the Section to interested Member States.

According to Ref. [I–8]:

> "Several IAEA Member States have embarked recently on initiatives to establish or reinvigorate nuclear power programmes. In response, the IAEA has developed several guidance and technical publications to identify with Member States the complex tasks associated with such an undertaking and to recommend the processes that can be used in the performance of this work. A major challenge in this undertaking, especially for newcomer Member States, is the process associated with reactor technology assessment (RTA) for near term deployment. RTA permits the evaluation, selection and deployment of the best technology to meet the objectives of the nuclear power programme".

The IAEA publication [I–8] presents the RTA methodology, which focuses on ranking the importance of key elements derived from a particular Member State's nuclear energy objectives and then ranking the key features of the reactor technology options. Table I–2 lists the 15 key elements and the numbers of key features and sub-features related to each element. Since the aim of the RTA is to support a technology specific decision (i.e. assessment or selection), the level of detail in the key elements 'nuclear plant safety', 'technical characteristics and performance' and 'economics' are treated with more detail than the other 12 key elements. The publication [I–8] describes the use of quantitative measures and metrics to evaluate the overall benefit derived from each technology option for each required key element. It recommends the Kepner–Tregoe and multi-attribute utility theory methods for the decision making processes and explains in detail how these methods can be employed to improve current practices for decision making on technology assessment while selecting the best fit reactor technology for near term deployment.

TABLE I–2. RTA KEY ELEMENTS, FEATURES AND SUB-FEATURES

Key elements	Number of key features	Number of key sub-features
Site specific considerations	7	7
Grid integration	5	5
Nuclear plant safety	18	47
Technical characteristics and performance	10	59
Nuclear fuel and NFC performance	13	13
Radiation protection	9	9
Environmental impact	4	4
Safeguards	1	1
Plant and site security	6	6
Owner's scope of supply	7	7
Supplier/technology holder issues	18	18
Project schedule capability	6	6
Technology transfer and technical support	7	9
Economics	5	26

I–2. RELATED STUDIES AND PROJECTS BY THE OECD NUCLEAR ENERGY AGENCY (OECD/NEA)

The OECD/NEA is an intergovernmental organization that brings together 31 countries from North America, Europe and the Asia-Pacific region in a common, non-political forum with a mission to assist the member countries in maintaining and further developing nuclear energy for peaceful purposes. The NEA provides authoritative assessments and forges common understandings on key issues in energy and sustainable development areas.

I–2.1. Trends in the NFC

Several NEA studies screen and evaluate the performance of advanced NESs using only simplified comparative evaluation techniques. Reference [I–9] provides a description of the developments and trends in NFCs with a focus on their potential to improve the competitiveness and sustainability of NESs in the medium and long term and presents criteria and indicators for future INES evaluations (see Table I–3). This study refers to two MCDM techniques, the multi-criteria method and life cycle analysis, but without applying them. The survey performed was based on the results taken from available life cycle analysis studies performed in the past. Regarding the multi-criteria analysis, the activities of the expert group were limited to the definition of criteria (indicators) and analysis of their applicability, and descriptive evaluation of different NFC options and future developments according to these criteria. Experts have not quantified either the criteria or the indicators for a concrete selection and prioritization process. Aggregation judgement, which would require the development of an adequate life cycle analysis framework, was beyond the scope of this study.

I–2.2. Advanced NFCs and radioactive waste management

The broad range and flexibility of advanced NFCs makes it possible to design economical NESs that address critical issues of both natural resource utilization and waste management efficiently. The impact of various advanced NFCs on the uranium consumption rate and radioactive waste management was analysed in Ref. [I–10] and compared to present industrial practices and current technologies. For the back end assessments of the fuel cycle, well established codes and tools (such as DARWIN, CESAR, MARNIE, TOUGH2 and PORFLOW, see Ref. [I–10] for further details) were used to analyse the long term performance (including safety aspects) of repositories located in granite, salt and boom clay formations. To estimate the representative waste inventory for the repository case studies, the nuclide compositions generated by three groups of fuel cycles were considered. The first group encompassed NFCs based on current industrial technologies and their possible extensions: once through NFC in pressurized water reactors (PWRs) and PWR based NFC options with only one plutonium recycling path. The second group included partly closed NFCs with multi-recycling of plutonium (transferring neptunium to waste). The analysed NFC options in group 2 differ, however, in their treatment of americium and curium (decay storage versus transfer to waste). The third group of NFCs envisages the deployment of advanced technologies with the potential and flexibility to fission transuranics (TRUs) (plutonium and minor actinides) while multi-recycling them in a closed cycle.

The study was completed with preliminary cost estimations. The results show that advanced NFCs with partitioning and transmutation (P&T) of TRUs offer various possibilities for strategic choices regarding the efficient use of uranium resource and the optimization of the footprint and capacity of waste repository sites. The NFCs of group 3 can minimize both the radiological impact on the repositories and the financial burden. The NES evaluation was based on eight metrics: uranium consumption; TRU loss/transfer to waste; activity after 1000 years; decay heat after 50 years; decay heat after 200 years; high level waste (HLW) including spent nuclear fuel (SNF) volume and maximum dose for repositories in granite, clay and tuff; NFC costs; and total electricity generation costs. This study did not propose any multi-criteria method for judgement aggregation in the comparative assessment. The judgements were performed in a qualitative way on the basis of indicator values. Final results showing the NFC performance were synthesized as presented in Fig. 5.56.

Under the guidance of the OECD/NEA Nuclear Science Committee and the mandate of the Working Party on Scientific Issues of the Fuel Cycle, further comparative analysis of NFCs was performed with respect to resource consumption and nuclear waste management performance. Expert groups assessed the impact of INESs including P&T technology on geological repository performance for different host formations [I–11 to I–13].

TABLE I–3. CRITERIA AND INDICATORS

	Criterion	Indicator	Measure
Economy	Economic competitiveness	Levelized NFC cost	US \$/kW·h (100%)
		Raw materials (U_3O_8 or Th)	US \$/t (%)
		Separation work	US \$/SWU (%)
		Conversion	US \$/kg HM (%)
		Fabrication	US \$/kg HM (%)
		Storage	US \$/kg HM (%)
		Reprocessing	US \$/kg HM (%)
		Transport	US \$/kg HM (%)
		Encapsulation and conditioning	US \$/kg HM (%)
		Disposal	US \$/kg HM (%)
	Financial expenditure	Total cost	US \$
	Technology availability	Research (govt) Development (non-govt) I: Basic R&D II: Laboratory/process III: Pre-industrial IV: Industrial	US \$ US \$ Years
Environment and Public Health	Use of non-renewable resources	Energy recovered per kg U	TW·h/kg U
	Energy intensity	Ratio of necessary energy input to obtained output	%
	Transportation	Range of tonne kilometres	t × km/kW·h
		Energy intensity ratio	%
	Land occupation	Land area used	km²/kW·h
	Greenhouse gas emission	Amount of greenhouse gas emitted	t CO_2 eq./kW·h
	Amount of waste	Total volume	m³/kW·h
		Volume at each life cycle step	m³/kW·h
		— emitters	kg/kW·h; Bq/kW·h
		— emitters	kg/kW·h; Bq/kW·h
	Confinement time of waste	— emitters	Years
		— emitters	Years
	Radiological impacts	Collective operational dose	person-Sv/kW·h
	Human health effects: acute fatalities	Operational accidents	Number of immediate fatalities per accident
Society	Human resources, work opportunities	Change in work opportunity	persons × year/kW·h
		Work opportunity	persons × year/kW·h
	Broad economic effects	Autonomy of resources	
		Induced industrial production	
	Social aspects	Acceptance and risk aversion	
	Proliferation resistance		

1–2.3. Potential benefits and impacts of advanced fuel cycles with partitioning and transmutation

In order to promote closer collaboration across the fields of nuclear science and geological disposal, the OECD/NEA Task Force on Potential Benefits and Impacts of Advanced Fuel Cycles with Partitioning and Transmutation carried out a comparative analysis of studies conducted in several international laboratories on the impact of advanced NESs with P&T on geological repository performance [I–14].

The outcomes of the analysis can be used to guide the development of appropriate P&T strategies in favourable combinations with geological disposal designs. The criteria selected for evaluations, such as peak dose rate, radiotoxicity, decay heat, waste form, volume and mass, mainly address repository performance evolution under normal and disturbed scenarios. The role of P&T in the management of uncertainty, which is an essential feature of the safety case for geological disposal, was discussed, as well as some miscellaneous aspects, such as proliferation and costs. No method was recommended for judgement aggregation.

1–2.4. The Generation IV International Forum (GIF) methodology

GIF offers a large R&D cooperation framework for preparing the development of six selected INES types seen as being the most promising Generation IV (Gen IV) systems. The Gen IV designs are: molten salt reactor, super critical water reactor, gas cooled fast reactor system, lead cooled fast reactor, sodium cooled fast reactor and high temperature reactor. These innovative systems will have enhanced safety, competitiveness and proliferation resistance, while using uranium in a more efficient way than the GEN III systems. Moreover, they allow the optimization of nuclear waste management. The Gen IV NESs are fully compliant with the concept of sustainable development. GIF proposed a methodology for detailed evaluation of NES performance. The aim is to formulate the necessary R&D efforts supporting future NES deployment.

The GIF methodology is mainly focused on advanced reactor technologies rather than the overall NFC, even though NFC metrics are used in the assessments. GIF, however, provides no guidelines regarding methods for integrated comparative evaluations.

The GIF cost estimation methodology allows two approaches: (1) a top down method based on scaling and detailed information from similar reactor systems and (2) conventional bottom up estimation techniques. To calculate the aggregated costs, the high level figures of merit listed below [I–14] are applied:

- Costs of research, development and demonstration of a reactor system;
- Capital at risk;
- Annual non-fuel operation costs;
- Annual NFC costs;
- Levelized unit of energy cost.

The GIF proliferation resistance and physical protection methodology represents a systematic approach to evaluate vulnerabilities in design concepts. For comparison, the IAEA/INPRO methodology for non-proliferation provides ‘rules of good practice’; therefore, both methods together could provide an overall approach to ensure a robust future design [I–15]. The GIF proliferation resistance and physical protection measures are:

(a) Proliferation technical difficulty: The inherent difficulty arising from the need for technical sophistication and materials handling capabilities required to overcome the multiple barriers to proliferation;
(b) Proliferation cost: The economic and staffing investment required to overcome the multiple technical barriers to proliferation, including the use of existing or new facilities;
(c) Proliferation time: The minimum time required to overcome the multiple barriers to proliferation (i.e. the total time planned by the host State for the project);
(d) Fissile material type: The categorization of material based on the degree to which its characteristics affect its utility for use in nuclear explosives;
(e) Detection probability: The cumulative probability of detecting a proliferation segment or pathway;
(f) Detection resource efficiency: The efficiency in the use of staffing, equipment and funding to apply international safeguards to the NES;

(g) Probability of adversary success: The probability that an adversary will successfully complete the actions described by a pathway and that it will generate a consequence;
(h) Consequences: The effects resulting from the successful completion of the adversary's action described by a pathway.

The GIF-IV integrated safety considerations are based on five distinct analytical tools or 'elements':

(1) Qualitative safety features review;
(2) Phenomena identification and ranking table;
(3) Objective provision tree;
(4) Deterministic and phenomenological analyses;
(5) Probabilistic safety analysis.

It is proposed that each element should be used to answer specific safety related questions with different degrees of detail and at different stages of design maturity.

I–3. UNITED STATES DEPARTMENT OF ENERGY (USDOE) RELATED STUDIES AND PROJECTS

I–3.1. The future of nuclear power and NFC

Two MIT studies on the future of nuclear power and NFCs were performed in 2003 and in 2011. The first interdisciplinary study analysed what is required to retain nuclear power as a significant option for reducing greenhouse gas emissions and meeting growing needs for electricity supply [I–16, I–17]. Three representative NFCs were considered and evaluated: (1) a conventional light water reactor (LWR) operating in a once through NFC; (2) TRs with reprocessing in a partly closed NFC (i.e. considering limited recycle); (3) fast reactors (FRs) with reprocessing in a balanced fully closed NFC where FRs are used to balance the LWRs. The NFCs were rated using different evaluation criteria including economics, waste management, non-proliferation, and reactor and NFC safety.

The second MIT study, on The Future of the Nuclear Fuel Cycle, considered relatively few NFC options and was specifically focused on NFC dynamics and transition issues, using designs that would not require FR technologies [I–18]. Both studies analysed the performance characteristics of different NFC options and compared them to the current United States open NFC (containing only LWRs). These studies used data characterizing NFC material flows and the requirements of NFC services peculiar to economics, waste management performance, nuclear proliferation risks and nuclear safety. These data, after aggregation in each performance area, could be used in comparative evaluations. Nonetheless, the MIT reports contain neither recommendations regarding the application of judgement aggregation methods nor tools for comparative evaluations. All the conclusions are made based on expert opinions.

I–3.2. NFC evaluation and screening

The Office of Nuclear Energy of the USDOE initiated a study in 2011 on the evaluation and screening of different NFC options that were relevant to the United States national situation [I–19]. The study considered the entire NFC from mining to disposal, including both once through and partly or fully closed NFCs with recycling of plutonium or TRUs recovered from used fuel. The goal was to identify a relatively small number of promising NFC options with the potential for achieving substantial improvements over the existing NFC. The results were intended to strengthen the basis for the prioritization of R&D activities.

Nine evaluation criteria were specified — representing safety, economic, environmental, non-proliferation, security and sustainability goals — to identify promising NFC options. The first six criteria are related to the potential for benefit and the last three reflect the challenges for developing and deploying a new NFC.

The NFC options were compiled into 40 so called evaluation groups (EGs) according to physics performance. The set of NFC options was to be as comprehensive as possible with respect to potential NFC performance. An approach based on considering the fundamental characteristics of the NFC rather than the specific NFC implementation technologies allowed the creation of a comprehensive set of options which included: once through and recycle NFCs; thermal, intermediate and fast neutron reactors; critical and sub-critical reactors (accelerator driven systems (ADS)); uranium and/or thorium for fuel, along with other distinguishing NFC features (see Table I–4 and Fig. I–3) [I–19]. Multi-attribute utility analysis with single-attribute utility step shaped functions for each metric, the proper trade-off factors and criteria weights determined using the swing technique were used to evaluate and compare alternative NFCs for multiple criteria simultaneously.

I–4. RESEARCH ARTICLES AND INITIATIVE STUDIES

An exhaustive set of research articles that give an overview of the experience gained in applying MCDM methods and tools in nuclear engineering and demonstrate the results of initiative studies may be found in various journals and at various web sites [I–20 to I–27]. The examples analysed in these studies show that the application of MCDM may provide added value to conventional analysis and increase the degree of clarity (better understanding). Moreover, MCDM provides reasonably stable, well interpreted and decision making oriented results, revealing the pros and cons of the considered alternatives on quantitatively and methodologically proven and well elaborated foundations.

TABLE I–4. NFCs IN THE EGs

EG	Short description indicative of NFCs in the EG	NFC type
	Once through	
EG01	Once through using enriched U fuel in thermal critical reactors	
EG02	Once through using enriched U fuel to high burnup in thermal or fast critical reactors	
EG03	Once through using natural U fuel in thermal critical reactors	
EG04	Once through using natural U fuel to very high burnup in fast critical reactors	***
EG05	Once through using enriched U/Th fuel in thermal or fast critical reactors	
EG06	Once through using Th fuel to very high burnup in thermal ADSs	**
EG07	Once through using natural-U fuel to very high burnup in thermal or fast ADSs	**
EG08	Once through using Th fuel to very high burnup in fast ADSs	**
	Limited recycle	
EG09	Limited recycle of U/TRUs with new natural U fuel to very high burnup in fast critical reactors	**
EG10	Limited recycle of ^{233}U/Th with new Th fuel in fast and/or thermal critical reactors	***
EG11	Limited recycle of ^{233}U/Th with new enriched U/Th fuel in fast or thermal critical reactors	
EG12	Limited recycle of U/Pu with new natural U fuel in fast and/or thermal critical reactors	
EG13	Limited recycle of U/Pu with new enriched U fuel in thermal critical reactors	
EG14	Limited recycle of U/Pu with new natural U fuel in both fast and thermal critical reactors	***
EG15	Limited recycle of U/Pu with new enriched U fuel in both fast and thermal critical reactors	
EG16	Limited recycle of U/Pu with new enriched U fuel in thermal critical reactors and fast ADS	
EG17	Limited recycle of Pu/Th with new enriched U/Th fuel in thermal critical reactors	
EG18	Limited recycle of ^{233}U/Th with new enriched U/Th fuel in thermal critical reactors	
	Continuous recycle	
EG19	Continuous recycle of U/Pu with new natural U fuel in thermal critical reactors	
EG20	Continuous recycle of U/TRUs with new natural U fuel in thermal critical reactors	
EG21	Continuous recycle of U/Pu with new enriched U fuel in thermal critical reactors	
EG22	Continuous recycle of U/TRUs with new enriched U fuel in thermal critical reactors	
EG23	Continuous recycle of U/Pu with new natural U fuel in fast critical reactors	*
EG24	Continuous recycle of U/TRUs with new natural U fuel in fast critical reactors	*
EG25	Continuous recycle of ^{233}U/Th with new enriched U/Th fuel in thermal critical reactors	

TABLE I–4. NFCs IN THE EGs (cont.)

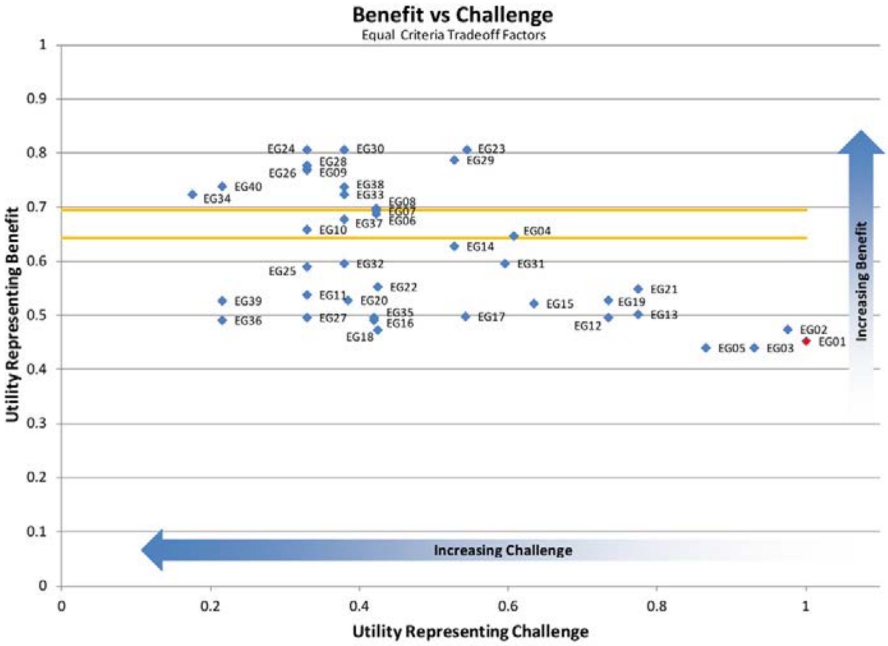
EG	Short description indicative of NFCs in the EG	NFC type
EG26	Continuous recycle of ^{233}U/Th with new Th fuel in thermal critical reactors	**
EG27	Continuous recycle of ^{233}U/Th with new enriched U/Th fuel in fast critical reactors	
EG28	Continuous recycle of ^{233}U/Th with new Th fuel in fast critical reactors	**
EG29	Continuous recycle of U/Pu with new natural U fuel in both fast and thermal critical reactors	*
EG30	Continuous recycle of U/TRUs with new natural U fuel in both fast and thermal critical reactors	*
EG31	Continuous recycle of U/Pu with new enriched U fuel in both fast and thermal critical reactors	
EG32	Continuous recycle of U/TRUs with new enriched U fuel in both fast and thermal critical reactors	
EG33	Continuous recycle of U/Pu with new natural U fuel in both fast ADSs and thermal critical reactors	**
EG34	Continuous recycle of U/TRUs with new natural U fuel in both fast ADSs and thermal critical reactors	**
EG35	Continuous recycle of U/Pu with new enriched U fuel in both thermal critical reactors and fast ADSs	
EG36	Continuous recycle of U/TRUs with new enriched U fuel in both thermal critical reactors and fast ADSs	
EG37	Continuous recycle of ^{233}U/Th with new enriched U/Th fuel in both fast and thermal critical reactors	**
EG38	Continuous recycle of ^{233}U/Th with new Th fuel in both fast and thermal critical reactors	**
EG39	Continuous recycle of ^{233}U/Th with new enriched U fuel in both thermal critical reactors and fast ADSs	
EG40	Continuous recycle of ^{233}U/Th with new Th fuel in fast ADSs and thermal critical reactors	**

Note: ADS — accelerator driven system (subcritical reactor), EG — evaluation group; ^{233}U/Th indicates recycle of uranium that is predominantly ^{233}U with thorium.

