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IAEA-TECDOC-2027

IAEA-TECDOC-2027

Comparative Evaluation of Nuclear Energy System Options

Final Report of the INPRO Collaborative Project CENESO

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COMPARATIVE EVALUATION OF NUCLEAR ENERGY SYSTEM OPTIONS

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA-TECDOC-2027

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FINAL REPORT OF THE INPRO COLLABORATIVE PROJECT CENESO

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2023

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Printed by the IAEA in Austria
August 2023

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Comparative evaluation of nuclear energy system options : final report of the INPRO collaborative project CENESO / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2023. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 2027 | Includes bibliographical references.
Identifiers: IAEAL 23-01612 | ISBN 978–92–0–143823–2 (paperback : alk. paper) |
ISBN 978–92–0–143723–5 (pdf)
Subjects: LCSH: Nuclear energy. | Nuclear energy — Evaluation. | Nuclear energy — Management. | Nuclear engineering..

FOREWORD

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 continuously 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 INPRO activities implemented in the Key Indicators for Innovative Nuclear Energy Systems (KIND) collaborative project was the development of an approach to comparative evaluation of nuclear energy system or nuclear energy evolution scenario alternatives and the examination of the applicability of this approach to a variety of problems, including those of interest to technology users and newcomer countries.

Drawing on lessons from the KIND collaboration project, the Comparative Evaluation of Nuclear Energy System Options (CENESO) collaborative project applied this comparative evaluation approach to new or refined case studies of practical interest to the project participants. Within the CENESO collaborative project, the approach was extended to include advanced analytical means to perform decision support and relevant sensitivity/uncertainty analyses for prioritization in programmes of nuclear technology research and development. Methodological and instrumental extensions made it possible to apply the comparative evaluations in new areas, including group decision making and classification, as well as screening studies.

This publication presents the results of the CENESO collaborative project, including the methodological and instrumental extensions, as well as national and country-neutral case studies, performed by interested Member States, on comparative evaluations, ranking and screening of various nuclear energy systems and their specific components, as well as comparisons of nuclear versus non-nuclear energy supply options.

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

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Within the framework of the collaborative project "Key indicators for innovative nuclear energy systems" (KIND) of the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) a new approach for comparing, ranking and sorting nuclear and/or non-nuclear energy systems (NESs) or scenarios has been developed and proven in trial applications [1.1].

The INPRO/KIND comparative evaluation approach has been developed to support the decision making process associated with prioritization in programmes of nuclear technology research and development. It is based on the application of a set of problem-tailored key indicators (KIs) in assessment areas of the INPRO methodology, state of the art judgement aggregations as well as uncertainty and sensitivity analyses.

This approach integrated the lessons learned and the best practices in the multiple criteria decision- making applications for nuclear engineering as well as the most significant recent findings in decision support, which were tailored for the collaborative project objectives. Due to this, the approach serves as a state of the art tool for comparative evaluations and ranking of NESs and related options.

Within the KIND collaborative project, several case studies have been performed on comparative evaluations of NES deployment scenarios, hypothetical NES options, NESs based on different reactor and fuel cycle technologies as well as nuclear and non-nuclear energy supply options. These case studies have demonstrated the applicability of the approach for the comparative evaluation and ranking studies as a part of nuclear energy planning and technology assessment endeavours.

At the moment, this approach is being extensively applied within and outside of IAEA's INPRO activities for comparative evaluations of various NES options at the scenario and technological levels, comparisons of nuclear fuel supply and waste management options, and for examination of cross-cutting issues that demonstrate the potential of the elaborated toolkit for decision support within a wide landscape of different practical nuclear engineering problems requiring expert judgment aggregations [1.2–1.4].

Following the growing interest of Member States in the national capacity-building in decision support as a part of medium term and long term strategic planning for the development of nuclear energy programmes including international collaboration, after completion of the KIND collaboration project, a new IAEA/INPRO collaborative project titled "Comparative evaluation of nuclear energy system options" (CENESO) was launched in 2017. The primary objective of the project was to extend, if appropriate, the KIND approach and to apply it in case studies on comparative evaluations of specific nuclear technologies and nuclear energy deployment scenarios in Member States that are INPRO members to exercise the utility of the comparative evaluation approach in support of decision making and prioritization for programmes of nuclear technology research and development being of practical interest to the CENESO participants.

1.2. OBJECTIVE

The CENESO collaborative project had the overall objective to systematically apply the KIND approach and its extensions in case studies on comparative evaluations of specific NESs, nuclear energy technologies and scenarios, performed by experts from interested Member States and to exercise the utility of the comparative evaluation approach in the support of decision making and in prioritization of programmes of innovative nuclear technology research and development. As already demonstrated within the KIND collaborative project, the developed approach could be effectively applied not only for comparisons of innovative and evolutionary nuclear energy technologies and components thereof but also for comparative evaluations of national, regional, and global nuclear energy deployment scenarios.

The specific objectives of the CENESO collaborative project were:

(1) To extend the comparative evaluation approach and relevant supporting tools in order to enhance presentations of ranking and sensitivity/uncertainty analysis results as well as to widen the scope of the approach application to new problems of potential interest to Member States;
(2) To revise early performed and develop new national and country-neutral case studies on comparisons of NES options and/or parts thereof, including non-nuclear energy supply options and climate change considerations, using the comparative evaluation approach and relevant tools;
(3) To examine the applicability of the comparative evaluation approach and relevant tools to support decision analysis and prioritization in the development of national nuclear energy programmes and capacity building in Member States;
(4) To provide feedback for further extension of the comparative evaluation approach including its integration with other scenario and decision analysis frameworks based on the lessons learned from case studies performed within the CENESO collaborative project.

1.3. SCOPE

The scope of work of the CENESO collaborative project included:

(1) Review and analysis of the case studies on the trial application of the comparative evaluation approach performed within the KIND collaborative project along with other practices on applications of different decision support frameworks in nuclear engineering, with the objective to elaborate directions for the extension of the comparative evaluation approach and relevant tools;
(2) Identification of tasks of interest and challenges for the new national and country-neutral case studies to be performed within the CENESO collaborative project as well as identification of Member States interested in participation, including possible collaborations among participants (cooperation among several participants interested in the same study was strongly encouraged);
(3) Extension of capabilities of the comparative evaluation approach and relevant tools in order to enhance presentations of ranking and sensitivity/uncertainty analysis results as well as to widen the scope of the approach by application to new problems;
(4) Performance and introspection of refined and new case studies on comparative evaluations of different innovative and evolutionary NES options, or nuclear energy deployment scenarios, or nuclear versus non-nuclear energy supply options, fuel cycles, or parts thereof, or other tasks of interest to the project participants using decision

support tools developed within the INPRO collaborative projects and/or other available decision support software.

Each case study was performed in the following stages:

(1) Elaboration and rationale of key indicator sets, including their structuring into an objective tree;
(2) Assessment of key indicators for each NES option/scenario under consideration based on the publicly available information (technical publications, calculated data, and expert opinions);
(3) Selection and rationale of a multi-criteria decision analysis method for judgement aggregation and its parameters furnished with weighting factors (typically, the multi attribute value theory[1] requiring specification of multi- and single attribute value functions);
(4) Application of decision support tools (typically, KIND-ET) to derive ranking results, overall scores of options under consideration and their scores at different levels of aggregation;
(5) Carrying out of sensitivity/uncertainty analyses regarding weighting factors, single attribute value functions and key indicators (typically, KIND-ET extensions);
(6) Presentation of ranking results in different formats (tables, graphs, diagrams, etc.) enabling effective interpretation and transparent communication of the outputs to interested stakeholders.

1.4. STRUCTURE

In general, this document describes the basics of the comparative evaluation approach and relevant supporting tools, including extensions providing capability to widen the scope of the approach application, a review of early performed case studies to identify points for follow-up with more detailed analyses, new or refined case studies of practical interest to the project participants, suggestions for applying the approach and lessons learned from its application.

Chapter 1 provides an introduction, defines the objectives, and explains the structure of the report.

Chapter 2 discusses the approach to the comparative evaluation and ranking of NES options and identifies the most essential directions for further expanding this approach to improve the presentation of the ranking and sensitivity/uncertainty analysis results as well as to widen the scope of the approach application to new problems such as multi-group decision making, dynamic decision support, classification, screening studies, etc. It also provides an incisive analysis of the case studies on the trial application of the comparative evaluation approach performed within the KIND collaboration project which compared different types of evolutionary and innovative reactors, nuclear and non-nuclear energy supply options, and NES deployment scenarios.

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[1] "Multi attribute Value Theory (MAVT) is a value-based Multi-Criteria Decisions Analysis (MCDA) method assuming judgement aggregation in terms of measured/evaluated costs, risks and benefits into an overall score using multi attribute value functions considering the experts and decision-maker preference strength. Within MAVT, single attribute value functions are evaluated for each indicator which transform diverse indicators' local natural values to universal, dimensionless scale, for example {0, 1}, reflecting judgments of subject matter experts and decision-maker. The single attribute value functions for each indicator are shaped over its variation range according to their significance for evaluator. The overall, i.e., aggregated scores indicate the ranks of the alternatives: the preferred alternative will have the highest overall score that is the highest rank" [1.1].

Chapter 3 contains 15 country case studies on comparative evaluations of NES options and deployment scenarios provided by project participants from Armenia, Bulgaria, Indonesia, Kenya, Mexico, Pakistan, Romania (2 case studies), the Russian Federation (4 case studies), Thailand, and Ukraine (2 case studies). The studies present comparative evaluations of NES deployment scenarios, evolutionary and innovative NES options at the technological level as well as nuclear and non-nuclear energy supply options. These case studies have demonstrated the applicability of the comparative evaluation approach and supporting toolkit for evaluating the merits and demerits associated with different energy supply options considering national specifics and priorities.

Chapter 4 includes three case studies not linked to any particular country which address not only comparison and ranking but also illustrate a possible screening procedure for scenarios and nuclear fuel cycle alternatives. These studies involve the dynamic multi attribute decision making model for comparative evaluations of global NES deployment scenarios and the multi-group decision support model for comparison of synergetic and non-synergetic NES deployment scenarios (these studies are based on the GAINS INPRO project results). Another study presented in Chapter 4 is that on examination of the INPRO comparative evaluation approach applicability for the fuel cycle evaluation and screening (the case study is based on the nuclear fuel cycle evaluation and screening study supported by the U.S. DOE).

Chapter 5 concludes the document by providing an overview of major findings and conclusions elaborated within the CENESO collaborative project along with discussions of the lessons learned from applying the comparative evaluation approach to particular problems of interest to Member States and indicating the paths forward.

Annexes to this report provide a review of the experience of applying multi-criteria decision making and other decision support approaches in nuclear engineering and related studies (Annex I) as well as a description of a decision support toolkit developed, verified, and applied within the KIND and CENESO collaborative projects for the comparative evaluation and ranking of NES options (Annex II). The annexes are available only in the electronic version of this report.

REFERENCES TO CHAPTER 1

[1.1] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Multicriteria Decision Analysis Methods to Comparative Evaluation of Nuclear Energy System Options: Final Report of the INPRO Collaborative Project KIND, IAEA Nuclear Energy Series No. NG-T-3.20, IAEA, Vienna (2019).

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[1.3] 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 2015 8(5) (2015) 3679–3719.

[1.4] 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, Article ID 910162, Sci. Technol. Nuclear Install. 2015 (2015).

2. COMPARATIVE EVALUATION AND RANKING OF NUCLEAR ENERGY SYSTEM ALTERNATIVES: OVERVIEW OF THE KIND APPROACH AND ITS EXTENSIONS

To ensure future sustainable nuclear energy deployment, nuclear technologies are currently being investigated and developed in many countries worldwide. Member States periodically need to compare possible energy and/or nuclear energy alternatives based on their anticipated performance, acceptability and costs or to analyse benefits and risks associated with them in order to prioritise the allotment of financing and other resources within national nuclear technology development programmes. Different expert groups may have different expert opinions: for their effective participation in the evaluation process, an approach and tools are required to aggregate such opinions and obtain an overall evaluation result with a confidence interval.

The INPRO collaborative project KIND developed an approach for comparative performance evaluations of NES options applicable both at the technological and scenario levels [2.1, 2.2]. The state of the art methods of expert judgement aggregation along with relevant sensitivity and uncertainty analysis frameworks have been carefully examined, cross-verified and adopted to enable effective comparative evaluations of such options. General guidance was worked out on developing a key indicator set, selecting scoring scales and single attribute value functions to make best possible use of the multi-criteria decision analysis (MCDA) potential for the comparative evaluation and ranking of NES options.

In the following, an overview of the approach to the comparative evaluation and ranking of NES options is given, including a description of the essential directions for further expanding this approach in order to improve presentation of ranking and sensitivity/uncertainty analysis results as well as to widen the scope of the approach application to new problems. An incisive analysis is also presented of the case studies on the trial application of the comparative evaluation approach carried out as part of the KIND collaborative project in order to compare different types of evolutionary and innovative[2] reactors, nuclear and non-nuclear energy supply options as well as NES deployment scenarios.

2.1. THE KIND APPROACH TO THE COMPARATIVE EVALUATION AND RANKING OF NES/SCENARIO ALTERNATIVES

Decision support in different areas is generally performed under complex circumstances of multiple objectives, involving conflicting interests and various stakeholders. The basic requirements for the decision support process are that such a process needs to be logical, transparent, comprehensive, reproducible and verifiable. Analytical support of multi-criteria decision analysis problems can be provided through application of MCDA methods. Use of MCDA could support decision makers in prioritizing of the available choices or in picking one or more of them as most preferable in view of the multiple conflicting criteria.

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[2] According to IAEA-TECDOC 936 [2.3], “an evolutionary design is an advanced design that achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining design proveness to minimize technological risks”, “an innovative design is an advanced design which incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice”.

2.1.1. Decision support with multi criteria decision analysis

Within the MCDA framework, the decision support process starts with the identification of the decision maker(s), a group of subject matter experts and the stakeholders (persons interested in a certain decision), and further goes through the following steps (Fig. 2.1): problem formulation and structuring, proposing/defining of alternatives, identification and evaluation of criteria and attributes, selection of the MCDA method and its parameters, sensitivity/uncertainty analysis, final conclusions and recommendations.

Application of the MCDA framework to comparative evaluations of NES options makes it possible to search for compromises among the various, and sometimes conflicting, indicators and attributes that determine the NES performance and sustainability, by calculating the corresponding trade-off rates, carrying outranking and sorting of the considered options and, if needed, selecting the most promising option based on different costs, benefits and risks.

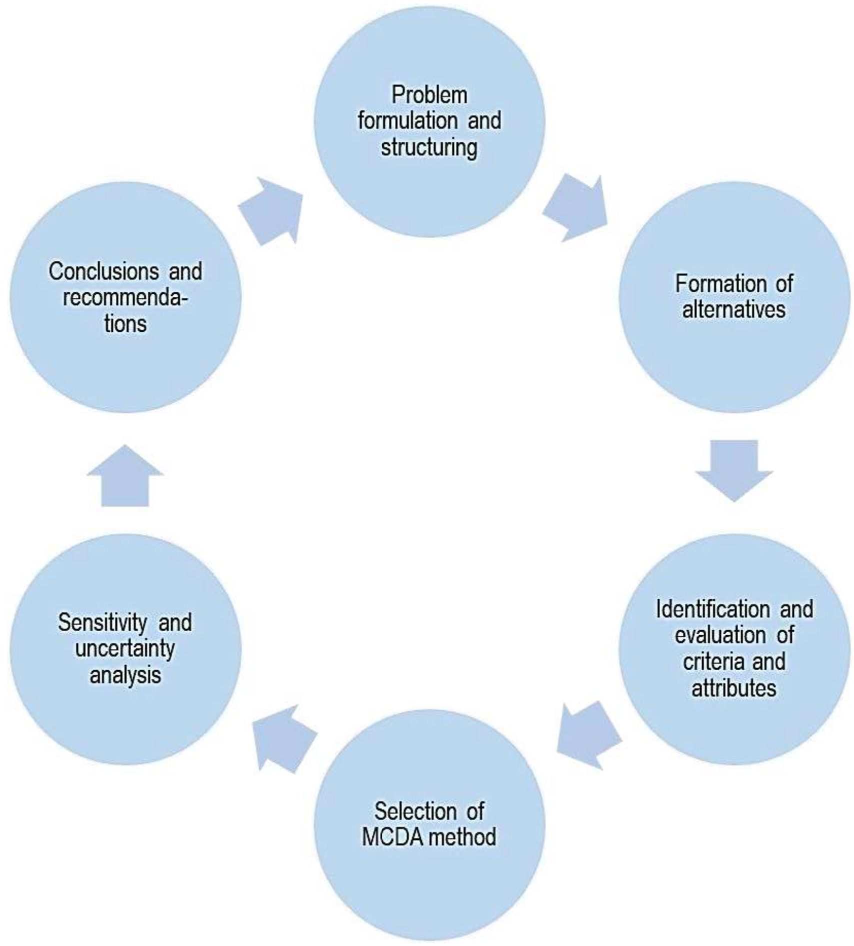


FIG. 2.1. The MCDA-based decision support flowchart (the starting point is at the very top).

MCDA methods provide analytical means for examining the hierarchy objective tree with a defined set of alternatives. The objective tree's structure facilitates aggregation in a multi-level modelling of the evaluation process and, thus, needs to be developed before performing a multi-criteria comparative evaluation. It defines the application rules for weighting factors and facilitates interpretation of the ranking results. A high-level evaluation might be simplified by focusing on a smaller number of the major objectives.

Due to the large number of MCDA methods (value-based, outranking, reference-based, hybrid methods), the selection of the most appropriate method is to be made based on the problem context analysis and the quality of the initial information provided by subject matter experts and decision-makers. Nevertheless, within the KIND collaborative project, it was shown that, despite some possible minor differences in the ranking of alternatives, the use of various MCDA methods for comparative evaluations of the NES performance and sustainability leads to well-coordinated and consistent results [2.4–2.6].

2.1.2. Multi attribute value theory based comparative evaluation: foundations of the KIND approach

The KIND comparative evaluation approach considers lessons learned and best practices in multi-criteria decision making applications for nuclear engineering, as well as the most significant recent findings in decision support, which were tailored for the KIND collaborative project objectives [2.5].

As part of the project, metrics and methods were investigated for comparative evaluations of NES options. The comparative evaluation approach is based on the selection of a problem-specific limited number of key indicators reflecting the costs, benefits and risks of the compared options and the use of an appropriate MCDA method for aggregating judgments, supplemented by basic robustness analyses of ranking results using simplified sensitivity/uncertainty analysis methods.

The proposed comparative evaluation approach is an iterative procedure using the top-down and bottom-up perspectives. This approach as a decision support process begins with the identification of the decision maker's problem and a group of subject matter experts and stakeholders (persons interested in a certain decision) and further iteratively goes through the following steps:

(1) Problem formulation and definition of objectives;
(2) Identification of indicators;
(3) Formulation of alternatives (NES options/scenarios);
(4) Evaluation of indicators, including uncertainties, performance table formation;
(5) Selection of MCDA method(s);
(6) Construction of objective tree and weight assignments, including uncertainties;
(7) Alternative ranking determination based on the selected MCDA method;
(8) Sensitivity and uncertainty analyses;
(9) Conclusion and recommendations.

The KIND approach provides advice and tools for a full cycle of the MCDA framework application to comparative evaluations of NES options, including [2.1]:

— Selection of a set of indicators and the objective tree structure;

- Selection of a scoring scale for evaluating indicators;
- Selection of MCDA methods (value-based, outranking, reference-based, other/hybrid methods);
- Identification of risk attitude parameters (risk neutrality, aversion, proneness);
- Evaluation of a value function shape (linear, polynomial, exponential, logarithmic, piecewise forms);
- Identification of weighting factors (direct, rating, ranking, pairwise comparisons, swing methods);
- Uncertainty and sensitivity analyses (direct, stochastic approaches);
- Presentation of results in graphic formats enabling effective communication of the results to various interested parties including technical and senior managers and policy decision makers (colour codes, heat maps, aggregation in costs-risks-benefits categories).

Despite the fact that simple scoring models and more sophisticated MCDA methods may both be used for NES comparative evaluations at technology and scenario levels, it was suggested in the KIND collaborative project by the project audience to apply simple methods for judgment aggregation, given the purpose of their application for comparing NES options, including less mature technologies.

The multi attribute value theory (MAVT) is one of such methods, which is widely used for different applied problems in general and, particularly, in nuclear engineering. A vast experience of applying this method, as summarized in different publications, and an extensive set of examples and software tools are the reasons to select MAVT as a basic method for NES comparative evaluations. However, it did not restrain experts from using other MCDA methods within the KIND collaborative project.

The basis of the MAVT method is the use of multi attribute and single attribute value functions. A multi attribute value function (overall score) represents a combination of single attribute value functions specified for all indicators to be weighted according to the experts/decision-makers' preferences. The overall values of multi attribute value functions (scores) point to the ranks of the compared options. The highest overall score corresponds to the preferred option.

To carry out a relevant expert examination, the proposed approach and specific advice are based on and take account of the NES specific features, including those potentially considered for deployment in a more distant future, as well as challenges related to the availability of data, potential financial and time resources. This approach was used by interested INPRO Member States to perform their own comparative evaluations of NES options on a trial basis.

To facilitate comparative evaluations of NES options within the KIND collaborative project, a decision support tool KIND-ET (KIND-Evaluation Tool) was developed [2.1]. The tool supports comparative examinations and evaluations of NES options, considering experts and decision makers preferences, to yield reasonably stable, well-interpreted and decision making oriented results clarifying the costs, benefits, and risks associated with the relevant options (Fig.2.2).

The developed approach can be used not only for nuclear energy technologies and systems at the technological level, including options for a distant future, but also for enhancing comparative evaluations of national or regional nuclear energy evolution scenarios, comparisons of nuclear versus non-nuclear energy systems along with other multiple cross-cutting issues of specific interest to technology holder, user and newcomer countries. The results of the studies could help to substantiate and make a more productive dialogue with the decision makers regarding the selection of particular NES options or NES evolution scenarios pursuant to the national energy strategy.

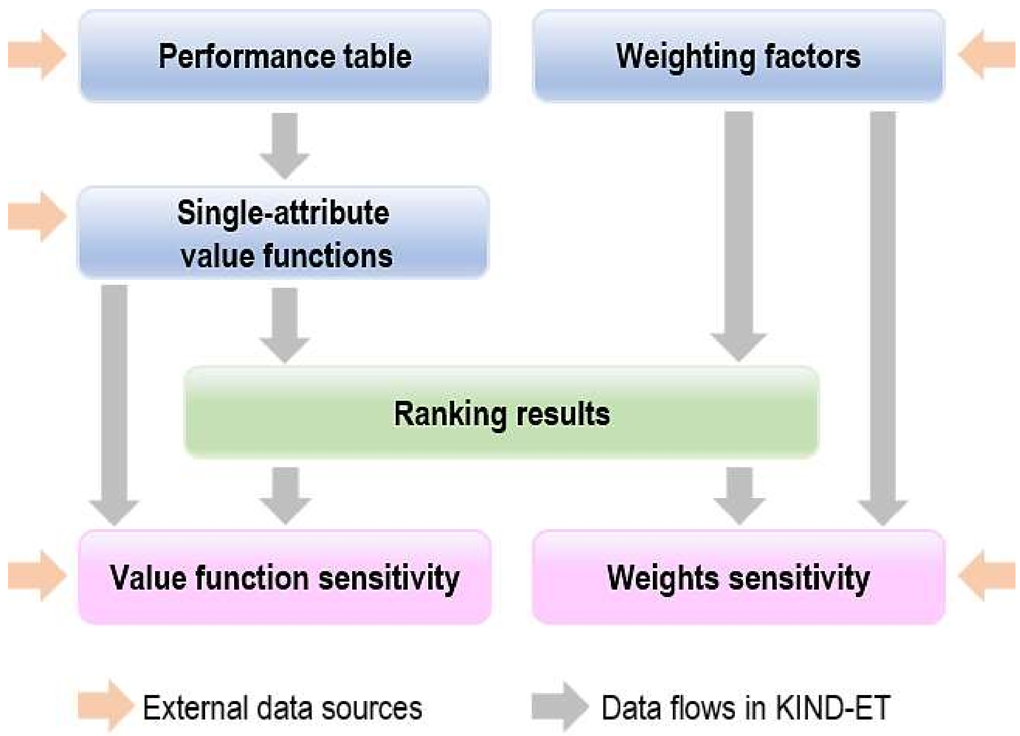


FIG. 2.2. The KIND-ET application flowchart.

2.1.3. Performing sensitivity analysis with KIND-ET

A sensitivity analysis helps to identify both the stability and robustness of ranks under specified uncertainties in model parameters as well as possible ways to revise and restructure the problem. The selection of the most suitable approach to perform a sensitivity analysis depends on the scope of the specific case study and related audience and expert preferences.

For most problems, simple approaches within a deterministic sensitivity analysis are sufficient to examine the impact of uncertainties due to the advantage of its straightforward implementation, intuitive appeal and capability to be implemented within different MCDA methods. With these approaches, the weights or indicators are varied as a single value. Within the MAVT method, a sensitivity analysis needs to explore the impact of changes in indicators, weights and single attribute value function on ranking results. A direct deterministic sensitivity analysis is implemented as a basic option for treating uncertainties within the KIND collaborative project in KIND-ET [2.1, 2.7]:

— A direct approach to a weight sensitivity analysis is a simple form of deterministic sensitivity analyses in which alternative ranking results are calculated for different weighting factor options.
— A direct approach used to determine the sensitivity of ranking results with respect to a single attribute value function type involves direct observation of how these ranking

results are affected by a change in one or more single attribute value functions, the type of which varies within certain limits.

— 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 on ranking results.

At the same time, more sophisticated methods may be required in cases when multiple sources of uncertainty are to be considered simultaneously, when dependence relationships among input data exist, and when there are no time constraints for uncertainty modelling. Further extension of the KIND comparative evaluation approach within the CENESO collaborative project is associated with the straightforward and systematic implementation of advanced uncertainty treatment techniques.

2.2. EXTENSION OF CAPABILITIES OF THE COMPARATIVE EVALUATION APPROACH AND RELEVANT TOOLS

This chapter presents and explains new methods, tools and applications developed in the CENESO collaborative projects as compared to its predecessor KIND [2.1].

2.2.1. Extension of the KIND comparative evaluation and ranking approach

In most cases, the MCDA-based decision support procedure is complicated by the uncertainties associated with input parameters and judgment aggregation methods requiring a specification, rationale, and selection of different assumptions. Consequently, one of the main challenges in the appropriate application of the MCDA framework, including analysing and interpreting the ranking results, is the multiple uncertainties in the input data: the most important of them are weighting factors and indicator performance values. Analysing the sensitivity of ranking results to various input parameter values as well as evaluating the impact of input data uncertainties on ranking results are inevitable components of the decision support process. The situation is complicated because traditional sensitivity analysis methods have numerous limitations when applied to MCDA, due to their orientation to situations where only a single input parameter is varied while, within the MCDA framework, multiple parameters are usually uncertain, and they all affect the overall scores and ranks of all options under consideration.

Uncertainty is ubiquitous in the MCDA-based decision support: each step of the decision making process is associated with different types of uncertainties which are not always possible to quantify. Uncertainties are inherent in the selection of a decision rule and judgment aggregation method, an indicator set and the way of its structuring, approaches used for assessing the indicator values and weighting factors. A multi-criteria and multi-group (stakeholders) decision support cannot reflect a pure technical or natural scientific point of view. Public acceptance and an increased social confidence level are important objectives as well. These factors also introduce uncertainties. In general, lack of information or its limitedness is the most common reason for uncertainty. Finding ways to properly treat uncertainty and reduce uncertainties are the most serious challenges in the MCDA-based decision support.

The uncertainty inherent in MCDA is the main reason for concern in decision support, raising doubts about the recommendations and observations received in the decision analysis process. Since there are no generally accepted approaches to handling uncertainty in MCDA, and considerable effort is required to perform and present the results of an appropriate uncertainty analysis, general estimates and rankings of options are usually given without any uncertainties or confidence intervals. This circumstance may well cause some distrust regarding the results and conclusions of a MCDA-based decision analysis.

Given these points, the extension of the INPRO comparative evaluation approach needs to provide capabilities for advanced uncertainty treatment and enhance representations of ranking and sensitivity/uncertainty analysis results, which, inter alia, will allow experts to widen the scope of the approach application to new problems. In particular, to make it possible the relevant methodological and instrumental extensions are:

- To identify options which would objectively be less attractive than others regardless of decision rules used (so-called dominated options);
- To perform advanced deterministic/probabilistic uncertainty/sensitivity analyses regarding weighting factors, key indicators and single attribute value functions;
- To present ranking results with uncertainties or confidence intervals as well as results of sensitivity/uncertainty analyses in user-friendly graphical forms;
- To consider different stakeholder groups so as to be able to perform multi-group decision analyses, screening and sorting studies, and dynamic multi attribute analyses.

2.2.2. Preliminary screening of options

An option is called ‘dominated’ if all its performance indicator values are worse than the performance indicator values for the options which dominate it (formally speaking, one option dominates another if its performance is at least as good as the dominated option on all indicators and better on at least one indicator). Dominated options may be excluded from further consideration since their overall scores will always be lower than the overall scores for the options which dominate them. This facilitates the comparison by minimising the options considered and makes the ranking results more stable.

To simplify the comparative evaluation process and make it more effective, preliminary determination of dominated and non-dominated alternatives among the set of the considered feasible ones, i.e., screening for dominance or preliminary screening of the options, could be very helpful. The more options are compared, the more valuable screening for dominance is. Identifying dominated and non-dominated options is especially useful within comparative evaluations of NES deployment scenarios.

Information regarding non-dominated and dominated options can be used to interpret the ranking results: in the ranking, the dominated options will always follow the options which dominate them. This step can be especially useful for screening studies, where it is necessary to filter out unsatisfactory and ineffective options from the overall set.

The described preliminary analysis (screening) offers an advantage in that at the moment of its performance there is still no need to select a decision rule and determine the weights. However, identification of non-dominated options is in itself not a comparative evaluation process that yields ranking. The comparative evaluation procedure with definition of the decision rule and its integration in the defined objective tree structure using weights reflecting the views and standpoints of experts, decision makers and other involved stakeholders then needs to be performed for the number of alternatives reduced through the preliminary analysis (screening).

2.2.3. Advanced uncertainty/sensitivity analysis

Uncertainty/sensitivity analyses play a crucial role in implementing the MCDA framework for decision support with the primary objective to form conclusions regarding the stability and robustness of the ranking results against key decision support model parameters being independent of whichever method is used or whatever model assumptions are chosen [2.1].

There is a difference between uncertainty and sensitivity analyses, but both of these frameworks effectively complement each other. An uncertainty analysis is carried out in order to evaluate the range of possible outcomes for a given set of inputs (where each input has some uncertainty) without specifying a contribution of each specific uncertain input to the outcome uncertainty. A sensitivity analysis is performed in order to understand how the output variables would change under the variation of each of the input parameters. Such analysis also helps to understand which input parameters when varied produce the strongest impact on the outputs.

Various forms of sensitivity and uncertainty analyses are widely used to increase the clarity of the choice of alternatives within the MCDA framework implementation: sensitivity analysis is used to examine changes in the overall scores and ranking order that arise as a result of modest changes in model input values (indicators, weights, single attribute value function), while uncertainty analysis is used to involve multiple uncertainty sources to provide the overall ranking results with uncertainty due to uncertainties in model input values (indicators, weights, single attribute value function).

The most widely known methods for evaluating the impact of uncertainty on the results in MCDA-based studies are based on the deterministic and probabilistic frameworks[3]. Both of them have their advantages and disadvantages. Some of the specific uncertainty/sensitivity analysis methods based on these frameworks are more or less universal for use in MCDA tools and the selection of the most suitable one is to be based on considerations of the time needed and available prerequisite knowledge for the implementation.

Generally, a deterministic analysis may be easily applied to uncertainty both in indicators and weights because a corresponding model parameter (weight or indicator value) can be varied separately; besides, little time is needed, and no additional information is required for such an analysis. At the same time, the range over which weights or indicator values are varied is usually chosen in an arbitrary way and all parameter values in the range are assumed to be equally probable. Moreover, a larger number of uncertain model parameters cannot be considered simultaneously within a deterministic analysis, so it does not provide an evaluation of the cumulative impact of uncertainty on multiple model parameters.

A probabilistic analysis requires specification of probability distributions for model parameters of interest (for instance, based on objective statistics or by eliciting information from subject matter experts) and considers uncertainty from multiple model parameters. It is important to note that analysing the influence of one variable at a time can be misleading if there are dependencies and correlations between the input variables. Probabilistic analyses, e.g., techniques such as Monte-Carlo simulations, can help to address this problem.

One can also distinguish between ‘global’ and ‘local’ uncertainty/sensitivity analyses. The simplest and most popular is the local approach involving the study of the impact of small

[3] Some other uncertainty treatment frameworks (such as, fuzzy set theory, interval judgments, Grey theory, etc.) may also be used for analysing uncertainties within MCDA, but they are less popular in terms of their application for real-life practice-oriented decision support.

variations in input parameters on the output of the model. The local approach has certain limitations, in particular, when assumptions are made regarding local variation ranges, linearity and normal distributions for input parameters. An alternative method has been proposed to overcome those, known as 'global' uncertainty and sensitivity analyses considering the entire range of inputs variations, in contrast to local analyses.

The selection of a specific method for performing uncertainty and sensitivity analyses within the MCDA framework depends on the information about uncertainties in the input data (small or large) and the type of data (i.e., indicators, weights, single attribute value function). In some cases, consideration may be limited to the use of 'local' methods while, in others, 'global' methods need to be applied. For some problems, the deterministic framework can be quite effective; for others, the probabilistic one is to be used. The more methods for uncertainty and sensitivity analyses are realized in a specific decision support toolkit, the more powerful and universal this toolkit is. Such a toolkit can be characterized by an extended application scope, including multi group decision making and dynamic decision support, conducting classification and screening studies along with many others.

2.2.4. The KIND-ET tool and its extensions

This chapter presents the newly developed tools and explains the relationship between tools developed in the CENESO project and those developed in its predecessor KIND [2.1].