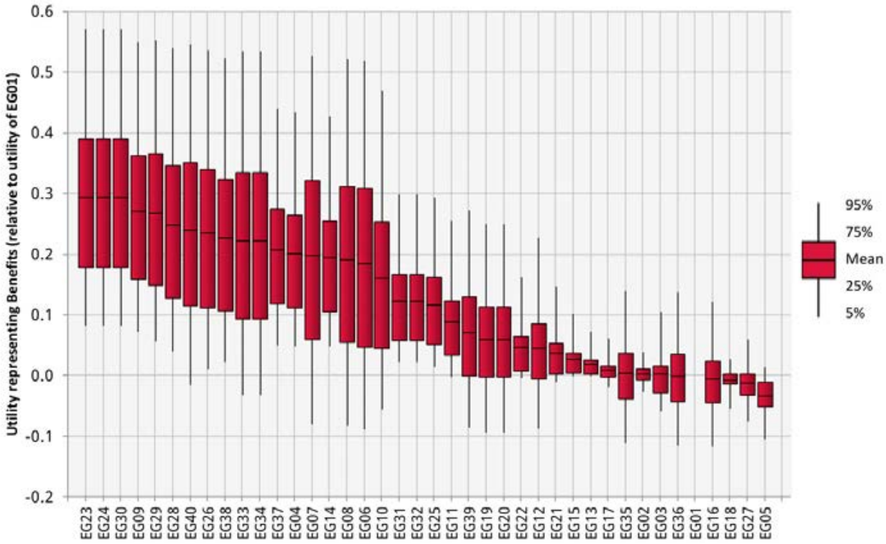
*: Most promising NFCs.

**: Additional potentially promising NFCs.

***: Other potentially promising NFCs.



(a)



(b)

FIG. I–3. NFCs considered and evaluation results. (a) Benefits versus challenges; (b) utility representing benefits.

REFERENCES TO ANNEX I

[I–1] INTERNATIONAL ATOMIC ENERGY AGENCY, International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) (2018),
www.iaea.org/INPRO.

[I–2] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems: INPRO Manual — Overview of the Methodology, IAEA-TECDOC-1575 (Rev. 1), IAEA, Vienna (2008).

[I–3] INTERNATIONAL ATOMIC ENERGY AGENCY, Framework for Assessing Dynamic Nuclear Energy Systems for Sustainability: Final Report of the INPRO Collaborative Project GAINS, IAEA Nuclear Energy Series No. NP-T-1.14, IAEA, Vienna (2013).

[I–4] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Energy Basic Principles, IAEA Nuclear Energy Series No. NE-BP, IAEA, Vienna (2008).
[I–5] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Energy General Objectives, IAEA Nuclear Energy Series No. NG-O, IAEA, Vienna (2011).
[I–6] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Fuel Cycle Objectives, IAEA Nuclear Energy Series No. NF-O, IAEA, Vienna (2013).
[I–7] INTERNATIONAL ATOMIC ENERGY AGENCY, Radioactive Waste Management Objectives, IAEA Nuclear Energy Series No. NW-O, IAEA, Vienna, (2011).
[I–8] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Reactor Technology Assessment for Near Term Deployment, IAEA Nuclear Energy Series NP-T-1.10, IAEA, Vienna (2013).
[I–9] OECD NUCLEAR ENERGY AGENCY, Trends in the Nuclear Fuel Cycle: Economic, Environmental and Social Aspects, OECD, Paris (2001).
[I–10] OECD NUCLEAR ENERGY AGENCY, Advanced Nuclear Fuel Cycles and Radioactive Waste Management, No. 5990, OECD, Paris (2006).
[I–11] OECD NUCLEAR ENERGY AGENCY, Transition towards a Sustainable Nuclear Fuel Cycle, No. 7133, OECD, Paris (2013).
[I–12] OECD NUCLEAR ENERGY AGENCY, Nuclear Fuel Cycle Synergies and Regional Scenarios for Europe, No. 6857, OECD, Paris (2009).
[I–13] OECD NUCLEAR ENERGY AGENCY, Potential Benefits and Impacts of Advanced Nuclear Fuel Cycles with Actinide Partitioning and Transmutation, No. 6894, OECD, Paris (2011).
[I–14] OECD NUCLEAR ENERGY AGENCY, Cost Estimating Guidelines for Generation IV Nuclear Energy Systems, Rev. 4.2, OECD, Paris (2007).
[I–15] BARI, R.A., WHITLOCK, J.J., THERIOS, I., PETERSON, P.F., Proliferation Resistance and Physical Protection Working Group: Methodology and Applications, No. 7141, OECD, Paris (2013).
[I–16] MASSACHUSETTS INSTITUTE OF TECHNOLOGY, The Future of Nuclear Power: An Interdisciplinary MIT Study, MIT, Cambridge, MA (2003).
[I–17] MASSACHUSETTS INSTITUTE OF TECHNOLOGY, Update of the MIT 2003 Future of Nuclear Power Study, MIT, Cambridge, MA (2009).
[I–18] MASSACHUSETTS INSTITUTE OF TECHNOLOGY, The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study, MIT, Cambridge, MA (2011).
[I–19] WIGELAND, R., et al., Nuclear Fuel Cycle Evaluation and Screening: Final Report, FCRD-FCO-2014-000106, United States Department of Energy, Washington, DC (2014).
[I–20] KEENEY, R., NAIR, K., Evaluating Potential Nuclear Power Plant Sites in the Pacific Northwest Using Decision Analysis, International Institute for Applied Systems Analysis, Laxenburg (1976).
[I–21] UNITED KINGDOM NIREX LIMITED, Review of 1987–1991 Site Selection for an ILW/LLW Repository, Nirex, Didcot (2005).
[I–22] DYER, J., BUTLER, J., EDMUNDS, T., JIA, J., A multivariate utility analysis of the alternatives for the disposition of surplus weapons-grade plutonium, Oper. Res. **46** 6 (1998) 749–762.
[I–23] HÄMÄLÄINEN, R.P., LINDSTEDT, M.R.K., SINKKO, K., Multi-attribute risk analysis in nuclear emergency management, Risk Anal. **20** 4 (2000) 455–467.
[I–24] BUTLER, J., et al., The United States and Russia evaluate plutonium disposition options with multiattribute utility theory, Interfaces **35** 1 (2005) 88–101.
[I–25] CHARLTON, W.S., et al., Proliferation resistance assessment methodology for nuclear fuel cycles, Nucl. Tech. **157** 2 (2007) 143–156.
[I–26] KIM, S.K., PARK, H.S., LEE, K.W., JUNG, C.H., "MAUT approach for selecting a proper decommissioning scenario", Proc. Waste Management Symp. 2007, Tucson, 2007, Curran Associates, Red Hook, NY (2008).
[I–27] INSTITUTE OF STUDIES FOR THE INTEGRATION OF SYSTEMS, NEEDS — New Energy Externalities Developments for Sustainability: Publishable Final Activity Report, ISIS, Rome (2009).
[I–28] KUZNETSOV, V., FESENKO, G., SCHWENK-FERRERO, A., ANDRIANOV, A., KUPTSOV, I., Innovative nuclear energy systems: State-of-the art survey on evaluation and aggregation judgment measures applied to performance comparison, Energies **8** (2015) 3679–3719.

Annex II

MATHEMATICAL BACKGROUND AND DETAILS OF MULTI-CRITERIA DECISION ANALYSIS (MCDA) METHODS

MCDA is a group of approaches for decision evaluation methods that are used for structuring problems and help individuals or groups to make decisions while considering several objectives. This sophisticated tool combines both objective measurements and the subjectivity of decision makers. MCDA helps decision makers understand and structure the problem, recognize the trade-offs and select the most preferred option [II–1 to II–7].

II–1. SCALE DEFINITION FOR KEY INDICATORS (KIs)

When the KIs relevant to performance evaluations are selected for criteria, it has to be determined how they can be represented. In general, the attributes of each alternative can be represented by different types of values: numerical, binary and nominal.

A numerical value includes any number. Typical examples for metrics that deliver numerical KI values are levelized energy products and service costs, R&D costs or radioactive nuclide inventory at different stages of the fuel cycle.

A binary value can only take two possible values: either 0 or 1. The KIs that typically take binary values are those measuring the availability of a feature, where 0 means ‘not available’ and 1 means ‘available’, or those assessing statements in Boolean terms, where 0 means ‘false’ and 1 means ‘true’. For example, the KI on flexibility for non-electrical services and energy products is a KI of the binary type.

A nominal value represents a qualitative characteristic of a system. An example could be whether the system needs a direct use nuclear material (e.g. plutonium or uranium with enrichment by uranium-235 exceeding 20%) as a fuel load or what design development/ licensing stage a system is currently placed at.

To make comparative assessment between options in the MCDA, all qualitative relations and numerical KI representations must be mapped onto a scale in which relations between different attributes (empirical relative) can be mirrored by analogous relations between values in the new scale (numerical relative). In other words, a scale may be interpreted as a function of the attribute values assigned to the KI of the NES performance, which provides the numerical representation of the qualitative or quantitative relations. Scales that are relevant for evaluation purposes can be of the nominal, ordinal, rating, cardinal or ratio type.

A nominal scale establishes the relationship of nominal values between different systems. There is neither order nor equidistance within the possible set of answers. A typical example for a nominal scale would be the metric reactor type (see Table II–1).

In general, *n* valued nominal scales can be transformed to binary nominal scales by the mapping, or, in other words, a nominal value can be measured by either its existence (1) or its non-existence (0).

TABLE II–1. EXAMPLE OF A NOMINAL SCALE

NES under ranking	Reactor type
NES 1	PWR
NES 2	PWR/AP1000
NES 3	CANDU
NES 4	MSR
NES 5	SMR
NES 1	PWR

If, for instance, the nominal value of the metric reactor type is ‘PWR’, the binary nominal scale would classify a system with 1 if it is a thermal spectrum system with pressurized water as coolant and moderator and with 0 if it does not. The binary nominal scales are used in checklists. The binary nominal scale also allows the combination of judgementally dependent nominal values. If, for instance, attribute A (PWR) asks for the existence of attribute B ‘core catcher’, the binary nominal scale allows the representation of this problem in the form shown in Table II–2.

This type of combination of features can be performed on *n* number of pairs of judgementally dependent attributes, always delivering a binary value as a result. Given that each nominal attribute in a list of attributes is judgementally independent and has the same weight, the extent to which different systems fulfil a set of attributes can be measured by summing up the binary values for the attributes. The system that scores the highest number is the best choice, as illustrated in Table II–3.

Table II–3 indicates that, given independence and the same weight, system NES 2 will be superior to systems NES 1 and NES 3, since the sum of the binary values representing the existence/non-existence of attributes is higher for NES 2 than those obtained for the other NESs.

An ordinal scale represents the relation of values that are elements of a pre-defined ordered set, where value 1 < value 2 <… < value n. Using an n point scale (e.g. a 5 point scale or a 10 point scale) assigns a rating to each alternative to show how well it satisfies a particular interest. For example, in a 5 point scale it might be: 5 = excellent; 4 = good; 3 = satisfactory; 2 = below average; 1 = poor. A typical example for a metric (see Table II–4) that can be represented in an ordinal scale is the level of technology development and the NES design stage, where the set of values for the design stages would be {feasible < conceptually developed < basic < detailed design} or in numerical terms: {1, 2, 3, 4}.

TABLE II–2. BINARY SCALE FOR COMBINATION OF DEPENDENT ATTRIBUTES

	NES 1	NES 2	NES 3	NES 4
Attribute A	1	1	0	0
Attribute B	1	0	1	0
A∩B	1	0	0	0

TABLE II–3. COMBINATION OF NOMINAL ATTRIBUTES ON A BINARY SCALE

	NES 1	NES 2	NES 3
Attribute 1	0	1	0
Attribute 2	1	1	0
Attribute 3	1	0	1
Attribute 4	0	1	1
Sum	2	3	2

TABLE II–4. EXAMPLE OF ORDINAL SCALE

Design stages	Indicator assessment scores
Feasibility study	1
Conceptual design	2
Basic design	3
Detailed design, pre-licensing negotiations	4

For a comparison of ordinal values, the principle of dominance has to be considered. The alternative **a** dominates **b** if for each indicator's value ai of **a**, $ai \geq bi$ for $i = 1, 2, ... q$ with $ai \geq bi$ in at least one case.

The efficient set, also known as the undominated set or the Pareto optimal set, is the set of all undominated alternatives: efficient set = {**a**∈A; for which **b**∈A does not exist, such that *b* dominates *a*}. The importance of the efficient set is that the decision maker can confine his or her attention to it, discarding all other alternatives, as a dominated alternative can never be optimal.

A given type of solution may require that certain minimum KI values be attained, which call for boundary conditions or aspiration levels [II–3] (i.e. thresholds). Solutions for which the performance value is below the threshold are eliminated. Consequently, in the assessment, the fulfilment of the boundary conditions must be checked first.

A 'rating scale' is a specific type of ordinal scale that encodes preferences between different objects of a set. While objects in ordinal scales are pre-ordered, objects in rating scales are ordered by the user in the rating process. The following example illustrates this. A subject in a terminology data test has to rate the importance of information categories in the terminology databank. The set of possible categories is as follows:

— Definitions;
— Context;
— Grammar;
— Graphics.

The answers given by the user are the following:

— Grammar;
— Definitions;
— Context;
— Graphics.

The question of discreteness is important for rating scale values: can one infer information about comparisons of differences from the scales? In other words, is number 3 three times better than number 1? If two options are rated on the same scale, and one evaluator obtains 1 and the other obtains 3, does this just mean that one object is better than the other? Or, that it is somewhat or clearly better than the other? Or, that it is three times better than the other?

A rating scale is a 'cardinal scale' when the ratings of alternatives can be transformed by a positive affine (linear) transformation. For example, a utility function $u(x)$ can be used to rank alternatives and also to evaluate risky lotteries that are defined on the set of outcomes $x \in X$. The same rankings of certain outcomes and of lotteries will be obtained if the utility function is transformed to $c + mu(x)$, where $m > 0$. The ability to transform cardinal scores by a positive linear transformation is the property that allows the scaling of the single-attribute utility functions to the range of 0 to 1. As a result, utility function scores provide a ranking, but scores should not be interpreted here as indicating that one alternative is n times better than another, where n specifies some constant.

'Ratio scales' might be characterized by:

— Value 1 < value 2 <…< value n;
— Equidistance.

They have a fixed origin or absolute initial point and, therefore, they are the only scales in which the concept 'x is n times as much as y' has some meaning. Consequently, differences in ratio scales can be compared across the systems. The analytic hierarchy process (AHP) is based on making preference comparisons on a ratio scale, although this notion is controversial, since it would imply the existence of an outcome with an absolute zero utility value. Alternative interpretations of the AHP ratio comparisons can lead to results that can be measured on a cardinal scale, and therefore are consistent with the scaling of a utility function.

II–2. KI MEASUREMENT ISSUES

Measurement consists of rules for assigning numbers to objects to represent valuation of attributes. These rules must be explicitly formulated for a measure to be valid and reliable. Validity refers to the extent to which it is possible to generalize from the experiment related circumstances to circumstances in real life. Reliability concerns the extent to which measurements are repeatable by the same individual using different measures of the same attribute or by different persons using the same measure of an attribute.

According to Ref. [II–8], an uncertainty is connected to any type of measurement, whether it is the measurement of the temperature of liquids, blood pressure or intelligence. Owing to their subjectivity, however, the measurement of psychological attributes is more error prone than that of physical attributes. The frequent use of rating scales in psychological measurement, moreover, stresses the problem of reliability. Reference [II–9] indicates the major problems related to reliability. Consequently, not only do the data rely on intuition, but so does the method.

There is high variability from evaluator to evaluator and from occasion to occasion. A cardinal way to increase reliability is to employ multiple evaluators and average their responses. Another means to increase test reliability is to make use of standardized measures. Standardization is achieved if different examiners give approximately the same scores to the same criteria. Apart from increasing reliability, the use of standardized measures saves money, provides more detailed information and allows the comparison of tests.

The nature of the experimental design is another important issue in measurement. Tests eliciting psychological attributes are frequently called quasi- or pseudo-experimental, since there are a number of individual variables that cannot be controlled. According to Refs [II–9 to II–11], the central features of quasi-experimental design are the use of comparison groups in which one group is given a specific treatment and the other (control group) is not, and observations or interviews are performed before and after the treatment. The typical sources of error in quasi-experimental design are: variations within tests, such as motivation, stress or health of subjects, and variations between tests, such as systematic differences in tests, subjective scoring, or change of attitude towards the subjects.

II–3. SELECTING THE RANGE OF KIs (ATTRIBUTES)

Prior to the preference value/utility function elicitation, the end points of the KI range have to be defined. There are different possible options that could be taken into account (Fig. II–1) [II–12]:

- The actual range (natural scale) in which upper and lower boundaries are determined by alternatives with the smallest or the highest KI value/amount, respectively;
- The acceptable range in which boundaries are determined by the numbers that the decision maker is willing to consider (subset of a natural range);
- The available range in which all available options, whether or not they are included in the decision alternatives, should be contained within the end points of the scale;
- The theoretically feasible range (i.e. the universal range that includes all alternatives).

The weights and scales are not independent and the elicitation techniques used must yield the appropriate mathematical relationship between the two. This has proven to be problematic. Experience has shown that those techniques advocated by Keeney and Raiffa [II–13], Clemen and Reilly [II–14], Goodwin and Wright [II–15] and many others, which are based on the use of local scales, tend to amplify small differences in attributes measured on natural scales, which may lead to erroneous conclusions. Attempts to mitigate the errors introduced by using local scales in conjunction with importance weights often focus on the range sensitivity principle, which mandates that the category weights applied to each criterion should be adjusted so that they are proportional to the ranges of the alternatives for that criterion: small ranges should yield correspondingly small weights, and vice versa.

However, decision makers have trouble in adequately adjusting the weights; some studies reported in the literature indicate that the range sensitivity principle is violated, often significantly, with range sensitivity indices rarely approaching 1.0 (ideal) and often staying well below 0.30 [II–16 to II–20]. Thus, when local scales were used, the category weights were often adjusted by substantially less than was mandated by the range sensitivity principle [II–21].

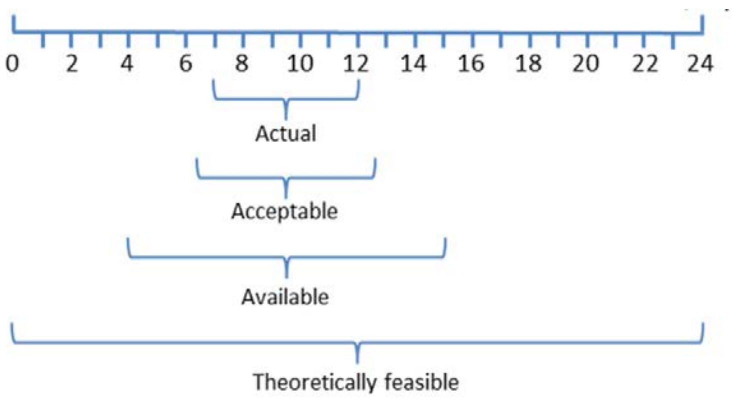


FIG. II–1. Example: possible ranges for the attribute working hours [II–12].