2.2.4.1. The KIND-ET tool

Within the KIND collaborative project, an Excel-based decision support tool – KIND-ET (KIND-Evaluation Tool) – was elaborated, verified and tested [2.1, 2.2, 2.7]. This evaluation tool based on a multi attribute value theory is intended to support the decision making process while the direction of technological NES development is being selected. KIND-ET can be applied to the NES multi-criteria comparative evaluation in accordance with the approach and advice elaborated in the KIND collaborative project in order to help the leaders of the industry, decision-makers and experts to formalise existing features of compared alternatives and synthetise the potential of examined NESs. Within the CENESO collaborative project, version 2.0 of KIND-ET was developed [2.1].

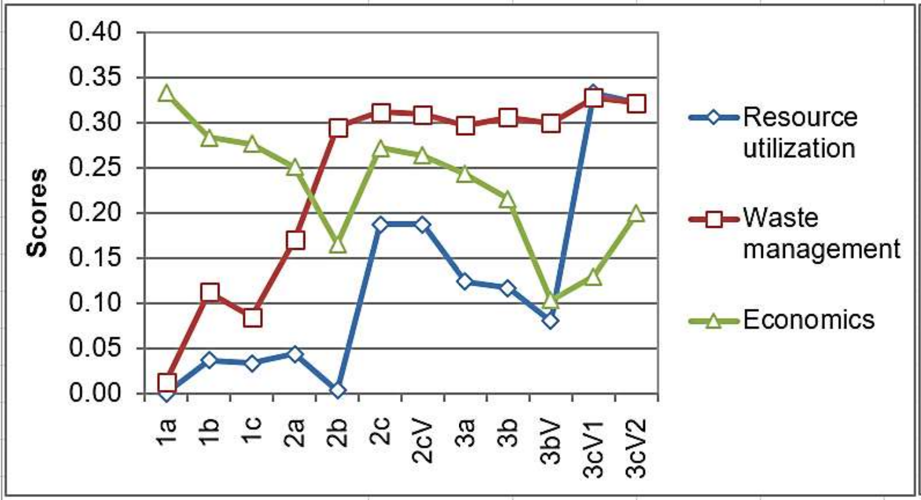
KIND-ET uses a limited set of relevant key indicators that is to be identified considering the particularities of the alternatives under consideration. The values of key indicators need to be assessed separately, and they are usually entered as a performance table to the tool. Since the MAVT-based comparative evaluation of NES options requires that single attribute value functions and weighting factors be assigned to all performance indicators and attributes, KIND-ET needs also to be populated with relevant data that can be prepared following the guidance on the comparative evaluation approach. When all the above steps are completed, KIND-ET can help to identify merits and demerits of compared nuclear (and other) technologies and evaluate their overall performances and ranks considering NES performance data as well as experts' and decision makers' judgments and preferences (Fig. 2.3).

The characteristic features of KIND-ET include ease of use, user-friendly interface, automation and visualisation of the capabilities for integrating the scores with convenient tools for managing and processing calculation results. KIND-ET provides some flexibility for exploring the implementation of the various forms of the MAVT method. KIND-ET was verified on a number of numerical examples by comparison with calculations based on commercial decision support software. The verification confirms that the KIND-ET tool provides correct evaluations and can be used for numerical case studies.

The scope of multi-criteria examinations of NES deployment scenarios as well as comparisons of NES options at the technological level can be extended to include the advanced sensitivity and uncertainty treatment techniques that will make it possible to enhance the quality of the ranking results presentation taking considering objective and subjective uncertainties as well as to widen the scope of the application of the approach to new problems.

As illustrations of the tool interface elements in this publication, Figure 2.3 provides screenshots of the decision support model for the case study presented in Chapter 4.2 on the comparative evaluation and ranking of nuclear fuel cycle options in terms of sustainable operation and waste management. This case study is an extension of the case study performed within the KIND collaborative project [2.1].

Levels	1a	1b	1c	2a	2b	2c	2cV	3a	3b	3bV	3cV1	3cV2
Multi-attribute value function	0.346	0.433	0.395	0.465	0.465	0.772	0.761	0.664	0.639	0.484	0.792	0.844
Areas scores												
Resource utilization	0.000	0.037	0.033	0.044	0.003	0.187	0.187	0.124	0.117	0.080	0.333	0.323
Waste management	0.013	0.112	0.085	0.170	0.296	0.312	0.310	0.297	0.306	0.300	0.328	0.322
Economics	0.333	0.284	0.277	0.251	0.166	0.272	0.264	0.243	0.216	0.103	0.130	0.199
Total	0.346	0.433	0.395	0.465	0.465	0.772	0.761	0.664	0.639	0.484	0.792	0.844



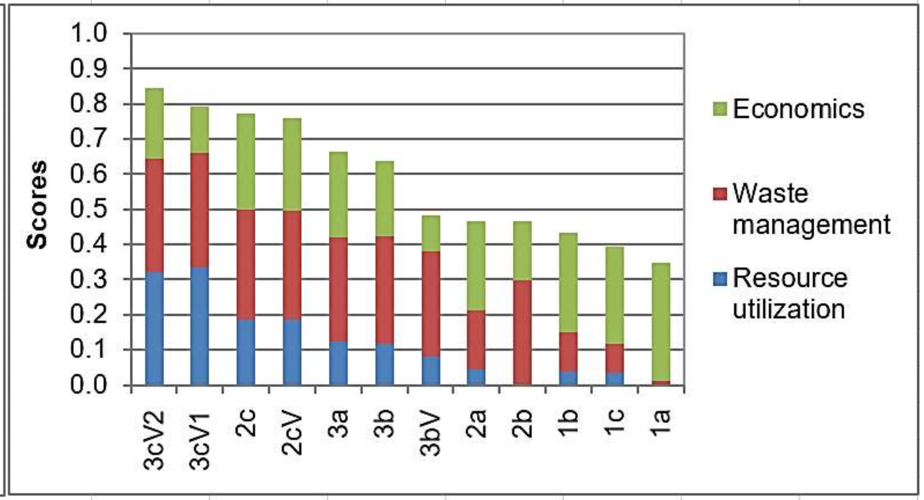


FIG. 2.3. The resulting worksheet of KIND-ET (screenshot)[4].

[4] Herein and below are screenshots of the tools populated with case study data on the comparative evaluation and ranking of nuclear fuel cycle options in terms of sustainable performance and waste management performed as part of the KIND collaborative project and extended within the CENESO collaborative project.

2.2.4.2. *Directions for the extensions of the comparative evaluation approach*

To facilitate screening studies involving the reduction of a large set of alternatives to a smaller one, which most likely contains the best choice, an appropriate analytical tool is to be provided to screen for dominance or to perform a preliminary analysis. This tool is expected to identify options that are objectively less attractive than others, regardless of the decision rules used. The main fundamental concept applied herein is the concept of dominated options, briefly described above. Also, information about non-dominated and dominated options can be useful for interpreting the ranking results, including the results of uncertainty/sensitivity analyses: the ranks of dominated options will be always less attractive than the ranks of options which dominate them.

The sensitivity treatment related to weighting factors which was implemented in KIND-ET is based on the deterministic direct approach, which allows implementing various specific forms of deterministic sensitivity analysis and, in particular, the quite popular 'linear weight' approach. This approach makes it possible to analyse the impact of the assigned weight on the ranking order of alternatives but only for one selected weighting factor at the selected level of the objective tree, i.e., either high-level objectives (top), or evaluation areas (intermediate), or key indicators levels. This approach helps to identify the weight values which might reverse the rank order and thus is helpful in verifying the robustness of ranking results. However, the drawback of the linear weight technique is that this procedure is limited to only one change in the single weighting factor at a time. The lessons learned from the case studies carried out as part of the KIND collaborative project indicate the need to develop an approach that would allow multi-dimensional 'weight space' treatment implying simultaneous variations in all or, at least, in a large subset of weighting factors. A new Monte Carlo-based simulation technique needs to be made available as an extension of KIND-ET. A probabilistic uncertainty analysis needs to imply a simultaneous random variation of weighting factors in the range of their definition and an identification of alternatives with the best potential for the corresponding weight combinations.

In some decision supporting studies, there might be no or very limited information about the structure of the objective tree and the priorities (weights) of experts or stakeholders. For both, the inter-criteria and the intra-criteria preferences target-oriented limitations imposed by experts on weights variation ranges are to be allowed. This means that a relevant instrument is to make it possible to assign to each indicator value a weighting factor interval with lower and upper bounds instead of only one discrete weight value. This range needs to be further considered in aggregating judgments in order to identify the preferred option. The probability distribution of the overall scores can be generated using these stochastic variations of weights and the relevant overall score and ranks spreads can be effectively represented as a box and whisker plot. Therefore, it was suggested to extend the KIND-ET capability with the help of data generation for building a box and whisker plot.

The effect of uncertainty in weights assigned to high-level objectives could be visualized as a rank mapping diagram. Such a representation based on an appropriate analytical tool will facilitate the interpretation of ranking results and identification of the most promising options for different priorities, which will allow experts to perform a multi-criteria classification (or sorting) of options.

As a rule, the exact values of indicators and forms of single attribute value functions are unknown; instead, the indicators and parameters of single attribute value functions are characterized by a certain range of values. In cases where an indicator or a single attribute value function parameter are evaluated qualitatively (for example, based on expert judgments), the uncertainty in their values may be caused by the ambiguity of reflecting expert qualitative judgments in a score scale. Thus, it may be important to analyse the sensitivity of the ranking results to the scatter in possible values of indicators or parameters of single attribute value functions. Sensitivity/uncertainty analyses with regards to single attribute value functions and key indicators examine the changes in the final results (ranks of alternatives) due to variations in single attribute value functions and key indicators. Providing relevant capabilities within KIND-ET is another important direction for the tool extension.

2.2.4.3. The KIND-ET extensions

Below is a short description of the functional extensions for KIND-ET [2.1]. These extensions are provided as separate Excel-based analytical tools in separate files and may be used by experts independently or in any combinations to deepen the analysis/expertise and enhance the quality of presented results. The data input to these tools is consistent with the formats used in KIND-ET and it is assumed that, for the effective application of these tools, a KIND-ET model is to be elaborated beforehand. All tools contain no macros – they are simply Excel spreadsheets.

These extensions enhance the KIND-ET capability to assist experts in performing sensitivity/uncertainty analyses regarding weights, key indicators and single attribute value functions. These tools provide a preliminary screening of options under consideration (in terms of identifying dominated/non-dominated options), uncertainty examination regarding weighting factors (at the highest and lowest levels of the objective tree), key indicators, single attribute value functions and presentation of results in a suitable and understandable form to experts specialising in issues related to nuclear energy planning and technology assessment.

Details regarding the decision support toolkit developed, verified and applied within the KIND and CENESO collaborative projects for comparative evaluations and ranking of NES options can be found in Annex II in the electronic version of this report.

Figure 2.4 shows the framework for utilising KIND-ET and its extensions to perform decision support and relevant sensitivity/uncertainty analyses with respect to key factors important to decision making.

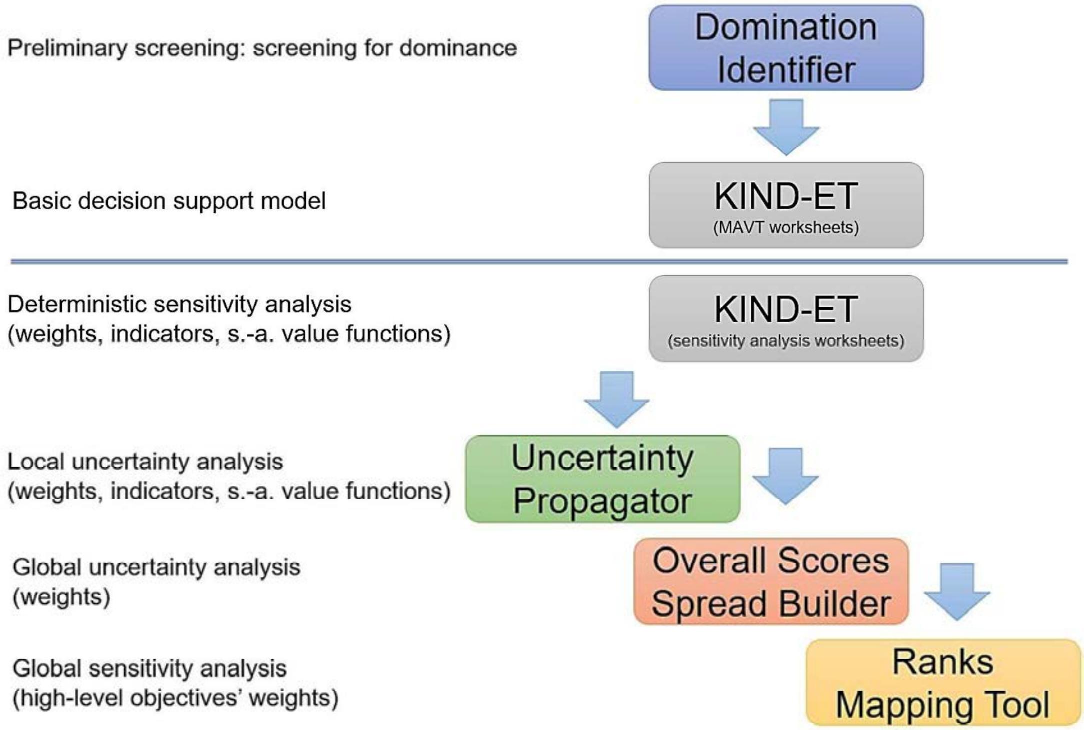


FIG. 2.4. The KIND-ET tool and extensions.

(a) KIND-ET extension-1: Domination Identifier

Domination Identifier is an Excel-based analytical tool extension for KIND-ET for identifying non-dominated and dominated options from a set of considered feasible options (Fig. 2.5). To identify dominated and non-dominated options within Domination Identifier, the following observation is used: in terms of the normalized values of the key indicators (assuming that the worst normalized value of a key indicator is zero and the best normalized value of a key indicator is unity), the normalized values of key indicators for a certain option (called 'dominated') will be lower than the normalized values of key indicators for an option called 'dominating'. Based on this observation, Domination Identifier builds a table demonstrating dominated and dominating options.

Domination table		Dominating options											
		1a	1b	1c	2a	2b	2c	2cV	3a	3b	3bV	3cV1	3cV2
Dominated options	1a		-	-	-	-	-	-	-	-	-	-	-
	1b	-		-	-	-	-	-	-	-	-	-	-
	1c	-	<		-	-	-	-	-	-	-	-	-
	2a	-	-	-		-	-	-	-	-	-	-	-
	2b	-	-	-	-		-	-	-	-	-	-	-
	2c	-	-	-	-	-		-	-	-	-	-	-
	2cV	-	-	-	-	-	-		-	-	-	-	-
	3a	-	-	-	-	-	-	-		-	-	-	-
	3b	-	-	-	-	-	-	-	-		-	-	-
	3bV	-	-	-	-	-	-	-	-	<		-	-
	3cV1	-	-	-	-	-	-	-	-	-	-		-
	3cV2	-	-	-	-	-	-	-	-	-	-	-	

FIG. 2.5. The resulting table of Domination Identifier (screenshot).

(b) KIND-ET extension-2: Overall Score Spread Builder

Overall Score Spread Builder is an express Excel-based tool extending the KIND-ET functionality for evaluations of an option's overall score and ranks spreads as well as probabilities for options to occupy certain places in the ranking caused by uncertainties in weighting factors and the objective tree structure (Fig. 2.6). Within this tool, the impact of weighting factor uncertainty on ranking results is examined using stochastic (probabilistic) variation of weighs that represent the relative importance of a single indicator. This approach makes it possible to determine the probability distributions of option scores and ranks as well as probabilities for options to occupy certain places in the ranking, considering uncertainties in weighting factors. Such examination allows one to make overall judgments about the ranking results despite the lack of final information usually obtained by involving experts and stakeholders in an iterative process.

Within this approach, it is assumed that all the weights are randomly and uniformly distributed in the range from 0 to 1, constrained only by the normalisation condition (global uncertainty analysis with respect to weights). All the other assumptions are unchanged. For each weight combination, the MAVT-based evaluation is performed to identify the overall scores and ranks for options and this information then used for evaluation of probabilities for options to take a certain rank. For a reliable estimation of probability distributions of overall scores and ranks, 10,000 weight combinations are considered.

This stochastic analysis demonstrates the spread of overall scores and ranks for each option, which makes it possible to draw a conclusion about the stability of ranks. The spread of overall scores and ranks for all the options considered due to uncertainties in weighting factors is represented as a box and whisker plot. Based on this information and selecting an appropriate decision rule for ranking options in case of uncertainty, the final option ranks may be obtained which would incorporate relevant uncertainties.

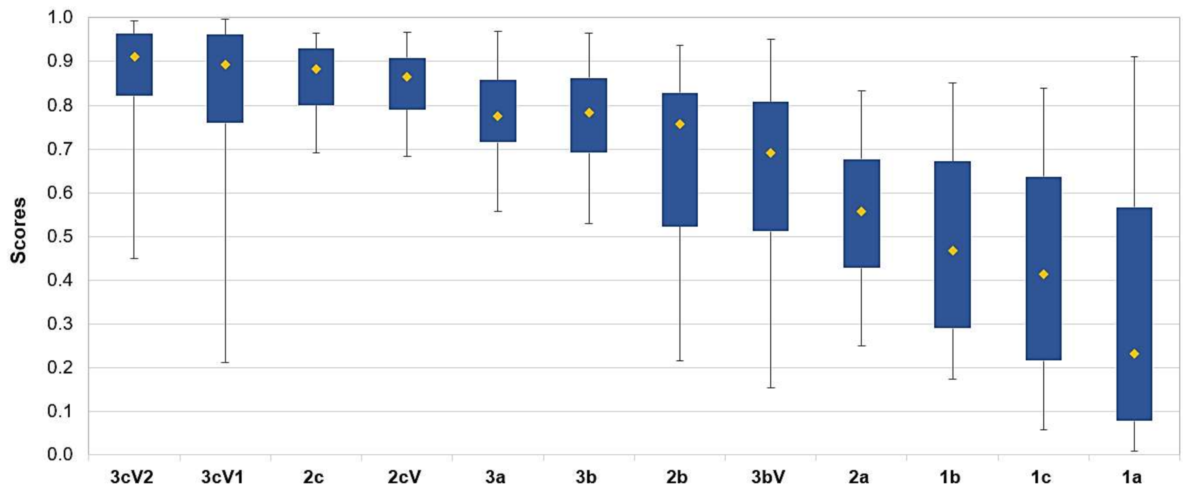


FIG. 2.6. The resulting diagram of the Overall Score Spread Builder.

(c) KIND-ET extension-3: Ranks Mapping Tool

Within the KIND approach, it is assumed that, at the highest level of the objective tree, two or three high-level objectives are to be specified in aggregated categories so as to be able to articulate merits and demerits associated with the options under consideration. A decision-maker is responsible for assigning the high-level objective weights within the MCDA-based comparative evaluation procedure. Relevant decision-maker's judgments are always subjective and need to be tailored to local national conditions.

To assist decision makers in reaching a better understanding of the most preferable options for different high-level objective weights, it seems useful to provide appropriate data in a convenient visual representation. In order to cope with this problem, a global sensitivity analysis of ranking results needs to be performed with respect to the high-level objective weights.

Ranks Mapping Tool is a visualisation Excel-based tool extending the KIND-ET functionality to identify the options taking the first rank and highlight related areas in the high-level objective weight space (Fig. 2.7). Relevant data presented in a tabulated form within Ranks Mapping Tool are visualized by means of Excel conditional formatting. The coloured areas indicate the combinations of weights for which a specific option takes the first rank. Thus, this picture demonstrates a map of preferences and provides a better understanding of how promising and robust each option ranking is in terms of high-level objective weights.

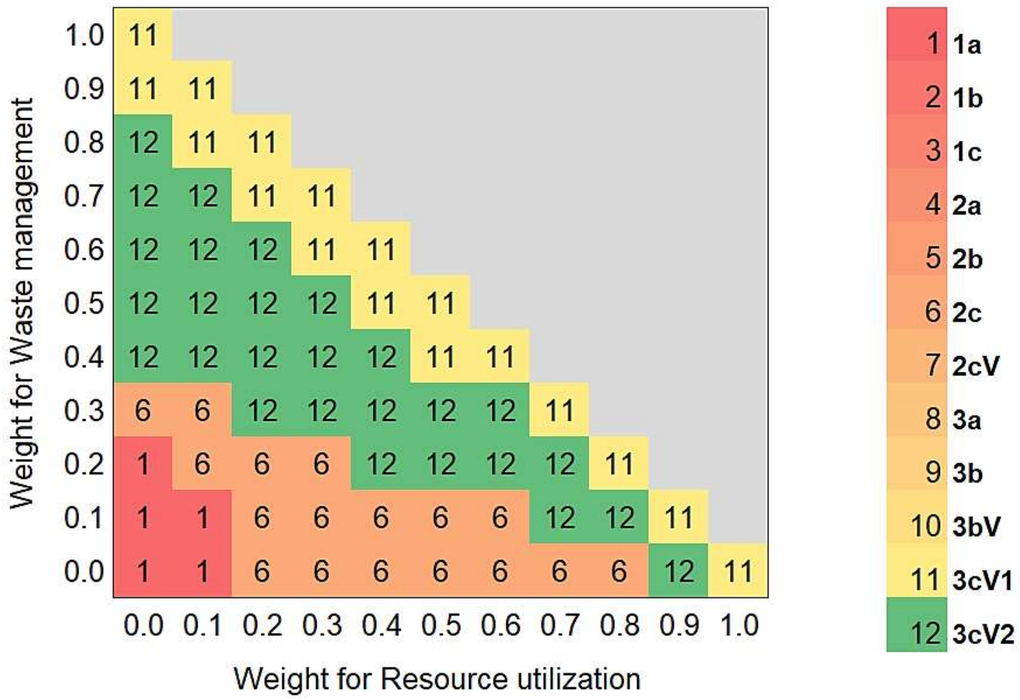


FIG. 2.7. The resulting diagram of Ranks Mapping Tool.

(d) KIND-ET extension-4: Uncertainty Propagator

Uncertainty Propagator is a KIND-ET extension based on the classical error analysis framework (local uncertainty analysis) [2.7] for evaluating uncertainties in the option overall scores due to uncertainties in the single attribute value function forms and key indicators (Fig. 2.8). Using Uncertainty Propagator, it is also possible to evaluate the contribution of uncertainties in weighting factors to overall scores' uncertainties, but this functionality can be applied only in cases where small uncertainties in weights are considered – the so-called 'local weights variations'. For more detailed evaluations of the weighting factors' contribution to overall scores' uncertainties, the Overall Score Spread Builder can be used.

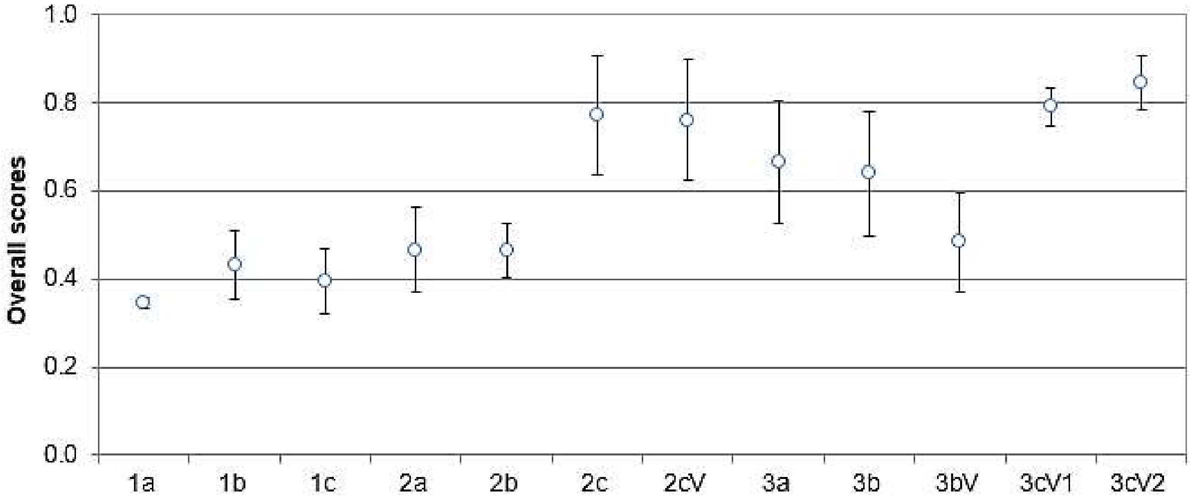


FIG. 2.8. The resulting diagram of Uncertainty Propagator.

2.3. LESSONS LEARNED FROM THE CASE STUDIES OF THE KIND COLLABORATIVE PROJECT AND PATH FORWARD

Based on the KIND comparative evaluation approach, several trial studies have been performed related to comparative evaluations of hypothetical NES options, NESs based on different types of evolutionary and innovative reactors, nuclear and non-nuclear energy systems, and NES deployment scenarios [2.1]. The quantitative numerical studies carried out as part of the KIND collaborative project and related to comparative evaluations of NES options can be roughly subdivided into three categories:

- Generic case studies on comparisons of hypothetical NES options;
- Comparative evaluations of national NES options on a trial basis: innovative versus innovative, evolutionary versus innovative, evolutionary versus evolutionary, and nuclear versus non-nuclear energy systems;
- Comparative evaluations of NES deployment scenarios.

All the case studies represent only trial applications of the KIND comparative evaluation approach. Nevertheless, they demonstrate the applicability of the approach and the tools developed within the project to comparative evaluations of NES options and their capability to bring out benefits and challenges associated with the various energy supply options under consideration that are of potential interest to technology holder, technology user, and newcomer countries.

Generic case studies on hypothetical systems are a quite common illustrative approach in various subject areas eliminating the need to prepare tables of characteristics of real systems that might require significant time and efforts. Several case studies on comparative evaluations of hypothetical NES options were performed to test the comparative evaluation approach and demonstrate the relevant decision analysis procedure. Within these hypothetical system related studies, the performance tables were formed randomly[5] while model parameters were selected in line with the suggestions of the KIND collaborative project.

[5] This is different from real world (non-hypothetical) systems for which performance tables are to include the values of key indicators either calculated or based on expert judgment.

Comparative evaluations of national NES options on a trial basis were performed in the framework of the KIND collaborative project by interested INPRO members in order to exercise a novel approach, support decision making processes and prioritisations in national programmes on nuclear energy development and rank NES options (or nuclear versus non-nuclear option in case it was more relevant for a national strategy).

Comparative evaluations of NES deployment scenarios performed in the KIND collaborative project addressed various technology options: conventional, evolutionary and innovative NES options, considering characteristic features of the related nuclear fuel cycles.

The activities performed under the KIND collaborative project demonstrated that the developed approach could be applied not only to comparisons of NES options at the technological level but also to comparisons of NES evolution scenarios to enhance the multifaceted examination of national or regional energy production strategies. It became evident that the application of the comparative evaluation approach provides the opportunity to establish an effective dialogue among proponents of NES options, decision makers, and other stakeholders.

In general, the case studies were of methodological nature and did not identify any possible directions of the countries' nuclear energy development; however, specific national conditions were addressed in the majority of the studies. These case studies were not deemed to reflect adequately 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 simply to understand how useful this approach could be to maintain the corresponding dialogue.

All the case studies of participating Member States include the following sections:

- 'Introduction' section presents the application context and background of a case study and relevance to the objective of the KIND project.
- 'Objective and problem formulation' section describes the objective of a particular case study; wording of questions to be answered.
- 'Formulation of alternatives (NES options)' section identifies a list of NES options to be evaluated in a study.
- 'Identification of indicators' section defines key and secondary indicators, objective tree and their detail description.
- 'Evaluation of indicators including uncertainties' section specifies input data used, indicators and their uncertainties, and performance tables.
- 'Selection of a MCDA method' section justifies the selection of the most suitable method(s) and its/their parameter(s).
- 'Determination of weights including uncertainties' section identifies and assigns weights according to the objective tree.
- '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 in simple terms clear to non-experts.
- 'Sensitivity and uncertainty analysis' section analyses weight sensitivity, value function sensitivity, indicators' uncertainty and their impact on NES ranking as well as the results of comparative evaluations;
- 'Conclusion' section contains conclusions of the study in the form of a summary.

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 an option to go down to lower aggregation levels and, when necessary, to particular indicators, sensitivities and uncertainties. Namely, this top-down analysis and representation could make a dialogue with decision-makers useful and productive.

2.3.1. Innovative versus innovative nuclear energy systems

The first case study on the comparison of innovative NES options based on fast reactors was performed for two deployment scales of nuclear energy: low power at 20 GW(e) and high power at 100 GW(e). Five key indicators from different areas of the INPRO methodology were investigated. A small number of key indicators in the comparative evaluation of NES options were selected to visualise the most significant trends and ensure their maximum independence from one another.

The objective of another study was to apply the KIND approach for a comparative evaluation of innovative NES options including both reactor and related fuel cycle facilities in the long term. This case study considered three NES options: NES based on thermal reactors, NES based on fast reactors, and mixed two-component NES based on thermal and fast reactors. All systems were considered as closed fuel cycle systems with recycling of all heavy nuclides (including U, Pu and minor actinides (MA)).

Lessons learned from the case studies identified the following features of the comparative evaluation approach:

- The comparative evaluation approach offers an opportunity to take long term sustainability issues into account.
- The final weights' definition technique significantly influences the ranking of results and can even result in overturning of the ranking order of the considered alternatives.
- For the comparative evaluation of NES options in a long term, it is preferable to use the single level objective tree with equal final weights to consider all aspects of the evaluated NESs without any favour to a particular area.
- The NES comparative evaluation needs to use key indicators related to the entire innovative NES (including fuel cycle) rather than a particular reactor.

Based on the experience gained from these case studies, it was suggested:

(a) To consider within the CENESO collaborative project not only the comparison of thermal reactors versus fast reactors, but ranking of a joint nuclear fuel cycle option associated with different NES options based on thermal and fast reactors;
(b) To proceed to dynamic multi attribute evaluations by applying the comparative evaluation approach for the selected scenarios;
(c) Due to significant macroeconomic uncertainties, to consider different scenarios hypothesising a high nuclear energy production demand up to demand stabilization;
(d) To address once again an identification and selection of weights, considering the KIND collaborative project findings, in order to reflect specific issues for near term and medium term nuclear industry development;
(e) To impose target-oriented limitations on weights;
(f) To enhance scenario studies within the CENESO collaborative project by performing sensitivity treatment regarding NES economic performance and by applying the

comparative evaluation approach to evaluate several Russian energy development strategies, including non-nuclear options.

Possible scenarios to be considered are:

(i) Nuclear phase-out, fossil fuel generation and renewables;
(ii) Transition to fast reactors with closed nuclear fuel cycle, fossil fuel generation and renewables;
(iii) Multi-component sustainable NES development on the basis of innovative technologies;
(iv) Two-component NES deployment with extended sensitivity and uncertainty analyses (the two-component NES is based on thermal and fast reactors).

In view of the new case studies proposed in the CENESO collaborative project, the capabilities of the comparative evaluation approach have been extended by adding a couple of more advanced features.

2.3.2. Evolutionary versus evolutionary nuclear energy systems

Within the relevant case study, it was assumed that the important issue for a technology user country is to choose a new nuclear option which will replace the existing unit after its decommissioning in 2026. The overall energy system development in the future was assumed to be based on competitive nuclear, natural gas and renewable energy technologies. In this, diversified fuel supply options were viewed as an important asset.

The main goal of this case study is to present how the KIND comparative evaluation approach and relevant tools can be used to clarify and select the most attractive nuclear option for the technology user country based on a comparative evaluation of evolutionary versus evolutionary nuclear energy systems.

Four nuclear plants– WWER-1000 (1000 MWe), CANDU-6 (700 MWe), SMR (360 MWe) and ACP-600 (600 MWe) – and one thermal power plant were selected for comparative evaluation. Eleven key indicators have been identified and grouped in six evaluation areas including economics, waste management, country specific, environment, maturity of technology, and public acceptance.

The main conclusions drawn from this case study are:

— The MAVT method makes it possible to implement different approaches for comparing and distinguishing alternatives as well as interpreting the ranking of results. It could be suggested for use in future evaluations.
— Decisions based on the evaluation outcomes can be considered as reasonable for development of future strategies.
— The KIND-ET tool provides enough flexibility in modelling different scenarios for comparative evaluations not only of NESs but also of non-nuclear energy supply options. It makes it possible to enlarge, modify and/or add spreadsheets to provide additional analyses in more specific ways.
— Future improvements of the KIND-ET tool can be based on the results and lessons learned from new evaluations which have been done as part of the CENESO collaborative project.

New case studies in the framework of the CENESO collaborative project could be based on the requirements of the UN Sustainable Development Goal 7[6]: "Ensure access to affordable, reliable, sustainable and modern energy for all" and Goal 13[5]: "Take urgent action to combat climate change and its impacts", as well as to take into consideration countries' obligations on GHG emissions reduction in the frame of the Paris Agreement.

Envisaged studies could include:

(a) Scenarios considering comparative evaluations of the integrated operation of variable renewables and nuclear options together with other generation sources;
(b) Performance of a joint study by a group of interested Member States in order to achieve better results.

Some project participants expressed interest in collaborating with partners involved in evaluating innovative and evolutionary NES technologies.

2.3.3. Evolutionary versus innovative nuclear energy systems

This case study performed as part of the KIND collaborative project highlighted the following important elements:

- Three NES technologies were chosen for the comparative multi-criteria analysis (CANDU 6 – operating NES technology in the country; Gen III+ Enhanced CANDU – evolutionary NES technology; and Gen IV lead cooled fast reactor (LFR) – innovative NES technology).
- A three-level objective tree with corresponding high-level objectives, areas of evaluation and key indicators was applied.
- Country-specific key indicators and elements for their evaluation were selected.
- Both working cases and sensitivity cases were defined for the comparative analysis; the overall scores and scores for specific areas of evaluation were used.

The KIND approach used for the comparative analysis of the evolutionary and innovative NES technologies made it possible to show the positive potential of the innovative technology by creating its correct image and considering the country's specific conditions.

New proposals for the CENESO collaborative project include:

(a) To apply the multi-criteria analysis and tools for the national NES development scenarios developed under the framework of the national project for the Nuclear Energy System Assessment (NESA) using the INPRO methodology;
(b) To refine some case studies performed in the KIND collaborative project by including the 3-level objective tree analysis based on benefits versus risks, elements of strategic importance, especially on the decision making level.