II–4. CONSTRUCTION OF KI VALUE/UTILITY FUNCTIONS

In multi-attribute value theory (MAVT), every criterion has a value function created for it. These functions transform diverse criteria evaluated in a natural scale to a single common, dimensionless scale or score (from 0 to 1) and are known as a single-attribute value functions. Their shape reflects the experts' and decision makers' judgements. These scores are used in further calculations.

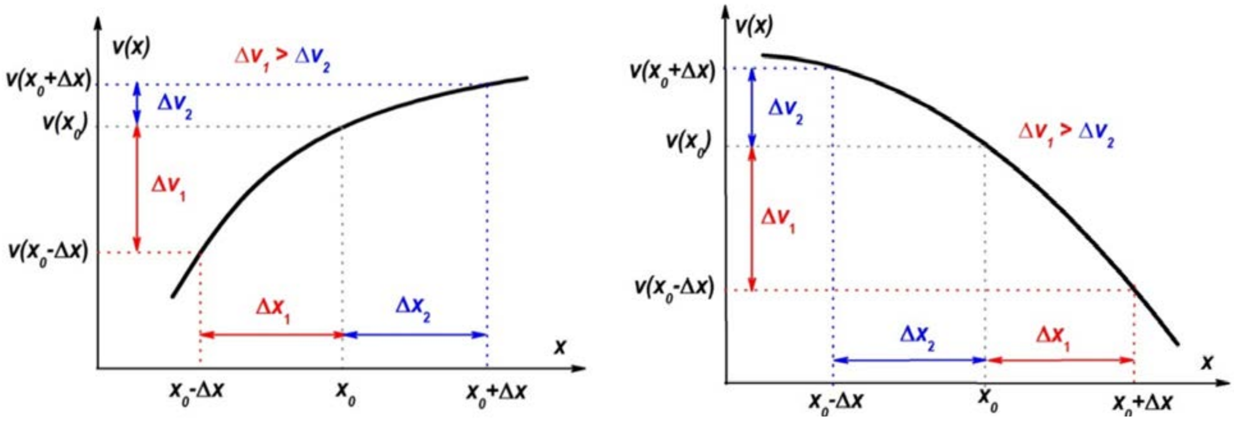
A significant problem for a particular decision maker is that a single-attribute value function type is not explicitly known. As applied to a comparative evaluation, a single-attribute value function describes the extent of decision makers' satisfaction with each indicator's value. It is impossible to construct such a function using only objective assessments.

In the case of certainty, a single-attribute value function can be assessed using several approaches, including the direct rating of performance levels when the subject matter expert is asked to reflect the relative importance (subjective value) of moving from a level *x1* on an indicator to a level of *x2* compared to that for moving from a value of *x3* to *x4*. In effect, the decision maker is being asked to compare the differences in the preference between pairs of points associated with an incremental change of indicator value (marginal value). Note that this approach to assessing a value function does not introduce risk in the form of lottery questions, and yet it is possible to obtain a concave downward value function that represents decreasing marginal values, a convex downward value function that represents increasing marginal value, and a value function that is a straight line indicating the constant marginal value of incremental units of the indicator.

Apart from the marginal value of additional units, the single-attribute function may also be affected by the risk attitude of the decision maker, and this influence can be compounded by the effects of marginal value. This becomes an issue if there is uncertainty associated with the estimates of the indicator values on which the single-attribute function is defined, and a distinction may be made by calling a single-attribute function a utility. Depending on the attitude towards risk, risk aversion, risk neutrality and risk proneness can be psychologically distinguished. Risk averse, prone and indifferent individuals evaluate losses and gains in different ways. In risk averse persons, emotional distress due to a decrease in the indicator's value is stronger than satisfaction due to an analogous increase. By contrast, for a risk prone decision maker, the psychological benefits from the possibility of acquiring additional indicator Δx units are greater than the distress caused by a potential loss of equivalent additional indicator units. For risk neutral persons, the representative utility function is a straight line expressing an equal attitude to gains and losses. Thus, the utility function may be convex upward (concave downward) for risk averse persons and convex downward (concave upward) for risk prone persons (Figs II–2 to II–4).

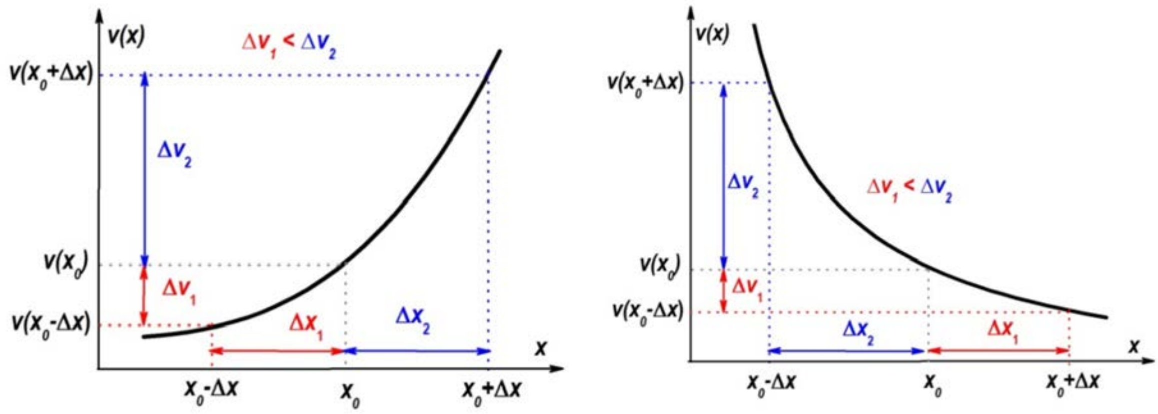
Note that similar shapes may be obtained for single-attribute value functions elicited on the basis of a logical interpretation relying on arguments related to increasing or decreasing marginal values instead.

The single-attribute value functions' shapes may be assessed by the experts appointed by the decision team. Different experts may provide single-attribute value functions for certain indicators in the corresponding areas. The development of a single-attribute value function is potentially a sensitive issue. Some types of single-attribute value functions are presented in Table II–5 and in Fig. II–5.



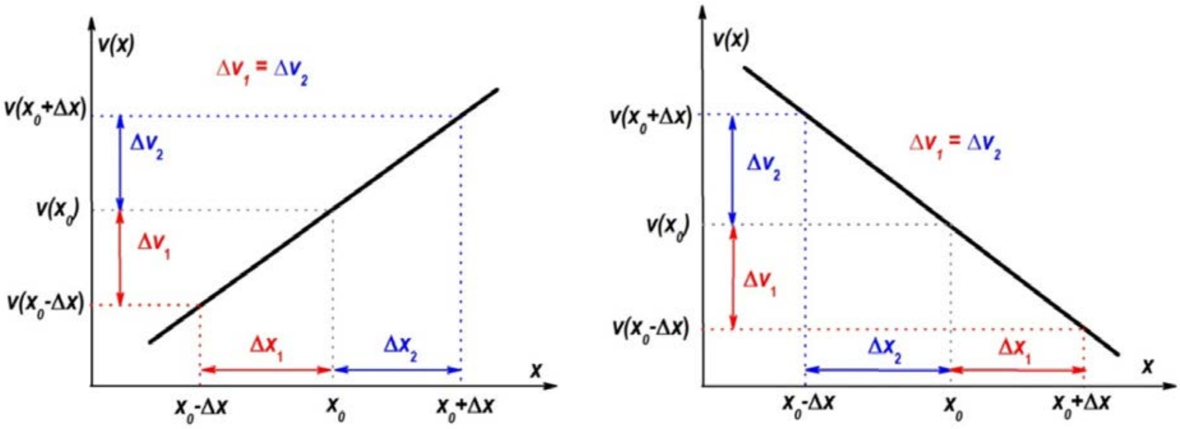
(a) (b)

FIG. II–2. Value function types reflecting risk aversion or decreasing marginal value when there is no uncertainty (convex upward or concave downward function type). (a) Increasing value function; (b) decreasing value function.



(a) (b)

FIG. II–3. Value function types reflecting risk proneness or increasing marginal value when there is no uncertainty (convex downward or concave upward function type). (a) Increasing value function; (b) decreasing value function.



(a) (b)

FIG. II–4. Value function types reflecting risk neutrality or constant marginal value when there is no uncertainty. (a) Increasing value function; (b) decreasing value function.

TABLE II–5. POSSIBLE TYPES OF SINGLE-ATTRIBUTE VALUE FUNCTIONS

Type	Increasing value functions	Decreasing value functions
Linear	$u(x)=\frac{x-x^{\min}}{x^{\max}-x^{\min}}$	$u(x)=\frac{x^{\max}-x}{x^{\max}-x^{\min}}$
	Additional parameter determination is not required	
Polynomial	$u(x)=\left(\frac{x-x^{\min}}{x^{\max}-x^{\min}}\right)^{a}$	$u(x)=\left(\frac{x^{\max}-x}{x^{\max}-x^{\min}}\right)^{a}$
	For any $a > 0$; if $a > 1$ — convex downward (concave upward) function; if $0 < a < 1$ — convex upward (concave downward) function; symmetric reflection if $a \rightarrow 1/a$.	
Exponential	$u(x)=\frac{1-\exp\left(a\cdot\frac{x-x^{\min}}{x^{\max}-x^{\min}}\right)}{1-\exp(a)}$	$u(x)=\frac{1-\exp\left(a\cdot\frac{x^{\max}-x}{x^{\max}-x^{\min}}\right)}{1-\exp(a)}$
	For any $a \neq 0$; if $a > 0$ — convex downward (concave upward) function; if $a < 0$ — convex upward (concave downward) function; symmetric reflection if $a \rightarrow -a$.	
Logarithmic	$u(x)=\frac{\ln\left(a\cdot\frac{x-x^{\min}}{x^{\max}-x^{\min}}+1\right)}{\ln(a+1)}$	$u(x)=\frac{\ln\left(a\cdot\frac{x^{\max}-x}{x^{\max}-x^{\min}}+1\right)}{\ln(a+1)}$
	For any $a > -1$; if $a > 0$ — convex upward (concave downward) function; if $-1 < a < 0$ — convex downward (concave upward) function; symmetric reflection if $a \rightarrow (1 - a)/a$.	
Piecewise	$u(x)=\sum_{i=1}^{N}\Delta u_i\cdot\Theta(x-x_i)$, Θ – Heaviside step function, $\Delta u_i > 0, \sum_{i=1}^{N}\Delta u_i = 1$	$u(x)=1-\sum_{i=1}^{N}\Delta u_i\cdot\Theta(x-x_i)$, Θ – Heaviside step function, $\Delta u_i > 0, \sum_{i=1}^{N}\Delta u_i = 1$
	It is necessary to determine additional parameters of a quantity that is equal to the number of steps into which the value function domain is divided	

In Table II–5, $x^{\max}$ and $x^{\min}$ are the minimal and maximal domain values of a single-attribute value function (end points of the indicator value range). In some cases, these values may be equal to the minimal and maximal indicator values specified in the performance table (local domain). In other cases, a global domain of a single-attribute value function may be used (from 1 to maximal scoring scale value).

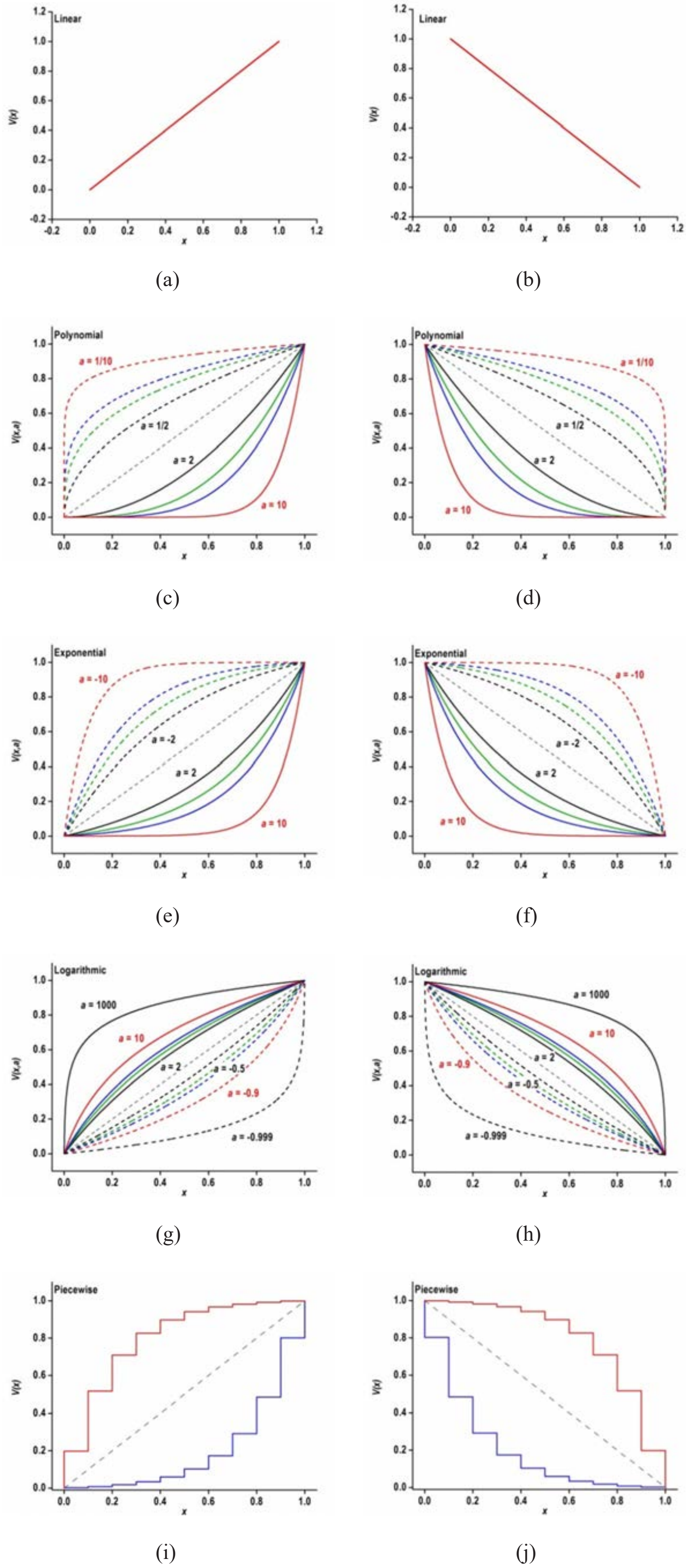


FIG. II–5. Value function types. (a) Linear increasing; (b) linear decreasing; (c) polynomial increasing; (d) polynomial decreasing; (e) exponential increasing; (f) exponential decreasing; (g) logarithmic increasing; (h) logarithmic decreasing; (i) piecewise increasing; (j) piecewise decreasing.

II–5. MODELLING OF DECISION MAKER'S PREFERENCE

In most MCDA methods, a numerical value is assigned to each criterion to express its relative importance. This value reflects the corresponding criterion weight. The selection of weights and their interpretation depends entirely on the decision model being applied. Utility based methods aim to establish an overall utility function that best represents the decision maker's preferences. This approach does not allow the incomparability relation between two alternatives. The estimation of weights is equivalent to the procedure used to determine substitution rates between criteria. The decision maker has to provide answers to questions such as 'What is the gain with respect to one attribute that compensates for a loss with respect to another?' and not in terms of the 'importance' of attributes.

Outranking methods that are not compensatory are based on different interpretations of weights (see Section 5.7.2.7).

In energy supply planning and decision making, one is seldom able to use multi-criteria methods requiring trade-offs from the decision makers. They usually feel uncomfortable in providing explicit rates of compensation between the criteria and do not have sufficient time to devote to this procedure. Moreover, it is extremely expensive and time consuming to perform consistency checks for weights or apply different procedures in the elicitation process. It should be noted that the selection of a particular weighting scheme may have important ethical consequences [II–22].

II–5.1.1. General example for assigning weights to attributes

Weights capture the essence of value judgements. A technique that is often used for assigning weights is hierarchical weighting. Weights are defined for each hierarchical level separately and then multiplied moving down the tree (Fig. II–6) [II–23].

The numbers resulting from a weighting process are in principle subjective. Different stakeholders, that is, people who have an interest in the object being evaluated, are likely to assign different sets of weights. A possible procedure to deal with conflicting weights as presented in Refs [II–2] and [II–24] is:

(a) Discuss the individual assessments and their differences with all stakeholders concerned;
(b) Perform a second weighting process;
(c) Average the second weighting from all stakeholders to arrive at a final set.

Following the above procedure, the weighting process is more likely to reflect the general preferences.

II–5.1.2. Approaches for weighting factor evaluation in MCDA

The representation of preferences among different criteria (weighting factor identification) is the most sensitive issue in the formal application of MCDA methods and requires accurateness and reasonableness. Weighting factors reflect the relative importance of the criteria, and thus, national preferences associated with nuclear energy development strategy. The weights required when applying different aggregation rules and methods have different interpretations and implications.

There are several rank ordering weight methods that can be applied for the conversion of the ordinal ranking of criteria into numerical weights. Among these methods, the direct, the rank sum, the rank exponent, the rank reciprocal and the well centroid weight techniques can be distinguished. The direct method requires minimal knowledge of the priorities of single criteria and, therefore, minimal input from an expert. In case no additional information on weight is available, it can be assumed that the 'true' weights are distributed uniformly over an *N*-fold Cartesian product of weights, each belonging to an interval [0,1]. The expected value of the uniformly distributed weight vector can be expressed as:

$$w_i^{\exp} = \frac{1}{N} \, for \, i = 1,...,N \qquad \text{(II–1)}$$

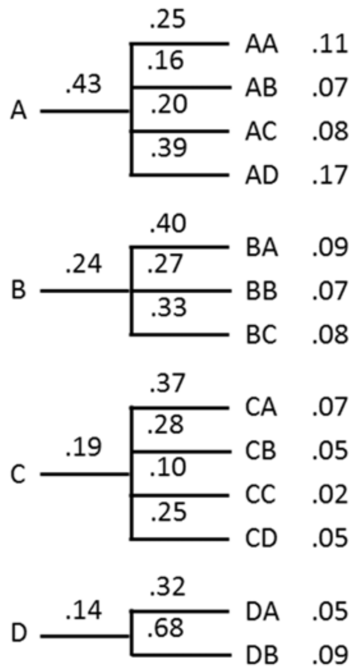


FIG. II–6. Hierarchical weighting.

In the rank sum (RS) technique the weight values are defined using the individual rank of the *i*th criterion r_i normalized to the overall sum of ranks:

$$w_i^{\mathrm{RS}} = \frac{N - r_i + 1}{\sum_{k=1}^{N} N - r_k + 1} = \frac{2(N + 1 - r_i)}{N(N+1)} \tag{II–2}$$

for $i = 1, 2, \ldots, N$.

The rank exponent (RE) method represents a generalization of the rank sum technique:

$$w_i^{\mathrm{RE}} = \frac{(N - r_i + 1)^p}{\sum_{k=1}^{N} (n - r_k + 1)^p} \tag{II–3}$$

where p is a parameter and $i = 1, 2, \ldots, N$; parameter p is to be chosen by an expert.

The inverse or reciprocal weights method uses a normalized reciprocal of individual ranks:

$$w_i^{\mathrm{RR}} = \frac{1/r_i}{\sum_{k=1}^{N} 1/r_k} \tag{II–4}$$

The rank order centroid (ROC) weight technique was developed on the basis of the formula:

$$w_i^{\mathrm{ROC}} = \frac{1}{N} \sum_{k=1}^{N} \frac{1}{r_k} \tag{II–5}$$

which delivers an assessment of weights that minimizes the maximum error of each weight by identifying the centroid of all possible weights and maintaining the rank order of objective importance. In particular, if the rank order of the 'true weight' is known, but the quantitative information is missing, then it can be assumed that the weights are uniformly distributed over the N-Cartesian product of rank order weights and the above written formula represents the expected value.

The weight selection methods are summarized in Table II–6.

TABLE II–6. METHODS FOR WEIGHTING FACTOR ASSESSMENT

Weighting method	Evaluation algorithm	Illustration
Direct method	An expert is asked to specify the weights directly for each KI.	$\left(w_i, w_2, \ldots, w_N\right), \sum_{i=1}^{N} w_i = 1$
Rating method	An expert has to define rating points for every KI; a 100 point scale should be assigned to the most important KI.	$\left(r_1, r_2, \ldots, r_N\right)$, where $r_i \in [1,100] \rightarrow$ $\left(w_1, w_2, \ldots, w_N\right), \sum_{i=1}^{N} w_i = 1$
Ranking method	An expert must specify the ranks for criteria; the most important criterion must have the rank 1.	$\left(r_1, r_2, \ldots, r_N\right)$, where $r_i \in [1, N] \rightarrow$ $\left(w_1, w_2, \ldots, w_N\right), \sum_{i=1}^{N} w_i = 1$
Rank sum method	An expert must specify the ranks for criteria; the most important criterion must have the rank 1.	$w_i^{\mathrm{RS}} = \frac{2\left(N+1-r_i\right)}{N\left(N+1\right)}$
Rank exponent method	An expert must specify the ranks for criteria; the most important criterion must have the rank 1.	$w_i^{\mathrm{RE}} = \frac{\left(N-r_i+1\right)^p}{\sum_{k=1}^{N}\left(n-r_k+1\right)^p}$
Reciprocal weights method	An expert must specify the ranks for criteria; the most important criterion must have the rank 1.	$w_i^{\mathrm{RR}} = \frac{1/r_i}{\sum_{k=1}^{N} 1/r_k}$
Rank order centroid method	An expert must specify the ranks for criteria; the most important criterion must have the rank 1.	$w_i^{\mathrm{ROC}} = \frac{1}{N}\sum_{k=1}^{N}\frac{1}{r_k}$
Pairwise comparisons	Pairwise comparison is used as a weighting technique in the AHP method. To realize this, it is necessary to fill the matrix of relative scores for every pair of elements in the Saaty scale. This should be carried out while considering the ranges over which the KIs may vary.	$\begin{pmatrix} 1 & a_{ij} & \ldots \\ 1/a_{ij} & 1 & \ldots \\ \ldots & \ldots & 1 \end{pmatrix}, a_{ij} \in [1,3,5,7,9] \rightarrow \begin{pmatrix} \lambda_1 \\ \ldots \\ \lambda_N \end{pmatrix} \rightarrow$ $\left(w_1, w_2, \ldots, w_N\right), \sum_{i=1}^{N} w_i = 1$
Swing method	Swings of criteria scales are taken into account along with corresponding relative importance. First, criteria must be ranked from the most important one to the least important; then, every criterion is considered to evaluate its relative importance concerning the most important criterion.	$\left(w_1, w_2, \ldots, w_N\right), \sum_{i=1}^{N} w_i = 1 \rightarrow$ $\left(w_1^*, w_2^*, \ldots, w_N^*\right), \sum_{i=1}^{N} w_i^* = 1$

II–6. DEFINING AGGREGATED VALUE/UTILITY

The additive weighted model assumes independence between the attributes' values. This independence is violated if the evaluation of an alternative with respect to one criterion depends on how the alternative performs with respect to the other one.

As Ref. [II–11] concludes from practical evaluation experience:

> "A frequently satisfied condition that makes the assumption of value independence very unlikely to cause trouble is monotonicity. The additive approximation will almost always work well if, for each evaluation dimension more is preferable to less or less is preferable to more throughout the entire range of the dimension that is involved in the evaluation, for all available values of the other dimensions."

According to Ref. [II–2], a clever analyst can structure virtually any evaluation problem so that an additive model is appropriate, doing away with value dependence through the restructuring processes, including, if necessary, combining or splitting up attribute measures. As an example, Table II–7 shows how the calculation of the aggregate utility for each option is performed based on the hierarchy structure illustrated in Fig. II–6. Hypothetical values are used for the different measures.

MAVT allows the aggregation of judgements by combining single-attribute value functions for each indicator or attribute into a multi-attribute value function. Different performance indicators can complement or compensate each other. In the complementary case, two or more indicators must work together to provide effective system performance. In the compensatory case, low values for a certain indicator may be compensated by higher values for other ones. A multi-attribute value function may be calibrated (adjusted) to represent both compensatory and complementary interactions by adjusting the range of weighting factors. The general algebraic expression of this multi-attribute value function is a well structured polynomial form. Such a form allows a synergetic interaction between the indicators or attributes under consideration and provides a representation of compensatory and complementary interactions between them [II–13, II–25].

TABLE II–7. CALCULATION OF AGGREGATE UTILITY FOR OPTION 1

Label	Weight w_i	Value $u_i(x_i)$	Weight × value $w_iu_i(x_i)$
AA	0.11	90	9.9
AB	0.07	50	3.5
AC	0.08	30	2.4
AD	0.17	90	15.3
BA	0.09	30	2.7
BB	0.07	40	2.8
BC	0.08	80	6.4
CA	0.07	20	1.4
CB	0.05	30	1.5
CC	0.02	20	0.4
CD	0.05	50	2.5
DA	0.05	60	3.0
DB	0.09	70	6.3
Sum	1.00	—	58.1

The general form of the multi-attribute value function is presented in Section 3.2 (by Eq. (3.1)). As the value of k ranges from negative to positive, the overall value function can reflect the compensatory and complementary types of interactions between individual components (Table II–8). In two extreme cases, when $k = 0$ or $k = \infty$, multi-attribute value functions take the simple additive and multiplicative forms.

In the case of compensation, the low performance of one indicator or attribute can be compensated by the high performance of other indicators or attributes. In the case of complementation, the good performance of one indicator or attribute is less important than balanced performance across all indicators or attributes.

For illustrative purposes, we shall consider the multi-attribute value function behaviour in a simple situation of two variables. In this case, the general form of the multi-attribute value function is as follows:

$$u(x) = k_1 u_1(x_1) + k_2 u_2(x_2) + k k_1 k_2 u_1(x_1) u_2(x_2) \tag{II–6}$$

where $1 = k_1 + k_2 + kk_1k_2$.

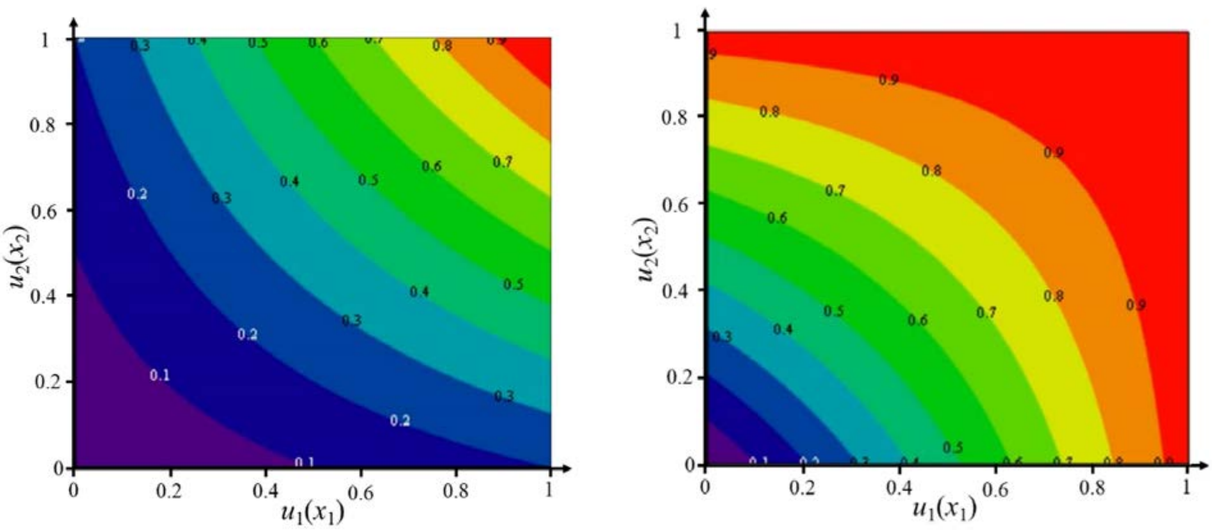
For the sake of illustration, let us assume that $k_1 = k_2$ (equal weights). Correspondingly,

$$k = (1 - 2k_1)\big/k_1^2, k_1 = \left(\sqrt{k+1} \pm 1\right)\big/k \tag{II–7}$$

In this expression, the first two terms provide a linear interaction between the multi-attribute value function and the single-attribute value functions. The last term denotes multiplicative interaction. The settings of the k_i and k determine how these linear and multiplicative terms interact (Fig. II–7).

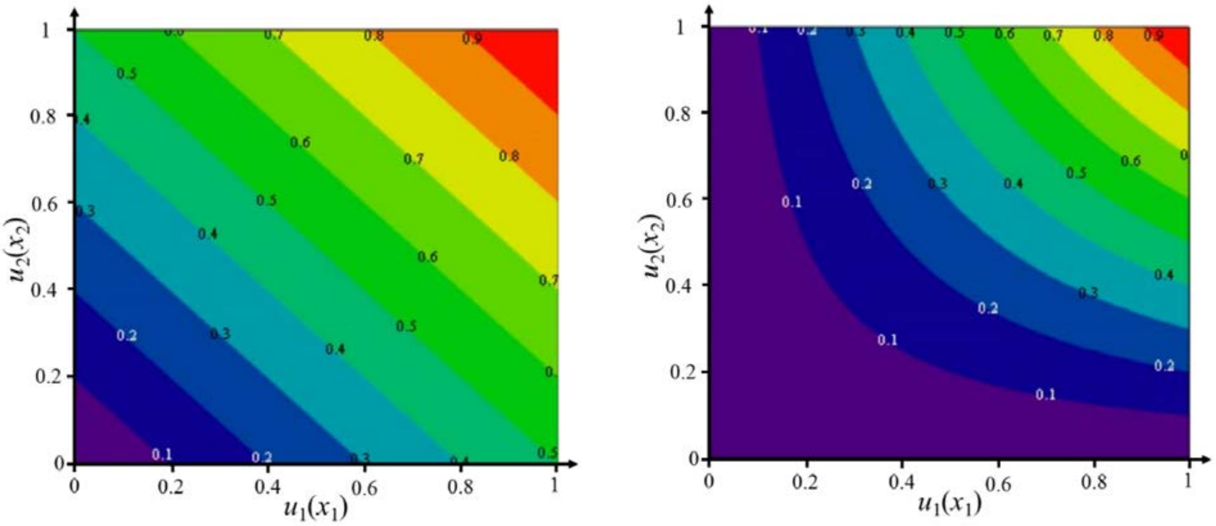
TABLE II–8. TYPES OF INTERACTION REPRESENTED BY RELATIONSHIPS BETWEEN *ki* AND *k*

k value	Σ*ki*	Type of interaction
Negative	>1.0	Compensatory
Positive	<1.0	Complementary
0	1.0	Additive
∞	0	Multiplicative



(a) (b)

FIG. II–7. Isovalue lines for (a) complementary and (b) compensatory cases.



(a) (b)

FIG. II–8. Isovalue lines for the (a) additive and (b) multiplicative cases.

If the experts' and/or decision makers' preferences are consistent with certain independence conditions, a multi-attribute value model may be decomposed into additive and multiplicative forms. The independence assumptions that justify the use of the additive model are reasonable in many cases because of the relationships among different indicators or attributes, and the analysis results are easier to interpret when the additive model is used. In the additive case, the performance of one component does not interact with the values of other components. The multiplicative form otherwise corresponds to an extreme complementary case: if a certain indicator takes its worst value (zero), then the whole system performance is zero (Fig. II–8).

REFERENCES TO ANNEX II

[II–1] BELTON, V., STEWART, T., Multiple Criteria Decision Analysis: An Integrated Approach, Kluwer Academic Publishers, Dordrecht (2002).

[II–2] VON WINTERFELDT, D., EDWARDS, W., Decision Analysis and Behavioral Research, Cambridge University Press, Cambridge (1986).

[II–3] KEENEY, R., RAIFFA, H., Decisions with Multiple Objectives: Preferences and Value Tradeoffs, Cambridge University Press, Cambridge (1993).

[II–4] KEENEY, R.L., Siting Energy Facilities, Academic Press, New York (1980).

[II–5] HOGARTH, R.M., Judgement and Choice: The Psychology of Decision, John Wiley & Sons, New York (1985).

[II–6] FRENCH, S., Decision Theory: An Introduction to the Mathematics of Rationality, Ellis Horwood, London (1986).

[II–7] SEN, P., YANG, Jian-Bo, Multiple Criteria Decision Support in Engineering Design, Springer, London (1998).

[II–8] NUNNALLY, J.C., DURHAM, R.L., "Validity, reliability, and special problems of measurement in evaluation research", Handbook of Evaluation Research, Vol. 1 (STRUENING, E.L., GUTTENTAG, M., Eds), Sage Publications, London (1975) 289–352.

[II–9] NUNNALLY, J.C., "The study of change in evaluation research: principles concerning measurement, experimental design, and analysis", ibid., pp. 101–137.

[II–10] NUNNALLY, J.C., WILSON, W., "Method and theory for developing measures in evaluation research", ibid., pp. 227–288.

[II–11] EDWARDS, W., GUTTENTAG, M., SNAPPER, K., "A decision-theoretic approach to evaluation research", ibid., pp. 139–181.

[II–12] HELSINKI UNIVERSITY OF TECHNOLOGY, Value Tree Analysis (2002), http://mcda.aalto.fi/value_tree/theory/theory.pdf

[II–13] KEENEY, R., RAIFFA, H., Decision with Multiple Objectives, John Wiley & Sons, New York (1976).

[II–14] CLEMEN, R.T., REILLY, T., Making Hard Decisions with DecisionTools, 3rd Edn, South-Western College Pub, Nashville, TN (2013).

[II–15] GOODWIN, P., WRIGHT, G., Enhancing strategy evaluation in scenario planning: A role for decision analysis, J. Manag. Stud. **38** (2001) 1–16.
[II–16] NITZSCH, R., WEBER, M., The effect of attribute ranges on weights in multiattribute utility measurements, Manag. Sci. **39** (1993) 937–943.
[II–17] FISCHER, G., Range sensitivity of attribute weights in multiattribute value models, Organ. Behav. Hum. Decis. Process. **62** (1995) 252–266.
[II–18] BEATTIE, J., BARON, J., Investigating the effect of stimulus range on attribute weight, J. Exp. Psychol. Hum. Percept. Perform. **17** (1991) 571–585.
[II–19] YEUNG, C., SOMAN, D., Attribute evaluability and the range effect, J. Consum. Res. **32** (2005) 363–369.
[II–20] GEDENK, K., SATTLER, H., Range effects in measuring attribute importance, University of Hamburg, Res. Pap. Mark. Retailing **20** (2005).
[II–21] MONAT, J.P., The benefits of global scaling in multi-criteria decision analysis, Judgm. Decis. Mak. **4** 6 (2009) 492–508.
[II–22] MUNDA, G., Social multi-criteria evaluation: Methodological foundations and operational consequences, Eur. J. Oper. Res. **158** (2004) 662–677.
[II–23] HÖGE, M., Towards a Framework for the Evaluation of Translators' Aids' Systems, University of Helsinki, Helsinki (2002).
[II–24] EDWARDS, W., ROBERT, J., Multiattribute Evaluation, Sage Publications, London (1982).
[II–25] MEYERS, C., LAMONT, A., SICHERMAN, A., Use of Multi-attribute Utility Functions in Evaluating Security Systems, Lawrence Livermore National Laboratory, LLNL-TR-405048, Livermore, CA (2008).

Annex III

METHODS OF UNCERTAINTY ANALYSIS IN MCDA

III–1. CONCEPTS OF UNCERTAIN NUMBERS

Uncertainty analysis refers to the quantification of the model output uncertainty resulting from the propagation of uncertainties in model parameters and model input data. The sources of uncertainties cover: (1) problem framing and structuring; (2) attribute evaluation; and (3) the components of the preference model (i.e. the choice of hierarchical aggregation function, the form of the marginal value/utility function, and the corresponding aggregation parameters (weights) in multi-attribute value theory (MAVT) or multi-attribute utility theory (MAUT)). In general, there are different approaches to deal with aleatory uncertainties in multi-criteria decision analysis (MCDA): probabilistic, interval arithmetic and fuzzy. It is worth mentioning that the uncertainty treatment can depend on the uncertainty type. A distinction can be made between uncertainty in the sense of risk characterized by known cause/effect and probabilistically quantifiable versus not quantifiable. Furthermore, ignorance or deep uncertainty that has unknown cause/effect and is not quantifiable can be distinguished. In the literature, the uncertainty due to randomness is classified as aleatory uncertainty, in contrast to epistemic uncertainty, which comes from lack of knowledge. The latter is sometimes quantifiable.

In general, there are two major types of problems in uncertainty quantification: forward propagation and inverse assessment. In the forward propagation method, various sources of uncertainty are propagated through the model to predict the overall uncertainty in the system response. The inverse assessment of model and parameter uncertainty tries to calibrate the model parameters simultaneously using test data. Different targets of uncertainty propagation analysis can be pursued, such as an evaluation of the following:

(a) Low order moments of the outputs;
(b) Reliability of the outputs;
(c) Complete probability distribution of the outputs.

III–1.1. Probabilistic model

The probabilistic model assumes that uncertain numbers can be represented by the random variables distributed over their domain according to realistic distribution functions (see Fig. III–1). As a result, algebraic operations on random numbers deliver a random variable that has its own distribution function. The latter can be similar to the one that both arguments have, if adding normally distributed variables, or radically different, if adding, for instance, uniformly distributed variables.

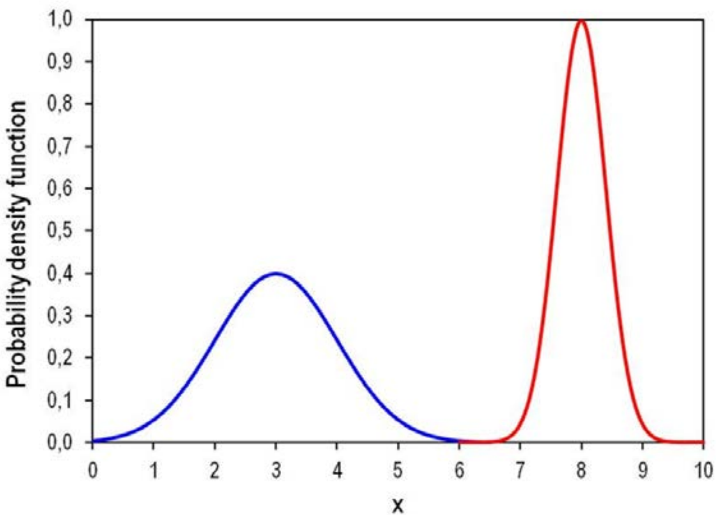


FIG. III–1. Probability density functions of random variables.

III–1.2. Interval model

Interval arithmetic is a different approach to considering rounding and measurement errors in mathematical computation. It replaces each exact value by a range of possible values. In an interval model, the uncertain number x is represented by the end of the interval that contains it (i.e. x_1 and x_2). Thus, instead of working with the uncertain number x, the interval model employs interval algebra. The interval $[x] = [x_1, x_2]$ specifies the range of possible values of x, but does not rely on the probability of x (i.e. specific value occurrence). It assumes that all numbers within the range of $[x_1, x_2]$ are equally possible. The basic arithmetic formulas with interval numbers can be represented as follows:

$$
\begin{aligned}
&[x]+[y]=\left[\underline{x}+\underline{y};\overline{x}+\overline{y}\right]\\
&[x]-[y]=\left[\underline{x}-\underline{y};\overline{x}-\underline{y}\right]
\end{aligned}
\qquad \text{(III–1)}
$$

$$[x]\cdot[y]=\left[\min\left(\left\{x\cdot y \mid x\in\left\{\underline{x},\overline{x}\right\}, y\in\left\{\underline{y},\overline{y}\right\}\right\}\right);\ \max\left(\left\{x\cdot y \mid x\in\left\{\underline{x},\overline{x}\right\}, y\in\left\{\underline{y},\overline{y}\right\}\right\}\right)\right]$$

$$\frac{[x]}{[y]}=\left[\min\left(\left\{\frac{x}{y} \mid x\in\left\{\underline{x},\overline{x}\right\}, y\in\left\{\underline{y},\overline{y}\right\}\right\}\right);\ \max\left(\left\{\frac{x}{y} \mid x\in\left\{\underline{x},\overline{x}\right\}, y\in\left\{\underline{y},\overline{y}\right\}\right\}\right)\right]$$

III–1.3. Fuzzy model

In a fuzzy model, the uncertain numbers do not refer to a certain value but rather to a set of possible values, each with its own weight between 0 and 1. This weight is called a membership function. The membership function is different from the probability density function because the normalization condition is not imposed (i.e. the membership function integral may have, in general, any value). Figure III–2 shows, for example, the membership functions of two fuzzy numbers x, with a roof (blue curve) and a trapezoid (red curve) membership function.