[6] https://sdgs.un.org/goals

2.3.4. Nuclear versus non-nuclear energy systems

A set of key indicators for newcomer countries was elaborated in this study because some key indicators in the comparative evaluation approach may be inapplicable in a country in which there are no nuclear power plants, but conventional energy and renewable energy systems are widely used and familiarly operated.

For the comparative evaluation between a NES and non-NES options, a 3-level objective tree with 2 high-level objectives, 4 areas of evaluation and 11 key indicators was conducted. For the NES, the average values from the 6 reference plants of ABWR, AP1000, ATMEA1, VVER-1200, ACPR-1200, and APR-1400 were evaluated. Coal fired power plants (CPPs) with integrated gasification combined cycle (IGCC) technology was considered for non-NES options.

The results show that CPPs became a more attractive option than NESs when the "Acceptability" high-level objective was more of concern than the "Economic" one. The variation in the weighting factor for the high-level objective presented an interesting result regarding the attractiveness of a NES. In the CENESO collaborative project, this study was extended by performing an additional sensitivity and uncertainty analysis and considering another scenario option.

2.3.5. Comparison of nuclear energy evolution scenarios

Two case studies on comparison of NES deployment scenarios were performed under the KIND collaborative project: a comparative evaluation of the GAINS NES deployment scenarios and a comparative evaluation of the OECD/NEA advanced fuel cycle options.

A case study on applying several MCDA methods to comparative evaluations of the NES deployment scenarios investigated in the INPRO collaborative project "Global architecture of innovative nuclear energy systems based on thermal and fast reactors including a closed fuel cycle" (GAINS)[7] was carried out to demonstrate the applicability of the KIND approach to comparisons of NES deployment scenarios.

Eleven GAINS scenarios were examined which were evaluated by 9 key indicators. Four weighting options were considered reflecting possible experts' preferences regarding the objectives that NESs are expected to achieve: (1) equal significance of all key indicators; (2) expert preferences based on the questionnaires of the INPRO meetings; (3) preference to investments minimisation; and (4) preference to wastes minimisation.

Considering the results of the sensitivity analyses, the additional analyses of alternatives by the supplementary methods and the entire set of graphical and attribute information, the most preferable NES options were identified for different experts' preferences regarding the NES objectives. Based on the comparative evaluation of NES deployment scenarios, it is also possible to identify potential merits and demerits concerning relevant nuclear technologies from the viewpoint of the complete NES, so as to provide recommendations for improvements of technology performance.

The technically oriented OECD/NEA study on "Advanced Nuclear Fuel Cycles and Radioactive Waste Management" launched in 2004 was focused on the impact of fuel cycle strategies on the uranium consumption and waste management. The examined nuclear fuel

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[7] https://www.iaea.org/sites/default/files/18/09/inpro-gains-2014.pdf

cycle options included once-through, recycling in thermal reactors, sustained recycle with a mix of thermal and fast reactors, and sustained recycle with fast reactors.

The objective was to identify nuclear fuel cycles that could provide benefits to the spent fuel/HLW repository programme, enhancing the use of uranium resources and the prospects for nuclear power. Within the case study, 12 fuel cycle options were considered which were evaluated by 8 key indicators. The comparison demonstrates that some partly closed fuel cycle options represent trade-off options providing benefits to the repository programmes and enhancements of the nuclear resource uses at suitable additional costs.

Within the CENESO collaborative project, it is possible to extend these studies by elaborating a relevant dynamic multi attribute decision making model for comparative evaluations of global NES deployment scenarios and a multi-group decision support model for comparing synergetic and non-synergetic NES deployment scenarios as well as performing an advanced sensitivity/uncertainty analysis for the comparative evaluation and ranking of nuclear fuel cycle options in terms of sustainable performance and waste management.

2.3.6. Other KIND approach-based studies

At the moment, the developed comparative evaluation approach is being extensively applied within and outside the INPRO activities for comparative evaluations of various NES options at the scenario and technological levels, comparisons of nuclear fuel supply and waste management options, and examination of cross-cutting issues that demonstrate the potential of the elaborated toolkit for decision support within a wide range of different practical nuclear engineering problems requiring expert judgment aggregations [2.8–2.14]. The following tasks are the primary problems of potential interest requiring judgment aggregation to provide ranking, sorting, and selecting NES options and their components, considering the preferences of experts, decision-makers and stakeholders:

- Comparative evaluation of energy supply mixes including a nuclear component in terms of sustainable performance;
- Comparative evaluation and selection of more preferable technological or structural parameters of NES options or components thereof balanced across different conflicting indicators and attributes;
- Comparative evaluation of the fresh fuel supply and spent fuel management options and/or final disposal of spent fuel and HLW in a national deep repository or through international cooperation in the back end of the fuel cycle;
- Identification of cost effective risk mitigation measures associated with the advanced NES deployment;
- Decision analysis to support the site selection studies for fuel cycle facilities (especially for the fuel cycle back-end);
- Multi-criteria support of effective R&D resource allocations for the advanced technologies providing sustainable and cost effective NES deployment.

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3. COUNTRY CASE STUDIES ON COMPARATIVE EVALUATIONS OF NUCLEAR ENERGY SYSTEM ALTERNATIVES AND EVOLUTION SCENARIOS

This chapter presents structured reports of the case studies done by experts from Member States.

3.1. COMPARATIVE EVALUATION OF INTEGRATED OPERATION OF VARIABLE RENEWABLES AND NUCLEAR OPTIONS TOGETHER WITH OTHER GENERATION SOURCES (ARMENIA)

This chapter presents structured report of a case study done by experts from the Republic of Armenia.

3.1.1. Introduction

Within the INPRO/IAEA collaborative project “Key indicators for innovative nuclear energy systems” (KIND) [3.1], the Republic of Armenia performed the case study on comparative evaluation of “Evolutionary versus evolutionary nuclear energy systems”. This case study has demonstrated the applicability of the KIND approach for the comparative evaluation of the benefits and risks associated with the selected energy system options. The lessons learned show the need of further development of the national capability to perform medium term and long term strategic planning for nuclear energy programmes including international collaborations. Thus, the experience of the KIND project and the KIND approach developed therein could be used to perform comparative evaluations of NES options/scenarios of practical interest to Armenia.

The overall objective of the CENESO project is to implement the lessons learned from the KIND project outputs and extend the KIND approach and the case studies on comparative evaluation of NES options/scenarios of interest to CENESO participants.

For this purpose, KIND-ET new functional extensions for their follow-up application in the CENESO collaborative project have been developed [3.1], namely:

- **Domination Identifier** – an analytical tool for identification of non-dominated and dominated options among the set of considered feasible options;
- **Overall Score Spread Builder** – an express tool for evaluation of option overall score spreads caused by uncertainties in weighting factors and the objective tree structure;
- **Ranks Mapping Tool** – a visualization tool to highlight the options taking the first rank for different combinations of high-level objective weights.

These extensions expand the KIND-ET capability to assist experts facing difficulties with evaluations of weighting factors. In particular, these tools provide a preliminary screening of options under consideration (in terms of highlighting dominated/non-dominated options), uncertainty examination regarding weighting factors (at the highest and lowest levels of the objective tree) and representation of results in a suitable and understandable form to nuclear experts. The extensions are available as separate Excel-based analytical tools in separate files and may be used by experts independently or in any combination to deepen the analysis/expertise and enhance the quality of represented results. The data inputting to these tools is consistent with the formats used in KIND-ET, and for the effective application of these tools, a KIND-ET model is to be elaborated beforehand.

The main goal of this study was to apply additional modules of the KIND-ET tool to the Armenian CENESO case study.

3.1.2. Identification of domination options

In the Armenian case study performed within the KIND project [3.1], four nuclear technologies (WWER-1000, CANDU-6, SMR (small modular reactor) with a capacity of 360 MW(e) and ACP-600) and one non-nuclear (thermal & renewables) technology have been assessed by 11 key indicators (KIs) briefly listed below:

— E.1: Levelized long term average NPP production cost;
— E.2: Power system long term average generation cost;
— E.3: New generation investment cost;
— E.4: Whole energy system cost;
— WM.1: Specific radioactive waste inventory;
— CS.1: Energy independency level;
— ENV.1: The amount of useful energy produced by the system from a unit of mined natural uranium/thorium;
— M.1: Design stage;
— M.2: Time needed to mature the technology for Armenia;
— M.3: Degree of standardization and licensing adaptability for Armenia;
— PA.1: Public acceptability to use nuclear energy.

These performance indicators have been grouped in six evaluation areas:

— Economics;
— Waste management;
— Country specific;
— Environment;
— Maturity of technology;
— Public acceptance.

Based on the requirements of the KIND approach, three high-level objectives (HLOs) characterized by aggregated goals, Cost, Performance and Acceptability were chosen and grouped as follows:

— HLO-1: Economics – for Cost;
— HLO-2: Waste management, Country Specific and Environment – for Performance;
— HLO-3: Maturity of technology and Public acceptance – for Acceptability.

Figure 3.1 summarizes the indicators arrangement in a hierarchical structure known as an objective tree.

The values of all key indicators for considered NESs were prepared in accordance with the assumptions regarding the goals to be achieved by each KI. Their assumptions, as well as explanations of numerical values of scores and weighting factors are already described in detail in the Armenia study report prepared for the KIND collaborative project and are given in the corresponding Performance table. The same Performance table has been used for the current study and is presented in Fig. 3.2. This figure is a screenshot from the KIND-ET tool, it does not show the units which actually are as follows:

— E.1: Levelized long term average NPP production cost, US $/MW(e)·h;
— E.2: Power system long term average generation cost, US $/MW(e)·h;
— E.3: New generation investment cost, billion US $;
— E.4: Whole energy system cost, billion US $;
— WM.1: Specific radioactive waste inventory, US $/MW(e)·h;
— CS.1: Energy independency level, fraction of indigenously produced energy;
— ENV.1: The amount of mined natural uranium/thorium needed to produce a unit of useful energy by the system[8], tonnes per million MW(e)·h;
— M.1: Design stage, five-point scoring scale;
— M.2: Time needed to mature the technology for Armenia, five-point scoring scale;
— M.3: Degree of standardization and licensing adaptability for Armenia, five-point scoring scale;
— PA.1: Public acceptability to use nuclear energy, two-point scoring scale.

According to the CENESO practice for identifying the domination options (Domination Identifier), the values of KIs have been normalized (Figs 3.3 and 3.4) and the Domination table (Fig. 3.5) has been created.

[8] For the 'No Nuke' case the mass of natural gas (in tonnes) required to produce one million kW(e)·h in a closed cycle gas turbine type thermal power plant was considered, resulting in a large ENV.1 number for this case, as seen in Fig. 3.2.

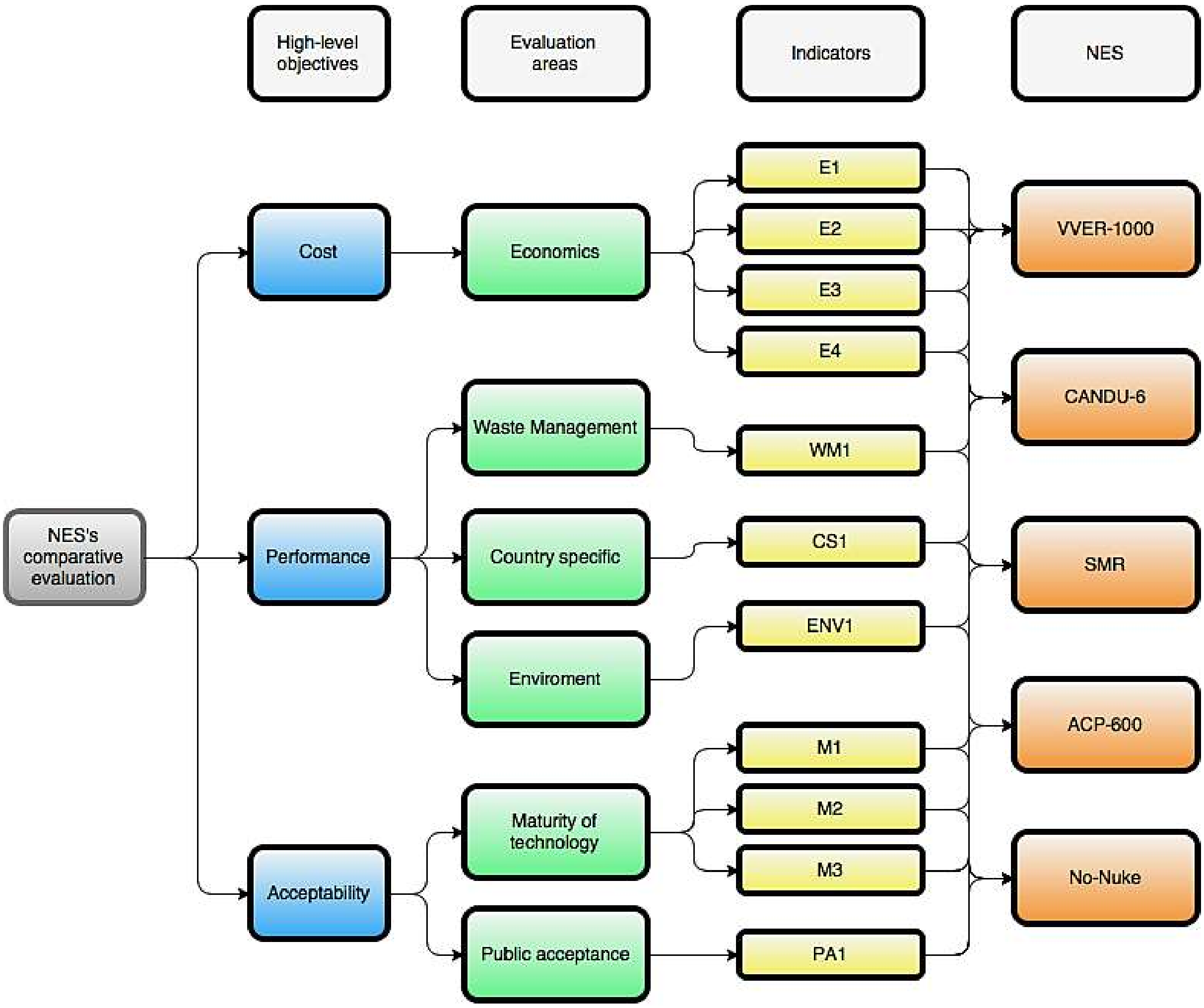


FIG. 3.1. The objective tree.

Indicators titles	Indicators abbr.	MIN score	MAX score	VVER-1000	CANDU-6	SMR	ACP-600	No Nuke
Levelized long-term average NPP production cost	*E.1*	70	110	91	73	97	71	103
Power system long-term average generation cost	*E.2*	60	80	75.9	69.2	77.1	73.2	78.3
Newgeneration investment cost	*E.3*	2000	9000	8566	6986	6896	5022	2431
Whole energy system cost	*E.4*	43000	45000	44555	43954	44701	44347	44868
Specific radwaste inventory	*WM.1*	1	8	1.7688	5.346	1.03	1.7688	8
Energy independency level	*CS.1*	0.3	0.6	0.5853	0.3310	0.5111	0.5000	0.3487
The amount of useful energy produced by the system from a unit of mined natural uranium/thorium	*ENV.1*	18	140000	22.4	18.1	21	21	137000
Design stage	*M.1*	1	5	1	1	5	4	1
Time needed to mature the technology for Armenia	*M.2*	1	5	2	5	4	3	1
Degree of standardization and licensing adaptability for Armenia	*M.3*	1	5	2	5	5	4	1
Public acceptability for use nuclear energy	*PA.1*	1	2	2	2	2	2	1

FIG. 3.2. Performance table in KIND-ET (screenshot).

Indicators titles	Indicators abbr.	Goal	Form	Exponent power	VF domain	MIN VF domain	MAX VF domain	VVER-1000	CANDU-6	SMR	ACP-600	No Nuke
Levelized long-term average NPP production cost	*E.1*	min	lin	1	local	71	103	0.375	0.938	0.188	1.000	0.000
Power system long-term average generation cost	*E.2*	min	lin	1	local	69.2	78.3	0.264	1.000	0.132	0.560	0.000
Newgeneration investment cost	*E.3*	min	lin	1	local	2431	8566	0.000	0.258	0.272	0.578	1.000
Whole energy system cost	*E.4*	min	lin	1	local	43954	44868	0.342	1.000	0.183	0.570	0.000
Specific radwaste inventory	*WM.1*	min	lin	1	local	1.0296	8	0.894	0.381	1.000	0.894	0.000
Energy independency level	*CS.1*	max	lin	1	local	0.33097243	0.58533479	1.000	0.000	0.708	0.665	0.070
The amount of useful energy produced by the system from a unit of mined natural uranium/thorium	*ENV.1*	min	lin	1	local	18.1	137000	1.000	1.000	1.000	1.000	0.000
Design stage	*M.1*	min	lin	1	local	1	5	1.000	1.000	0.000	0.250	1.000
Time needed to mature the technology for Armenia	*M.2*	min	lin	1	local	1	5	0.750	0.000	0.250	0.500	1.000
Degree of standardization and licensing adaptability for Armenia	*M.3*	min	lin	1	local	1	5	0.750	0.000	0.000	0.250	1.000
Public acceptability for use nuclear energy	*PA.1*	max	lin	1	local	1	2	1.000	1.000	1.000	1.000	0.000

FIG. 3.3. Single attribute value functions in KIND-ET (screenshot).

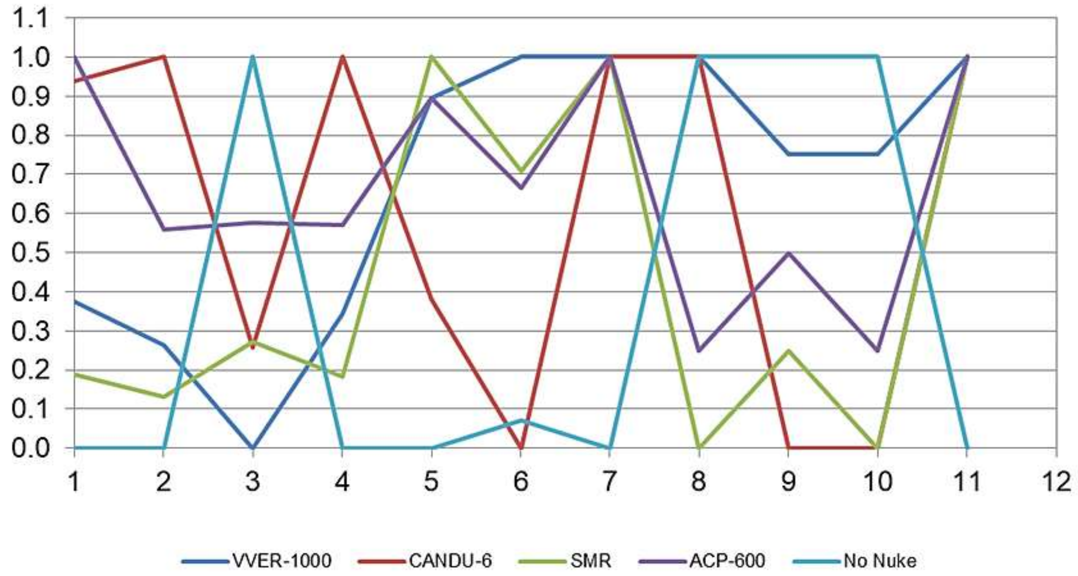


FIG. 3.4. Value path chart (normalized KI values).

Domination table		Dominating options				
		VVER-1000	CANDU-6	SMR	ACP-600	No Nuke
Dominated options	VVER-1000		-	-	-	-
	CANDU-6	-		-	-	-
	SMR	-	-		-	-
	ACP-600	-	-	-		-
	No Nuke	-	-	-	-	

FIG. 3.5. Domination table in Domination Identifier (screenshot).

The domination table shows that no one of the options is dominated; therefore, all options have been accepted for further evaluation.

3.1.3. Overall score spread builder analysis

An examination of the weighting factor uncertainty impact on ranking results was performed by the provided Overall Score Spread Builder tool, which consist of three Excel files:

(1) **Overall Score Spread Builder – Weight Generator**: this component generates 10,000 combinations of weighting factors uniformly distributed in the range from 0 to 1, constrained only by normalization conditions, and provides the capability to select weight combinations satisfying some restrictions.

(2) **Overall Score Spread Builder – Randomizer**: this is an accessorial component of Overall Score Spread Builder allowing one to change conditions for weights randomizations.
(3) **Overall Score Spread Builder – Score Evaluator**: this component evaluates overall scores of options for each weight combination and build the resulting box and whisker chart, demonstrating the spread of overall scores for all options considered due to uncertainties in weighting factors.

All the steps for preparation of **Score Evaluator** Excel file have been performed in accordance with requirements described in the User Instructions. Results are presented in Fig. 3.6.

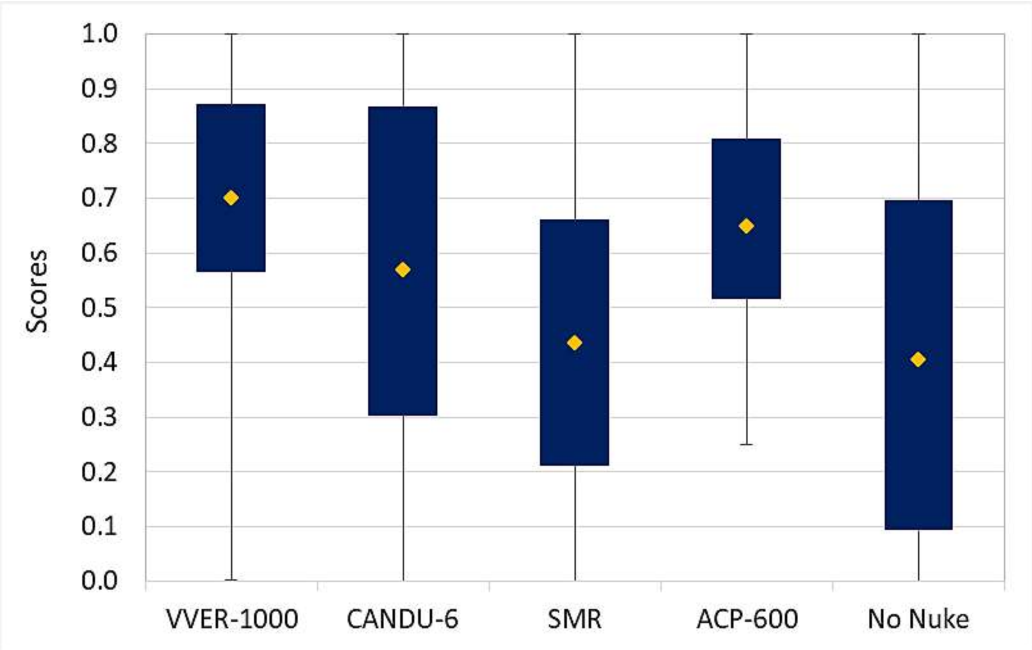


FIG. 3.6. Box and whisker chart for the overall score spreads.

3.1.4. Ranks mapping tool-based analysis

In accordance with the description of the main steps to work with the Ranks Mapping Tool extension presented in the User Instruction (item 3.3), the necessary steps to fill out the tables were accomplished.

The high-level objective (HLO) scores from the KIND project have been moved to the 'HLO scores' worksheet of the Excel file titled 'Ranks Mapping Tool' (see Fig. 3.7). Based on the provided values, Rank Mapping Tool evaluated and highlighted the options taking the first rank (Fig. 3.8) and relevant areas in the high-level objective weight space. It also calculated and visualized overall scores for options given for each weight combination by means of summation of all multiplications of high-level objective scores and relevant weights. These scores are shown on separate worksheets (Figs 3.9–3.13)[9]. Figure 3.14 presents the results of maximum overall scores calculation for all selected NES options: VVER-1000, CANDU-6, SMR, ACP-600, and the non–nuclear options (No Nuke).

	VVER-1000	CANDU-6	SMR	ACP-600	No Nuke
Score for HLO-1	0.131	0.441	0.088	0.305	0.075
Score for HLO-2	0.287	0.076	0.256	0.237	0.010
Score for HLO-3	0.169	0.074	0.081	0.116	0.140

FIG. 3.7. Scores of high-level objectives in Ranks Mapping Tool (screenshot).

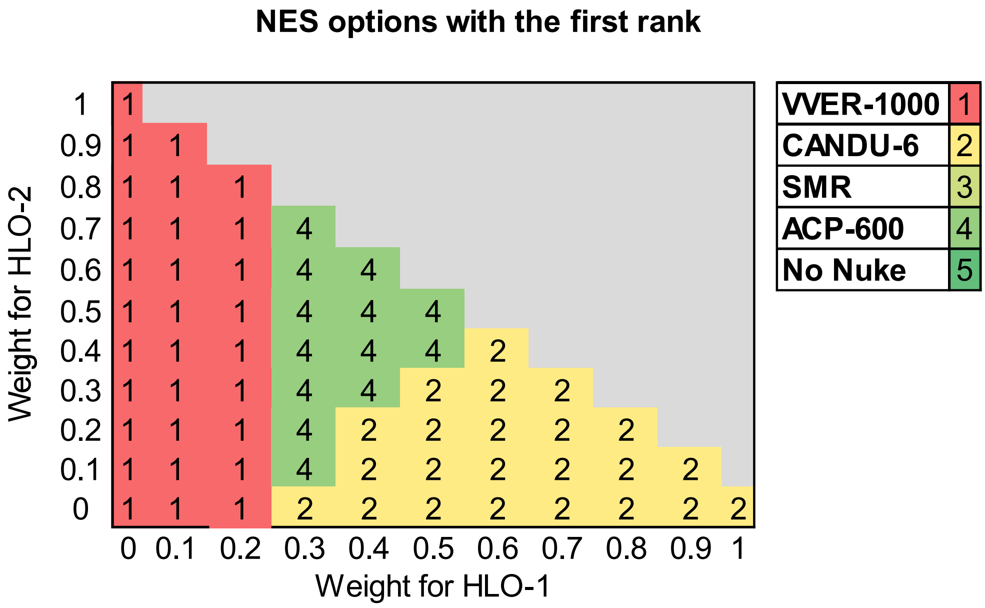


FIG. 3.8. Resulting diagram of the NES options with the first rank.

[9] The colours seen in the figures have no particular meaning, they represent a standard Excel option to help visually differentiate between different numbers (large and small, and intermediate) by attributing a certain colour to all numbers that appear to have close values.

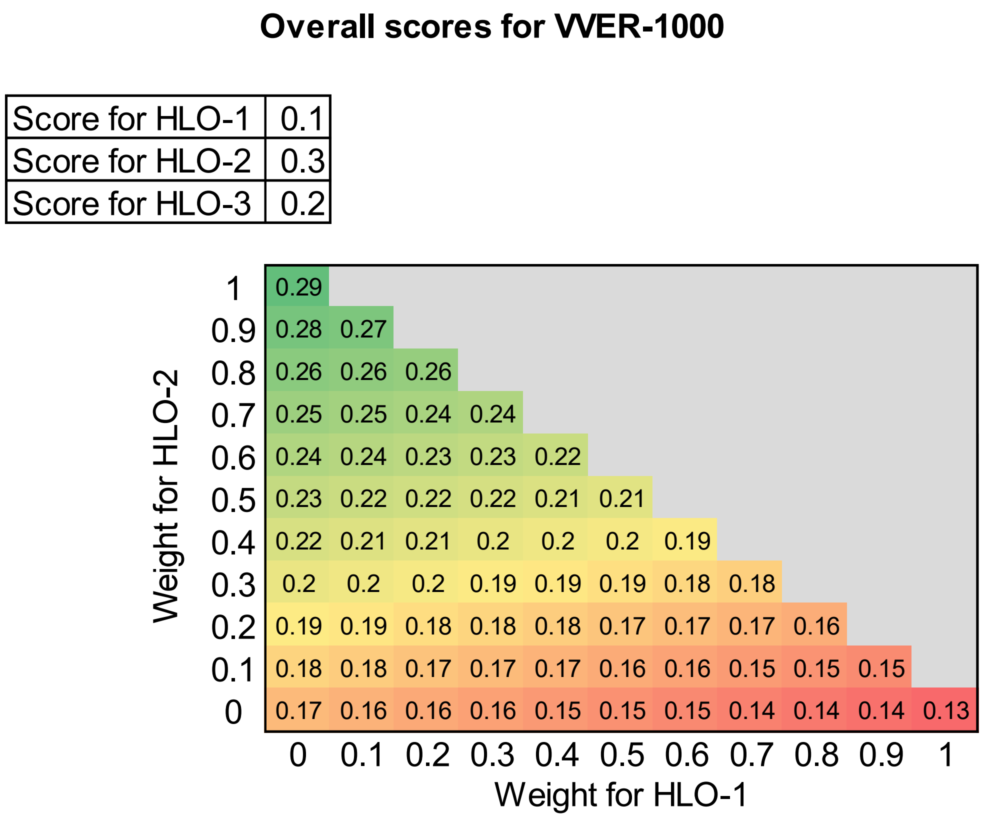


FIG. 3.9. Resulting diagram of the NES options with the first rank.

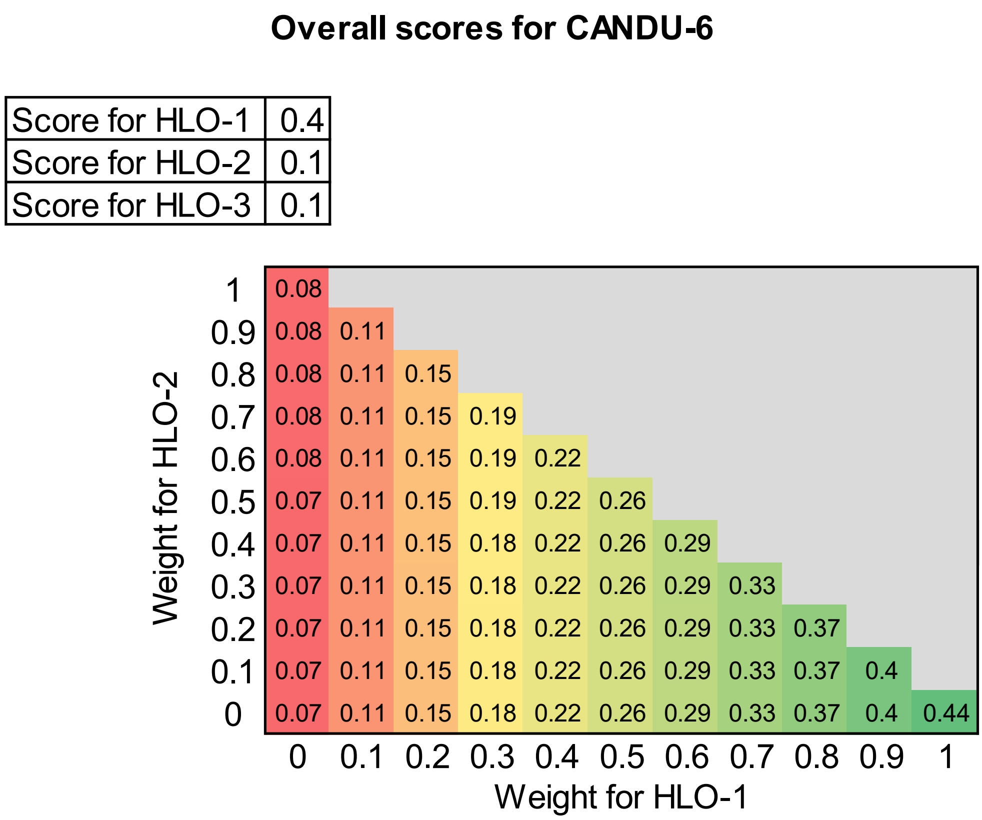


FIG. 3.10. Overall scores for CANDU-6.

Overall scores for SMR

Score for HLO-1	0.1
Score for HLO-2	0.3
Score for HLO-3	0.1

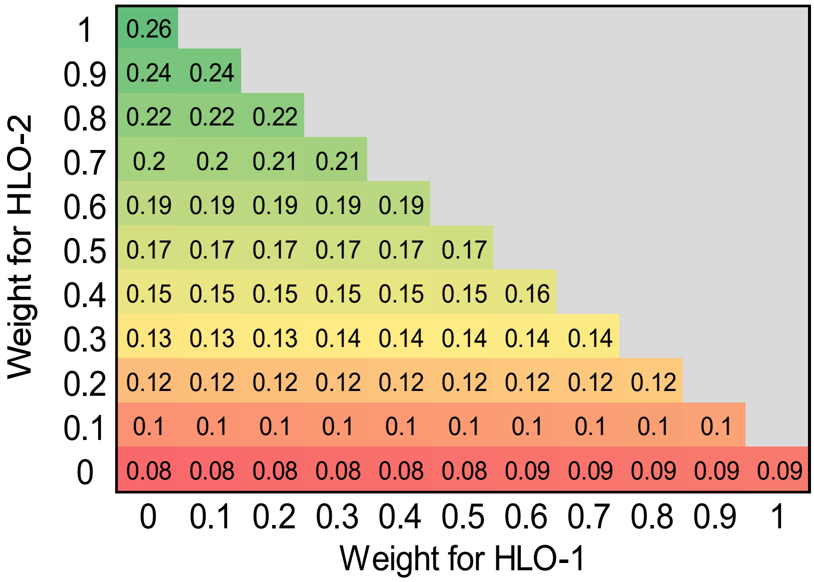


FIG. 3.11. Overall scores for Small Modular Reactors (SMR).

Overall scores for ACP-600

Score for HLO-1	0.3
Score for HLO-2	0.2
Score for HLO-3	0.1

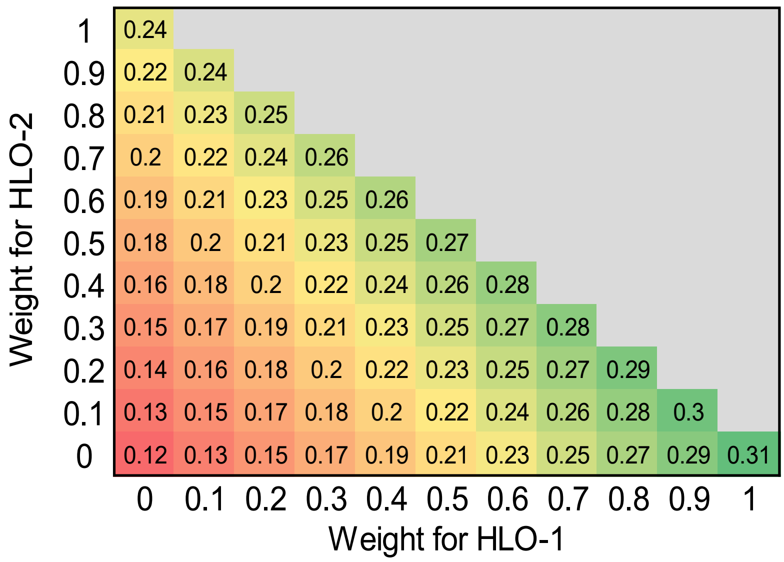


FIG. 3.12. Overall scores for ACP-600.