Arithmetic operations are performed on the fuzzy numbers using so called fuzzy set defuzzification. Defuzzification is a process for producing a quantifiable result in crisp logic for given fuzzy sets and corresponding membership degrees. It is the process that maps a fuzzy set to a crisp set. A crisp set is a conventional set for which an element is either a member of the set or not. Therefore, defuzzification is a fuzzy number discretization with a subdivision into the finite number of member function levels, each of which corresponds to an interval.

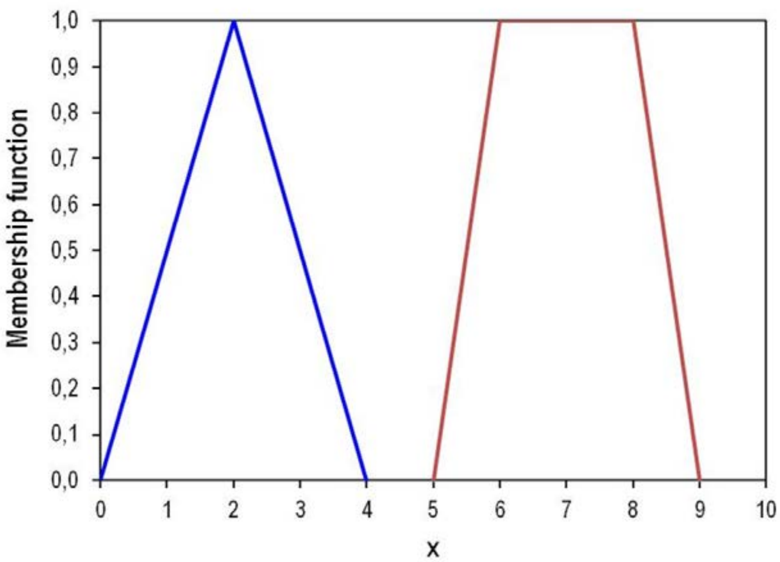


FIG. III–2. Fuzzy numbers with a roof (blue) and a trapezoid (red) membership function.

III–2. APPROACHES TO UNCERTAINTY TREATMENT IN MCDA

An uncertainty analysis is a step that improves the basis for judgements and examining the stability and robustness of ranking results. Therefore, studies related to the comparative evaluation of the performance and sustainability of nuclear energy systems (NESs) that are based on MCDA tools should definitely include uncertainty analysis. Although taking into account both objective (indicator) and subjective (weights) uncertainties may greatly enhance the decision maker's judgement process, such methods require more information about system features and experts' preferences. It is important to treat an uncertainty correctly to avoid a situation that may arise when all alternatives become indistinguishable (for example, the 90% confidence intervals of uncertainties in aggregated indices are overlapping) owing to uncertain initial data used in the analysis.

In any MCDA tool, criteria weights and performance scores may be a source of uncertainty. The uncertainty arising from performance scores may be associated with the difficulty of forecasting attribute values, such as the cost of constructing an NPP based on a novel design, or the operating efficiency of an innovative power plant based on new technology. In contrast, uncertainty in the criteria weights may reflect differences in experts' evaluations of the relative importance of the criteria used for the assessment of the overall performance of an alternative. The specific parameters used in a particular MCDA tool may be an additional source of uncertainty; for instance, there may be uncertainties associated with the shape of single-attribute value/utility functions (in MAVT/MAUT) or preference functions (PROMETHEE).

Uncertainty in the indicator values should be treated correctly, keeping in mind that large uncertainties in the initial data (for instance, nuclear fuel cycle (NFC) unit costs) will not always lead to large uncertainties in the indicators (for instance, levelized unit electricity cost). Correct evaluation of uncertainty in the indicator values requires the modification of the calculation tools being employed, mainly because the conventional tools available for the assessment of NES performance usually utilize point estimates for the technology characteristics and parameters.

Uncertainty treatment can be based on a general theoretical or problem oriented approach. The uncertainty treatment methods used in MCDA based studies may be broken down into different categories: deterministic or probabilistic sensitivity analysis, fuzzy set theory, and other approaches and frameworks such as interval arithmetic, grey theory, and percentile uncertainty estimates. The advantages and disadvantages of these approaches are discussed in Refs [III–1 to III–3].

III–2.1. Deterministic sensitivity analysis

Some widely used types of deterministic sensitivity analyses are: 'what if' or scenario, parametric and marginal sensitivity.

A what if/scenario analysis is based on the investigation of how the changes in a model parameter (weight or indicator value) will impact the ranking results.

A parametric analysis examines the impact of the variation of a single model parameter (weight or indicator value) on the ranking results, which are considered to be robust if they do not change.

A marginal sensitivity analysis (or threshold analysis) provides an answer to questions about how much model parameters need to be changed before a rank reversal occurs.

The main advantages of deterministic sensitivity analysis are: (1) it may be applied easily to uncertainty in both indicators and weights, because a corresponding model parameter (weight or indicator value) is varied as a single value, and (2) it only takes a short time and additional information may not be required to implement such an analysis.

The main disadvantages of deterministic sensitivity analysis are: (1) the range over which weights or performance scores are varied is usually arbitrarily chosen and it is assumed that all parameter values in the range are equally probable, and (2) a larger number of uncertain model parameters cannot be taken into account simultaneously, which does not provide an evaluation of the cumulative impact of uncertainty in multiple model parameters. These drawbacks may lead to a biased view of the impact of uncertainty on the decision.

Deterministic sensitivity analysis may use the local sensitivity coefficients method to determine the impact of uncertainties in input parameters on the uncertainty in the final result. If the functional Y, which depends on the parameters X_i, takes a value Y_0 as a result of calculations, the uncertainty can be expressed as a fixed (deterministic) value ΔY, which an analyst prescribes to quantify the impact on the uncertainty exerted by all parameters X_i. In this case, the possible value of Y lies within the range:

$$Y = Y_0 \pm \Delta Y \tag{III–2}$$

Applying the concept of the sensitivity coefficient with respect to the X_i with parameters determined as:

$$P_{Yi} = \lim_{\Delta x_i/\Delta x \to 0} \frac{\Delta Y/Y}{\Delta X_i/X_i} \tag{III–3}$$

an analyst can obtain a relative change in Y_0 due to the uncertainty in X_i with an accuracy up to the second order (when parameters X_i are independent):

$$\frac{\Delta Y}{Y} = \sum_{i=1}^{n} P_{Yi} \cdot \frac{\Delta X_i}{X_i} \tag{III–4}$$

where $\frac{\Delta X_i}{X_i}$ is the relative change in the parameter *i*.

If X_i are not independent, more sophisticated analysis based on correlation coefficients may be applied, which complicates the task significantly.

III–2.2. Probabilistic sensitivity analysis

A probabilistic sensitivity analysis requires the specification of probability distributions for the examined parameters of the model (for instance, based on objective statistics or elicitation of information from subject matter experts). It allows the uncertainty originating from multiple parameters of the model to be taken into account. The probability distribution of the parameters may be chosen with dependence on the quality of the initial information starting from uniform (for non-informative distribution with no evidence) and ending at the Dirac delta function like probability distributions. The process of assigning probability distributions is usually time consuming and requires the subject matter experts and decision makers to be familiar with the theoretical concepts. These issues are the major drawbacks of probabilistic sensitivity analysis.

For specified model parameters, probability distributions may be simulated using the Monte Carlo method, delivering the probability distributions of alternatives' scores. This stochastic technique enables probabilistic judgements to be made with respect to the probability of the rank order of the alternatives.

The Monte Carlo methods are based on the concept that the uncertainties in the input parameters can be assumed to be probabilistic in nature and are distributed according to the probability density function with its corresponding parameters. Combinations of stochastic parameters lead to the stochastic function value Y with its own probability density function. Possible deviations ΔY of Y are probabilistic in nature (i.e. they are confidence intervals of Y). Confidence intervals consist of a range of values (interval) that act as good estimates of the unknown population parameter with a certain probability. The specification of numerical characteristics for the probability density functions of such deviations can be associated with the concept of uncertainty analysis.

A number of simplified statistical methods for uncertainty analysis were developed on the basis of the Wilks formula and are widely applied, for instance by GRS (Germany), IPSN (France) and ENUSA (Spain). This method enables the specification of uncertainty sources in the form of random variables with known distribution [III–4]. By using a set of input parameters with known probability density functions, a set of functionals can be calculated. In the general case, the probability density function for it is unknown. In the absence of information about the probability density function, an analyst can determine the confidence interval of the resulting functional according to the Wilks formula:

$$P\left[\int_{L_1}^{L_2} f(y)dy \geq \beta\right] = \alpha \tag{III–5}$$

where α is the confidence level, β is the corresponding probability, and L_1 and L_2 are the tolerance interval limits. The number of simulation runs depends on the requested probability content and the confidence level of the statistical tolerance limits used in the uncertainty treatment of the results. The required minimum number of simulation runs N can be determined from the following equation:

$$1-\beta^N - N\cdot(1-\beta)\cdot\beta^{N-1} \geq \alpha \qquad \text{(III–6)}$$

For two sided tolerance limits, $\beta \times 100$ is the confidence level (in %) that the maximum value of the functional will not be exceeded with the probability α, $\alpha \times 100$ (percentile) of the corresponding output distribution, which is to be compared to the acceptance criterion. If N simulation runs are performed simultaneously verifying the uncertain input parameters according to their distribution, the N values obtained for overall scores as output parameters can be ordered as $Y_1 < Y_2 < \ldots < Y_N$. On the basis of this ranking, a 95th percentile value with a confidence level of 95% is obtained by selecting Y_{N1}, with N_1 determined by Eq. III–6 for one sided and two sided statistical tolerance limits. A 5th percentile value with a confidence level of 95% is obtained by selecting Y_1 with N_2. For a two sided tolerance limit, 0.95 × 0.95 ≈ 0.90, the resulting interval can be identified as a 90% confidence interval.

III–2.3. Fuzzy set theory

Sometimes, the probability distributions may be considered to be unjustified and less natural than the application of fuzzy numbers within a multi-criteria problem. The uncertainty modelling of both indicator values and weighting factors can be performed using fuzzy sets [III–5].

In fuzzy set theory, elements have a degree of membership to a set, which is expressed as a number between 0 and 1. Degrees of membership between 0 (not a member of the fuzzy set) and 1 (completely a member of the fuzzy set) indicate ambiguous set membership. If all memberships are equal to 0 or 1, fuzzy set theory corresponds to conventional set theory. Within the MCDA, weighting factors and indicators may be represented by fuzzy sets and membership functions to capture the identified ambiguity. Fuzzy sets can be visualized through plots of membership functions that are similar to the plots of probabilistic density functions.

Notwithstanding that fuzzy set theory is more adequate than other approaches at characterizing ambiguities in human judgements, the implementation of fuzzy set theory requires a laborious definition of fuzzy sets and the familiarization of decision makers with the main concepts of this theory in order to assure its correct application.

III–2.4. Other approaches and frameworks such as interval arithmetic, grey theory, percentile uncertainty estimates

Many approaches and frameworks are known for uncertainty analysis within MCDA, but they are not widely applied to decision support in the field of engineering. Moreover, there is limited implementation of them in the decision supporting tools. Some particular methods will be described briefly below.

III–2.4.1. Interval judgements

Interval judgements are a means of treating preferential and informational uncertainty in MCDA. They are applied in various MCDA methods. Intervals are used to characterize the range of allowed variation in weights and indicators due to imprecision. Such intervals can be assigned directly or by setting bounds for model parameters (for instance, value functions). Based on this initial information, the intervals for alternative ratings are calculated by linear programming techniques to determine the imprecision in final ratings. As a result, alternatives' ratings are represented as intervals that characterize the possible variation in the ratings caused by the assumed variation in weights and indicators [III–6].

III–2.4.2. Percentile uncertainty estimates

Another example of uncertainty treatment is a methodology developed at the National Research Center "Kurchatov Institute" by A. Rumiantsev. This special statistical methodology was developed on the basis on the 'scarce knowledge' concept, which involves percentile uncertainty estimate methods [III–7].

This concept is founded on the analytical methods of percentile estimates of high entropy logarithmic probability distribution. For a wide range of symmetrical distributions *F(X)* of the random quantity *X* with an entropy factor of $\kappa > 1.7$, the integral curves of probability distribution functions *F(X)* within the 0.05th and 0.95th percentiles intersect in a very narrow interval of values $\left|X - X_0\right|/\sigma(X) = 1.6 \pm 0.05$. Here, X_0 is the distribution centre, which coincides with the median and mathematical expectation. The values of the 0.05th and 0.95th distribution percentiles, mathematical expectation and root mean square deviation are governed in this case by the approximate relation:

$$X_{0,05} = X_0 - 1{,}6 \cdot \sigma(X)\ ;\ X_{0,95} = X_0 + 1{,}6 \cdot \sigma(X) \qquad \text{(III–7)}$$

Using Eq. (III–7) with specified values of the deviation and mathematical expectation, the boundary values of the double sided 90% confidence interval can be found as the percentiles 0.05 and 0.95.

III–2.4.3. Grey theory

The uncertain values can be represented in grey theory as so called black, white, or grey numbers. Grey numbers are numbers whose values are not exactly known and are thus used to indicate the magnitude of uncertainty [III–8]. They are represented with ranges. The black numbers stand for complete lack of knowledge (e.g. their range is (−∞, ∞)), whereas the white numbers represent perfect knowledge (e.g. the white number could correspond to the range [13,13]). The grey numbers are placed between these boundaries (for instance, [0,10]). They may be described by verbal statements. The application of grey theory within MCDA requires that decision makers provide the lower and upper bounds for weights or indicators that will lead to grey overall scores.

III–3. UNCERTAINTY TREATMENT IN OPTIMIZATION MODELS

Optimization models are used for studies that are focused on the optimization of NESs using deployment scenarios. The implementation of a robust and stochastic optimization approach for the optimization models (such as MESSAGE, FCOPT and TOBAS) is a promising way to treat uncertainties [III–9] in nuclear energy utilization planning.

Optimization models are usually based on various deterministic methods adapted to large scale optimization problems (with linear programming). Data uncertainty is caused here by (1) lack of exact data, which are instead replaced by the evaluations, and (2) the impossibility of measuring the data exactly, so that their true value flows around the measured value. Often, even small data uncertainty can make the nominal solution infeasible and practically meaningless.

Stochastic and robust optimizations are complementary approaches to the treatment of data uncertainty. They have, however, their own advantages and drawbacks. An uncertainty immunized solution to an optimization problem with uncertain data is possible with robust and stochastic optimizations. In the stochastic optimization, the uncertain numerical data are assumed to be random. In the simplest case, these random data obey a probability distribution that is known in advance. In the robust optimization, it is not required to know the probability distribution of uncertain parameters. A decision maker constructs a solution that is optimal for any realization type of the uncertainty in a given input set.

III–4. SENSITIVITY OF WEIGHTS

Although often used as a synonym for uncertainty, the term sensitivity analysis refers to the study of how the uncertainty in the output can be apportioned to different sources of uncertainty in the model input. This section contains several recommendations regarding possible techniques for uncertainty treatment within the KIND framework. These techniques (both simple and sophisticated) have been used within the KIND project as best practice methods.

Weight sensitivity analysis is a tool for understanding the influence of assigned weights on the ranking order of alternatives. This analysis evaluates the impact of weights' values on the outcomes (alternatives' scores and ranks) that are being modified by the weighting factor variation. If weights' ranges do not change the overall results, the analysis is insensitive to the weighting factors.

III–4.1. Direct approach

A direct approach to weight sensitivity represents the simplest form of deterministic sensitivity analysis. Within the direct approach, a set of different weights has to be proposed by the experts and the ranking results are determined for the weights sets being considered.

Another possible strategy for the examination of weight sensitivity may be realized in the following way: each of the weights is changed by a certain percentage (for instance, ±10%) while maintaining the 100% sum of all weights. If these changes do not result in a change in the alternative rankings, the decision analysis is considered to be a stable or robust one. If the ranking order of alternatives changes due to the weight variations, it is necessary to collect additional information or explain the impact of potential biases in weights.

III–4.1.1. The linear weight and walking weight procedures

The linear weight and walking weight procedures are also widely used approaches to weight sensitivity analysis, representing a kind of deterministic sensitivity analysis. Both demonstrate the impact of different weighting factors on the ranking results of alternatives. In both procedures, the experts have to select a weight to be examined and analyse how the ranking of alternatives and their overall scores will change while a given weight varies from 0 to 1 (the other weights are automatically adjusted in a proportional manner in order to hold the sum of all weights equal to unity).

Within the visualization of the linear weight procedure, a series of lines is provided to demonstrate the overall scores for each alternative as a function of a given weight value (see Fig. 3.5 in Section 3.3). In the walking weight procedure, it is assumed that one makes an interactive examination of the dependence of the alternatives' overall scores and ranks on a given weight value. A slider for the weight is provided, which can be moved over the range from 0 to 1, subsequently changing the overall scores of the alternatives, which are represented in the traditional bar chart format. Based on this information, the impact of the weight on the alternative ranks can be identified for each weight, and additionally, weight sensitivity areas are determined.

III–4.2. Advanced MCDA tools

The uncertainty of decision makers' preferences (weights) may be taken into account by utilizing the concepts of fuzzy numbers, probability theory or interval algebra, as implemented in special versions of MCDA software, for example, fuzzy MAVT or ASPID [III–10 to III–12].

III–4.2.1. Fuzzy MCDA methods

Several techniques for ranking fuzzy numbers may be applied for the ranking of alternatives. Such techniques are based on different defuzzification methods and methods for the comparison of fuzzy numbers.

Fuzzy MAVT is, for instance, intended for uncertainty treatment using the 'value function' concept. Indicator values, single-attribute value functions and weights are considered as fuzzy numbers in fuzzy MAVT: singleton, triangular, trapezoidal or piecewise (see Fig. III–3). The ranking procedure is based on the comparison of the overall fuzzy scores.

III–4.2.2. ASPID method

The ASPID method is based on the 'general indices' concept, which is quite close to MAVT. It includes the following steps:

(a) Initial indicators $x_1,...,x_m$ for the objects being considered are evaluated.

(b) Indices (single-attribute value functions) $q_1,...,q_m$ for the fixed quality evaluation are chosen and represented in the form $q_i = q_i(x_i)$, $0 \le q_i \le 1$, $i = 1,...,m$.