Overall scores for No Nuke

Score for HLO-1	0.1
Score for HLO-2	0
Score for HLO-3	0.1

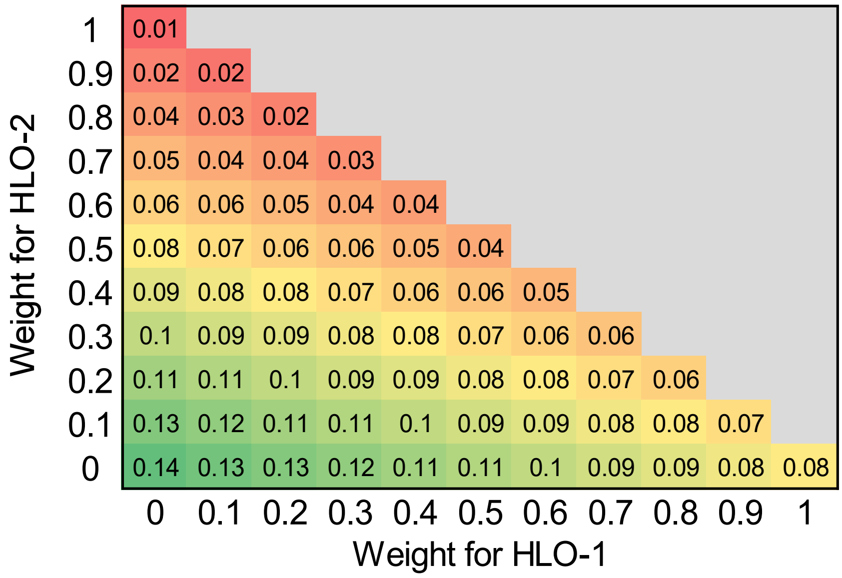


FIG. 3.13. Overall scores for No Nuke option.

Maximal overall scores for all NES options

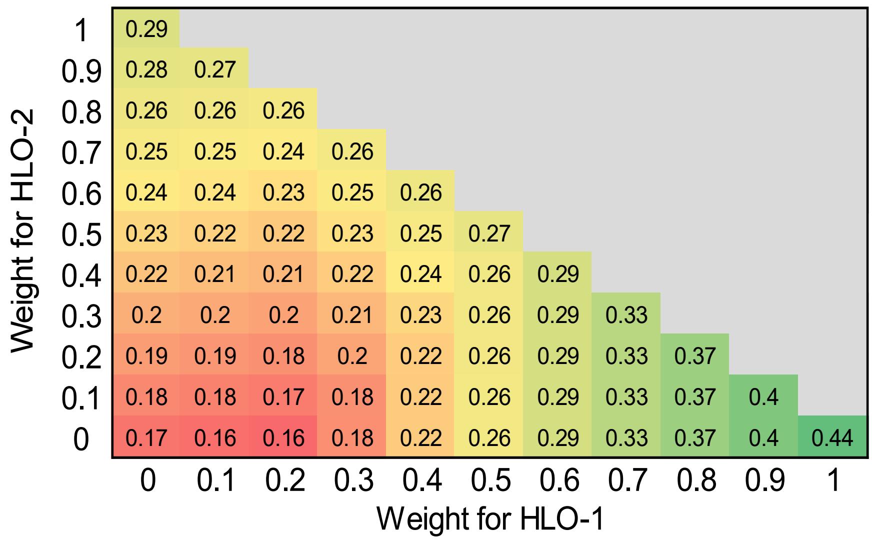


FIG. 3.14. Maximal overall scores for all NES and No Nuke options.

3.1.5. Conclusions

The main conclusions of this study are as follows:

- No dominant option of the considered NESs has been identified by domination option analysis. Such a result implies that all of the options are to be considered in further evaluations.
- Overall score spread and Rank mapping-based analyses of the selected options show that more predictable development could be proposed for VVER-1000 followed by ACP-600. More uncertainties on future implementation in the Armenian energy system exist for the SMR, CANDU and No Nuke options. These are reasonable results taking into consideration some geographical, logistic, operational and other country specific restrictions.
- The developed new functional extensions for KIND-ET are easy-to-use Excel based tools that have been implemented into the IAEA/INPRO collaborative project "Comparative evaluation of nuclear energy system options" (CENESO).

3.2. COMPARATIVE EVALUATION OF INNOVATIVE VERSUS EVOLUTIONARY NES (BULGARIA)

This chapter presents a structured report of a case study done by experts from the Republic of Bulgaria.

3.2.1. Introduction

In this case study a comparative evaluation of different options for new nuclear technology implementation in a small country specific context is examined. The performed evaluation is based on the approach developed in the frame of the INPRO[10] collaborative projects "Key indicators for innovative nuclear energy systems" (KIND) [3.20], [3.1] and "Comparative evaluation of nuclear energy system options" (CENESO).

The present analysis is performed using available public information for Bulgaria, as a reference small nuclear country, and the experts' judgment of Key Indicators (KIs) for different nuclear energy systems development. The set of KIs used in this case study was developed within the framework of the INPRO KIND project in accordance with Bulgarian country specific conditions, nuclear energy development, nuclear programme, energy strategy, infrastructure and resources.

A comparative evaluation of two hypothetical Nuclear Energy Systems (NESs) has been performed: an evolutionary design (based on Gen III/III+ LWRs) and an innovative design (based on GenIV LFR/SFR technology), respectively.

The comparison has been done by means of the INPRO KIND Evaluation Tool (KIND-ET) based on the Multi Attribute Value Theory (MAVT) method [3.1] and taking into consideration country specifics for Bulgaria (nuclear technology user country with limited domestic energy resources).
New functional extensions developed for KIND-ET [3.1] have been applied in the study:

— **Overall Score Spread Builder** – an express tool for evaluation of option overall score spreads caused by uncertainties in weighting factors and the objective tree structure;
— **Ranks Mapping Tool** – a visualization tool to highlight the options taking the first rank for different combinations of high-level objective weights;
— **Uncertainty Propagator** –an instrument based on the traditional error analysis framework for evaluating uncertainties in options' overall scores due to uncertainties in single attribute value function forms and key indicators.

3.2.2. Nuclear energy development in Bulgaria: vision and priorities

According to the classification of the INPRO methodology [3.3], Bulgaria represents a small technology user country.

The Bulgarian nuclear energy programme was launched in 1974 with the commissioning of the first nuclear power unit of the Kozloduy Nuclear Power Plant. Nuclear power in the country is concentrated at the Kozloduy NPP site where six units have been built. Two WWER-1000

[10] https://www.iaea.org/services/key-programmes/international-project-on-innovative-nuclear-reactors-and-fuel-cycles-inpro

reactors are currently in operation, while four WWER-440 reactors have been shut down for decommissioning.

The National Energy Strategy document [3.4] includes the statement “nuclear energy will be supported institutionally not only as a promising resource for generation of emission-free electricity, but also due to the accumulated successful experience and professional capability for operation of nuclear capacities. The support will be accompanied by high requirements with respect to security, safety, nuclear waste management and decommissioning.”

The National Energy Policy and the Energy Strategy of the Republic of Bulgaria to 2020 foresee the preservation of the share (of about 32%) of nuclear energy in the electricity generation. Active efforts are made towards extending the lifetime of Kozloduy NPP units 5 and 6, and opportunities for a new NPP are being considered. The existing infrastructure in Bulgaria involving a comprehensive legal and institutional base and provided with sufficient human and financial resources is rated as capable of sustaining the expansion of nuclear power in the country.

Possible impediments for expanding the nuclear power programme in Bulgaria are financial issues due to economic turmoil or significant increases of the investment per unit of installed capacity, mainly due to increasing the safety requirements. Also, nuclear projects require a large amount of money to be invested for construction, in comparison with other power sources. Some other challenges are:

- The reduction of the number of students in the field of nuclear engineering due to decreasing of the attractiveness of the profession.
- Limited human resources, both in terms of number of experts and quality of expertise, which could become critical. This is not acceptable for high-tech sectors such as nuclear power generation.
- Maintaining a political long term commitment to nuclear development, as commissioning of NPPs is a significantly long process that could be performed during different politically oriented governments. Some politicians could be against continued implementation of a project started during another government. So, the long term strategy is a mandatory condition for nuclear energy option development.

The First National Report under the Directive 2009/71/EURATOM [3.5] states: “Assuming that the use of nuclear energy for peaceful purposes contributes to economic and social development of the country and enhancement of the standard of living, Bulgaria reaffirms that during the use of nuclear energy, the protection of the health of individuals, the population as a whole, including future generations, and the environment have first and highest priority”.

3.2.3. Selection of indicators in the specific context of Bulgaria

As mentioned above, Bulgaria is a technology user country in the field of nuclear industry, with limited resources compared to other large and well-developed countries. In general, the technology user countries are likely to develop and improve their nuclear energy systems according to the world trends for development of nuclear energy technologies providing reliability, stability, security and long term sustainability considering areas of economics, infrastructure, safety, environment, waste management, and proliferation resistance. This is the principal basis for the selection of indicators in the specific context of Bulgaria.

At the first level of the objective tree, the following High -Level Objectives (HLOs) presenting the major objectives have been selected:

— Cost;
— Performance;
— Acceptability.

On the second level, the following Assessment Areas, presenting the areas of interest in the frame of HLOs have been selected:

— Economics for Cost;
— Waste management, Safety and Proliferation resistance for Performance;
— Infrastructure, Public acceptance and Maturity of technology for Acceptability.

As the third level of the objective tree, 12 Key indicators (KIs) have been selected for this study. They are elaborated according to the advice provided in the frame of the INPRO KIND project [3.1] and the country specific considerations. The selected KIs, together with their abbreviations are presented below:

— E.1: Levelized cost of energy product and services;
— E.2: Start-up cost (initial investment for construction of plant);
— WM.1: Specific (long term) RAW inventory;
— S.1: Design concept specific safety inherent and passive features and systems;
— S.2: Core damage and large early release frequencies;
— S.3: The potential to prevent release;
— PR.1: Attractiveness of nuclear material;
— I.1: Government policy;
— I.2: Availability of human resources;
— PA.1: Survey of public acceptance;
— M.1: Design stage;
— M.2: Degree of standardization and licensing adaptability.

3.2.3.1. Determination of key indicator values

In order to ensure the maximal possible objectivity and representativeness in assessing the values of the key indicators, a questionnaire has been distributed to 20 Bulgarian experts from 11 representative organizations in the field of nuclear technology, on the principle of an anonymous (blind) survey. The results of the survey have been compared with our preliminary experts' opinion and then summarized; on this basis the values of the key indicators have been determined assuming their average.

The following assumptions have been considered by experts included in the survey when evaluating KI values: each indicator has been evaluated in a 10-point scoring scale; the value 1 was the worst possible indicator value and the value 10 was the best one. This broader scoring scale is preferred in this case because it provides a clearer differentiation of the alternatives, reducing the probability of obtaining similar results.

For most of the key indicator values (concerning areas of economics, waste management and safety) there are negligible differences between our preliminary assessment and the aggregate judgement of the other experts. Surprisingly, significant differences between KI values could be observed in the area of proliferation resistance. Some rather small differences have been also observed in assessment of the public acceptance and maturity KIs.

The study among numbers of experts and organizations was very useful and helped to obtain a more representative key indicator values assessment.

The assessed average values of all key indicators for considered NESs are presented in the performance table (Table 3.1).

TABLE 3.1. PERFORMANCE TABLE

High-level objectives	Assessment areas	Key Indicators	KIs abbr.	Gen III+ LWR	Gen IV LFR, SFR
Cost	Economics	Levelized cost of energy product and services	E.1	7	6
		Start-up cost (initial investment for construction of plant)	E.2	7	5
Performance	Waste Management	Specific (long term) radioactive waste inventory	WM.1	5	8
	Proliferation Resistance	Attractiveness of nuclear material	PR.1	7	7
	Safety	Design concept specific safety inherent and passive features and systems	S.1	8	8
		Core damage and large early release frequencies	S.2	8	8
		The potential to prevent release	S.3	8	8
Acceptability	Infrastructure	Government policy	I.1	7	5
		Availability of human resources	I.2	8	4
	Public acceptance	Survey of public acceptance	PA.1	7	5
	Maturity of technology	Design stage	M.1	9	5
		Degree of standardization and licensing adaptability	M.2	9	4

3.2.3.2. Selection of an MCDA method

Multi-criteria decision analysis (MCDA) represents a system of approaches for evaluation and decision making which support decision makers to perform numerous and conflicting assessments to find the best alternative. The MCDA paradigm has been comprehensively discussed and explained in [3.6]. Authors have discussed MCDA process steps: "problem formulation, specification of alternatives, criteria identification, criteria assessment, selection of MCDA method, uncertainty and sensitivity analysis, final conclusions and recommendations" [3.6]. In [3.6] it was summarized that "given a wide range of problems having multi-criteria character in the area of NESs … sustainability assessments with different possible range of assessment, the MCDA technique is recommended to be applied for comparative analysis and assessment as the most suitable among alternatives. Implementation of the MCDA methods may provide useful new information for ranking of the considered options with a set of performance indicators considering experts and the decision-maker preferences on hand."

The comparative evaluation in this case study was performed using KIND-ET: an excel tool based on multi attribute value theory (MAVT) developed within the INPRO KIND collaborative project [3.1] and improved in the CENESO Collaborative Project by new functional extensions.

3.2.3.3. Multi-criteria comparative evaluation by means of the INPRO KIND-ET tool

(a) Alternatives

The options compared in this study are two hypothetical Nuclear Energy Systems (NESs):

— NES 1 – based on GEN III/III+ - so called evolutionary design (based on GEN III/III+ LWRs);
— NES 2 – based on GEN IV – so called innovative design (based on knowledge of the LFR/SFR technologies).

(b) Performance table

The indicators involved in the comparative evaluation have been arranged hierarchically in a three-level objective tree with 3 high-level objectives, 7 assessment areas and 12 key indicators, as mentioned above. The performance table (see Table 3.1) has been prepared, determining the values of the KIs (see 3.2.3.1 section). Arranging of the criteria in the three-level objective tree is suggested as the most appropriate approach in the evaluation of the weighting factors: to simplify weighing of the criteria and to make ranking results clearer to allow their detailed analysis.

The assumptions taken for KIs are described in section 3.2.3.1.

(c) Weighting factors

The next step in the comparative evaluation requires evaluation of the weighting factors for each key indicator in accordance with the hierarchical weighting method. The weighting factor values reflect expert's opinion for the importance (weight) of each high-level objective (cost, performance, acceptability) according to the specific country conditions. At each level of the objective tree, the sum of corresponding weighting factors is required to be equal to 1.

As the base case, in the present study all high-level objectives were assumed to have equal importance. Corresponding to the HLOs, the assessment areas (Economics for Cost; Waste management, Safety and Proliferation resistance for Performance; Infrastructure, Public acceptance and Maturity of technology for Acceptability) were assumed also to be equally important based on the requirement that the sum of all weighting factors at each level of the objective tree is to be equal to unity. The same assumption is valid for the weighting factors associated to the key indicators, at the third level of the objective tree. Table 3.2 presents the considered weighting factors.

TABLE 3.2. WEIGHTING FACTORS CONSIDERED FOR THE BASE CASE

High-level objectives	High-level objective weights	Assessment areas		KI	KI 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	0.333	WM.1	1	0.111
		Proliferation Resistance	0.333	PR.1	1	0.111
		Safety	0.333	S.1	0.333	0.037
				S.2	0.333	0.037
				S.3	0.333	0.037
Acceptability	0.333	Infrastructure	0.333	I.1	0.5	0.056
				I.2	0.5	0.056
		Public acceptance	0.333	PA.1	1	0.111
		Maturity of technology	0.333	M.1	0.5	0.056
				M.2	0.5	0.056

For the weight sensitivity analysis, the weighting factors on the level of HLOs have been changed as follows: Cost – 50% importance, Performance – 20% importance, Acceptability – 30% importance (Table 3.5, Fig. 3.18).

(d) Single attribute value function

KIND-ET applied to this study, as mentioned above, is based on the MAVT method, so the next step in the calculations is the determination of the single attribute value function for each indicator. In the calculations, a linear form and increasing type of the single attribute value function (which means that the higher values of the KI correspond to a more attractive system condition [1.1]) was selected. The global domain of the single attribute value function was chosen.

Local domain: the minimum and the maximum values of arguments of each single attribute value function are equal to the minimum and the maximum values of the corresponding KI, determined by experts for each NESs in the performance table [1.1].

Global domain: all values from the minimum possible score to the maximum possible score determined as the best and the worst value of the domain (for a 10 point scale, these are from 1 to 10, respectively).

As a first attempt, the calculations were performed using the local domain for single attribute value functions, but this significantly increased the differences in both alternatives and, at the same time, the scores at the level of HLOs and assessment areas could not be clearly distinguished. Using global domains of single attribute value functions in this case allows both alternatives to be well differentiated and supports examination of the scores at the level of HLOs and assessment areas in order to explain in which areas an alternative shows better results, respectively, and in which areas it could be improved.

(e) Ranking results and their interpretation

The ranking results presented in Table 3.3 and Fig. 3.15 show that NES 1 (Evolutionary design - Gen III+, LWR) is the most preferred alternative for Bulgaria. Total overall scores for Gen III+ and Gen IV (LFR, SFR) are **0.685 and 0.549**, respectively. Table 3.3 and Fig. 3.16 present the multi attribute value functions decomposition at the level of HLOs. It is seen that the score for the Performance HLO is better for Gen IV design, but the Cost and Acceptability HLOs for Gen III+ have better results.

TABLE 3.3. HIGH LEVEL OBJECTIVE SCORES FOR COMPARED NES OPTIONS

	Cost score	Performance score	Acceptability score	Total score
GEN III+	0.222	0.210	0.253	0.685
GEN IV	0.167	0.247	0.136	0.549

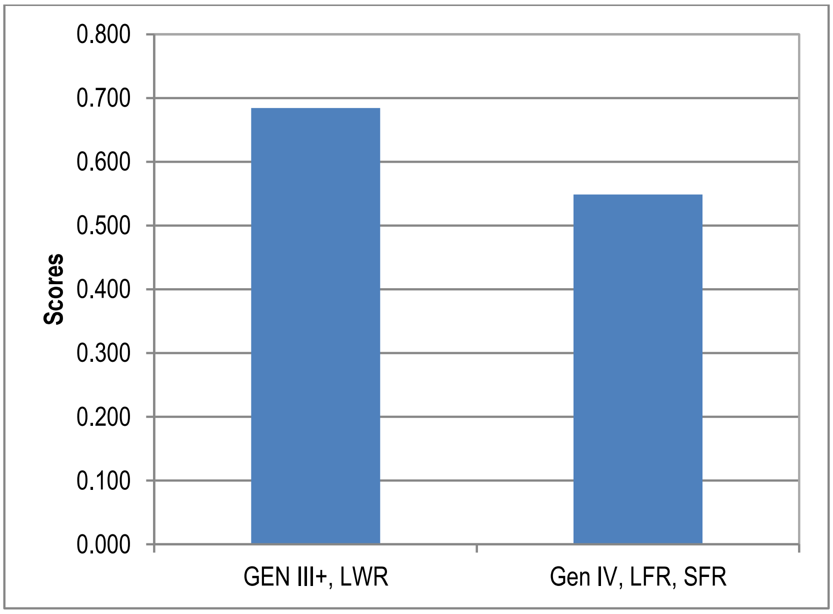


FIG. 3.15. Ranking results for compared NESs.

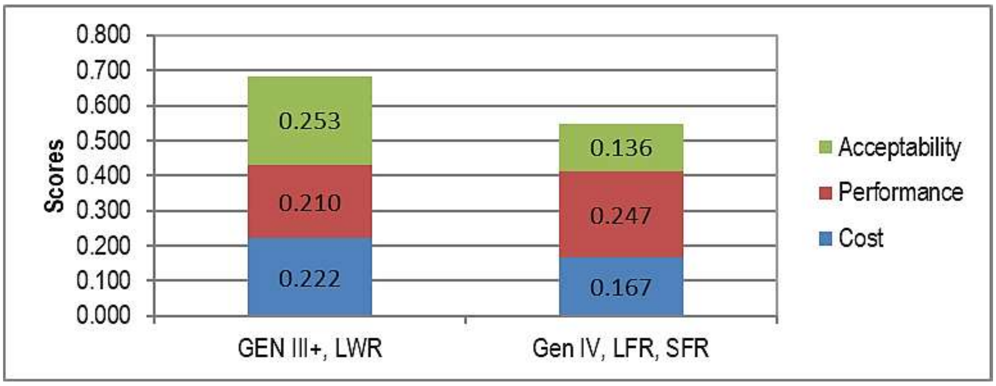


FIG. 3.16. High level objective scores for compared NESs.

From Table 3.4 and Fig. 3.17, multi attribute value functions decomposition at the level of assessment areas could be seen.

TABLE 3.4. ASSESSMENT AREAS SCORES FOR COMPARED NES OPTIONS

	Economics	Waste management	Safety	Proliferation resistance	Infra-structure	Public acceptance	Maturity of techno-logy
GEN III+	0.222	0.049	0.086	0.074	0.080	0.074	0.099
GEN IV	0.167	0.086	0.086	0.074	0.043	0.049	0.043

Gen III+ obtained better scores than Gen IV in most of the assessment areas excepting waste management area. In the areas of safety and proliferation resistance both systems obtained equal scores. In the area of waste management Gen IV shows better result.

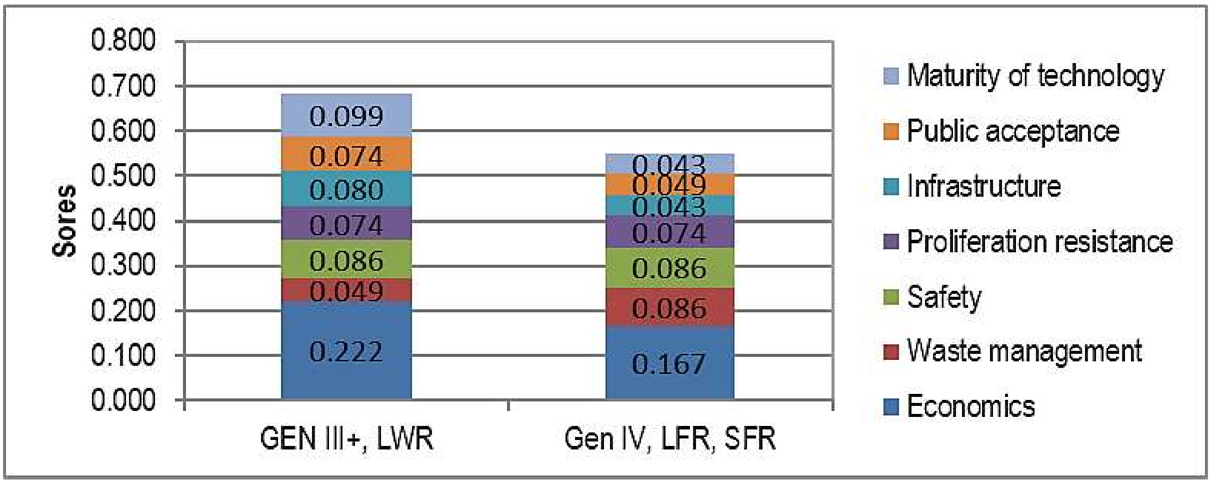


FIG. 3.17. Assessment areas scores for compared NESs.

(c) Weight sensitivity analysis

The weight sensitivity analysis performed by using the KIND-ET tool considers the influence of the assigned weights on the ranking results for the compared alternatives. Table 3.5 and Fig. 3.18 show the alternative ranking results for different values of weighting factors: base case and modified weights options.

As mentioned above, for the base case in this study, at all the objective tree levels equally importance was assumed for the considered high-level objectives, assessment areas and key indicators, respectively.

As a modified case, the weighting factors on the level of high-level objectives were changed as follows: Cost – 50%, Performance – 30%, Acceptability – 20%

TABLE 3.5. OVERALL SCORES FOR COMPARED NES OPTIONS AT THE BASE AND MODIFIED CASES

	GEN III+	GEN IV
Base case	0.685	0.549
Modified	0.674	0.554

By this modification, the Gen III+ option score decreases, and the Gen IV option score increases, the difference between the two options scores becomes smaller, but Gen III+ still remains the preferred option.

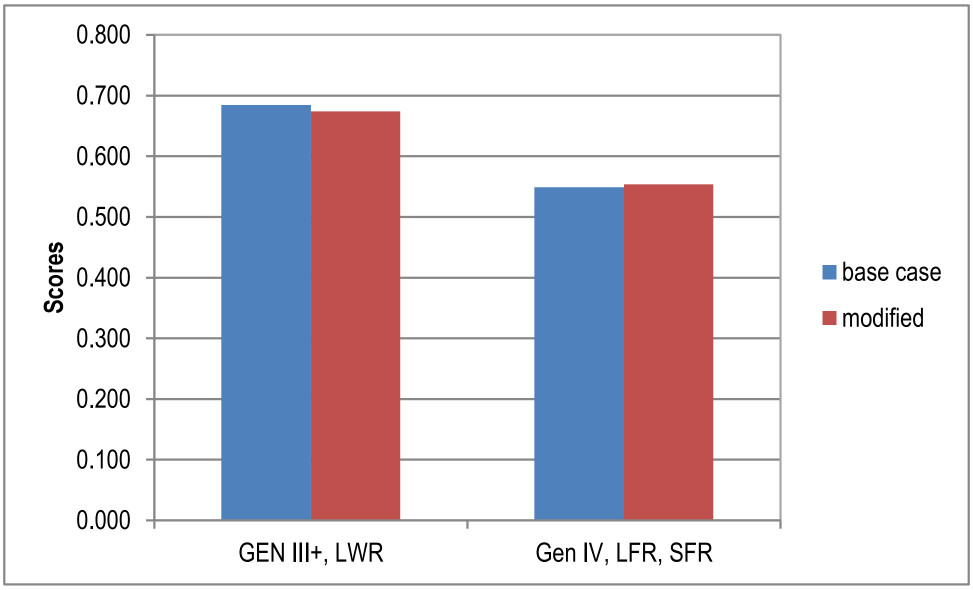


FIG. 3.18. Weight sensitivity results: base case and modified case.

(f) Discussion of results

For a nuclear technology user country with limited resources such as Bulgaria, the cost and especially start-up cost (initial investment for construction of a plant) appears the most important area and limitation at the same time when considering a new nuclear power plant.

Other important areas associated with the decision for new NES development are Infrastructure, Public acceptance and Maturity of technology. Results show that the global sustainable development of nuclear energy is a key factor for a small technology user country in developing a sustainable nuclear energy programme.

There is a difference in achieving sustainable NESs for countries which already use nuclear energy and for newcomers. For countries with significant experience in operation of a specific nuclear power plant type (such as LWR) it will be difficult to replace it with an entirely new (GEN IV) or even different (such as HWR) technology. For such countries, the international collaboration is directly connected with resolving the tasks and challenges in supporting sustainability of their own nuclear energy systems.

3.2.3.4. Uncertainty analysis performance

There are various sources of uncertainties in the input data that could lead to the uncertainties of the results of the comparative evaluation. In general, the sources of uncertainties could be divided into two groups: subjective – due to the experts' opinions in their evaluation of indicators, and objective – due to limited information about some indicators for a less mature technology. Therefore, the sensitivity and uncertainty analyses enable consideration of the impact of the input uncertainties on the ranking results and their stability.

In this study, an uncertainty analysis was performed using the new functional extensions for KIND-ET [3.1], provided in the frame of the CENESO collaborative project, namely "Overall Score Spread Builder", "Ranks Mapping Tool" and "Uncertainty Propagator". The extensions are available as separate Excel-based analytical tools, the input data needed being provided by KIND-ET.

Overall Score Spread Builder, as described in the user instructions [3.1], is "an express tool for evaluation of option overall score spreads caused by uncertainties in weighting factors and the objective tree's structure". This tool enables a reliable estimation of probability distributions of the options' scores and ranks to be performed.

Detailed application instructions about how to realize the spread of overall scores for the options considered due to uncertainties in weighting factors, representing it as a box and whisker plot were provided, including user-friendly prepared excel tools which significantly facilitate performance of uncertainty analysis.

Overall Score Spread Builder has three components – **weight generator** that generates 10,000 combinations of weighting factors uniformly distributed in the range from 0 to 1, constrained only by normalization conditions; **randomizer** allowing one to change conditions for weights randomizations and **score evaluator** which evaluates overall scores of options for each weight combination and builds the resulting box and whisker chart, demonstrating the spread of overall scores for all options considered due to uncertainties in weighting factors.

Figure 3.19, Table 3.6 and Fig. 3.20 present some steps in applying of score evaluator for the NESs considered in the case study. In Fig. 3.19 data from KIND-ET single attribute value functions worksheet, which are KI values transformed to dimensionless scoring scale (from 0 to 1), are inputted.

Single-attr. value functions		KI-1	KI-2	KI-3	KI-4	KI-5	KI-6	KI-7	KI-8	KI-9	KI-10	KI-11	KI-12
Please input here data regarding single-attr. value functions from the KIND-ET model	GEN III+	0.667	0.667	0.444	0.778	0.778	0.778	0.667	0.667	0.778	0.667	0.889	0.889
	GEN IV	0.556	0.444	0.778	0.778	0.778	0.778	0.667	0.444	0.333	0.444	0.444	0.333

FIG. 3.19. Single attribute value functions worksheet in KIND-ET (screenshot).

The next step is to fill in the weight options worksheet (the number of weight combinations depends on the number of the key indicators, i.e., 12 weights options in this case) with sample weights taken from Weight Generator. After that, the overall scores for compared NESs for each weight combination are calculated through summation of all multiplications of relevant weights and single attribute value functions. The last step is building a box and whisker chart for the overall score spreads for the compared NESs which is presented in Table 3.6 and Fig. 3.20.

TABLE 3.6. THE OVERALL SCORE SPREADS FOR THE COMPARED NES OPTIONS

	GEN III+	GEN IV
Mean	0.511	0.388
Standard deviation (SD)	0.239	0.195
Maximum value (Max)	0.889	0.778
Quartile (Q3, 75%)	0.698	0.520
Median	0.575	0.406
Quartile (Q1, 25%)	0.329	0.246
Minimum value (Min)	0.000	0.000

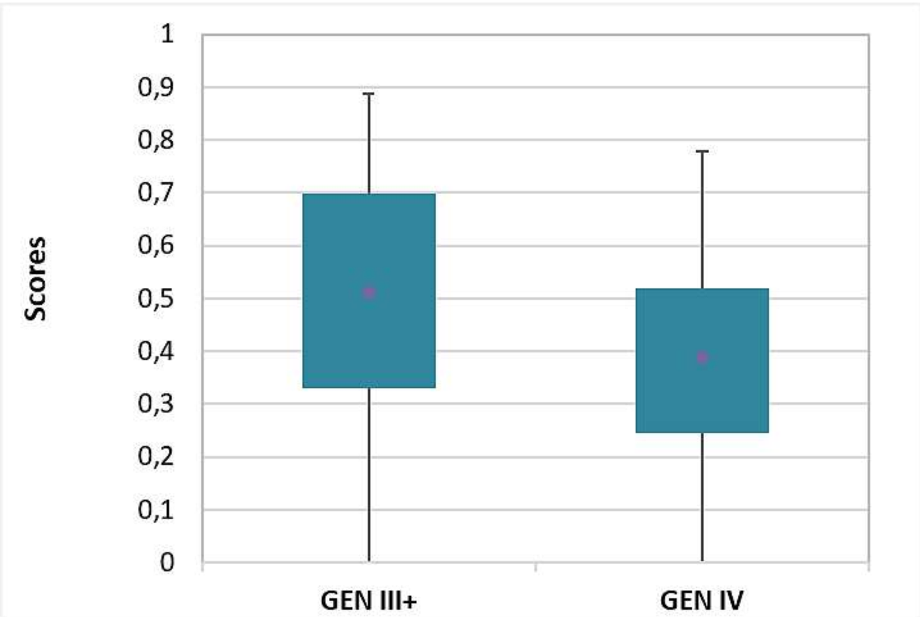


FIG. 3.20. Overall score spreads.

From the box plot shown the following observations can be made:

- It appears that the Gen III+ based NES option obtains higher overall scores than the Gen IV NES option, i.e., the higher probability for Gen III+ to take the first rank which is in correspondence with the comparative evaluation performed by the KIND-ET tool.
- It appears that the overall scores range for Gen III+ is slightly larger than that for Gen IV.

The Ranks Mapping Tool, as described in the user instructions [3.1], is "a visualization tool to highlight the options taking the first rank for different combinations of high-level objective weights." This tool allows the results of uncertainty examinations through variations of high-level weights to be presented. The weights values in this case are specified deterministically (in the case of overall score spread builder it was done probabilistically) and their combinations cover the whole high-level objective weight space. Weights for the three high-level objectives could be simultaneously varied over a range from 0 to 1 with a step of weight variation assumed to be equal to 0.1. Because of the normalization condition constraining their summation to be equal to unity, only two of three high level objectives could be selected as independent weight parameters and the third one is calculated as w3=1–(w1+w2).

Table 3.7 presents the input data for Ranks Mapping Tool: the scores for HLOs from the "Ranking results" worksheet of KIND-ET. In this case the "Cost" and "Performance" weights are independent parameters, but the calculations could be performed for other HLOs combinations.

Figure 3.21 presents the first rank option on a map of preferences. It could be seen that the preferable option is GEN III+. The Gen IV option could become the preferred alternative only if the "Performance" HLO importance is increased over 60%, and the "Cost" HLO importance is reduced under 40%, accordingly.

TABLE 3.7. SCORES FOR HIGH LEVEL OBJECTIVES

High-level objective	GEN III+	GEN IV
Score for the Cost HLO	0.222	0.167
Score for the Performance HLO	0.210	0.247
Score for the Acceptability HLO	0.253	0.136

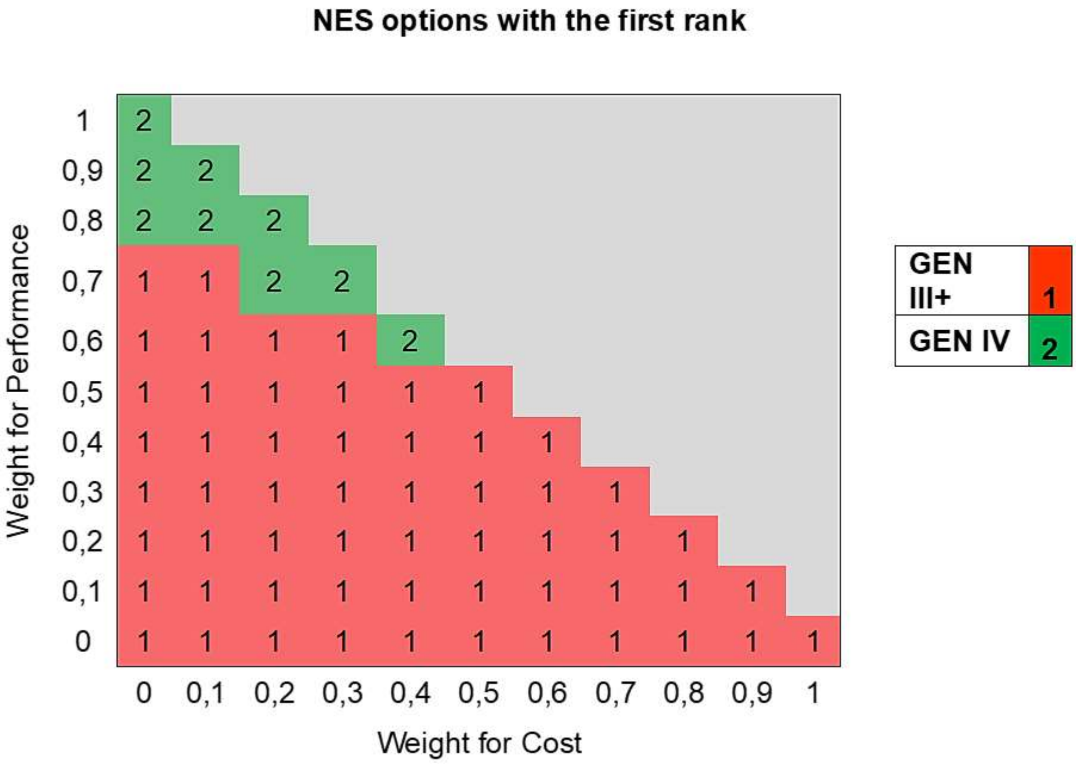


FIG. 3.21. The first rank option.

Uncertainty Propagator, as described in the user instructions [3.1], is "the KIND-ET extension based on the classical error analysis framework for evaluating uncertainties in the options' overall scores due to uncertainties in the single attribute value function forms and key indicators." The theoretical background, excel realization, application instructions, Excel templates, as well as demo cases have been provided. Uncertainty Propagator implements a method for evaluating uncertainties in the case of the uncorrelated input but also allows considering the correlations between KIs and evaluating uncertainties in the case of the correlated input to produce the correct/realistic evaluation of uncertainties in overall scores due to KI uncertainties.

As previously mentioned, in order to ensure the maximal possible objectivity and representativeness in assessing the values of the key indicators in this case study, a questionnaire has been distributed to twenty Bulgarian experts from 11 organizations in the field of nuclear technology on the principle of anonymous (blind) survey. In this case, it is very useful to evaluate uncertainties in overall scores due to KI uncertainties resulting from the different scores provided by these experts. Table 3.8 and Fig. 3.22 present overall scores and uncertainties obtained by applying the Uncertainty Propagator in the case of the uncorrelated input, following the application instructions.

TABLE 3.8. OVERALL SCORES AND UNCERTAINTIES IN CASE OF UNCORRELATED INPUT (UNCERTAINTY PROPAGATOR)

Overall scores and uncertainties	GEN III+, LWR	GEN IV, LFR, SFR
Best estimate	0.674	0.538
Absolute uncertainties	0.086	0.080
Contribution due to uncertainties in key indicators	0.069	0.069
Contribution due to uncertainties in single attribute value functions	0.045	0.037
Contribution due to uncertainties in weights	0.022	0.018

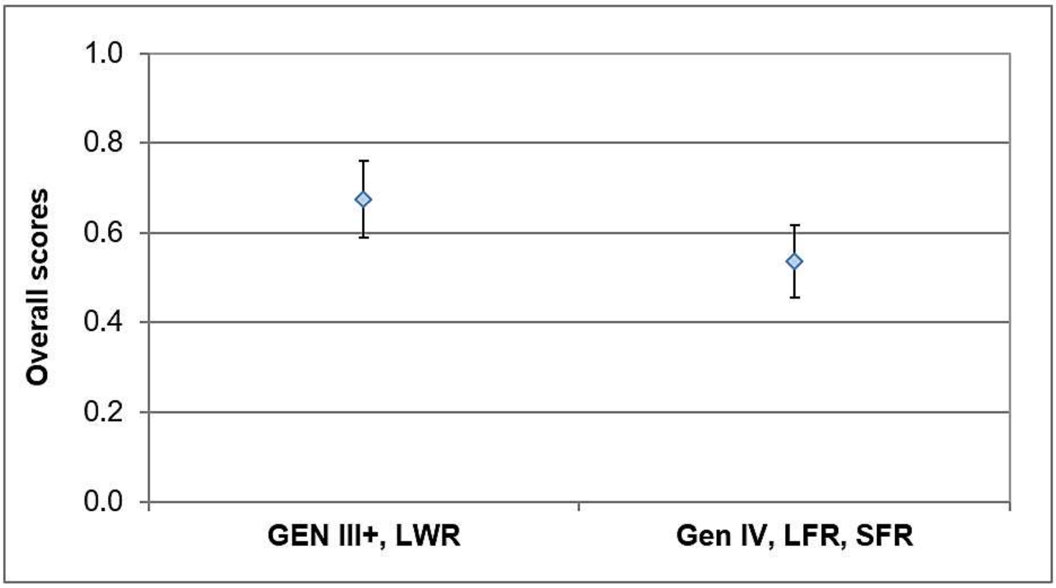


FIG. 3.22. The Overall scores with uncertainty (Uncertainty Propagator).

The overall scores for Gen III+ and Gen IV (LFR, SFR), calculated by the basic KIND-ET model are 0.685 and 0.549. However, in the calculations, the linear form of the single attribute value function was chosen, while in the Uncertainty Propagator an exponential form of the single attribute value function was used. Using the linear form of the single attribute value function in the Uncertainty Propagator, best estimates scores (mean overall scores) are the same as in the basic KIND-ET model. These scores have been calculated, using average KIs.

It could be seen from Table 3.8, that the absolute uncertainties are 0.086 for Gen III+ and 0.080 for Gen IV, mainly due to the uncertainty in key indicators which has the greatest contribution.

The calculations performed by averaging the overall scores, specified for each expert, show 0.698 for Gen III+ and 0.554 for Gen IV. This approach allows additionally being evaluated probabilities for preference of certain option (85 and 15 % for Gen III+ and Gen IV, respectively). The results of these calculations are presented in Table 3.9.

TABLE 3.9. OVERALL SCORES AND UNCERTAINTIES

Parameter	Gen III+	Gen IV
Mean overall scores (best estimate evaluations using average KIs)	0.685	0.549
Mean overall scores (best estimate evaluations using averaging overall scores, specified for each expert)	0.698	0.554
SD (uncertainty 1σ)	0.139	0.093
Precision, %	20	17
Probability of preference, %	85	15

Uncertainties have been calculated by the Uncertainty Propagator for the case of the correlated input, following application instructions [3.1]. Evaluation of uncertainties in overall scores due to KI uncertainties for the case of the correlated input shows that the uncertainties in the overall scores are: Δ (GEN III+) = ± 0.139 and Δ (GEN IV) = ± 0.093.

Considering these uncertainties, the ranking results can be considered as robust ones and options can be considered as to be well resolved.

3.2.4. Conclusions

The INPRO KIND-ET tool based on the MAVT method provides a reasonable and user-friendly approach to judge and comparatively evaluate innovative nuclear systems, as well as evolutionary nuclear systems and non-nuclear energy sources.

The key indicators evaluation is an issue that requires special attention. The different importance of the criteria for comparative evaluation needs to be considered in order to support the process of decision making. The criteria need to be selected considering possible changes during the long time of operation due to various reasons such as price fluctuations of resources or the development of a newer technology.

The performed evaluation by using the MAVT method demonstrates its flexibility. The method allows implementation of different approaches in comparing and differentiating alternatives as well as interpreting the ranking results. By using the INPRO KIND-ET tool, the advantages and disadvantages of investigated NES options in different conditions can be demonstrated.

In general, it can be stated that the developed toolkit based on MAVT method is an advanced means that successfully allows the comparative evaluation of different nuclear technologies to be performed in the context of the future sustainable NES development in a country specific context.

The comparative analysis performed in this study is to be considered only as an exercise for the KIND-ET application for the comparison of different NESs.

New functional extensions for KIND-ET, provided in the frame of the CENESO collaborative project, allow in a user-friendly manner uncertainty analysis to be performed in point of view of weighting factors uncertainties and key indicators uncertainties with subjective or objective sources and their impact on the ranking results and their stability to be considered.

3.3. COMPARATIVE EVALUATION OF NUCLEAR FUEL TECHNOLOGY (INDONESIA)

This chapter presents a structured report of a case study done by experts from the Republic of Indonesia.

3.3.1. Introduction

Indonesia is an archipelago country consisting of thousands of islands with large variation in size and population density. At present, Indonesia has two large electricity grids covering Sumatera, Java, Madura and Bali Islands. Those islands are large islands with a dense population. Other large islands like Kalimantan, Sulawesi and Papua have less dense population and their settlements are distantly separated by rivers, forests, valleys and hills, so for these islands there are only many small and isolated electricity grids because economically it is not feasible to build large grids there. The rest of the thousands of islands are small islands with a lower population and less electricity demands, and they have also only small and isolated grids.

For large grids, Indonesia considers proven water cooled nuclear reactor technology like the BWR or PWR, but for small grids, the gas cooled nuclear reactor technology with inherently passive systems like the HTGR [3.7] could be preferred. For this reason, Indonesia is considering a 10 MWth HTGR (with an electrical rating of about 3 MWe) for very small grids, and this project can be developed to a larger one to supply power for small grids.

To support fuel for both type of reactors, Indonesia conducts research and development for pin type fuel used by BWRs or PWRs and for pebble type fuel used by HTGRs. Indonesia has two laboratory scale facilities for the fuel pin fabrication and kernel fabrication. It was interesting to make an evaluation of the two type fuels production facilities using the KIND-ET tool within the CENESO project. The evaluation, of course, is not intended to give comprehensive pictures of Nuclear Fuel Cycles, but rather is intended only to apply the KIND-ET tool for the comparative evaluation of the Indonesian facilities based on national experiences and judgements. Later on, the comparative evaluation can be extended to cover whole different NFCs not only reactors or a component of NFC separately.

Two nuclear fuel technologies are chosen based on the existing experience and facilities available in Indonesia; NFC-1 is a pin type fuel technology and NFC-2 is a pebble type fuel technology, respectively. The main characteristics of those fuel technologies are listed in Table 3.10.

TABLE 3.10. MAIN CHARACTERISTIC OF NFC OPTIONS

Parameter	NFC-1: Pin fuel	NFC-2: Pebble fuel
Raw material	UO_2 powder, 5% enrichment	UO_2 powder, 8% enrichment
Unit active Fuel	UO_2 pellet	UO_2 micro sphere/kernel
Structure material	Zirconium alloy tube	Graphite-SiC layers
Fabrication Process	Simple and dry	Complex and wet
Waste	grinding waste and contaminated water	Contaminated chemical liquid and solution
Safety concern	UO_2 powder from raw material and pellet grinding process	UO_2 powder from raw material and toxic chemical material hazard

KIND-ET based on the Multi Attribute Value Theory (MAVT) method has been used to compare the two different fuel fabrication technologies.

3.3.2. Determination of key indicators, values and weighting factors

The high-level objectives chosen for consideration were cost, performance and acceptability. Five assessment areas and six key indicators were then selected as presented in the performance table (Table 3.11) together with the KIs values.

TABLE 3.11. PERFORMANCE TABLE

High-level objectives	Assessment areas	Key Indicators (KIs)	KIs values	
			NFC-1	NFC-2
Cost	Economics	Production cost (C.1)	0	1
Performance	Waste Management	Toxic, hazardous and radioactive waste (WM.1)	1	0
	Safety	Potential to prevent release toxic, hazardous and radioactive materials (S.1)	1	0
		Criticality accident (S.2)	1	0
	Environment	Material scarcity (E.1)	0	1
Acceptability	Maturity of technology	Degree of technology verification (M.1)	1	0

Because there are only two NFC to be assessed, two values for the KIs were chosen, the worst is 0 and the best is 1. The KI production cost C.1 was determined on basis of fissile material weight. The production cost of NFC-1 was considered higher than the one of NFC-2, due to use of expensive zirconium alloy for structural material (and in spite of more complex processes in

NFC-2 than NFC-1), so the best value of the KI C.1 is for NFC-2. NFC-1, due to using dry and simple mechanical process, produces less waste than NFC-2, so the best value of the KI WM.1 is for NFC-1. As a result, the use of toxic and hazardous chemical liquids in NFC-2 it is more prone to a release resulting in the chemical exposure of personnel, the facility and the environment, so the worst value of KI is for NFC-2. Also, NFC-2 uses higher enrichment material that has more potential to have a criticality accident, so the values of KI S.2 are also worst for NFC-2. Using graphite and silicon carbide rather than zirconium alloy make NFC-2 better than NFC-1 because graphite and silicon are more abundant than zirconium, but NFC-2 is a relatively new technology that is not proven yet, so the NFC-2 is the worst in KI M.1.

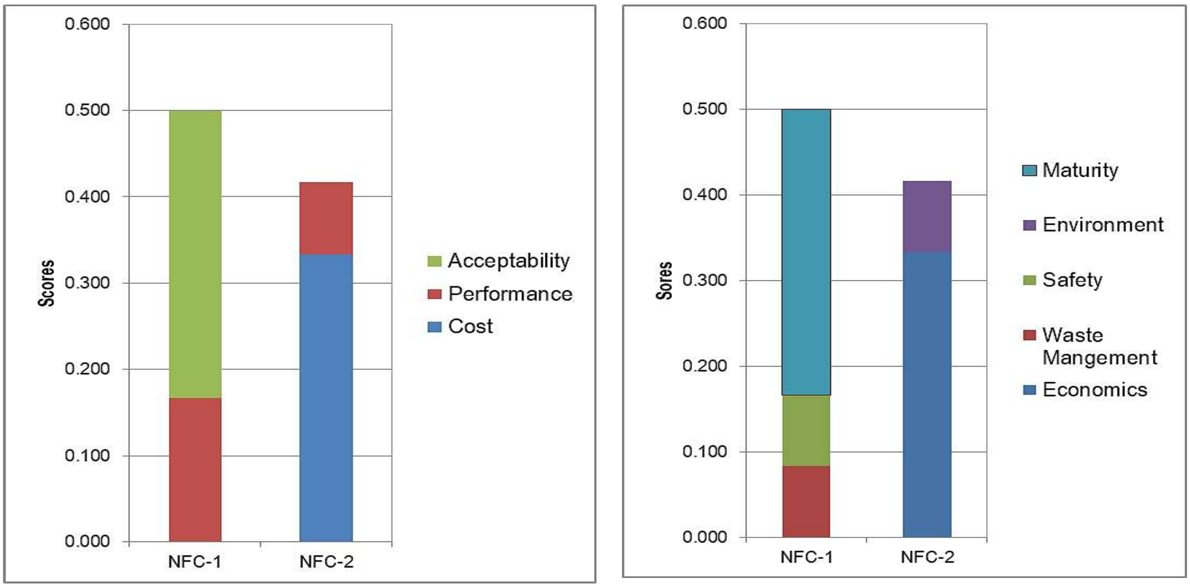
In this evaluation, all high-level objectives (HLOs) have the same importance, as is reflected by the same weighting factor values. The same assumption was also considered for corresponding assessment areas weights and KIs weights. Table 3.12 shows the weighting factors for the present comparative evaluation.

TABLE 3.12. WEIGHTING FACTORS

High-level objectives	HLO weights	Assessment areas	Area weights	KIs	KI weights	Final weighting factors
Cost	0.333	Economics	1	C.1	1	0.333
Performance	0.333	Waste Management	0.333	WM.1	1	0.111
		Safety	0.333	S.1	0.5	0.056
				S.2	0.5	0.056
		Environment	0.333	E.1	1	0.111
Acceptability	0.333	Maturity of technology	1	M.1	1	0.333

3.3.3. Results and discussion

The evaluation results as a ranking score for the two NFCs is shown in Fig. 3.23, decomposed both for the HLOs and for the considered assessment areas.



(a) *(b)*

FIG. 3.23. Overall ranking results of considered NFC-1 and NFC-2 decomposed for: (a) high level objectives, (b) corresponding evaluation areas.

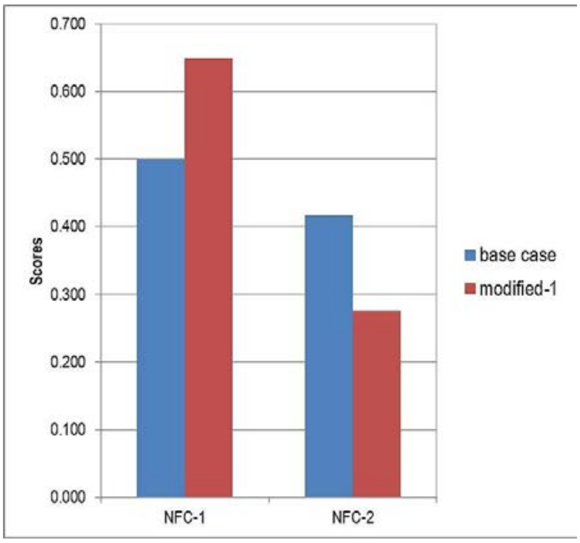
It is clear from Fig. 3.23 that the ranking score of NFC-1 is better than the one of NFC-2. The highest overall ranking score of NFC-1 resulted from only two high level objectives, mainly dominated by the Acceptability HLO. The Cost HLO has no role for the score of NFC-1. On the contrary, the Cost HLO is dominant on the overall ranking score of NFC-2, and the Acceptability HLO has no contribution. The Performance HLO in NFC-2 has second importance as in the NFC-1 case, but the associated score is far lower.

The Maturity evaluation area dominates the overall score of NFC-1, while the Economics evaluation area dominates the score of NFC-2. Environment and Economics evaluation areas have no role in NFC-1 scoring; on the contrary, these two evaluation areas play a significant role in NFC-2 scoring. The Waste management evaluation area has impact only on NFC-1 scoring.

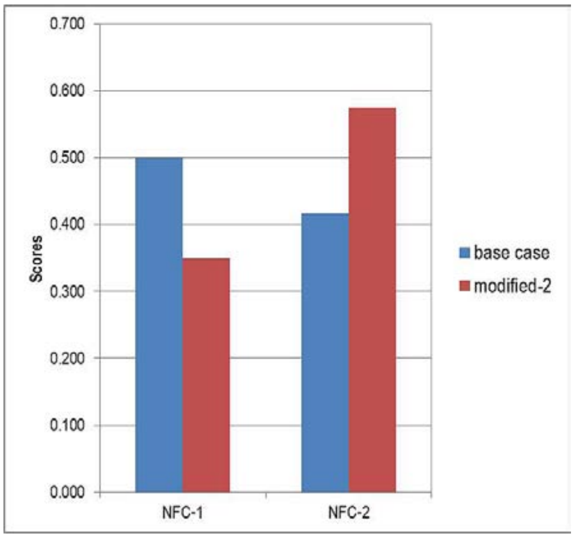
Uncertainties of HLOs weight values on ranking score have great impact on ranking score. A small variation of HLOs weight, as shown in Table 3.13, can significantly change the ranking score values, and can even change or reverse the ranking order as presented in Figure 3.24.

TABLE 3.13. WEIGHT VALUES VARIATION

HLOs	Weight values		
	Base case	Modified case 1	Modified case 2
Cost	0.333	0.2	0.5
Performance	0.333	0.3	0.3
Acceptability	0.333	0.5	0.2



(a)



(b)

FIG. 3.24. Comparison of overall ranking results between: (a) base case and modified case 1, (b) base case and modified case 2.

In modified case 1, the HLO's equal weight (33.33%) was changed to: 50% weight for the Acceptability, 20% weight for the Cost, and 30% weight for the Performance. This change is reflected in Fig. 3.24 (a) by an increase in the overall score of NFC-1, while the overall score of NFC-2 decreases.

In modified case 2, the HLO's equal weight (33.33%) was changed to: 50% weight for the Cost, 20% weight for the Acceptability, and 30% weight for the Performance. This change is reflected in Fig. 3.24 (b) by a decrease in the overall score of NFC-1, while the overall score of NFC-2 increases.

Figure 3.24(a) shows lowering cost weight and raising acceptability weight will widen score gap between score of NFC-1 and NFC-2, but the ranking order will remain the same. Fig. 3.24(b) shows raising cost weight and lowering acceptability will reverse the order of ranking. An increased acceptability weight is better for NFC-1 but worse for NFC-2, so raising the weight of acceptability will raise the score of NFC-1 and lowering this weight will yield an inverse effect. The cost weight value will have the opposite effect compared to that of acceptability. Combination of the two will make the difference in scores more pronounced.

3.3.4. Conclusions

Comparison evaluation of two different NFC technologies of interest for Indonesia, using the KIND-ET tool, showed that NFC-1 (pin fuel fabrication technology) has better ranking score than NFC-2 (pebble fuel fabrication technology).

However, results of sensitivity analysis showed that the ranking score is more or less sensitive to choices of HLOs weight values, so in order for the analysis to give more useful results, accurate and realistic weight values for Indonesia's case are needed.

3.4. SELECTION OF THE SUITABLE REACTOR TECHNOLOGY USING THE COMPARATIVE EVALUATION APPROACH (KENYA)

This chapter presents structured report of a case study done by experts from the Republic of Kenya.

3.4.1. Introduction

The Vision 2030, which is Kenya's blueprint for economic development, gives an outline of the government's policy and strategy for transforming Kenya into an industrialized and middle-income country. Vision 2030 has also identified energy as an enabler of the long term development strategy and subsequently identified the need for diversification of the nation's energy mix. As a result, nuclear electricity generation has been proposed for inclusion in the national energy mix in a decision based on projected long term energy demand in Kenya. The Ministry of Energy through the Kenya Nuclear Electricity Board (KNEB), the Nuclear Energy Programme Implementation Organisation (NEPIO), is implementing the nuclear power programme which is envisioned to contribute to meeting future energy needs through electricity generation. Amongst the activities in the nuclear power programme, the selection of the most suitable reactor design from various technology options that are available for the Kenya nuclear energy plan is considered. As a potential 'technology user', Kenya is undertaking a Reactor Technology Assessment (RTA) which is identified as a decision making process that would involve evaluation, selection and deployment of the most preferable technological option to comply in full with the policy objectives of the national nuclear power programme. As such, the RTA is to be carried out during the feasibility study, preparation and evaluation of bid invitation specifications, and as an evaluation tool during Nuclear Power Plant (NPP) deployment. This analysis needs to be done on a range of reactor designs based on a range of indicators derived from assessment elements such as environment, economics, waste management, safety, safeguards and proliferation.

3.4.2. Objective and problem formulation

In order to select a suitable nuclear reactor technology, it is important to use a method that is justifiable. In the selection of a suitable nuclear reactor technology for Kenya's electricity generation, policy makers are keen to ensure that the technology is suitable for the country's technical, performance and financial capability. In addition to using the various characteristics of available technologies, the current status of the country's nuclear infrastructure is also considered in this comparative evaluation in order to make an optimum choice.

The case study conducted aims at utilising the Key Indicators for Innovative Nuclear Energy Systems (KIND) approach to enhance decision making on a suitable reactor technology for Kenya. The technologies for the comparison were selected based on capacity (large, medium and small), level of standardization, maturity, diversity and the rapid detailed licensing review process the reactors are currently undergoing. These technologies were compared using key indicators adopted from the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) methodology for nuclear energy system assessment. [3.3]

3.4.3. Inputs, methods and assumptions used

The inputs, methods and assumptions used in the case study are presented in a structured way in this chapter.

3.4.3.1. Formulation of alternatives (NES options)

The reactor technology assessment project aims at identifying the best technology to adopt in the nuclear power programme for Kenya. Based on the experience gained in the above project, the team identified three categories of nuclear technologies currently in the market or undergoing development, based on electrical power output: The Large-sized Reactors (700 MWe and above); the Medium sized Reactors (between 300 MWe and 700 MWe); and the Small and/or Modular Reactors (SMRs) (up to 300 MWe). The above categories present various strengths and weaknesses when compared against each other, based on the selection criteria identified by the RTA team. The selection criteria are broadly based on the following key high-level objectives: cost, performance, and acceptability.

For each category of the Nuclear Energy Systems (NESs) a representative technology was chosen. They include:

— NES 1: The 1550 MWe GE-Hitachi Economic Simplified Boiling Water Reactor (ESBWR) to represent Large-sized Power Reactors [3.8];
— NES 2: The 600 MWe Westinghouse Advanced Passive (AP)-600 reactor to represent Medium sized Power Reactors[11];
— NES 3: The 50 MWe NuScale Power module, to represent Small Modular Reactors (SMRs) [3.9].

Table 3.14 outlines some of the technical parameters of the three reactor technologies selected for comparative evaluation.

TABLE 3.14. MAIN TECHNICAL PARAMETERS OF THE NES TECHNOLOGIES

Parameter	NES 1: ESBWR	NES 2: AP-600	NES 3: NuScale SMR
Reactor type	BWR	PWR	PWR
Fuel type/Enrichment %	UO_2/4.2	UO_2/4.8	UO_2/4.95
Capacity (MWe)	1550	600	50/ module
Plant capacity factor (%)	>90	87	>95
Efficiency (%)	34	31	30
Average burnup (MW·d/kg)	50	55	>30
Plant life (years)	60	60	60

3.4.3.2. Identification of Key Indicators and assumptions

In the selection of the Key Indicators (KIs) for the comparative evaluation in the Kenyan case the key indicators developed within the INPRO Methodology, which are related to the areas of evaluation for sustainable development of nuclear energy systems, were used. The INPRO advice was used to identify the high-level objectives, assessment areas and subsequent key indicators. The high-level objectives selected by the team for consideration were cost,

[11] https://www.iaea.org/resources/databases/advanced-reactors-information-system-aris

performance and acceptability. Seven (7) assessment areas and seventeen (17) key indicators were then selected as shown in Table 3.15 and Fig. 3.25.

The three NESs considered in this case study have not been deployed. Therefore, the data used is as given in technical documents (theoretical /supplier claims) and may change once the plants are built and operated.

TABLE 3.15. IDENTIFICATION OF KEY INDICATORS

High-level objectives	Assessment Areas	Key Indicator
Cost	Economics	Levelized Unit Electricity Cost (LUEC) (E.1)
Performance	Environment	Amount of U/Th used per unit of usable energy produced (GW·d/t) (EVN.1)
	Waste Management	Waste Generated (ton/yr.MW) (WM.1)
	Safety	Emergency planning zone radius (SS.1)
		Large Early Release Frequency (SS.2)
		Core Damage Frequency (SS.3)
	Infrastructure	Industrial and economic infrastructure (I.1)
		Grid Integration (I.2)
	Country Specifics	Flexibility for non-electrical services and energy products (S.1)
		Political support (S.2)
Acceptability	Maturity of Technology	Degree of technology verification (M.1)
		Degree of standardization and licensing adaptability (M.2)
		Licensing Status (M.3)
		Vendor Profile (M.4)

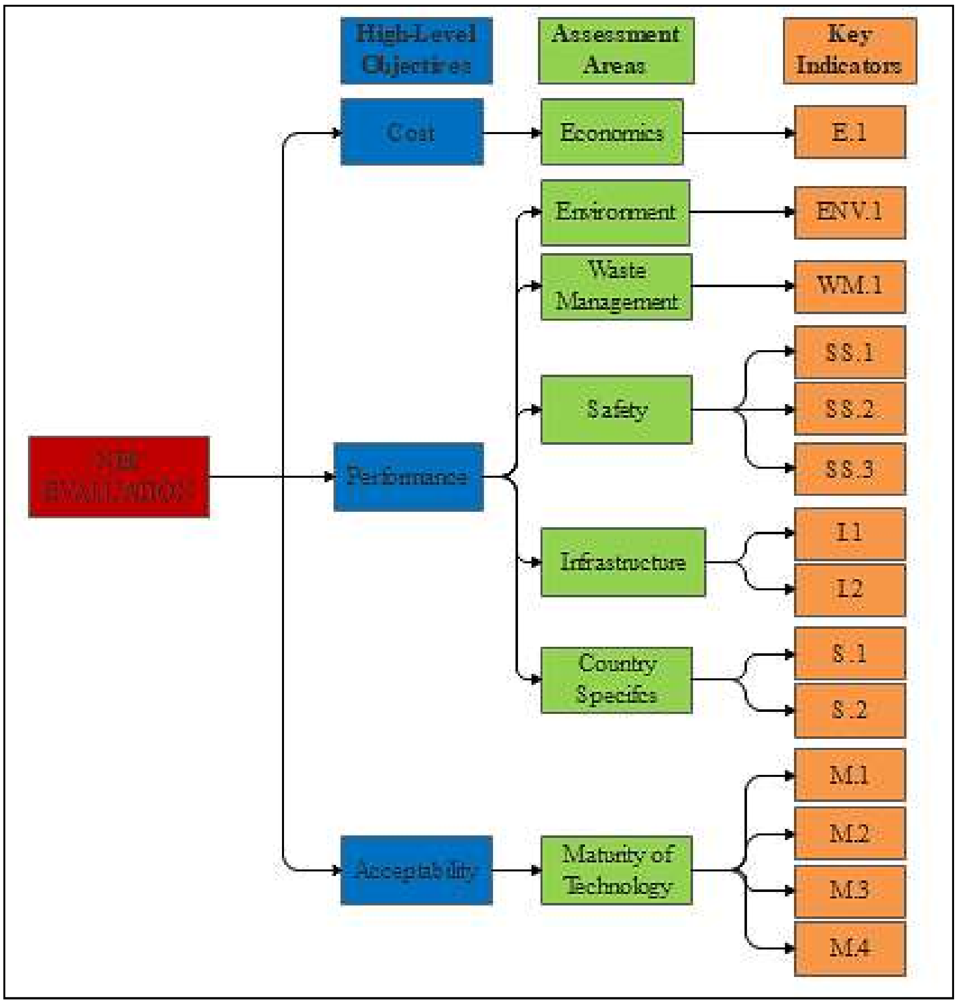


FIG. 3.25. Structure of objective tree for Kenya case study.

Once the set of key indicators was developed, a decision was made on how to evaluate each of the key indicators against the three nuclear energy systems. For measurable key indicators, data were collected mainly from vendor provided technical information as well as the IAEA Advanced Reactors Information System database.

The definition and parameters of measurement for the key indicators and score determining factors are indicated in Table 3.16.

TABLE 3.16. SCORE DETERMINING FACTORS

Key Indicators	Definition	Score determining factor(s)
Levelized unit electricity cost (LUEC)	The total cost incurred over the lifetime of a plant divided by the total electricity produced over its lifetime. It includes all aspects (licensing, construction, operation, maintenance and decommissioning etc.) that affect the total cost.	The highest score was assigned to the NES with the lowest LUEC
Amount of U/Th used per unit of usable energy produced (GW·d/t).	—	The highest score was assigned to the NES with the highest burnup.
Waste generated (tonnes/yr·MW)	—	The highest score was assigned to the NES with the lowest amount of waste generated.
Emergency planning zone radius	Emergency planning zone (EPZ) radius (e.g., as per licensing in the country of origin).	The highest score was assigned to the NES with the smallest EPZ
Large early release frequency (LERF)	"The frequency of those accidents leading to significant, unmitigated releases from containment in a time frame prior to effective evacuation of the close-in population such that there is the potential for early health effects"[12].	The highest score was assigned to the NES with the lowest LERF value.
Core damage frequency (CDF)	"The sum of the frequencies of those accidents that result in uncover and heat up of the reactor core to the point at which prolonged oxidation and severe fuel damage involving a large fraction of the core (i.e., sufficient, if released from containment, to have the potential for causing offsite health effects) is anticipated"[11].	The highest score was assigned to the NES with the lowest CDF value.
Industrial and economic infrastructure	The industrial and economic infrastructure of a country planning for a NES needs to be adequate to support the project during planning, construction and operation.	The highest score was assigned to the NES that is compatible with the Kenya economic capability for funding and one which can be supported by the industrial status.
Grid integration	Degree of complexity associated with NPP integration into the grid, including topics related to both grid upgrade requirements and compliance with the existing regulations.	The highest score was assigned to the NES with the least grid integration requirements.

[12] https://ocw.mit.edu/courses/nuclear-engineering/22-091-nuclear-reactor-safety-spring-2008/lecture-notes/MIT22_091S08_lec11.pdf

TABLE 3.16. SCORE DETERMINING FACTORS (cont.)

Key indicators	Definition	Score determining factor(s)
Vendor profile	Demonstration by the technology owner (vendor) on the history of successful technology deployment.	The highest score was assigned to the NES with a rich history in terms of successful technology deployment.
Flexibility for non-electrical services and energy products	Ability of a NES to serve other applications beyond electric power production.	The highest score was assigned to the NES with the highest flexibility.
Political support	The degree to which a NES can easily draw support from the policy makers based on demonstrated benefits to the public.	The highest score was assigned to the NES with the highest level of political support.
Degree of technology verification	Degree at which a technology demonstrates ability to perform intended function through testing and/or operation, preferably over a long period of time.	The highest score was assigned to the NES that demonstrates the highest degree of technology verification.
Degree of standardization and licensing adaptability	Developing standard reactor designs which harmonize industry standards and requirements.	The highest score was assigned to the NES that exhibits the highest level of standardisation in its design.
Licensing status	Pre-licensing possible in country of origin.	The highest score was assigned to the NES with possibility of pre-licensing in country of origin

The scores of all KIs for the three NESs considered in the comparative evaluation are presented in Table 3.17. The score for each KI corresponding to the three NES alternatives were determined using a 7-point scoring scale. The highest score was 7, and the lowest 1, with the highest score being the best. In developing the performance table, it was assumed that if the evaluation outcome of a certain indicator for the alternatives is the same, the alternatives are assigned the same score. However, such scores do not affect the final ranking results of the NES alternatives.