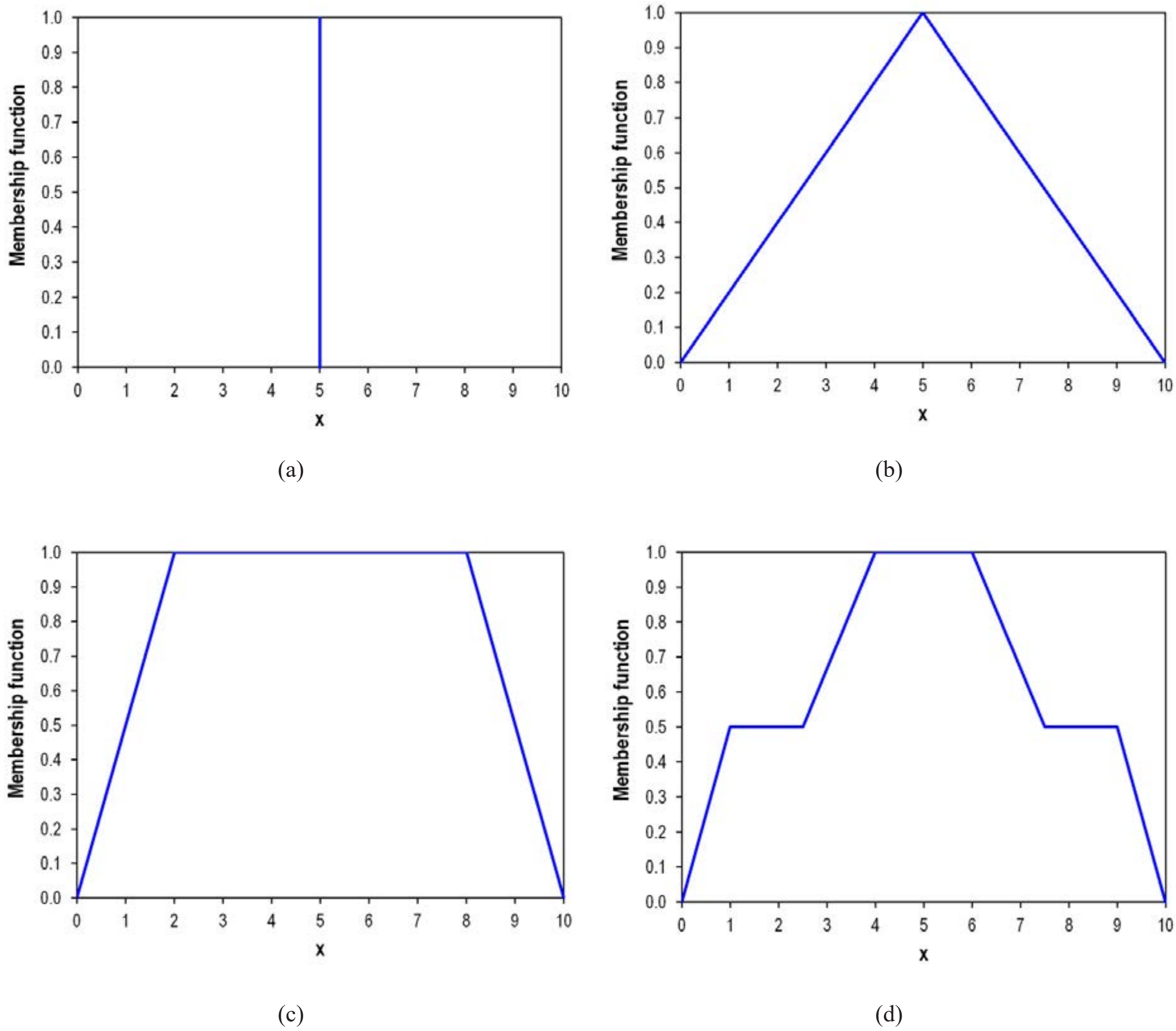


FIG. III–3. (a) Singleton fuzzy number, (b) triangular fuzzy number, (c) trapezoidal fuzzy number and (d) piecewise fuzzy number.

(c) A general index (multi-attribute value function) $Q(q;w) \in [0,1]$ is selected for $q = (q_1,...,q_m)$ and weights $w = (w_1,...,w_m)$, $w_i \geq 0$, $w_1 + ... + w_m = 1$ (usually the additive form $Q(q;w)$ is used).

(d) A unique set of weights $w = (w_1,...,w_m)$ is chosen from the set $W = \{w = (w_1,...,w_m) : w_i \geq 0, w_1 + ... + w_m = 1\} \subset E^m$ of all possible weights. Each weight w_i is a measure of the ith index contribution q_i to the general index $Q(q;w)$.

The ASPID weight evaluation stage utilizes a special procedure for the identification and treatment of weights in cases where there is a shortage of information about exact numerical values and assumes that only non-numeric (ordinal) information and/or non-exact (interval) information is available to characterize the possible weight values represented by a system of inequalities and intervals.

This procedure assumes that an increment of weight value is proportional to a step $h = 1/n$, where n is a positive integer. Thus, the infinite set of weights W may be approximated by a finite set of weights with discrete components as:

$$W(m,n) = \left\{ w^{(t)} = \left(w_1^{(t)},...,w_m^{(t)} \right) : w_i^{(t)} \in \left\{ 0, 1/n, 2/n, ..., 1 \right\}, w_1^{(t)} + ... + w_m^{(t)} = 1 \right\} \tag{III–8}$$

The number of elements of the set $W(m,n)$ may be calculated using the formula:

$$N(m,n) = \binom{n+m-1}{n} = \binom{n+m-1}{m-1} = \frac{(n+m-1)!}{n!(m-1)!} \tag{III–9}$$

Uncertain determination of the discrete weights may be interpreted in probabilistic terms. Uncertain selection of weights $w = (w_1, ..., w_m)$ from the set $W(I;m,n)$ may be modelled by a random choice with uniform distribution over the set. Such randomization of uncertainty delivers random sets of weights $\tilde{w}_1(I), ..., \tilde{w}_m(I)$. Mathematical expectation $\bar{w}_i(I) = M\,\tilde{w}_i(I)$ of the ith random weight $\tilde{w}_i(I)$ may be used as a numerical estimation of the ith particular index. The significance and precision of this estimation may be characterized by the standard deviation $s_i(I) = \sqrt{D\tilde{w}_i(I)}$ of the random variable $\tilde{w}_i(I)$.

If a set of all admissible weights $W(I;m,n)$ has been fixed, then a set of all admissible general indices $Q(I;m,n) = \{Q^{(s)}(q) = Q\ (q;w^{(s)}), s = 1, ..., N(I;m,n)\}$ may be evaluated. A function $Q^{(s)}(q)$ from the set $Q(I;m,n)$ determines a general index value $Q^{(s)}(q^{(j)})$, $s = 1, ..., N(I;m,n)$ for each object $x^{(j)}$.

The average general index $\bar{Q}(q;I)$ may be calculated by the formula:

$$\bar{Q}(q;I) = \frac{1}{N(I;m,n)} \sum_{s=1}^{N(I;m,n)} Q^{(s)}(q) = \frac{1}{N(I;m,n)} \sum_{s=1}^{N(I;m,n)} Q\left(q;w^{(s)}\right) \tag{III–10}$$

where $w^{(s)} \in W(I;m,n)$.

The accuracy of the average general index value $\bar{Q}(q^{(j)};I)$ of the jth object's performance may be characterized by the standard deviation:

$$S_j = S\left(q^{(j)};I\right) = \sqrt{\frac{1}{N(I;m,n)} \sum_{s=1}^{N(I;m,n)} \left[Q^{(s)}\left(q^{(j)}\right) - \bar{Q}\left(q^{(j)}\right)\right]^2} \tag{III–11}$$

The reliability of the preference relation between objects $x^{(j)}, x^{(l)} \in X$ (for instance, assuming $\bar{Q}(q^{(j)};I) > \bar{Q}(q^{(l)};I)$) for corresponding average general indices) may be characterized by the ratio:

$$P(j,l;I) = \frac{|\left\{s : Q^{(s)}\left(q^{(j)}\right) > Q^{(s)}\left(q^{(l)}\right)\right\}|}{N(I;m,n)} \tag{III–12}$$

where $|\{s:...\}|$ is the number of elements of the finite set $\{s:...\} \subseteq \{1, ..., N(I;m,n)\}$.

III–5. SENSITIVITY OF VALUE FUNCTIONS

Single-attribute value function sensitivity analysis makes it possible to demonstrate the impact of single-attribute value function shape on the final rankings of alternatives. Value function sensitivity analysis may only be implemented for value-based MCDA tools, such as MAVT and MAUT.

III–5.1. Direct approach

A direct approach involves the direct observation of how the ranking results are affected by a change of function type. The value function can be changed through adjustments such as selecting a new shape function or the parameters used, or by changing the parameterization.

Based on this procedure, the main components affecting the ranking results can be identified if the strategy for modifying the value function types allows the discovery of certain quantitative regularities influencing the ranking results. It is a common practice in decision support systems to implement the direct approach exactly in a sensitivity analysis. Other potentially realizable approaches are based on the use of statistical sensitivity analyses, as well as improved analytical tools that incorporate uncertainties directly into the analysis (i.e. designing the decision rule).

III–5.2. Statistical approach

A statistical approach to value function sensitivity may be considered as a supplement to the direct approach. It is reasonable to implement this approach in situations where there is a lack of understanding concerning single-attribute value function forms. This approach assumes the random generation of a set of single-attribute value functions (from a certain set of functions) and the identification of alternative ranks for them. In this way, the rank distribution may be evaluated for each alternative considered (see Fig. 3.6 in Section 3.3).

Using the probability rank distributions for each alternative, we can obtain the most probable rank values and their characteristics, such as average values and average squared deviation.

The application of this approach requires that special attention be paid to determining the boundaries of value function variation, which should be neither too narrow nor too wide to avoid indistinguishability.

III–5.3. Comparison with other MCDA methods

Comparing the results obtained using different MCDA methods is another possible option to examine the overall stability and robustness of ranking results. The experience gained in the Roadmaps for a Transition to Globally Sustainable Nuclear Energy Systems (ROADMAPS) collaborative project for this procedure [III–9] provides a means for comprehensive evaluation according to different criteria that will significantly increase the confidence level.

The MCDA methods may be categorized into the following groups: value based, outranking, reference based and others. Value based methods (for instance, MAVT, MAUT and the analytic hierarchy process (AHP)) are based on the evaluation of a single overall score for each alternative, assuming that low scores on one indicator can be compensated by higher scores on another one. In outranking methods (for instance, PROMETHEE), low scores for a certain indicator may not be compensated by higher scores on another indicator and incomparability between the indicator scores of alternatives is allowed. Reference based methods (for instance, TOPSIS) determine the similarity of alternatives to an ideal and anti-ideal alternative.

In general, if two different expert groups analyse a multi-criteria problem, the final ranking of the alternatives may not overlap, even when the same judgement aggregation method is used. This is caused by different viewpoints regarding elements such as weights, the types and parameters of value, and utility and preference functions. A similar situation may happen when two expert groups perform their study under the supervision of other experts who are skilled in using different methods. In this case, the probability of obtaining the same ranking result, even if these groups have similar judgements about the problem, is even smaller. Moreover, the results of weight identification may differ significantly if different methods (for example, swing and pairwise procedures) are applied within the same MCDA framework.

Differences in the rank order may occur due to different representations of a performance table that contains qualitative and quantitative performance scores for alternatives on each criterion, especially in cases when the experts use different MCDA methods. Unfortunately, there are no specific rules for conversion of the variants of the performance table into a universal form that is suitable for use in different methods. This is especially true for the AHP method, which is based on pairwise comparisons. Although a pairwise comparison of alternatives with regard to quantitative criteria is useful, the results of automatic conversion of quantitative assessment to pairwise comparison ratios may differ from the coefficients that experts assign directly on the scale of the AHP method.

III–6. SENSITIVITY OF INDICATORS

As a rule, the exact values of indicators are unknown. The indicators are thus biased. In a situation where the indicators characterize a certain measured value, this bias may be due to an error. In cases where an indicator is assessed qualitatively, for example, based on expert judgements, the uncertainty in the indicator value is caused by the ambiguity of reflecting expert qualitative judgements in a score scale.

Sometimes assessments of indicator uncertainties may be reduced while implementing one or another MCDA method for analysing sensitivity to other model parameters (for example, within the MAVT method, an indicator uncertainty may be reduced to an uncertainty of value function type). Therefore, it is necessary to identify the source of uncertainty (objective or subjective) clearly to avoid dual accounting.

III–6.1. Direct approach

A direct approach implies a direct observation of how the ranking results are affected by changes in the values of one or more indicators while these values are varied within certain limits. This approach allows modifications such as the simultaneous variation of several indicators and the generation of indicator values according to specific rules.

The direct approach to analysing sensitivity to indicator values is used for a qualitative (often visual) analysis. An expert modifies the indicator values and directly observes changes in the alternative ranking results and the overall scores of the alternatives. The expert then gains a posteriori experience, improving his or her understanding of the sensitivity of the ranking results to indicator values.

III–6.2. Advanced MCDA methods

Two MCDA methods that allow uncertainties in indicator values to be considered are presented below.

III–6.2.1. MAUT

MAUT is closely related to MAVT, but is based upon expected utility theory. Therefore, MAUT extends MAVT by using probabilities and expectations in order to deal with uncertainties. An uncertainty of the indicator value is represented in MAUT by a random variable with a given probability density function. Thus, the utility function for each alternative can consequently be considered as a random variable. The ranking of alternatives within the MAUT framework is based on the comparison of expected utilities. One alternative is ranked higher than the other if the mathematical expected value of a utility function for this alternative is greater than the corresponding expected utility of the other alternative. The MAUT method has been applied to many decision making problems requiring the multi-criteria comparative evaluation of nuclear reactors, related NFCs, NESs and technology development areas.

III–6.2.2. Fuzzy MCDA methods

This method involves considering uncertainties in indicator values by using fuzzy numbers as described previously.

It is not required to introduce any additional restrictions for the assignment of fuzzy numbers to indicators. However, the difficulty of interpreting the results in a meaningful way may be a disadvantage of this approach. The weights need to be assigned by uncertain numbers such as singlets if the contribution of uncertainties is only being assessed in indicator values.

III–6.3. Overall uncertainty analysis

The overall sensitivity analysis approach, which includes weight, indicator and value function sensitivity, was proposed in a study on the evaluation and screening of different NFC options relevant to the national situation in the United States of America [III–13] that was performed for the United States Department of Energy’s Office of Nuclear Energy. The study applied multi-attribute value analysis with step single-attribute value functions to evaluate and compare alternative NFCs simultaneously with regard to multiple criteria.

The calculated overall value scores vary when different value functions and weights are used. Each combination of value functions and weights represents a different set of value judgements (or perspectives) that a decision maker might hold; thus, there is no ‘right’ set of judgements. When all of the value functions and weights are considered to illustrate the sensitivity of the results, over 25 000 perspectives are created for a corresponding scenario. The analysis focused on the illustration of benefit criteria scores versus challenge criteria scores for each evaluation group in one scenario.

To examine the impact of these numerous perspectives on the overall results at the scenario level, simulation studies were conducted. In these simulations, one value function was sampled at random from the set being considered, one set of weights for each criterion was sampled at random from the set defined for that criterion, and the resulting benefit and challenge criteria scores for each option were calculated using the weights defined for the scenario being evaluated. All of the value functions and weight sets were sampled independently. The simulation was run for 10 000 iterations. To test the sufficiency of the number of iterations, several tests were run with up to 1 million iterations. For the purposes of this evaluation and screening, 10 000 iterations appeared to be sufficient to identify both the robust options and any groups that were promising under a subset of perspectives.

In these sensitivity studies, samples were generated from the set of all possible single-attribute value functions and weights for the included criteria, the benefit and challenge scores were calculated, and analyses were conducted to determine which options lay in a potentially promising set, and what the incremental benefit to incremental challenge ratio was for each of those promising options. This analysis helped to identify the options that were robust to different perspectives — those that were in a potentially promising set in the largest number of perspectives, and those that were only considered to be promising in a few perspectives (see Fig. I–3).

REFERENCES TO ANNEX III

[III–1] FIGUEIRA, J., SALVATORE, G., MATTHIAS, E., Multiple Criteria Decision Analysis: State of the Art Surveys, Springer, Boston, MA (2005).

[III–2] DURBACH, I.N., STEWART, T.J., Modelling uncertainty in multi-criteria decision analysis, Eur. J. Oper. Res. **223** (2012) 1–14.

[III–3] BROEKHUIZEN, H., GROOTHUIS-OUDSHOORN, C.G.M., VAN TIL, J.A., MARJAN HUMMEL, J., IJZERMAN, M.J., A review and classification of approaches for dealing with uncertainty in multi-criteria decision analysis for healthcare decisions, PharmacoEconomics **33** 5 (2015) 445–455.

[III–4] GLAESER, H., GRS method for uncertainty and sensitivity evaluation of code results and applications, Sci. Technol. Nuclear Install. **2008** (2008).

[III–5] KAHRAMAN, C., Ed., “Fuzzy multi-criteria decision making: Theory and applications with recent developments”, Optimization and Its Applications, Vol. 16, Springer, Istanbul (2008).

[III–6] MUSTAJOKI, J., HAMALAINEN, R.P., SALO, A., Decision support by interval SMART/SWING — Incorporating imprecision in the SMART and SWING methods, Decision Sci. **36** 2 (2005) 317–339.

[III–7] ANDRIANOV, A., PONOMAREV-STEPNOY, N., RUMYANTSEV, A., Approaches to and Methods for Quantitative Assessment of Nuclear Proliferation Risk, INPE NRNU MEPhI, Obninsk (2011).

[III–8] KUANG, H., HIPEL, K.W., KILGOUR, D.M., “Evaluation of source water protection strategies in Waterloo region based on grey systems theory and PROMETHEE II”, Proc. Conf. IEEE International Conference on Systems, Man and Cybernetics, Seoul, 2012, Institute of Electrical and Electronics Engineers, Piscataway, NJ (2012) 2775–2779.

[III–9] KUZNETSOV, V., FESENKO, G., SCHWENK-FERRERO, A., ANDRIANOV, A., KUPTSOV, I., Innovative nuclear energy systems: State-of-the art survey on evaluation and aggregation judgment measures applied to performance comparison, Energies **8** (2015) 3679–3719.

[III–10] WANG, Xuzhu, KERRE, E.E., Reasonable properties for the ordering of fuzzy quantities, Fuzzy Sets Syst. **118** (2001) 375–385.

[III–11] ABDULLAH, L., Fuzzy multi criteria decision making and its applications: A brief review of category, Procedia Soc. Behav. Sci. **97** (2013) 131–136.

[III–12] HOVANOV, N., “ASPID-METHOD: Analysis and synthesis of parameters under information deficiency”, EURO Summer Course on Sustainable Assessment of Clean Air Technology, Lisbon (2000).

[III–13] WIGELAND, R., et al., Nuclear Fuel Cycle Evaluation and Screening: Final Report, FCRD-FCO-2014-000106, United States Department of Energy, Washington, DC (2014).

Annex IV

VERIFICATION OF THE KIND APPROACH THROUGH STATISTICAL ANALYSIS

IV–1. ASSUMPTIONS FOR STATISTICAL EXAMINATION OF THE KIND APPROACH

The multi-attribute value theory method can be tailored to solve a specific decision making problem in different ways by selecting appropriate model parameters (number of indicators used, scoring scales for indicator evaluation, shapes and domains of single-attribute value functions, etc.). When comparing technical systems, it is desirable to elaborate robust decision making support models, which provide an appropriate resolution of alternatives and low sensitivity of ranking results to model parameters.

A statistical examination of the KIND approach based on Monte Carlo simulation was performed to work out a detailed comparative evaluation procedure for NESs and establish recommendations aimed at reducing the risk of the alternatives being indistinguishable and the ranking results being sensitive to model parameters. These recommendations indicate directions for modifying model parameters to provide better differentiation of alternatives (see Section 4).

Within the statistical analysis, comparisons of 2, 5 and 10 hypothetical NESs were considered. The performance of these NESs was characterized using 15 and 30 indicator sets evaluated using 3, 5 and 10 point scoring scales with linear and exponential (with exponent powers lying in an interval of [−10,+10]) single-attribute value functions defined on local and global domains. It was assumed that the equal weights option for weighting factors and all indicators should be minimized (decreasing single-attribute value functions). A total of 10 000 randomly generated and uniformly distributed NES performance indicators were considered for each case. In order to provide good statistics, each set of model parameters was examined 10 000 times. The maximal variation in scores and rank reversal index statistical indices were considered to draw conclusions about the impact of the model assumptions on the overall scores and ranks.

Maximal variation in scores is a statistical index representing the resolution of alternatives and serves as a measure of the distinguishability of alternatives. It is specified by the difference between the maximum and minimum overall scores for a given set of alternatives. The higher this value is, the more distinguishable the alternatives will be (see Fig. 4.1(a)).

The value of this statistical index, above which alternatives may be considered as resolvable or distinguishable, can only be determined by taking into account the results of the sensitivity analysis as part of a specific task solution. Therefore, a priori, it is impossible to define the preferred value of this indicator to provide a good resolution of alternatives. A conclusion about the distinguishability of alternatives can be drawn from the problem context analysis, taking into account the results of the sensitivity analysis.

The rank reversal index is a statistical index specifying the robustness of the ranks of the alternatives (Fig. 4.1(b)) and represents a measure of the maximum possible change in the ranks as a result of the transition from linear to exponential forms of single-attribute value functions averaged over the entire set of the hypothetical (randomly generated) NESs being considered. This index can be assessed as follows: determine the changes in ranks for each alternative as a result of the modification of the single-attribute value functions, select the maximum value of these changes, and then average these changes for the entire set of systems being considered. Note that this index cannot exceed $N-1$, where N is the number of NESs being compared (this situation corresponds to the case where the best alternative becomes the worst one).

Due to the limited scope of the study, the sensitivity analysis for the single-attribute value function forms was limited to the consideration of linear and exponential single-attribute value functions with exponent powers lying in the range from –10 to +10 (Fig. IV–1).

Each set of model parameters used to perform the statistical analysis was examined 10 000 times to provide good statistics. These runs correspond to 10 000 hypothetical NESs having been considered. For the above mentioned model assumptions, the statistical evaluation made it possible to evaluate the probability density functions and some of their statistical characteristics (i.e. 5th percentile, median, mean, 95th percentile). A percentile is a measure that is used in statistics to indicate the value below which a given percentage of observations falls in a group of observations. For example, the 5th percentile is the value (or score) below which 5% of the observations may be found, the median is the 50th percentile and the mean is the average value.

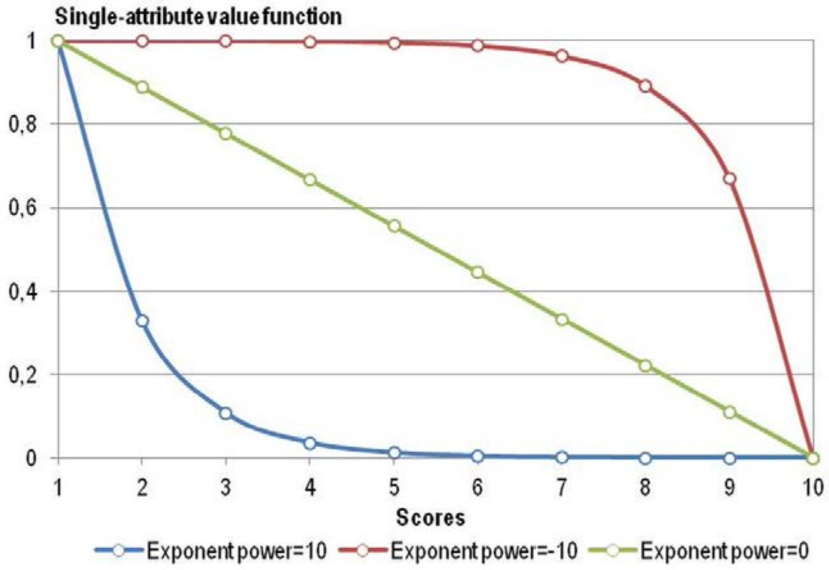


FIG. IV–1. Single-attribute value functions.

The 5th and 95th percentiles, median and mean values of the used statistical indices were evaluated for corresponding statistical distributions [IV–1]. The difference between the 95th and 5th percentiles is a measure of statistical dispersion. The median is a corresponding measure of the central tendency. For some cases, the probability distributions of statistical indicators have been built. Graphical representations of the statistical characteristics used are presented in Fig. 4.2.

IV–1.1. Resolution of alternatives as a function of model assumptions

Figure IV–2 shows the probability density function for the assumption of the maximal variation in scores statistical index when considering the cases of 2 and 10 NES comparisons, performed by means of 15 and 30 indicators assessed on 3 and 10 point scoring scales using linear single-attribute value functions defined on local and global domains. More detailed information regarding the statistical measures of the corresponding statistical distributions is presented in Tables IV–1 to IV–4.

It is obvious from the results that the farther removed the distribution is from the origin of the coordinates to the region of high values of the statistical index, and the more widely it is dispersed, the more confidently we may speak of the distinguishability of the alternatives being compared. Therefore, it is advisable to select model parameters that will lead to such changes as a distribution function of the relevant statistical index. These illustrations demonstrate the impact of different model parameters on possible dispersion in the values of multi-attribute value functions for NESs. The following trends may be outlined:

(a) With an increase in the number of NESs being compared, the resolution of alternatives will increase and the risk of alternatives being indistinguishable will be reduced.
(b) The riskiest case is one where two NESs are compared, in which the probability of obtaining the value of the maximal variation in scores statistical index in the area near to zero is large enough (this necessitates increased requirements for the selection of model parameters for the case where two NESs are compared to provide good resolution and differentiation of the compared alternatives).

The comparison of a large number of NESs is less sensitive to model parameters, which makes it possible to generalize the formulation of universal guidelines regarding model parameters.

The data presented in Tables IV–1 to IV–4 and Fig. IV–2 make it possible to formulate the following main trends regarding the factors leading to the reduction of the risk of alternatives being indistinguishable:

(a) Reduction of the number of indicators used in the comparative evaluation procedure;

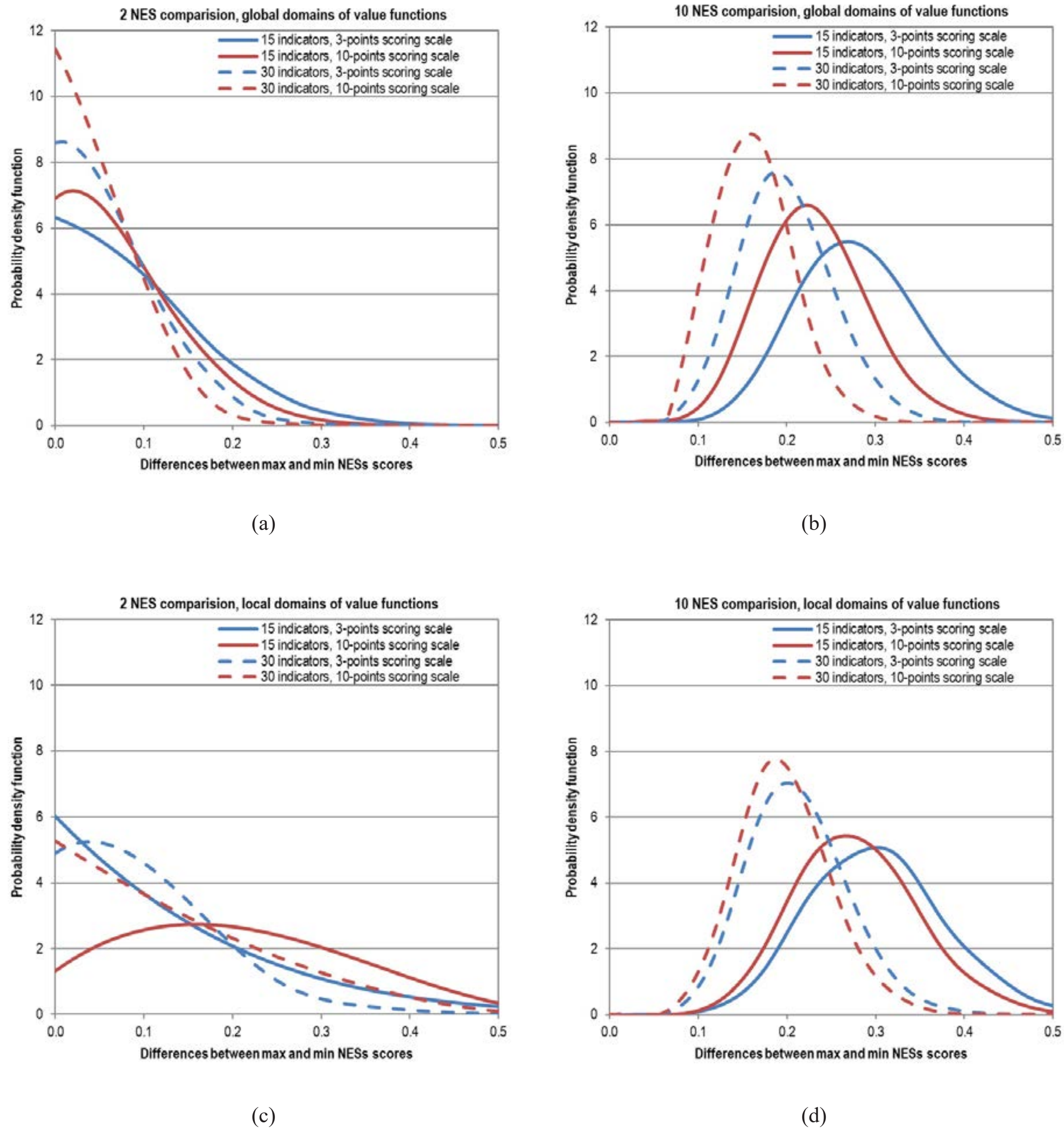


FIG. IV–2. Statistical distribution of maximal variation in scores index. (a) 2 NESs, global domains of value functions; (b) 10 NESs, global domains of value functions; (c) 2 NESs, local domains of value functions; (d) 10 NESs, local domains of value functions.

(b) Use of a local domain for single-attribute value functions instead of the global one;
(c) Use of a reduced scoring scale to assess indicators.

The last point is not valid for the case when two NESs are compared using a local domain for single-attribute value functions. In this case, the trend is reversed (i.e. an extended scoring scale is preferable because it provides a more precise differentiation of alternatives and it is less likely that the same value of a certain indicator will be encountered for these two alternatives).

Finally, it should be noted that the difference between the maximum and minimum values of multi-attribute value functions for different alternatives obtained using the exponential forms of single-attribute value functions in comparison with the linear ones may be estimated by the formula: $\Delta \pm 0.1$, where Δ is the value of the maximal variation in scores statistical index, corresponding to the linear forms of single-attribute value functions. This result shows that there are no significant changes in the dispersion of the values of multi-attribute value functions during the transition from linear to exponential forms of single-attribute value functions.

TABLE IV–1. MAXIMAL VARIATION IN SCORES (15 KIs, GLOBAL DOMAIN OF SINGLE-ATTRIBUTE VALUE FUNCTIONS)

		Score scale (5th percentile; median; mean; 95th percentile)		
		3	5	10
NESs	2	0;0.1;0.101;0.233	0;0.083;0.089;0.217	7.4×10^{-3};0.074;0.085;0.207
	5	0.1;0.2;0.212;0.367	0.083;0.183;0.184;0.3	0.074;0.17;0.176;0.289
	10	0.167;0.267;0.279;0.4	0.15;0.233;0.244;0.35	0.141;0.23;0.232;0.333

TABLE IV–2. MAXIMAL VARIATION IN SCORES (30 KIs, GLOBAL DOMAIN OF SINGLE-ATTRIBUTE VALUE FUNCTIONS)

		Score scale (5th percentile; median; mean; 95th percentile)		
		3	5	10
NESs	2	0;0.067;0.072;0.183	8.3×10^{-3};0.058;0.064;0.158	3.7×10^{-3};0.052;0.06;0.148
	5	0.067;0.15;0.151;0.25	0.058;0.125;0.13;0.217	0.056;0.122;0.124;0.204
	10	0.117;0.2;0.198;0.283	0.108;0.167;0.173;0.25	0.1;0.163;0.165;0.241

TABLE IV–3. MAXIMAL VARIATION IN SCORES (15 KIs, LOCAL DOMAIN OF SINGLE-ATTRIBUTE VALUE FUNCTIONS)

		Score scale (5th percentile; median; mean; 95th percentile)		
		3	5	10
NESs	2	0;0.133;0.163;0.4	0;0.133;0.183;0.467	0;0.133;0.194;0.467
	5	0.133;0.267;0.27;0.433	0.117;0.256;0.26;0.428	0.112;0.249;0.254;0.419
	10	0.167;0.3;0.301;0.433	0.172;0.278;0.283;0.406	0.172;0.275;0.279;0.4

TABLE IV–4. MAXIMAL VARIATION IN SCORES (30 KIs, LOCAL DOMAIN OF SINGLE-ATTRIBUTE VALUE FUNCTIONS)

		Score scale (5th percentile; median; mean; 95th percentile)		
		3	5	10
NESs	2	0;0.1;0.116;0.267	0;0.1;0.127;0.3	0;0.1;0.135;0.333
	5	0.083;0.183;0.191;0.317	0.083;0.178;0.185;0.306	0.077;0.172;0.177;0.293
	10	0.133;0.217;0.213;0.317	0.119;0.197;0.199;0.289	0.12;0.194;0.197;0.286

IV–1.2. Sensitivity of ranking results to the form of the single-attribute value function

Figure IV–3 shows the values of the rank reversal index for the cases of 2 and 10 NES comparisons made by means of 15 and 30 indicators evaluated on 3 and 10 point scoring scales and the modification of linear single-attribute value functions to exponential ones (with the exponent power within the range −10 to +10) defined on local and global domains. The exponent power is used as an *x*-axis parameter. More detailed information on the values of the rank reversal index for an exponent power equal to 10 is shown in Tables IV–5 to IV–8.

As already noted, the statistical rank reversal index to some extent characterizes the stability of the ranking results against the forms of the single-attribute value functions and equals the number of reversals in the ranks of alternatives as a result of changes in the forms of the single-attribute value functions. Due to the limited scope of the study, only the switch from linear to exponential forms of the single-attribute value functions was considered. Nevertheless, this analysis appears to reveal some general trends regarding the sensitivity of the ranking results to the forms of the single-attribute value functions.

It is clear that the smaller the index value, the lower the sensitivity of the ranking results to the value function form. Therefore, for a comparative evaluation of alternatives, it is reasonable to select model parameters that will give the smallest possible value of the statistical index. In this case, the ranking results of the alternatives will be less sensitive to the value function form. Ideally, the ranking results should be independent of the value function form and this index value should be equal to zero.

As can be seen from the graphs, these dependences are symmetrical and tend to reach a plateau at high exponent power values. The graphs for small exponent power values are identical for all cases. The small fluctuations at larger exponent values are due to scarce statistics, but they do not affect the overall conclusions regarding the dependence of the statistical index being considered on model parameters.

Looking at ways to reduce the sensitivity of the ranking results to the form of the single-attribute value functions is important in the context of the solution of applied problems, because this minimizes the effort required to elaborate single-attribute value functions and perform a sensitivity analysis regarding the form of the single-attribute value functions.

When comparing two NESs using the single-attribute value functions defined on a local domain, there is no dependence of the ranking results on the single-attribute value function forms. This obstacle is displayed graphically in the form of horizontal lines along the zero ordinate. This fact makes possible a simple evaluation of the values of the overall scores for each alternative when comparing two NESs.

Given the above, the main trends that can provide improved stability and reduced sensitivity of the ranking results to the forms of the single-attribute value functions are as follows:

(a) Use of a smaller number of indicators (the most critical factor);
(b) Use of a reduced scoring scale for indicator evaluation;
(c) Use of the local domain of single-attribute value functions.

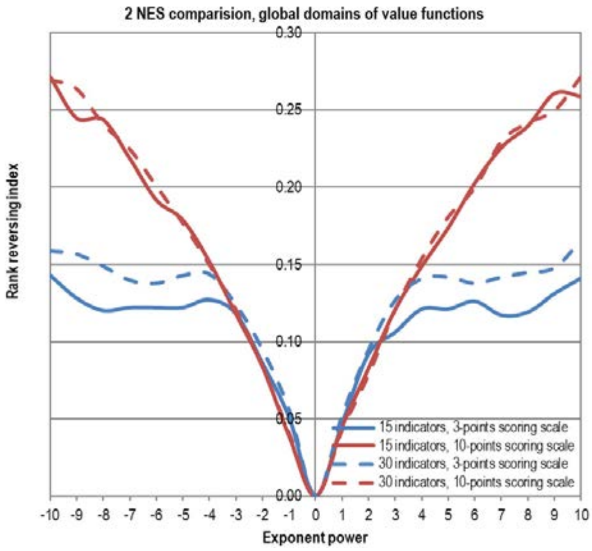
The smaller the number of alternatives compared, the lower the sensitivity of the ranking results to the forms of the single-attribute value functions, and the more these results may be considered to be stable.

The ranking results demonstrate sensitivity to the form of the single-attribute value functions. At the same time, the ranking results are not drastically dependent on the type of single-attribute value functions employed. This is a positive point that makes it possible to reduce the efforts related to the elaboration of single-attribute value functions.

In this regard, it can be recommended to use linear forms of single-attribute value functions for all indicators as a first approximation in NES comparative evaluation studies, or to use the exponential form of these functions if it is necessary to reflect increasing or decreasing marginal values of the indicators mixed with a risk attitude.

The outlined trends for the rank reversal index statistical index correlate with the trends for the maximal variation in scores statistical index. Due to this impediment, general recommendations on the selection of the most suitable model parameters can be formulated. The corresponding section of the report provided a summary of recommendations on the impact of model parameters and assumptions to ensure the steady resolution of alternatives and the stability of the ranking results.

Based on these conclusions, the comparative analysis of different NESs and NES evolution scenarios was performed, demonstrating the efficiency and correctness of the assumptions, as well as the possibility of improving the procedure for comparative evaluations in order to make the ranking results for alternatives less sensitive to model parameters [IV–2, IV–3].



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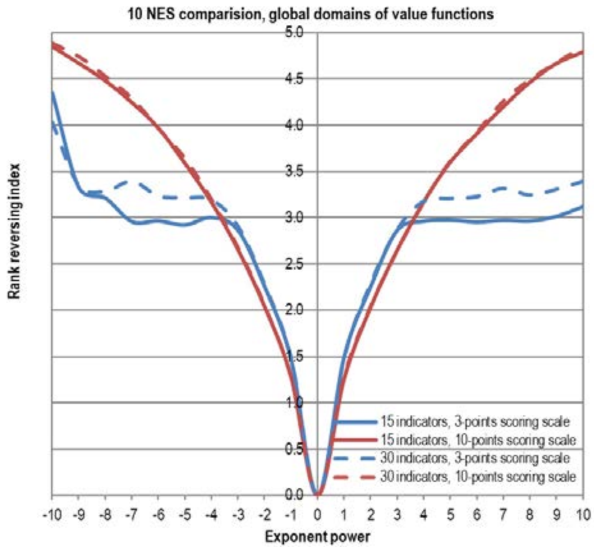

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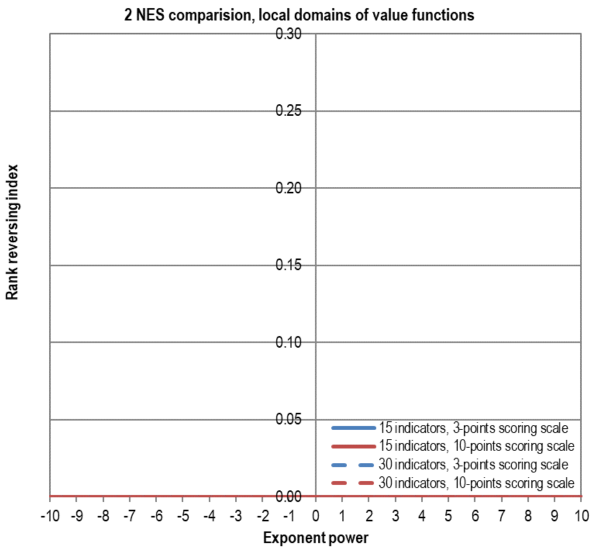

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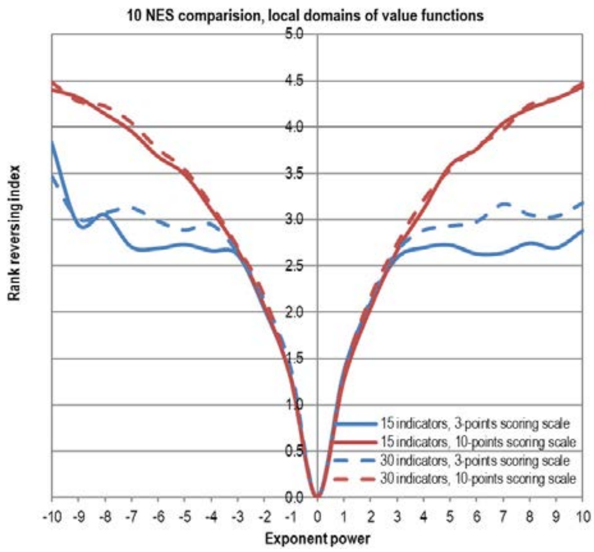

(d)

FIG. IV–3. Values for rank reversal index. (a) 2 NES comparison, global domains of value functions; (b) 10 NES comparison, global domains of value functions; (c) 2 NES comparison, local domains of value functions; (d) 10 NES comparison, local domains of value functions.