TABLE 3.17. SCORING CRITERIA FOR NES

High-level objectives	Areas titles	Indicators titles	Qualitative Evaluation			7 – Point scoring scale		
			NES-1	NES-2	NES-3	NES-1	NES-2	NES-3
Cost	Economics	Levelized unit electricity cost (LUEC)	×*			7	3	5
Performance	Environment	Amount of U/Th used per unit of usable energy produced (GW·d/t U).		×		6	7	4
	Waste management	Waste generated (tonnes/yr·MW)		×		6	7	4
	Safety	Emergency planning zone radius			×	3	3	6
		Large early release frequency			×	5	4	6
		Core damage frequency	×			6	3	5
	Infrastructure	Industrial and economic infrastructure			×	3	5	7
		Grid integration			×	3	5	7
	Country specifics	Flexibility for non-electrical services and energy products			×	2	2	7
		Political support			×	3	5	6
Acceptability	Maturity of technology	Degree of technology verification		×		4	6	2
		Degree of standardization and licensing adaptability			×	3	4	5
		Licensing status	×	×		7	7	3
		Vendor profile	×			6	4	3

*x is a pointer for the NES, which provides the best performance on a corresponding KI.

3.4.3.3. 'Value paths' and 'radar chart' visualization of performance table

Visualization of the performance table may be presented in the form of 'value path' and 'radar chart' diagrams. The *'value paths'* diagram as shown in Fig. 3.26 displays variations in the values of all KIs for the three NESs and allows estimating quantitatively how much improvement in the value of one KI deteriorates the values of other KIs due to the transition from one NES to another. The *'radar chart'* diagram as shown in Fig. 3.27 displays multivariate data in the form of a two-dimensional chart of the 17 key indicators represented on axes starting from the same point. As shown in Fig. 3.26 and 3.27 all alternatives are non-dominated, which means that each alternative has some advantages over others.

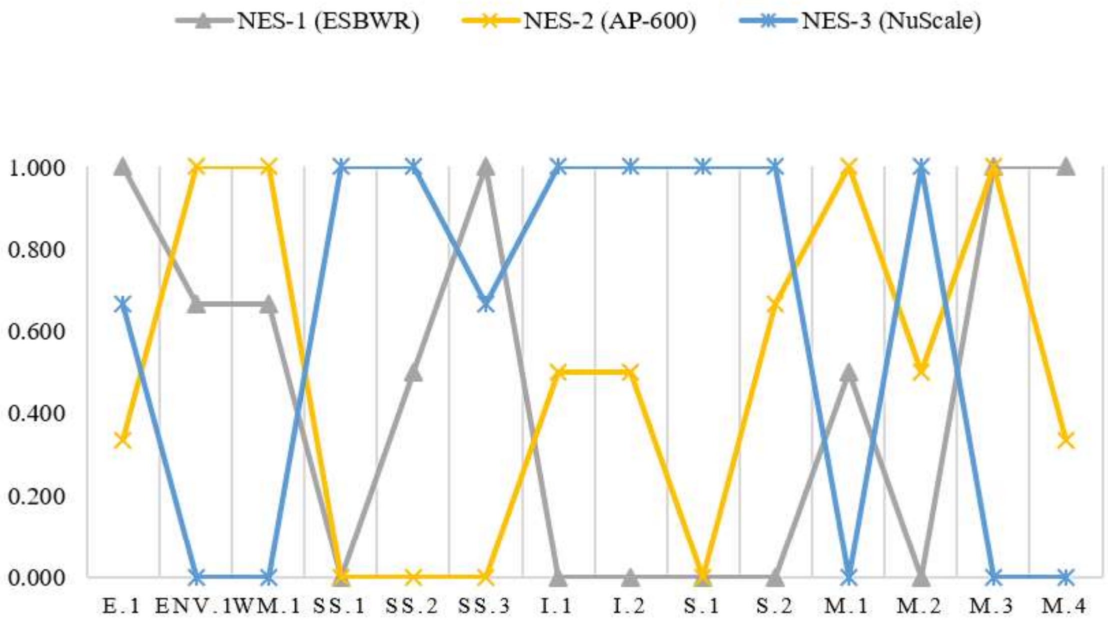


FIG. 3.26. Value path diagram.

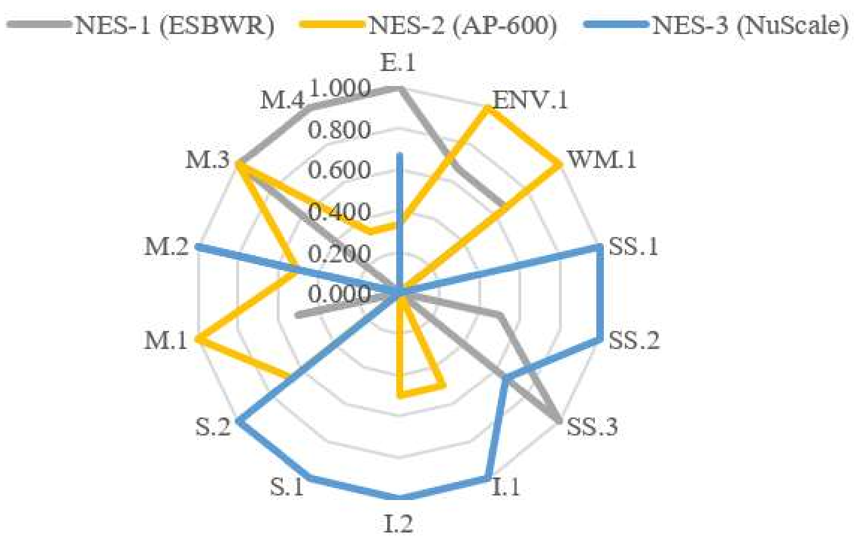


FIG. 3.27. Radar chart.

3.4.3.4. Determination of weights including uncertainties

The weights of the high-level objectives, assessment areas and KIs were determined by both pairwise comparison and direct method. The weights for the three assessment levels were determined by the assessment team guided by technology attributes and country specifics. In this case study, the most important high-level objective is 'performance' and was assigned 0.400, 'acceptability' and 'cost' were assigned an equal weight of 0.300. Table 3.18 indicates the weights for the three levels as assigned through expert judgement and the final weights as calculated using KIND-ET.

TABLE 3.18. WEIGHTING FACTORS

High-level objective titles	High-level objective weights	Area titles	Area weights	Indicator abbr.	Indicator weights	Final weights
Cost	0.300	Economics	1	E.1	1	0.300
Performance	0.400	Environment	0.083	ENV.1	1	0.033
		Waste management	0.2002	WM.1	1	0.080
		Safety	0.1992	SS.1	0.121	0.010
				SS.2	0.535	0.043
				SS.3	0.344	0.027
		Infrastructure	0.166	I.1	0.400	0.027
				I.2	0.600	0.040
		Country specifics	0.3516	S.1	0.300	0.042
				S.2	0.700	0.098
Acceptability	0.300	Maturity of technology	1	M.1	0.347	0.104
				M.2	0.116	0.035
				M.3	0.298	0.089
				M.4	0.240	0.072

3.4.3.5. Selection of a Multi-Criteria Decision Analysis method

In order to conduct this comparative evaluation of NESs, judgment aggregation was applied due to the multi-criteria character of the problem. Multi-Criteria Decision Analysis (MCDA) and Multi-Objective Decision Making (MODM) are the main Multiple Criteria Decision Making (MCDM) classes of methods helping to solve complex decision problems. An expanded set of different MCDA tools (i.e., more representative ones) was considered within the KIND project framework which has been applied to perform comparative evaluations of the three nuclear energy systems.

3.4.4. Ranking results and analysis

The ranking results and analysis for this case study are presented in a structured form below.

3.4.4.1. Ranking alternatives with the selected MCDA method

A 'linear' single attribute value function was selected for the evaluation of the NES. This is because it is risk neutral and the relationship between the input and outputs is linear and is also a good starting point for the first approximation as compared to other forms. For the domain type, a "local domain" was considered since few NES options are considered and there is need to enhance their distinguishability. However, a global domain was selected for the key indicators under the economic assessment area. Table 3.19 summarizes the results of the shapes and domains of the single attribute value function used in this case study.

TABLE 3.19. SINGLE ATTRIBUTE VALUE FUNCTION

Indicator abbr.	Goal	Form	Exponent power	VF domain	MIN VF domain	MAX VF domain	NES-1 (ESBWR)	NES-2 (AP-600)	NES-3 (NuScale)
E.1	Max	lin.	1	global	1	7	1.000	0.333	0.667
ENV.1	Max	lin.	1	local	4	7	0.667	1.000	0.000
WM.1	Max	lin.	1	local	4	7	0.667	1.000	0.000
SS.1	Max	lin.	1	local	3	6	0.000	0.000	1.000
SS.2	Max	lin.	1	local	4	6	0.500	0.000	1.000
SS.3	max	lin.	1	local	3	6	1.000	0.000	0.667
I.1	max	lin.	1	local	3	7	0.000	0.500	1.000
I.2	max	lin.	1	local	3	7	0.000	0.500	1.000
S.1	max	lin.	1	local	2	7	0.000	0.000	1.000
S.2	max	lin.	1	local	3	6	0.000	0.667	1.000
M.1	max	lin.	1	local	2	6	0.500	1.000	0.000
M.2	max	lin.	1	local	3	5	0.000	0.500	1.000
M.3	max	lin.	1	local	3	7	1.000	1.000	0.000
M.4	max	lin.	1	local	3	6	1.000	0.333	0.000

The overall ranking results are shown in Fig. 3.28 and Table 3.20. Out of the three NES options considered for this evaluation, NES-1 (ESBWR) is the most preferred option with an overall score of 0.637. NES-2 (AP-600) and NES-3 (NuScale) took the second and third place, respectively, with a score of 0.547 and 0.512, based on the multi attribute value function score.

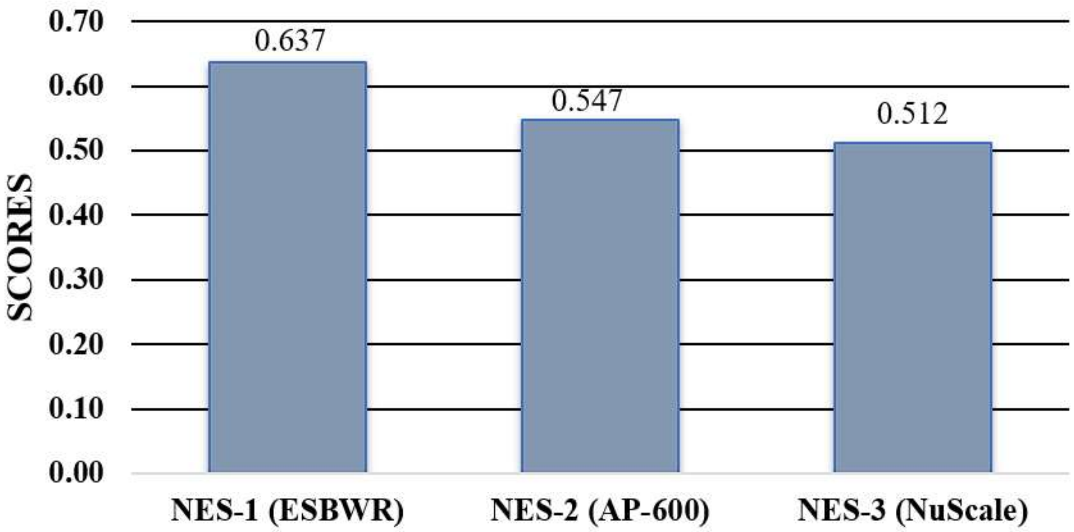


FIG. 3.28. Overall ranking results.

The results of decomposition of the analysis into individual components in accordance with the high-level objectives are as shown in Table 3.20 and Fig. 3.29. As shown in Table 3.20, the score on the aggregated high-level objective 'Cost' for the NES-1 is the highest amongst the three NESs. NES-2 and NES-3 are slightly comparable in the aggregated high-level objectives' score with a score difference of 0.035. NES-3 has the lowest score (0.035) in terms of 'Acceptability', amongst the NESs which highly influences its level of attractiveness and makes it the least preferable option, despite its highest score in terms of 'Performance'.

TABLE 3.20. HIGH LEVEL AGGREGATED OBJECTIVE SCORE

Nuclear energy system (NES)	High-level objective scores			
	Cost	Performance	Acceptability	Overall Score
NES-1 (ESBWR)	0.300	0.124	0.213	0.637
NES-2 (AP-600)	0.100	0.212	0.235	0.547
NES-3 (NuScale)	0.200	0.278	0.035	0.512

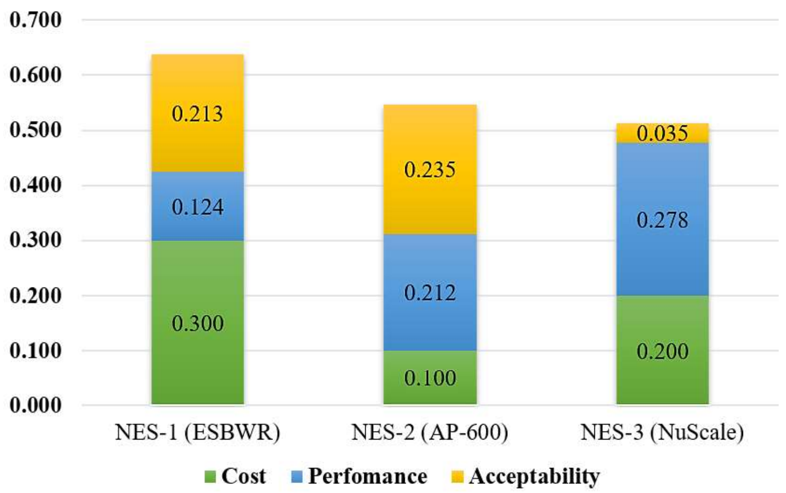


FIG. 3.29. High level objective aggregated score.

A comparison of the aggregated scores for all the evaluation areas provides an opportunity to examine the contribution of these areas to the value function of high-level objective. Hence more detailed explanation on dominance of one NES alternative over another can be provided to the decision makers/expert/stakeholders. For the easy interpretation of the ranking results, the multi attribute value functions were decomposed into individual components in accordance with the objective tree levels (high-level objectives, and evaluation areas) as shown in Table 3.20 and Table 3.21.

TABLE 3.21. ASSESSMENT AREA SCORES

NES	Assessment area						
	Economics	Environment	Waste management	Safety	Infrastructure	Country specifics	Maturity of technology
NES-1 (ESBWR)	0.300	0.022	0.053	0.049	0.000	0.000	0.213
NES-2 (AP-600)	0.100	0.033	0.080	0.000	0.033	0.066	0.235
NES-3 (NuScale)	0.200	0.000	0.000	0.071	0.066	0.066	0.035

From the evaluation, NES-3 has the highest score in terms of safety, and infrastructure assessment areas. However, it has the lowest score in environment, waste management and maturity of technology assessment areas. Regarding safety, NES-3 has the highest score because amongst the three NESs it needs the smallest emergency planning zone and also has the lowest large early release frequency. In terms of grid integration, the electric grid in Kenya can easily accommodate NES-3 with no/minimal modification as compared to the other NES. Additionally, due to the economic status of the country, the NES-3 would be more competitive against other non-nuclear energy systems due its unit size compared to large and medium size reactors. These reasons contribute to the high score for NES-3 in the area of infrastructure.

The most attractive NES alternative in terms of economics is NES-1 (ESBWR), while NES-2 (AP-600) is the least attractive. However, NES-1 has the lowest scores (0.00) in infrastructure and country specifics compared to the other two NES options. This is mainly due to its unit size which presents disadvantages in terms of grid integration and economic competitiveness (a complete contrast to NES-3). Regarding maturity of technology and waste management, the best NES option is NES-2. The high score in this assessment area is due to the fact that NES-2 nuclear reactor technology is the reference design of the AP1000 which is currently in operation. On the other hand, NES-3 has the least score in this area because it is a first of a kind technology and is therefore not proven. The assessment area scores can be presented on a radar chart shown in Fig. 3.30.

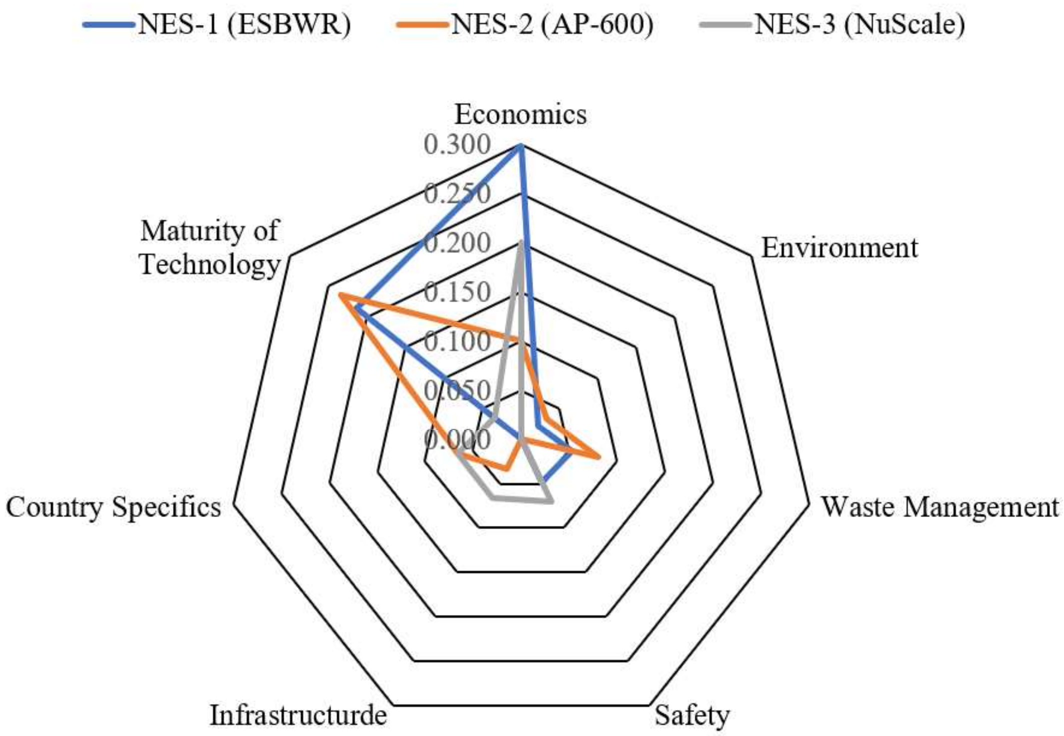


FIG. 3.30. Assessment area score radar chart.

3.4.4.2. Sensitivity and uncertainty analysis

Weight sensitivity

Sensitivity to weighting factors was carried out for ‘high level objective’ weights in three scenarios. In each scenario the weight for one of the high-level objectives was increased to 0.6 against the other two which were given equal weights. As can be seen in Fig. 3.31 (a), (b), and (c) the following can be concluded on the options’ rank sensitivity to an increase in the weighting factor for each high-level objective, separately:

— If the weight for Performance is greater, the NES-1 is the preferred option.
— If the weight for Cost is greater, the NES-1 is the preferred option with a large score margin between it and NES-3 of 0.261.
— If the weight for Acceptability is greater, the NES-1 is the preferred option, while NES-3 is least preferred.

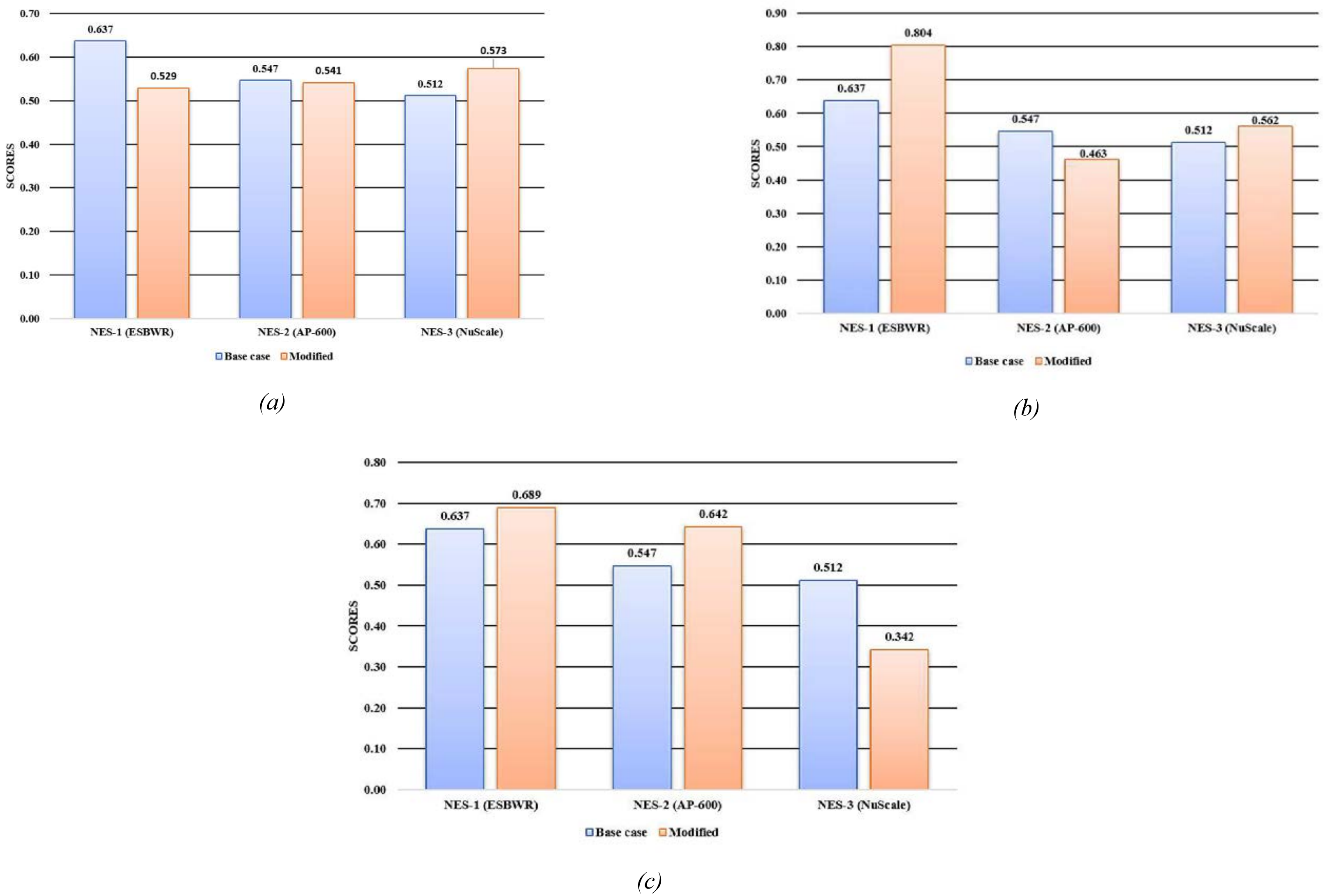


FIG. 3.31. Results for weight sensitivity: (a) weight sensitivity to increasing the performance weighting factor, (b) weight sensitivity to increasing the cost weighting factor, (c) weight sensitivity to increasing the acceptability weighting factor.

Sensitivity to single attribute value function form

Single attribute value function sensitivity analysis evaluates the impact on the final ranking results of the NES alternatives with respect to changes in single attribute value function form (‘linear’ or ‘exponential’), goal (‘min’ or ‘max’) and domain (‘local’ or ‘global’). For the sensitivity analysis, four working cases including the base case were considered. The goal for the key indicator in all the workings cases was retained to be ‘max’ as shown in Table 3.22.

TABLE 3.22. SINGLE ATTRIBUTE VALUE FUNCTION FORM SENSITIVITY CASES

Working cases	Goal	Value function form	Value function domain
Base case	max	Linear	Local/Global
Case 1	max	Linear	Global
Case 2	max	Exponential	Local
Case 3	max	Exponential	Global

The results were tabulated, and a bar graph shows the changes in the final ranking for the NESs in each case as shown in Table 3.23 and Fig. 3.32.

TABLE 3.23. RESULTS OF SINGLE ATTRIBUTE VALUE FUNCTION FORM SENSITIVITY

Working case	NES alternatives		
	NES-1 (ESBWR)	NES-2 (AP-600)	NES-3 (NuScale)
Base case	0.637	0.547	0.512
Case 1	0.724	0.593	0.603
Case 2	0.612	0.437	0.429
Case 3	0.833	0.753	0.766

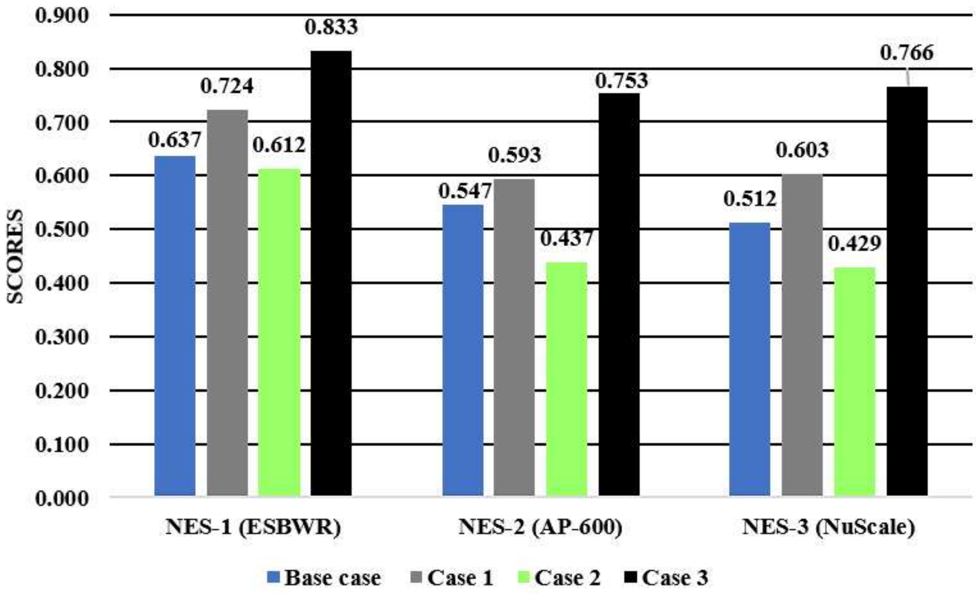


FIG. 3.32. Value function sensitivity results.

From the value function sensitivity analyses, changes of the value function form and domain for the single attribute function result in an increase in the Multi Attribute Value Function (MAVF) values in Case 1 and Case 3. However, this doesn't affect the final ranking results, i.e., NES-1(ESBWR) remains the most preferred option.

3.4.5. Conclusions

The objective of this case study was to understand and apply KIND-ET for the assessment of deployable/practical NESs. The tool was applied in the comparative evaluation of three reactor technologies which are differentiated in terms of their unit size (large, medium and small/modular). Based on the results for the NES options, ESBWR is regarded as the best option. However, it needs to be noted that the results for both AP600 and NuScale are closely competitive, and therefore can be considered as alternative options.

In this case study the reactor technologies selected are at various stages of development but have not been deployed. Subsequent use of the tool will consider NESs that are in operation as the nuclear power programme in Kenya advances to stages such as preparation of the bid invitation specification.

The tool provides a reasonable and user-friendly approach to judge and comparatively evaluate NESs. Additionally, the tool allows manipulation of input data, comparing and differentiating options as well as interpreting the ranking results. Hence the tool can be used to demonstrate the merits and demerits of NESs in different conditions.

3.5. COMPARATIVE EVALUATION OF LONG TERM NUCLEAR ENERGY DEPLOYMENT SCENARIOS (MEXICO)

This chapter presents structured report of a case study done by experts from the United Mexican States.

3.5.1. Introduction

Mexico is a nuclear technology user country with low participation in technological solutions for the nuclear energy fuel cycle. In 2018, the total power capacity installed in Mexico from all technologies was 70,053 MW[13], the nuclear share being 2.3% with an annual generation of 13,199 GW·h [3.10]. Nuclear power in Mexico operates as a baseload technology in the dispatch. Currently, there is only one Nuclear Power Plant (NPP) in operation in Mexico, with two BWRs of 654 MWe each. Both reactors are operated by the Federal Commission of Electricity (CFE, from the Spanish acronym, Comisión Federal de Electricidad) at the site of Laguna Verde, Veracruz. Unit 1 has been in operation since 1990 and Unit 2 since 1995. An upgrade to 105% of power for both reactors was made in 1999, and another one to 120% in 2011. Since the start of reactor operation, nuclear fuel has been imported from the Global Nuclear Fuel Company. Now, an open fuel cycle is operating in the country; the spent nuclear fuel (SNF) is stored on the site of the NPP. There is not yet a specific plan for the management of the SNF in the long-term. The KIND-ET application to the selection of waste management options could be very useful for the Mexican government.

The Mexican government recognises Global Warming as a real problem for human sustainability. “Mexico has been an active player in international efforts to tackle climate change for the past two-and-a-half decades, helping to advance” global “climate change negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) and through” the G20 forum [3.11]. Mexico “became the first developing country to submit an Intended Nationally Determined Contribution leading up to the adoption of the Paris Agreement” [3.11]. Since 2012 the parliament passed the General Law on Climate Change (GLCC) having among its goals to “increase electricity generation from clean sources to 35 % by 2024 and to reduce fossil fuel subsidies” [3.11]. In 2013, as a planning instrument to implement this Law, the National Climate Change Strategy (NCCS) [3.12] with targets on emissions and energy generation was published. It sets targets of reducing Green House Gas (GHG) emissions by 30% by 2020, and 50% by 2050 compared to 2000 levels. Concerning clean energy targets, clean technologies’ share needs to be 35% by 2024, 40% by 2034, and 50% by 2050. The NCCS considers as clean energies: renewables, nuclear, high-efficient cogeneration, and power generation with carbon capture and storage.

Mexico is a signatory country of the Paris Agreement, and therefore, Mexico outlined and communicated its post-2020 climate actions through its nationally determined contributions (NDCs). In this context, in 2015, the Federal Official Gazette in Mexico published the decree issuing the Energy Transition Law (ETL) [3.13]. The ETL “aims to regulate the sustainable use of energy and articulate the electric industry's obligations” according to the country's “need to transition using clean” energy “and cutting polluting emissions, while at the same time maintaining Mexico's productivity and competitiveness on the world stage” [3.13]. As mentioned before, the NCCS considers nuclear as clean energy, in this context the National Electric System Development Programme (PRODESEN, from the Spanish acronym, Programa de Desarrollo del Sistema Eléctrico Nacional) which is a programme annually published by the Mexican Secretariat of Energy for a planning period of 15 years, considered nuclear energy in

[13] Page 21 of V PRODESEN 2019-2033.

the editions for (a) 2015-2029[14] [3.14], (b) 2016-2030[15] [3.15], (c) 2017-2031[16] [3.16] and (d) 2018-2032[17] [3.17]. These four PRODESENs had planned to deploy nuclear capacity, in synergy with renewables, to meet the clean energy targets of the NCCS in the years that correspond to the end of the period in each edition. No more information than the location and indicative characterization of the power plants was put in each PRODESEN. Even though the use of nuclear energy had been considered as an option to produce clean energy in Mexico, little information about specific actions to put in place these nuclear programmes was published by the Mexican Secretariat of Energy. It became a necessity to carry out studies of different nuclear scenarios that could help the Mexican government to make decisions based on sustainability analysis. However, the current Mexican government does not have a nuclear deployment programme, and in the PRODESEN 2019-2033 [3.10] there are no nuclear plants planned for the period.

Sustained commitment is required for the successful implementation of realistic actions in Mexico to provide clean electricity generation by the various electricity generating sectors.

Nuclear energy could reduce the GHG emissions drastically in Mexico; however, public acceptance in Mexico as well as in many other countries, including those that have a mature nuclear industry, has questioned its safety and also its energy and environmental sustainability concerning the use of natural resources and disposition of nuclear fuel wastes. In this regard, decision making is to be based on a sustainability analysis of a set of nuclear energy scenarios by using appropriate analytical tools proved by experts in the world, especially those developed by the IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) [3.18] to supporting the IAEA Member States to evaluate the initial nuclear plant deployment or expansion of their nuclear energy programmes. Mexico, as many other Member States of the IAEA, has recognized the increasing need to model future nuclear power scenarios to develop strategies for sustainable nuclear energy systems.

The National Autonomous University of Mexico (UNAM, from the Spanish acronym, Universidad Nacional Autónoma de México), as the leading university in the country, has among its several goals to conduct research aimed at solving national problems, and to contribute to the education of future human resources. The UNAM has an Energy Planning Unit (EPU) integrated by an interdisciplinary group of professionals and academics who generate tools and knowledge for the planning of energy systems with economic, environmental and social goals. In this regard, academics from the EPU-UNAM decided to use the INPRO methodology and the INPRO analytical tools to study long term scenarios with closed multi-recycled plutonium fuel cycles for fast reactors, combined with the current types of light water reactors, called nuclear energy systems (NESs). The main objective of the study is to build capacities among postgraduate students and academics to use the INPRO tools to evaluate different nuclear energy systems for the long term in Mexico. Another goal of this study is to learn how to use the tools and how to develop a methodology to analyse country-specific future energy systems.

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[14] Page 53 of PRODESEN 2015-2029 with addition of NPPs in years 2026, 2027, and 2028 (1222 MW, 1222 MW & 1400 MW

[15] Page 92 PRODESEN 2016-2030 with addition of NPPs in years 2028, 2029, and 2030 (1360 MW, 1360 MW & 1360 MW).

[16] Page 262-263 PRODESEN 2017-2031 with addition of NPPs in years 2029, 2030, and 2031 (1360 MW, 1360 MW & 1360 MW).

[17] Page 232-233 PRODESEN 2018-2032 with addition of NPPs in years 2029, 2030, and 2031 (1360 MW, 1360 MW & 1360 MW).

In the present case study, KIND-ET [3.1] was applied to prospective reactor technologies selection in alternative long term nuclear energy systems (NESs).