TABLE IV–5. RANK REVERSAL INDEX (15 KIs, GLOBAL DOMAIN OF SINGLE-ATTRIBUTE VALUE FUNCTIONS)

		Score scale (5th percentile; median; mean; 95th percentile)		
		3	5	10
NESs	2	0;0;0.142;1	0;0;0.223;1	0;0;0.268;1
	5	0;1;1.148;3	0;2;1.662;3	0;2;1.897;4
	10	1;3;3.13;6	2;4;4.281;7	2;5;4.796;7

TABLE IV–6. RANK REVERSAL INDEX (30 KIs, GLOBAL DOMAIN OF SINGLE-ATTRIBUTE VALUE FUNCTIONS)

		Score scale (5th percentile; median; mean; 95th percentile)		
		3	5	10
NESs	2	0;0;0.164;1	0;0;0.24;1	0;0;0.275;1
	5	0;1;1.286;3	0;2;1.764;3	0;2;1.911;4
	10	2;3;3.398;6	2;4;4.575;7	2;5;4.849;7

TABLE IV–7. RANK REVERSAL INDEX (15 KIs, LOCAL DOMAIN OF SINGLE-ATTRIBUTE VALUE FUNCTIONS)

		Score scale (5th percentile; median; mean; 95th percentile)		
		3	5	10
NESs	2	0;0;0;0	0;0;0;0	0;0;0;0
	5	0;1;0.705;2	0;1;1.163;3	0;1;1.456;3
	10	1;3;2.85;5	2;4;3.853;6	2;4;4.404;7

TABLE IV–8. RANK REVERSAL INDEX (30 KIs, LOCAL DOMAIN OF SINGLE-ATTRIBUTE VALUE FUNCTIONS)

		Score scale (5th percentile; median; mean; 95th percentile)		
		3	5	10
NESs	2	0;0;0;0	0;0;0;0	0;0;0;0
	5	0;1;0.843;2	0;1;1.225;3	0;1;1.504;3
	10	1;3;3.12;5	2;4;4.012;7	2;4;4.447;7

REFERENCES TO ANNEX IV

[IV–1] UPTON, G., COOK, I., Understanding Statistics, Oxford University Press, Oxford (1996) p. 55.

[IV–2] KUZNETSOV, V., FESENKO, G., ANDRIANOV, A., KUPTSOV, I., INPRO activities on development of advanced tools to support judgment aggregation for comparative evaluation of nuclear energy systems, Sci. Technol. Nuclear Install. **2015** (2015).

[IV–3] KUZNETSOV, V., FESENKO, G., ANDRIANOV, A., “INPRO collaborative project on key indicators for innovative nuclear energy systems (KIND)”, Innovative Designs and Technologies of Nuclear Power, Proc. IV Int. Scientific and Technical Conf., JSC NIKIET, Moscow (2016) 292.

Annex V

KIND-ET TOOL AND USER GUIDE

V–1. GENERAL DESCRIPTION

This annex presents a description of the KIND evaluation tool (KIND-ET), a multi-attribute value theory (MAVT) based Excel toolkit from the INPRO collaborative project Key Indicators for Innovative Nuclear Energy Systems (KIND), which developed guidance and tools for assessing the sustainability of innovations. KIND-ET was developed for the multi-criteria comparative evaluation of nuclear energy systems (NESs) in accordance with the methodology 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. 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 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.

V–2. BASIC FEATURES OF THE TOOL

The characteristic features of KIND-ET include ease of use, a user friendly interface, automation and visualization capabilities. KIND-ET integrates different convenient options for management and post-processing of the calculation results. The following basic features were implemented in KIND-ET design and development:

(a) Problem orientedness and integration — KIND-ET is designed as a problem oriented tool that combines all necessary capabilities into a single application with only one interface and common operational logic in accordance with the KIND approach.
(b) User friendliness and intuitive obviousness — All decision support stages (input preparation and editing, data display, calculation, automatic analysis and results processing, etc.) are reflected visually on Excel worksheets located on separate graphical panels. This allows a high level of information content, which is easy to adapt and use, allows fast perception of results, and offers coupling capabilities with other calculation and visualization tools.
(c) Automation and improvability — All operations are carried out automatically to increase the user's productivity in computation modelling. The user only needs to be aware of the problem statement while performing studies. At the same time, unified rules of data input, calculation control and results processing are implemented.
(d) Self-sufficiency, multifunctionality and validation — All necessary functionalities that offer high reliability of calculations are offered to the user. The algorithms have been verified and validated to ensure the high accuracy of calculations. KIND-ET was verified on a number of numerical examples by means of comparisons with calculations performed on commercial decision making software. This confirmed that this tool provides correct evaluations and may be applied for the numerical case studies of the KIND project. Therefore, KIND-ET can be used as a tool for research and educational purposes.
(e) Openness and extensibility — KIND-ET allows easy modification while keeping high user quality by providing the user with abundant opportunities to edit and expand functional capabilities. New approaches may be developed and implemented in KIND-ET in order to keep the front end level of the tool up to date and comply with advances in the KIND approach development.
(f) Microsoft Office and web integration — KIND-ET is designed to provide simple data exchange with Microsoft Office applications and also web integration, offering remote access. Microsoft Excel spreadsheets

were chosen for KIND-ET implementation because Excel contains a broad list of functions that can be useful for advanced users. Further, Excel is available on both Windows and Macintosh computers.

V–3. FUNCTIONALITIES AND CAPABILITIES

KIND-ET supports the decision making process by performing the following steps: problem formulation, formulation of alternatives, criteria identification, criteria evaluation, selection and implementation of MCDA method, uncertainty and sensitivity analysis, final conclusions and recommendations.

In order to perform a multi-criteria comparison, the user needs to do the following:

(a) Prepare a performance table;
(b) Determine single-attribute value functions for each indicator;
(c) Evaluate weighting factors;
(d) Perform sensitivity analysis;
(e) Interpret ranking results and formulate recommendations.

The following major assumptions are made in KIND-ET by default, in line with the recommendations of the KIND approach: a three level objectives tree, 15 indicators, linear and exponential forms of single-attribute value functions (both decreasing and increasing cases), local and global domains of single-attribute value functions, direct method for the evaluation of weighting factors, and no restrictions on scoring scales for the evaluation of indicators. KIND-ET inputs and outputs are given in Tables V–1 and V–2 and Fig. V–1.

More detailed information may be found in the user instructions available on the CD-ROM attached to this report. This CD-ROM contains a short description of the MAVT method adopted for the KIND project, and information regarding the KIND indicators, the KIND approach and recommendations, the functionalities and capabilities of the KIND-ET tool, and the necessary steps for the comparative evaluation of NESs, together with some examples demonstrating the implementation of the tool.

TABLE V–1. INPUTS OF KIND-ET

High level objective titles	Areas titles	Indicators titles	Indicators abbr.	Min. score	Max. score	NES-1	NES-2	NES-3	NES-4	NES-5
Cost	Economics	Levelized energy product or service cost	E.1	1	5	1	2	3	2	4
Cost	Economics	R&D cost	E.2	1	5	2	4	2	1	2
Performance	Waste management	Specific radioactive waste inventory	WM.1	1	5	5	1	1	3	3
Performance	Proliferation resistance	Attractiveness of nuclear material	PR.1	1	5	2	3	1	4	3
Performance	Proliferation resistance	Attractiveness of technology	PR.2	1	5	5	5	3	3	4
Performance	Proliferation resistance	Safeguards approach identified	PR.3	1	5	4	5	3	2	4
Performance	Environment	The amount of useful energy produced by the system from a unit of mined natural uranium/thorium	ENV.1	1	5	3	4	1	2	3
Performance	Country specifics	The potential to prevent release	S.1	1	5	4	3	4	3	4
Performance	Country specifics	Design concept specific safety inherent and passive features and systems	S.2	1	5	3	4	3	2	3
Performance	Country specifics	Core damage and large early release frequencies	S.3	1	5	3	4	2	3	4
Performance	Country specifics	Source term	S.4	1	5	2	2	4	3	5
Performance	Country specifics	Short term and long term accident management	S.5	1	5	2	4	2	4	2
Acceptability	Maturity of technology	Design stage	M.1	1	5	4	2	4	4	1
Acceptability	Maturity of technology	Time needed to mature the technology	M.2	1	5	4	3	3	5	3
Acceptability	Maturity of technology	Degree of standardization and licensing adaptability	M.3	1	5	3	4	3	5	4

TABLE V–2. SCORE VALUES FOR KIND-ET OUTPUTS

Levels	NES-1	NES-2	NES-3	NES-4	NES-5
Multi-attribute value function	0.550	0.478	0.677	0.483	0.516
			High level objective scores		
Cost	0.278	0.111	0.167	0.278	0.111
Performance	0.106	0.126	0.288	0.206	0.127
Acceptability	0.167	0.241	0.222	0.000	0.278
			Area scores		
Economics	0.278	0.111	0.167	0.278	0.111
Waste management	0.000	0.083	0.083	0.042	0.042
Proliferation resistance	0.028	0.009	0.074	0.056	0.032
Environment	0.028	0.000	0.083	0.056	0.028
Country specifics	0.050	0.033	0.047	0.053	0.025
Maturity of technology	0.167	0.241	0.222	0.000	0.278

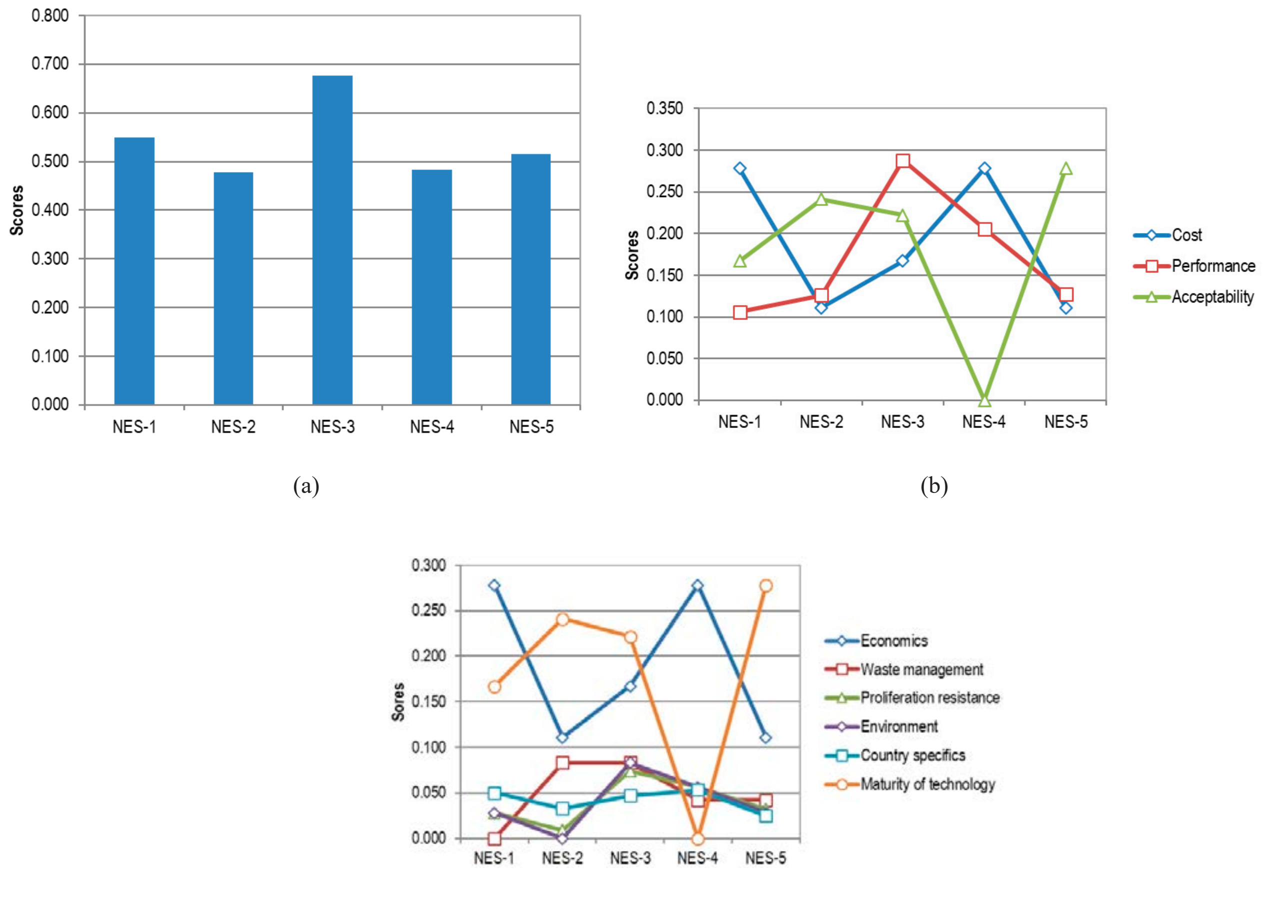

FIG. V–1. Kind-ET outputs. (a) Overall score; (b) area scores; (c) high level objective scores.

ABBREVIATIONS

ADS	accelerator driven system
AHP	analytic hierarchy process
ALWR	advanced light water reactor
BO	better outcome
BR	breeding ratio
CANDU reactor	Canada deuterium–uranium reactor
CE	certainty equivalence
CNFC	closed nuclear fuel cycle
CPP	coal power plant
DDS	degree of dependence on supplier
EG	evaluation groups
ELECTRE	élimination et choix traduisant la réalité (elimination and choice expressing reality)
ENES	evolutionary nuclear energy system
EP	evaluation parameter
FPs	fission products
FR	fast reactor
GAINS	Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle
GIF	Generation IV International Forum
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit GmbH
HLW	high level waste
ILW	intermediate level waste
INES	innovative nuclear energy system
INFCE	International Nuclear Fuel Cycle Evaluation
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
IRR	internal rate of return
KI	key indicator
KIND	Key Indicators for Innovative Nuclear Energy Systems
KIND-ET	KIND evaluation template
LLW	low level waste
LUEC	levelized unit electricity cost
LWR	light water reactor
MA	minor actinide
MAUT	multi-attribute utility theory
MAVT	multi-attribute value theory
MCDA	multi-criteria decision analysis
MCDM	multiple criteria decision making
MIT	Massachusetts Institute of Technology
MOX	mixed oxide
MSR	molten salt reactor
NES	nuclear energy system
NESA	nuclear energy system assessment
NEST	NESA Economic Support Tool
NFC	nuclear fuel cycle
NPP	nuclear power plant
OECD/NEA	Nuclear Energy Agency of the Organization for Economic Co-Operation and Development
PHWR	pressurized heavy water reactor
PR	proliferation resistance
PROMETHEE	preference ranking organization method for enrichment evaluations
PWR	pressurized water reactor

R&D	research and development
ROI	return on investment
RTA	reactor technology assessment
SFR	sodium fast reactor
SI	secondary indicator
SMR	small modular reactor
SNF	spent nuclear fuel
SWU	separative work unit
TOPSIS	technique for order preference by similarity to the ideal solution
TR	thermal reactor
TRUs	transuranics
USDOE	United States Department of Energy
WACC	weighted average cost of capital
WO	worse outcome

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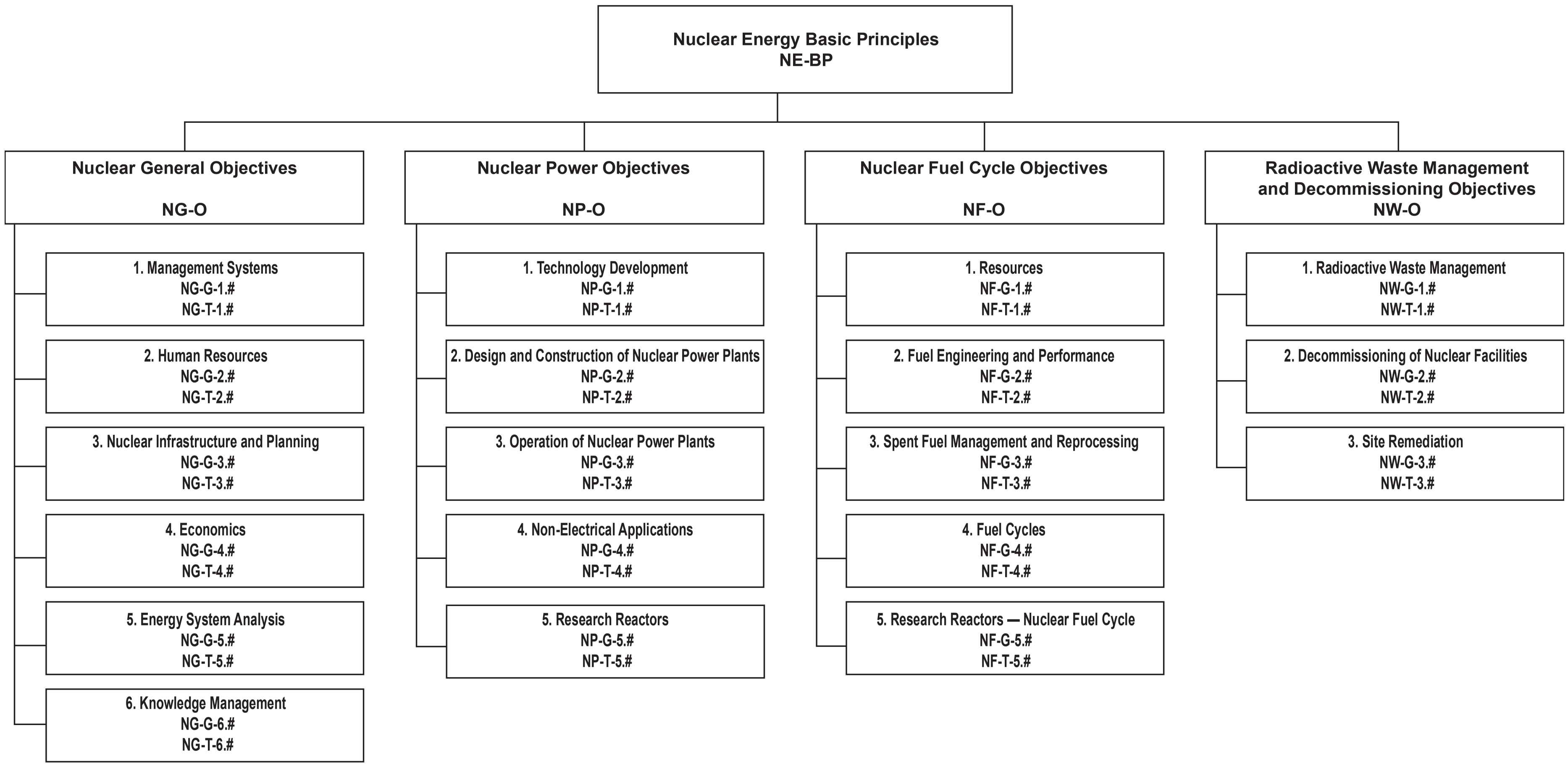

Key

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