3.5.2. Objective and problem formulation

The case study aims to make a preliminary comparison of NESs at the technological level looking for long term sustainable systems in terms of the use of natural resources and waste management. It is necessary to consider all NFC material flows in specific units (per unit energy production) to bring them to a comparable form. Examples are the natural resources used, nuclear fuel cycle performance and economics.

A secondary objective of the study, almost as relevant as the previous one, is to obtain knowledge on how to properly apply INPRO tools to investigate future energy systems for Mexico in the new national and global conditions.

The KIND approach and the KIND-ET tool, as an evaluation toolkit based on MAVT, were applied to evaluate the sustainability of six long term nuclear energy systems until the year 2100, in which light water reactors and advanced fast reactors are added with a different share in each NES that was explored. The approach made it possible to compare the sustainability of the NESs even when they have dissimilar maturity levels.

It is a given that the specific sets of KIs used in the KIND-ET tool can vary depending on the objective of the study. The areas to be considered by INPRO are safety, economics, waste management, proliferation resistance and physical protection, environment, the maturity of the technology and country-specific area. The environment area traditionally covers aspects related to the utilization of natural resources, as well as 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.

Some questions to be answered with this first case study in which KIND is used are:

- Is it environmentally sustainable to develop in Mexico a nuclear power system based on a closed fuel cycle?
- Is it better for Mexico to develop a nuclear power system that uses reactors with MOX fuel with recycled plutonium?
- Is it environmentally sustainable to develop a closed fuel cycle nuclear power system with fast reactors?

The above three questions have obvious responses for experts with nuclear knowledge; however, it is relevant to make a serious report with conclusions based on an adequate methodology and the visualization of consistent data and results to be presented to decision makers of the Mexican government. It is also an essential step in developing human resources with capabilities to investigate future energy systems.

3.5.3. Methodology

Figure 3.33 presents the methodology sequence used in the study. Six hypothetical scenarios of NESs were created with relevant differences among them to obtain through the KIND tool the answers to the three above questions. For the simulation of the flow of nuclear materials of the six NESs, the Nuclear Fuel Cycle Simulation System (NFCSS) was used. NFCSS is a scenario-based system for estimating the service requirements and flows of nuclear materials involved in the Front-end and Back-end of fuel cycles[18][3.19].

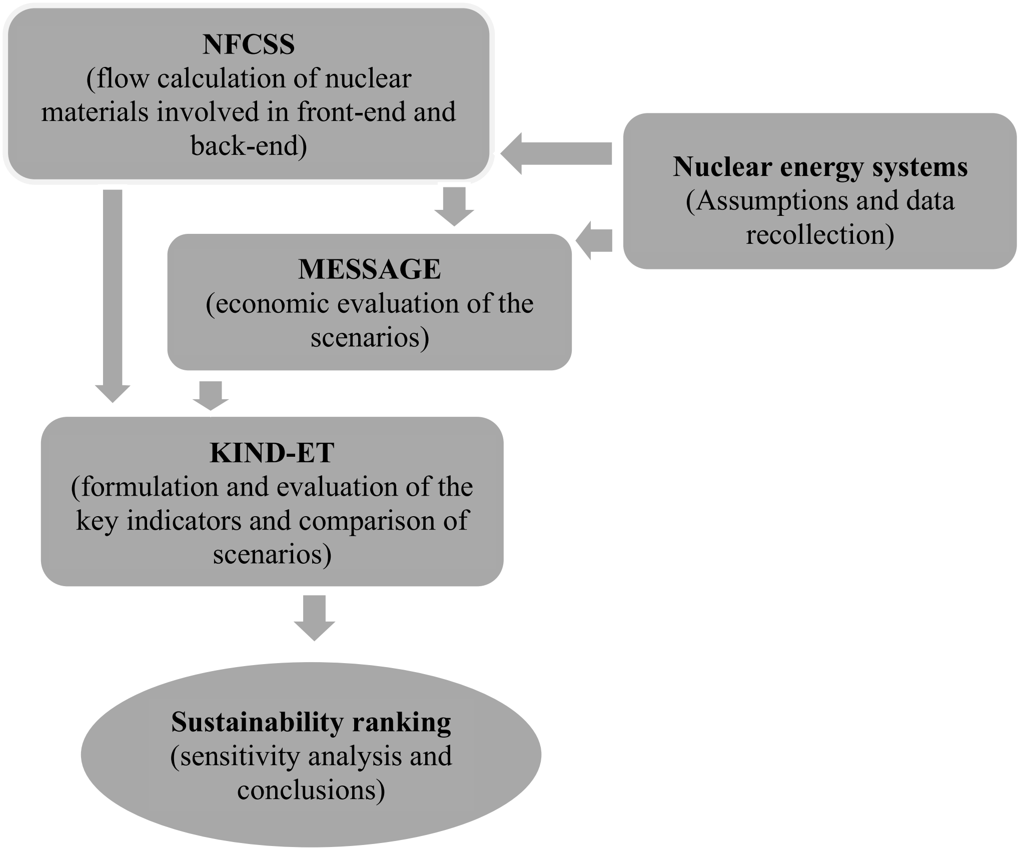


FIG. 3.33. General methodology.

NFCSS can calculate the amounts of natural uranium, conversion, enrichment, fuel fabrication, amounts of uranium saved using MOX fuel, and many variables involved in the nuclear fuel cycle. Some output parameters calculated with NFCSS were selected as Key-indicators in the KIND-ET tool, as will be explained later.

The MESSAGE [3.20] software was used to obtain an economic evaluation associated with each NES in which the amounts of nuclear materials obtained with NFCSS simulations were used as main inputs. In the last step, the KIND-ET and related tools were used to make a comparative evaluation of the sustainability of six NESs through a set of key indicators for a multicriteria evaluation.

3.5.3.2. Description of NE scenarios

The main assumptions for the six hypothetical NESs are:

- The period of study is from 2030 to 2100.
- The current two BWRs of the Laguna Verde nuclear power plant are in operation by 2030 and will be retired at the end of their life, which is assumed to be in the year 2050 and 2055 for Unit-1 and Unit-2 respectively.

[18] https://www.iaea.org/resources/databases/integrated-nuclear-fuel-cycle-information-system-infcis

- The BWR capacity in Mexico by 2030 is assumed to be 1552 MW with an average annual electricity production of 10874.6 GWh.
- In 2030 new nuclear capacity will be added to the Mexican power system to start a new NES.
- Nuclear energy will cover only 10% of the total annual electricity demand expected for Mexico by 2100, and that means an annual generation of 150,000 GWh.
- Only the generation of electricity from different nuclear technologies and its implications are examined, without any relationship to non-nuclear technologies.
- The total annual energy generation is the same in the six NESs, and it is the sum of the energy produced by the different nuclear technologies in the mix.
- The energy production for each intermediary year from 2030 to 2100 is obtained by linear interpolation between nuclear energy generated in both years.
- Technical and economic parameters of power plants and fuel cycle facilities are indicative.
- The capacity of different technologies in each year was calculated through the average capacity factor of the reactors that are participating in producing annual target energy in all the scenarios.

The main parameters characterizing the considered reactor technologies in NFCSS tool to simulate the considered six scenarios are given in Table 3.24. A synthetic description of each scenario is as follows:

- NES-1 assumes the addition of new nuclear capacity based on AP1000 (pressurized water reactor) with 100% UOX (AP1000) of 1110 MW every four years from 2030 to 2094.
- NES-2 assumes the addition of new nuclear capacity based on AP1000 with 100% UOX (AP1000) of 1110 MW every four years from 2030 to 2058, and EFR (sodium fast reactor) of 1086.63 MW every four years from 2062 to 2094.
- NES-3 assumes the addition of new nuclear capacity based on AP1000 with 70% UOX and 30% MOX (AP1000MOX30) of 1110 MW every four years from 2030 to 2094.
- NES-4 assumes the addition of new nuclear capacity based on AP1000 with 70% UOX and 30% MOX (AP1000MOX30) of 1110 MW every four years from 2030 to 2058, and EFR of 1086.63 MW every four years from 2062 to 2094.
- NES-5 assumes the addition of new nuclear capacity based on AP1000 with 70% UOX and 30% MOX (AP1000MOX30r50) of 1110 MW every four years from 2030 to 2094. In this scenario, 50% of fuel discharged from LWRs is reprocessed and used in fuel for MOX of AP1000MOX30r50.
- NES-6 assumes the addition of new nuclear capacity based on AP1000 with 70% UOX and 30% MOX (AP1000MOX30r80) of 1110 MW every four years from 2030 to 2058, and EFR of 1086.63 MW every four years from 2062 to 2094. In this scenario, 80% of the fuel discharged from LWRs is reprocessed and used in fuel for MOX of AP1000MOX30r80.

TABLE 3.24. REACTOR PARAMETERS USED IN NFCSS

Reactor parameter	Unit	BWR	AP1000	EFR
Power	MW	776	1110	1086.63
Burnup	GW·d/t HM	43.5	60	80
Load factor	%	80	93	95
Fuel residence time	yr	4	4	4
Efficiency	%	33.5	35	40

Table 3.25 summarizes the fuel description used in the NFCSS tool to simulate the six scenarios. For the AP1000 technology, the fuel can be only uranium-oxide (UOX) or UOX combined with mixed-oxide (MOX) or only MOX. MOX fuel, as used in present light water reactors, is a mixture of uranium and plutonium oxides. Masses of heavy metals are tracked and traced in the material flow analysis performed (the units are tonnes of Heavy Metal). The main parameters used for material calculation in the NFCSS simulations are given in Table 3.26.

TABLE 3.25. FUEL PARAMETERS USED IN NFCSS

Fuel parameter	Unit	BWR	AP1000-UOX	AP1000-MOX	EFR
Power density	kW/kg	25.9	37.5	37.5	86.27
Cooling time	yr.	6	6	7	7
Manufacturing time	yr.	1	1	1	1
Reprocessing time	yr.	1	1	1	1
Uranium content	%	^{235}U(4) ^{238}U(96)	^{235}U(4) ^{238}U(96)	^{235}U(0.3)	^{235}U(0.02)
Plutonium content	%	—	—	^{238}Pu(1.36) ^{239}Pu(60.10) ^{240}Pu(21.62) ^{241}Pu(11.70) ^{242}Pu(5.20)	^{238}Pu(2.27) ^{239}Pu(59.05) ^{240}Pu(25.89) ^{241}Pu(6.81) ^{242}Pu(5.97)

TABLE 3.26. PERFORMANCE OF NFC PROCESSES IN NFCSS

Process performance	Unit	Value
Tails Assay	%	0.3
Loss in Conversion	%	0.5
Loss in Enrichment	%	0.5
Loss in Fabrication	%	0.5
Loss in Reprocessing	%	0.5
Volume of HLW Generated in Reprocessing	%	0.15
Volume of ILW Generated in Reprocessing	%	0.35

In order to analyse the six scenarios, a MESSAGE model was developed, and corresponding simulations were performed.

The economic parameters for reactor technologies used in MESSAGE are shown in Table 3.27.

TABLE 3.27. REACTOR PARAMETERS USED IN MESSAGE [3.20]

Technologies and associated costs	Unit	AP1000	EFR
NPP investment cost	US$/kW(e)	3000	3500
Fixed O&M cost	US$/kW/yr.	50	55
Plant life	yr.	60	60
Fuel fabrication cost	US$/kg	300	1700
Variable O&M cost	US$/kW·yr.	10	10
Reprocessing plant investment cost	US$/kg/yr.	5000	—
Reprocessing plant O&M cost	US$/kg	400	

Table 3.28 presents the fuel processes associated costs used in MESSAGE simulations where each NES was built using as input the nuclear material balances obtained from NFCSS's output. The values of the economic parameters in Tables 3.27 and 3.28 have broad uncertainties. The most relevant will be examined using the KIND-ET tool.

TABLE 3.28. COSTS OF FUEL PROCESSES USED IN MESSAGE[19] [3.20],

Process name	Unit	Value
Conversion	US$/kg U as UF_6	14
Natural uranium	US$/kg	46
SWU Enrichment	US$/SWU	110
UO_2 fuel fabrication cost	US$/kg	300
MOX fuel fabrication cost	US$/kg	1200
EFR fuel fabrication cost	US$/kg	1700
Cooling cost for LWR	US$/kg	5
Cooling cost for EFR	US$/kg	7.5
Cooling cost for LWR(MOX)	US$/kg	7.5
Interim storage cost	US$/kg	4
Plutonium storage cost	US$/kg	2000
Plutonium from LWR recovered	US$/kg	62310

Figure 3.34 shows the evolution of the installed capacity in the considered period and Figure 3.35 presents the annual energy produced in each scenario. The six proposed scenarios produce the same annual amount of electricity. The cumulative amount of electricity produced during the period 2030–2100 is close to 6252 TW·h. The contribution of each reactor technology in the total value is a result of the installation schedule of each NES as can be observed in Figures 3.36–3.41.

[19] https://www.uxc.com/p/data/uxc_AboutUraniumPrices.aspx; https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx

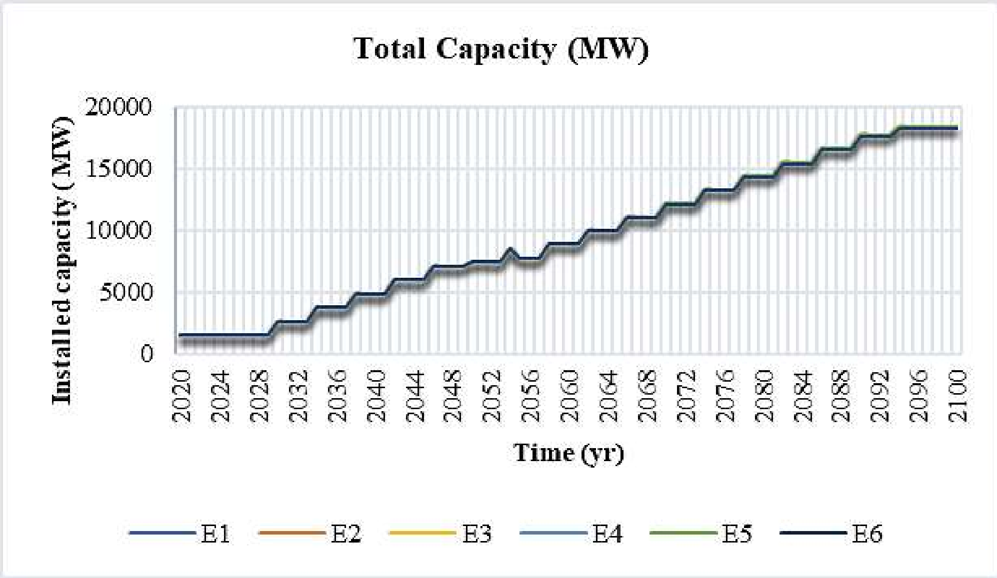


FIG. 3.34. Total installed capacity in NES-1 to NES-6.

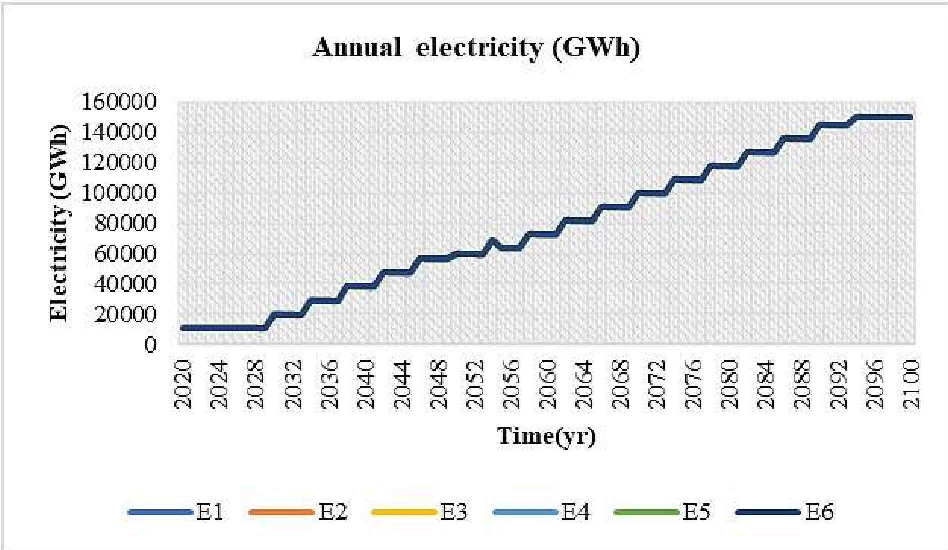
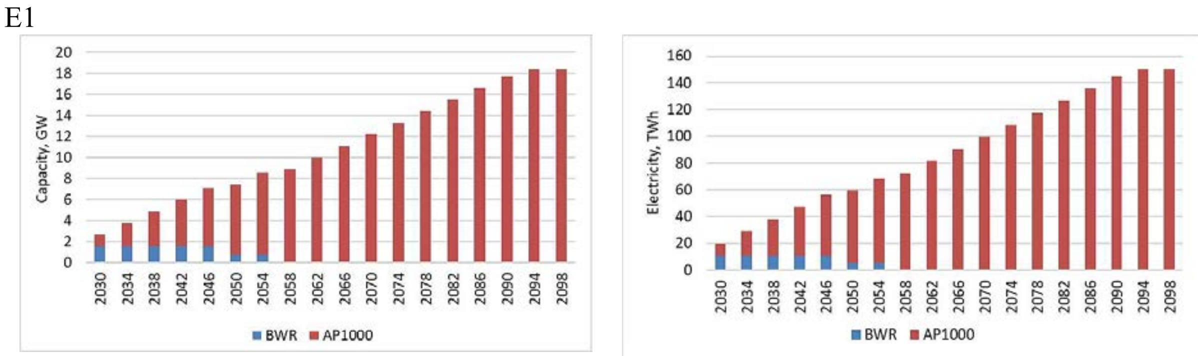


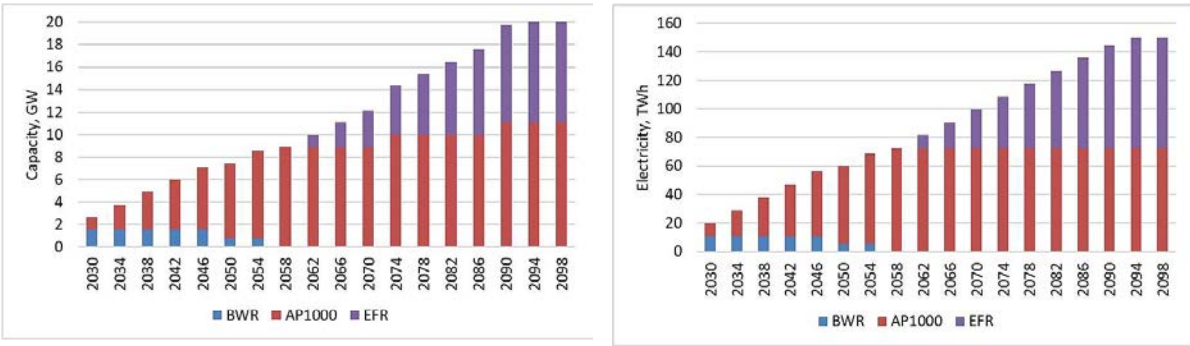
FIG. 3.35. Total energy generated in NES-1 to NES-6.



(a) (b)

FIG. 3.36. Installed capacity (a) and electricity (b) generated in NES-1.

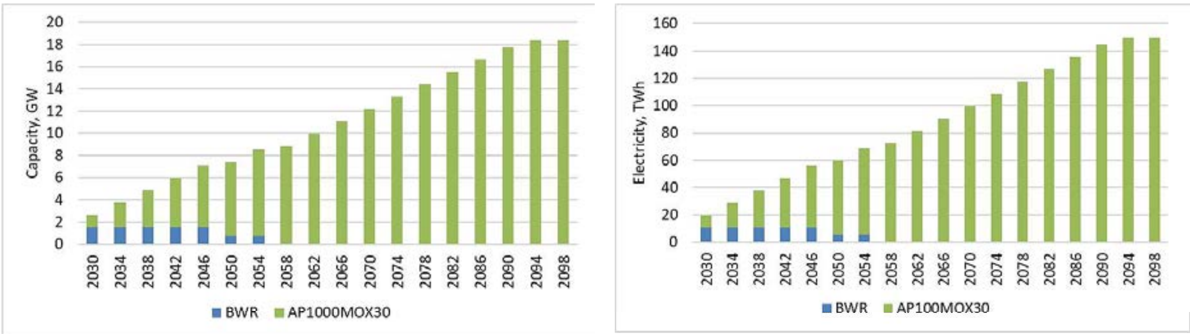
E2



(a) *(b)*

FIG. 3.37. Installed capacity (a) and electricity (b) generated in NES-2.

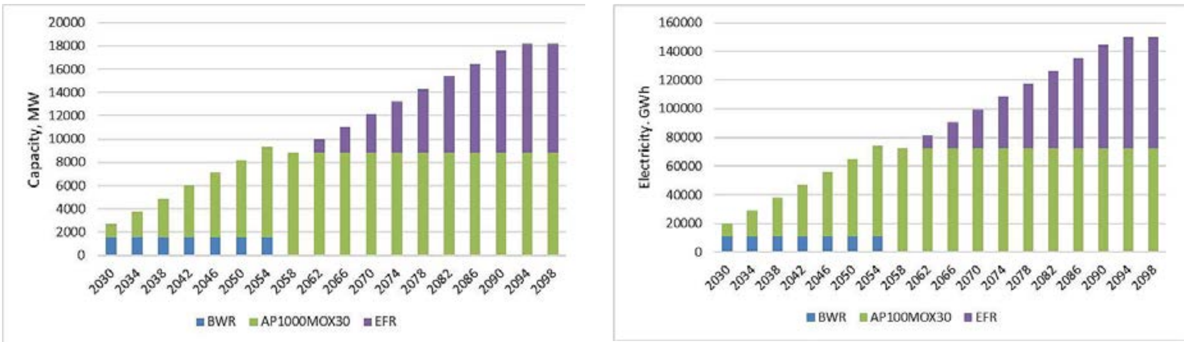
E3



(a) *(b)*

FIG. 3.38. Installed capacity (a) and electricity (b) generated in NES-3.

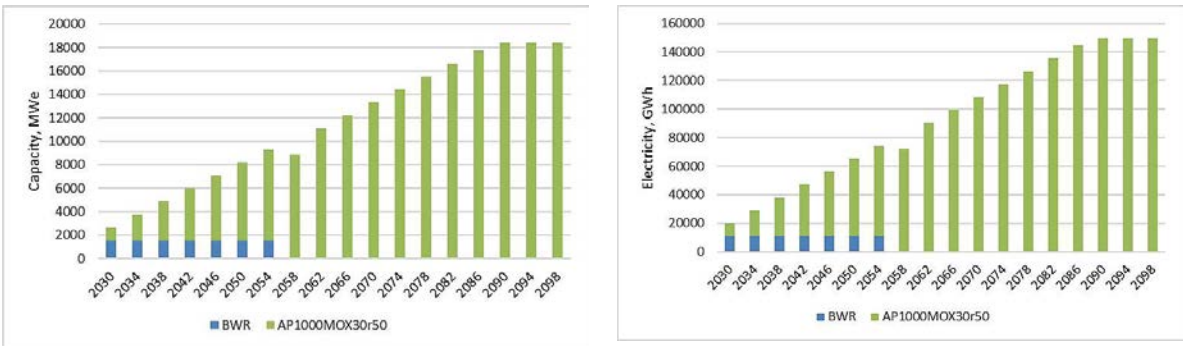
E4



(a) *(b)*

FIG. 3.39. Installed capacity (a) and electricity (b) generated in NES-4.

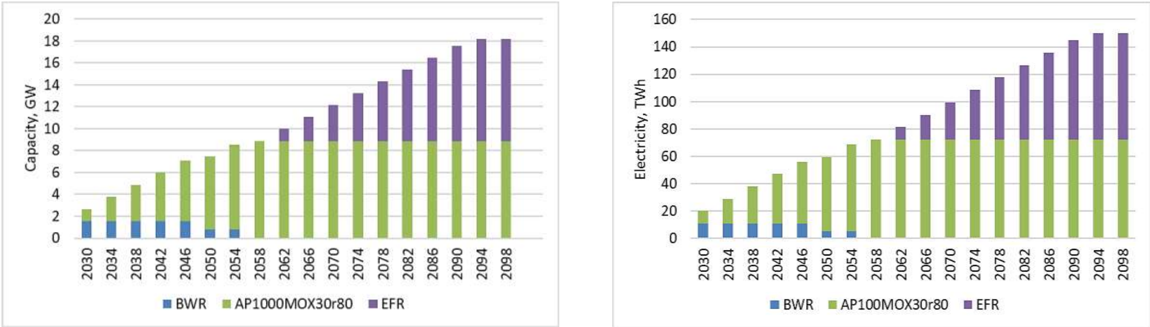
E5



(a) *(b)*

FIG. 3.40. Installed capacity (a) and electricity (b) generated in NES-5.

E6



(a) *(b)*

FIG. 3.41. Installed capacity (a) and electricity (b) generated in NES-6.

3.5.3.3. NFCSS simulations and results

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, 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 nuclear 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 particular material flow over a given time frame.

The flowcharts in Figs 3.42–3.47 represent the annual flow of nuclear materials by 2100 calculated by the NFCSS simulations for the scenarios NES-1 to NES-6. All the nuclear energy systems produce 150000 GWh annually by 2100. As seen in Fig. 3.42, scenario NES-1 demands the highest amount of natural uranium (2706.9 t) given that it is a scenario that considers AP1000 type reactors that use UO_2 in a once-through fuel cycle.

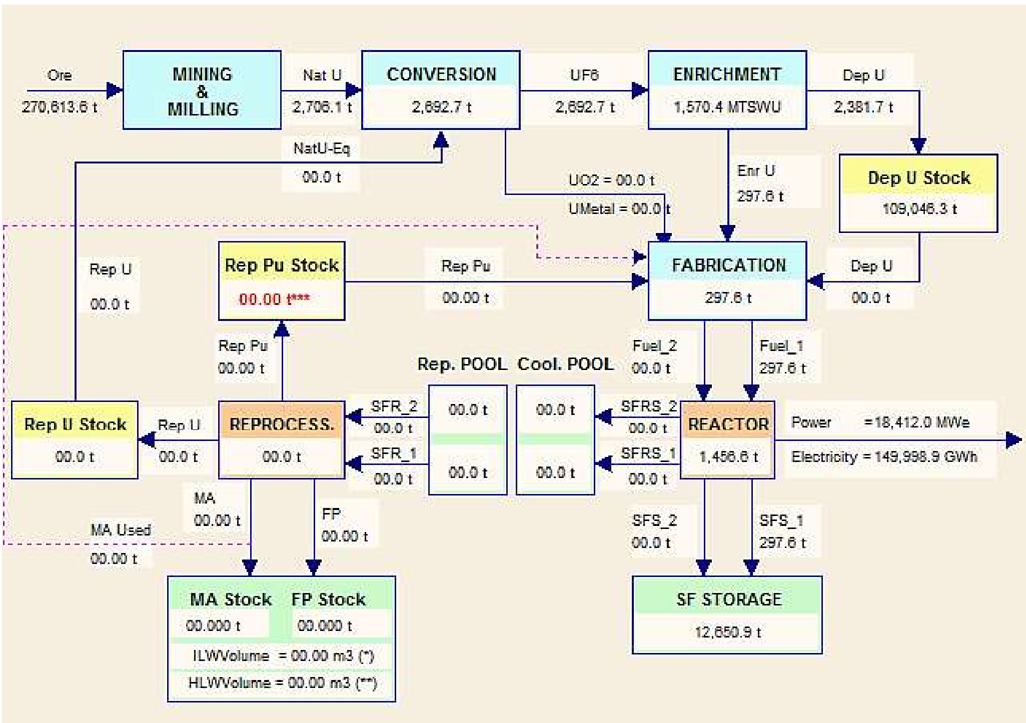


FIG. 3.42. Nuclear material flow for NES-1 in NFCSS by 2100 (screenshot from NFCSS).

A decrease in the demands on natural resources and spent nuclear fuel stock is obtained in scenario NES 2 being 1305.2 t and 11409.6 t respectively (see Fig. 3.43), which, as previously explained, NES 2 proposes the incorporation of fast reactors (EFR) and AP1000 reactors.

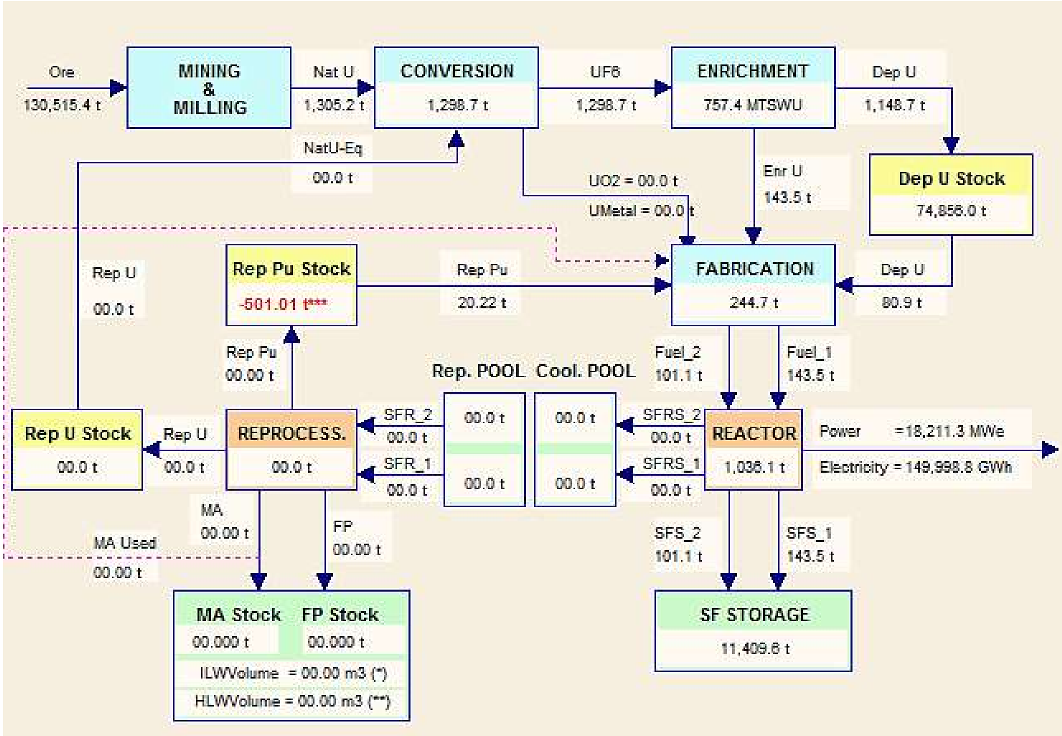


FIG. 3.43. Nuclear material flow for NES-2 in NFCSS by 2100 (screenshot from NFCSS).

The flowchart of nuclear materials and power production for NES-3 is shown in Fig. 3.44. This scenario was built with AP1000 reactors using 30% MOX fuel. In NES-3, the depleted uranium stock, spent fuel, and natural uranium requirements show higher values than in NES-2, highlighting a better utilization of natural uranium resources and reprocessed plutonium in EFRs used in NES-2.

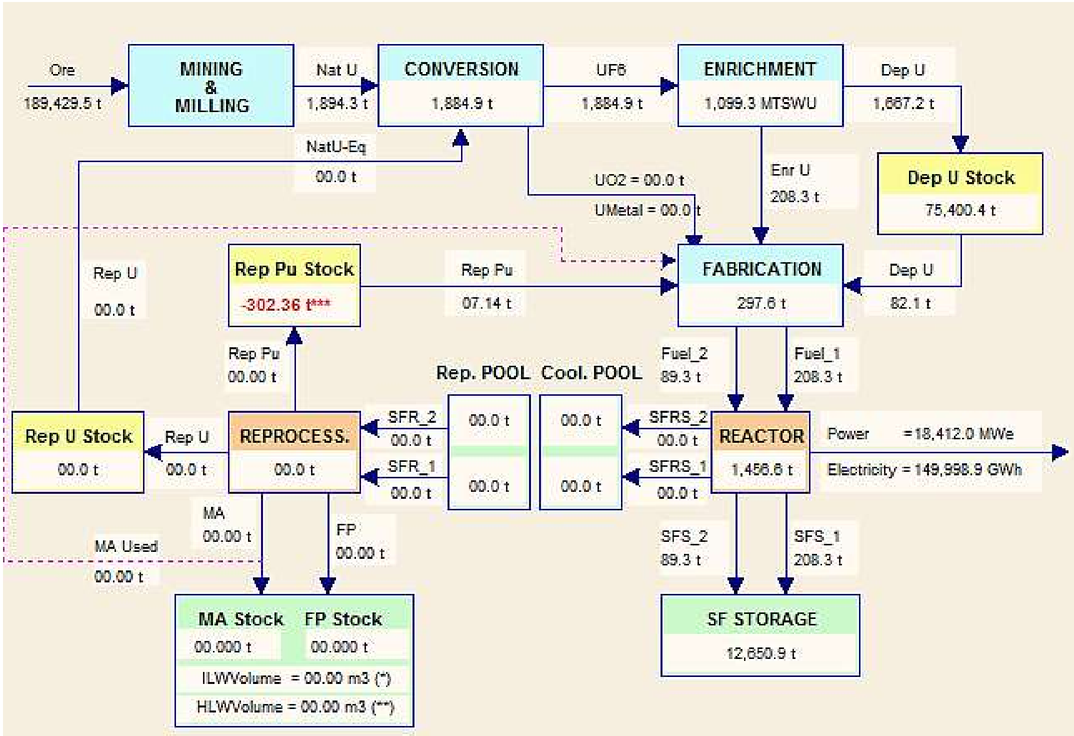


FIG. 3.44. Nuclear material flow for NES3 in NFCSS by 2100 (screenshot from NFCSS).

A substantial improvement in the nuclear fuel cycle is achieved with the configuration made in the NES-4 (see Fig. 3.45). The natural uranium demand decreases below 1000 tons. This scenario considers AP1000 reactors operating with 30% MOX fuel and fast reactors. Thus, the depleted uranium stock is significantly reduced to (52018.8 t) due to its use in the manufacture of MOX fuel.

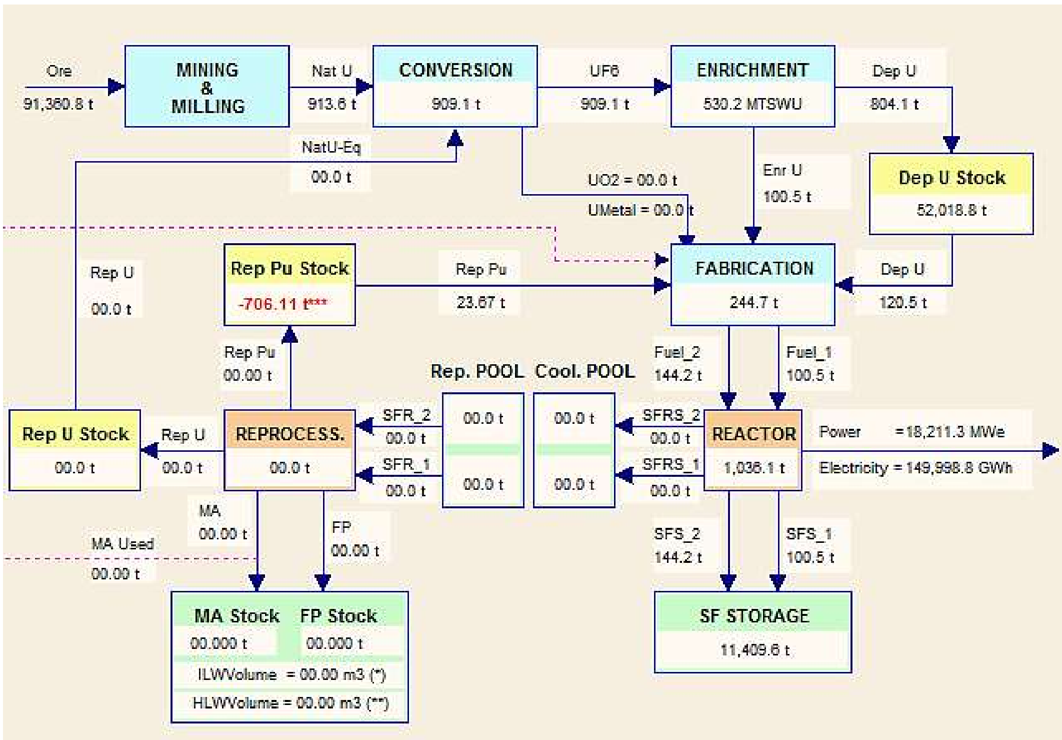


FIG. 3.45. Nuclear material flow for NES4 in NFCSS by 2100 (screenshot from NFCSS).

Scenario NES-5 stands out for reducing the stock of spent fuel to 8420.1 t (see Fig. 3.46), due to the reprocessing of nuclear fuel increased up to 50% of the total fuel discharged from LWRs, but, since it is a scenario that does not consider EFRs, there are high demands on natural uranium resources. Which means that this alternative is less attractive than NES-4.

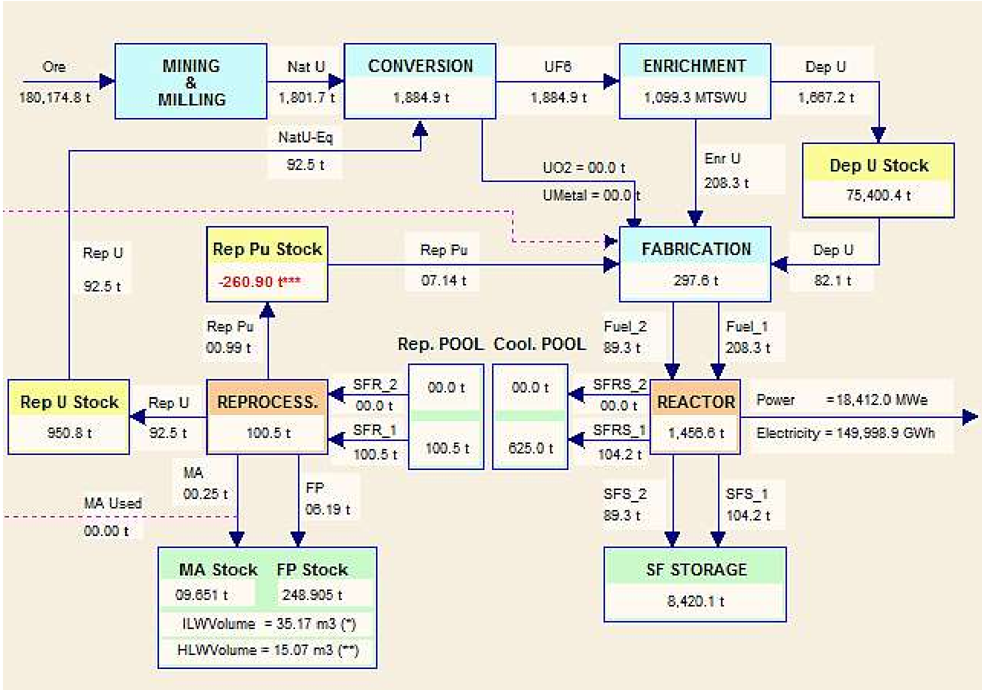


FIG. 3.46. Nuclear material flow for NES5 in NFCSS by 2100 (screenshot from NFCSS).

Figure 3.47 shows a summary of the nuclear fuel cycle for scenario NES-6 in the year 2100, which includes AP1000 reactors using MOX fuel, with reprocessed fuel up to 80% of discharged fuel from the LWRs.

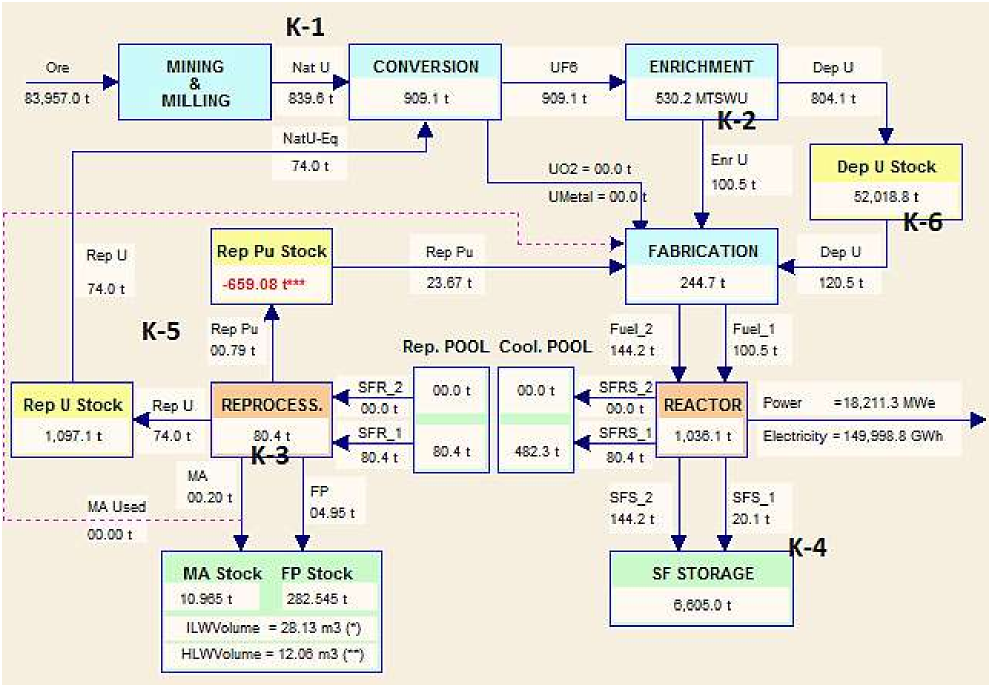


FIG. 3.47. Nuclear material flow for NES-6 in NFCSS by 2100 (screenshot from NFCSS).

In Fig. 3.47, the k-indicators K-1 to K-6 are associated with the parameters of the nuclear fuel cycle. K-1 is for Natural Uranium consumption, K-2 is for Separate work units required, K-3 is for Reprocessing requirement, K-4 is for Stock of spent fuel, K-5 is for Plutonium reprocessed stocks, and K-6 is for Depleted uranium stocks.

3.5.3.4. MESSAGE simulations and results

The MESSAGE [3.20] calculation tool is included in the software and applications package focused on the planning and evaluation of nuclear energy systems (NESs). MESSAGE is offered by the IAEA to the global nuclear community. The "underlying principle of a model built using MESSAGE, is the optimisation of an objective function under a set of constraints that define the feasible region containing all possible solutions" to the topic [3.20]. "The value of the objective function helps to choose the solution considered best according to the criteria specified. In general, models built using MESSAGE belong to the class of "mixed-integer programming models as they may contain some integer variables" [3.20]. In this work, the six scenarios proposed for the different configurations of the NES and the fuel cycles associated with them were modelled without optimization. The nuclear material flows involved in the front-end and the back end that were calculated with NFCSS were input into MESSAGE. The amounts of energy planned in the time horizon considered in NFCSS were set in MESSAGE, as well as the installed capacity and the years of operation of the nuclear reactors. From the output of MESSAGE two key indicators were obtained to evaluate the economics of each NES.

3.5.4. KIND approach

To perform a multi-criteria comparison using the MAVT method, it is required to select a set of key indicators and identify a structure of the objective tree. In the present case study, three high-level objectives were considered, five evaluation areas and eight key indicators, as shown in Fig. 3.48.

The following steps are to prepare the performance table and to determine single attribute value functions for each indicator. Considering the tree of Fig. 3.48, it is relevant to say that the Economics high level objective considers a Cost area which is investigated through two key indicators related to costs obtained by the MESSAGE simulation of each NES. The rest of key indicators are evaluated by means of parameters from the material flows from NFCSS simulation of each NES. To rank the NESs according to their sustainability, it is necessary to identify which indicator is to be minimized (Min) and which is to be maximized (Max) as a goal. All the above information is used to build the performance table in KIND-ET. Table 3.29 shows the components and goals of the performance table in KIND-ET in the present case study. The goal for indicators 3 and 5 is to maximize, for the other six indicators is to minimize.

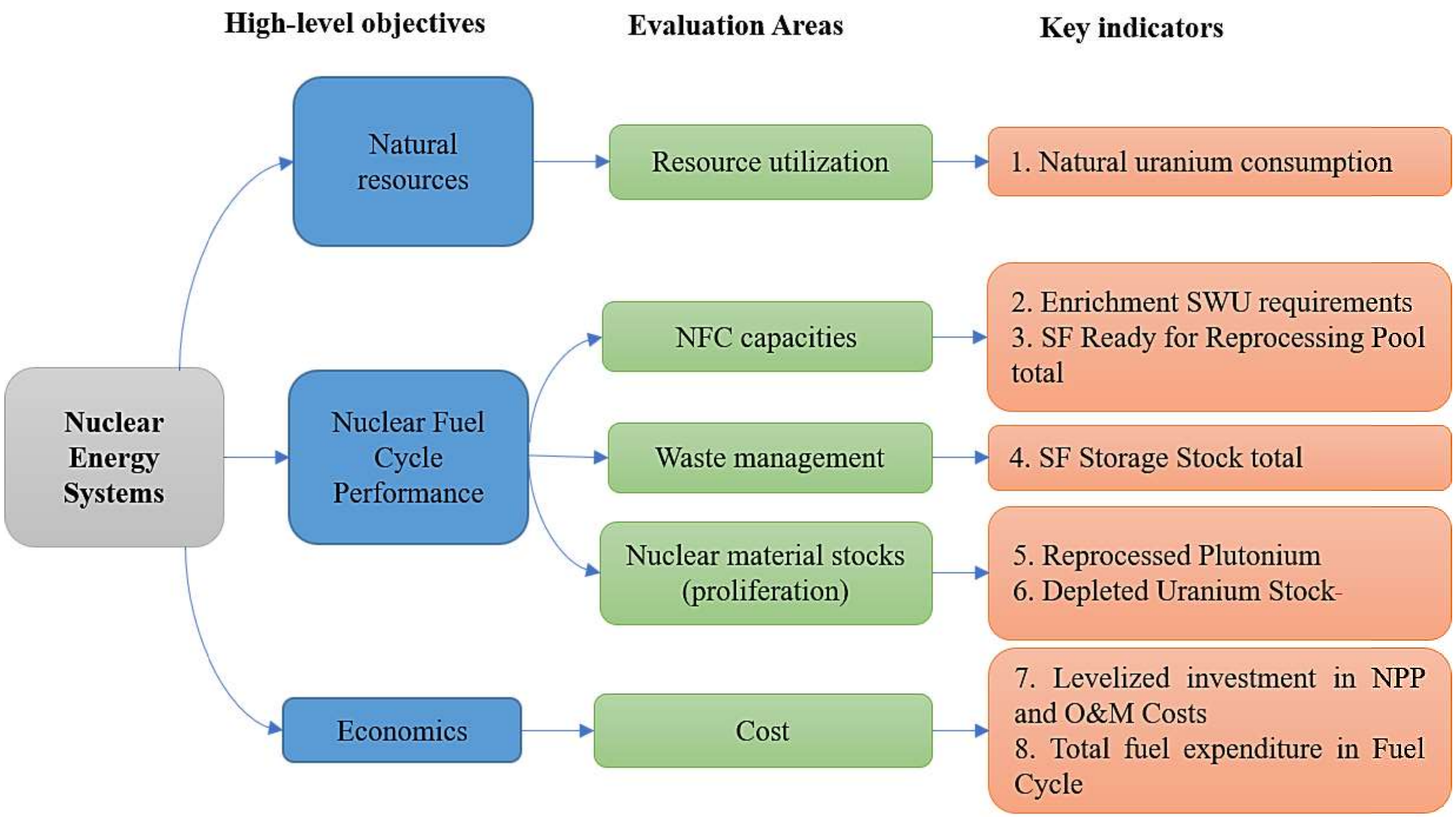


FIG. 3.48. Objective tree.

TABLE 3.29. PERFORMANCE TABLE

High-level objective titles	Area titles	Indicator titles	Indicator abbr.	Goal
Natural resources	Resource utilization	Natural uranium consumption	1 cumNatU	Min
Nuclear fuel cycle performance	NFC capacities	SWU requirements	2 cumSWU	Min
Nuclear fuel cycle performance	NFC capacities	Reprocessing spent fuel requirement	3 cumSF	Max
Nuclear fuel cycle performance	Waste management	Stock of spent nuclear fuel	4 cumSFsto	Min
Nuclear fuel cycle performance	Nuclear material stocks (proliferation)	Plutonium reprocessed stocks	5 cumPuR	Max
Nuclear Fuel Cycle Performance	Nuclear material stocks (proliferation)	Depleted uranium stocks	6 cumDUsto	Min
Economics	Cost	Levelized investment in NPP and O&M costs	7 LUAC+LUOM	Min
Economics	Cost	Total fuel expenditure in fuel cycle	8 exFC	Min

In Table 3.30 the values of key indicators are represented by the corresponding NFCSS and MESSAGE outputs. The values from NFCSS, for indicators KI-1 to KI-6, are cumulative values of materials divided by cumulative values of electricity generated during the period 2030 to 2100. KI-7 is an average value for the same period and indicator KI-8 is a cumulative value over the period.

TABLE 3.30. PERFORMANCE TABLE WITH KEY INDICATOR VALUES

Indicator abbr.	MIN score	MAX score	NES-1	NES-2	NES-3	NES-4	NES-5	NES-6	Units
1 cumNatU	9.2	19.4	19.4	13.5	13.9	9.8	13.4	9.2	t HM*10^3/GW·h
2 cumSWU	5.6	11.2	11.2	7.8	8.0	5.6	8.0	5.6	Mtswu*10^3/GW·h
3 cumSF	0.0	0.7	0.0	0.0	0.0	0.0	0.6	0.7	t HM*10^3/GW·h
4 cumSFsto	16.2	56.5	56.5	53.6	56.5	53.6	39.1	16.2	t HM*10^3/GW·h
5 cumPuR	0.0	0.8	0.0	0.0	0.0	0.0	0.7	0.8	t HM*10^3/GW·h
6 cumDUsto	310.0	507.5	507.5	423.4	367.4	310.0	367.4	310.0	t HM*10^3/GW·h
7 LUAC+LUOM	324.4	348.2	324.4	348.15	324.4	341.49	324.4	338.0	US$/kW·yr.
8 exFC	1.6	15.8	15.8	5.8	6.7	4.6	2.2	1.6	US$/$10^9$

The next step is to evaluate the weighting factors. Special attention is to be paid to the assignment of weighting factors to high-level objectives, evaluation areas and key indicators, since they will have a direct impact on the total evaluation of the NES, so the areas of greater importance for each region or country, in particular, needs to be defined beforehand, in order to make the best selection of indicators and their weight allocation. The set of weights assigned to objectives, areas and indicators in the case study are shown in Table 3.31.

TABLE 3.31. WEIGHT FACTORS FOR OBJECTIVES, AREAS AND INDICATORS

High-level objective	HL obj. weight	Area	Area weight	Indicator abbr.	Indicator weight	Final weight
Natural resources	0.35	Resource utilization	1	1 cumNatU	1	0.350
Nuclear fuel cycle performance	0.35	NFC capacities	0.3	2 cumSWU	0.9	0.095
				3 cumSF	0.1	0.011
		Waste management	0.4	4 cumSFsto	1	0.140
		Nuclear material stocks (proliferation)	0.3	5 cumPuR	0.2	0.021
				6 cumDUsto	0.8	0.084
Economics	0.3	Cost	1	7 LUAC+LUOM	0.65	0.195
				8 exFC	0.35	0.105

3.5.5. Results

The first result obtained by using KIND-ET is a table with the single attribute value functions vs indicator. In the present case study, the table is obtained by a linear normalization using a local domain of value functions. Figures 3.49 and 3.50 show graphs with the single attribute value functions obtained with the corresponding table. Both graphs show that NES-1 and NES-2 are poorly qualified compared to others. The same conclusion is confirmed by the graph in Fig. 3.51, where the bars show the multi attribute value function for the base weights presented in Table 3.31.

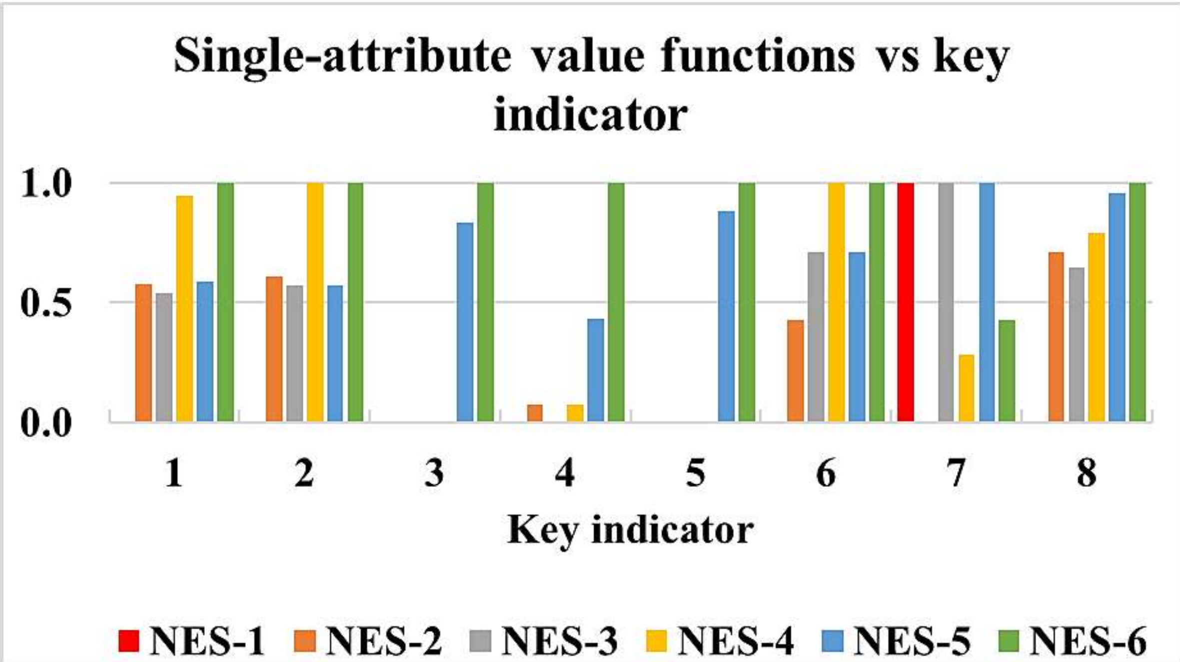


FIG. 3.49. Single attribute value functions vs indicator.

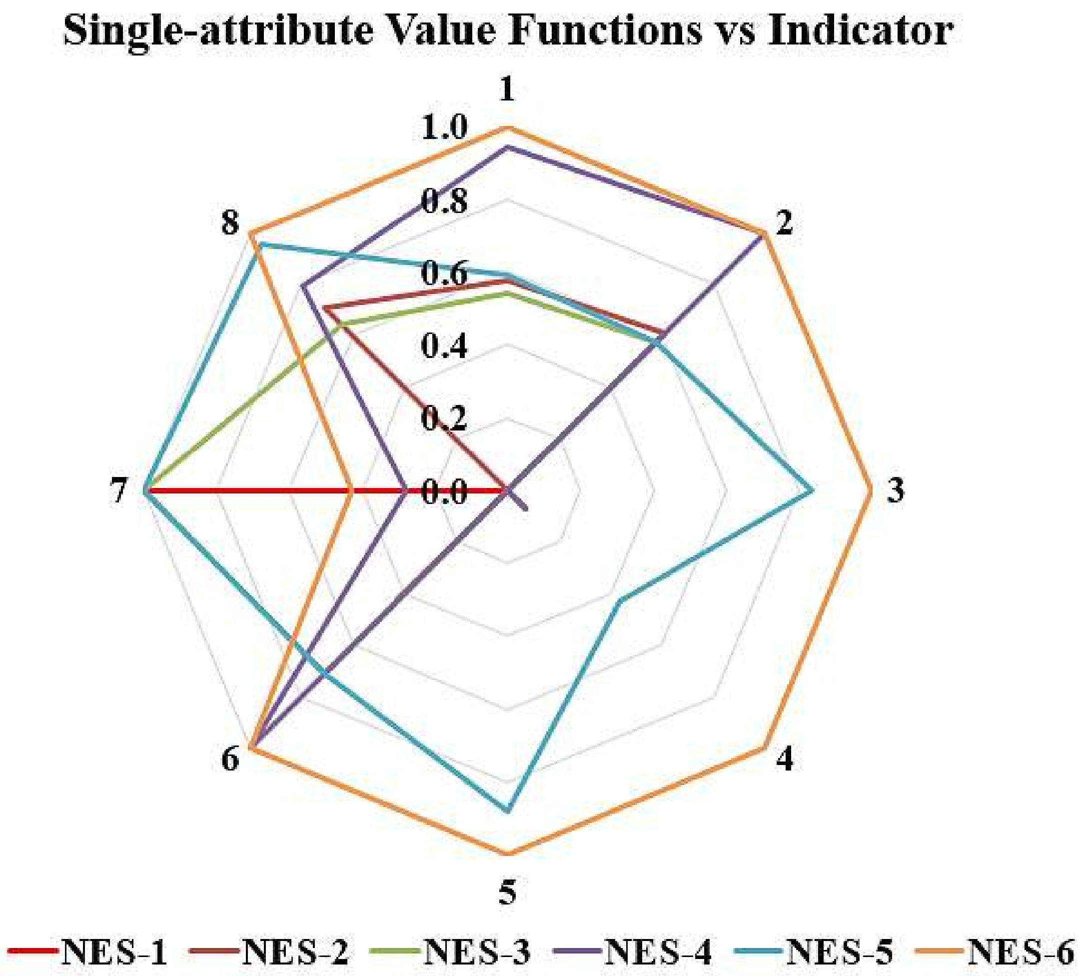


FIG. 3.50. Single attribute value functions.

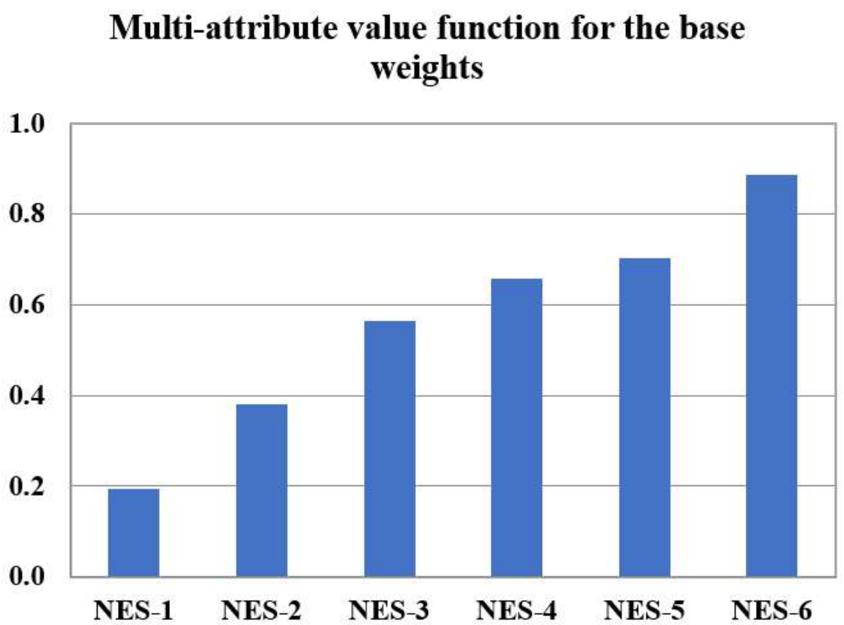


FIG. 3.51. Ranking results for the base weights.

Figures 3.52 and 3.53 present the high-level objective scores and the areas scores for the base weights. These two graphs help decision makers to identify the contribution of objectives and areas to the overall score.

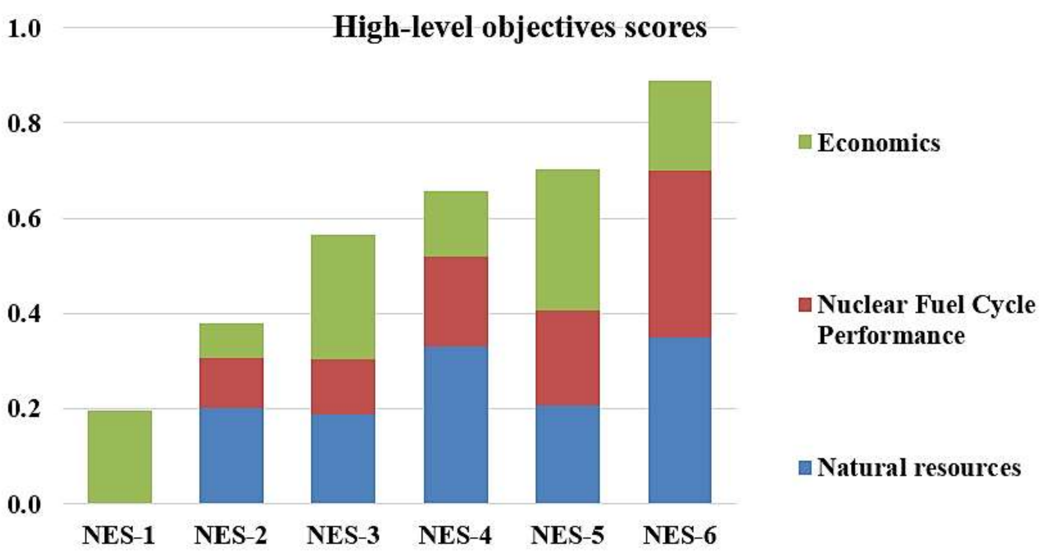


FIG. 3.52. Scores of high-level objectives for the base weights.

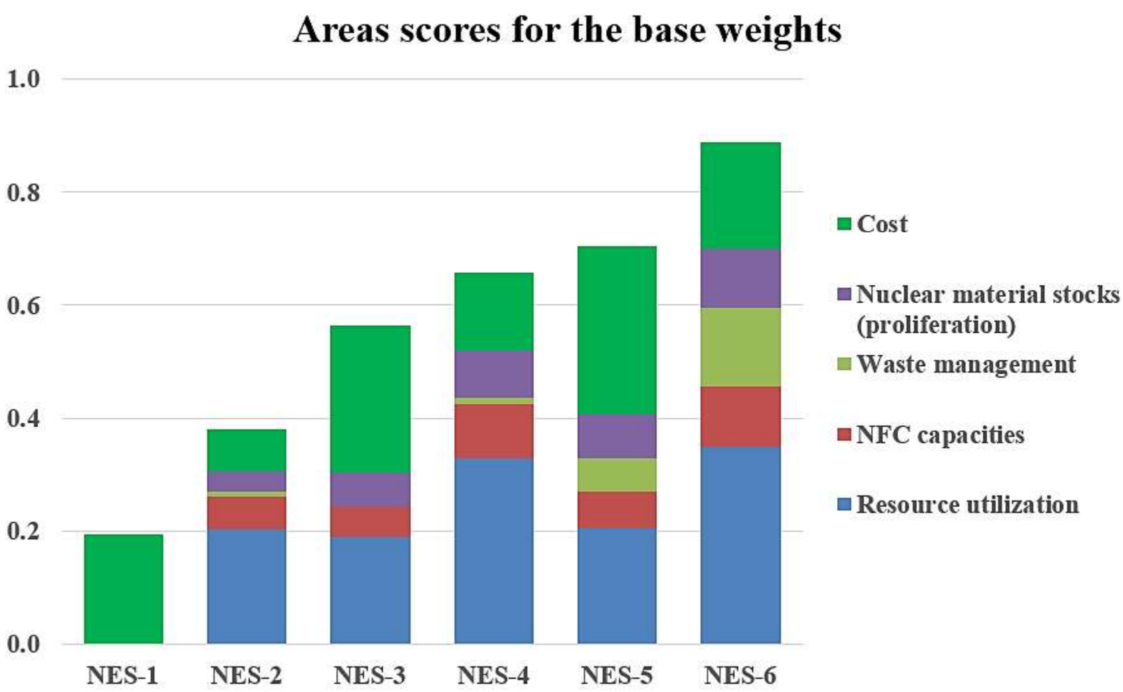


FIG. 3.53. Scores of areas for the base weights.

Another step in the KIND approach is to perform a weights sensitivity analysis. In the present case study two sets of modified weights were applied with values shown in Fig. 3.54, namely: modified case 1 - 50% for Natural resources HLO, 30% for NFC Performance HLO, and 20% for Economics HLO; modified case 2 - 20% for Natural resources HLO, 40% for NFC

Performance HLO, and 40% for Economics HLO. Ranking results of the NESs are shown in Fig. 3.55 by comparing the impacts on the ranking of both modified weights to the base weights. The conclusion obtained is that NES-6 is the best for the three weights.

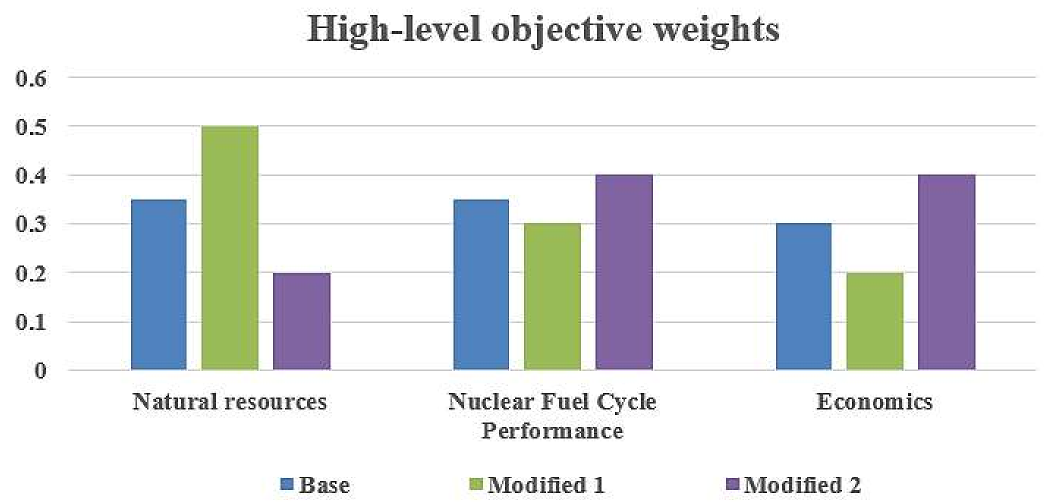


FIG. 3.54. High-level objective weights.

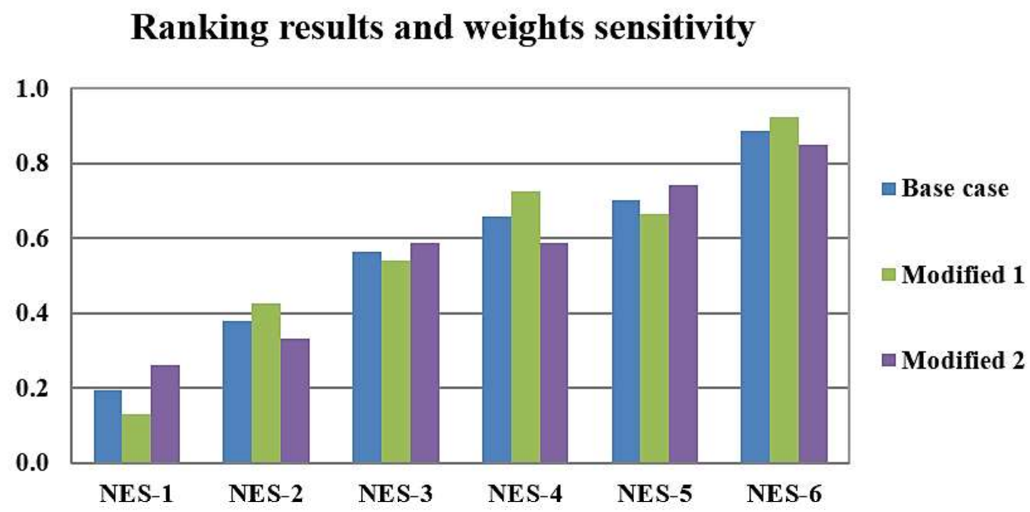


FIG. 3.55. Ranking results for weight sensitivity.

A value function sensitivity was evaluated considering a change in the investment cost of the EFR, from 3500 to 4000 US$/kW, into the input data of the MESSAGE calculations. As a consequence, the single attribute value function of KI-7 changed for NES-2, NES-4 and NES-6, as it is shown in Table 3.32. These values of K1-7 were used together with the other seven unchanged key indicators to generate the corresponding ranking results of NESs in the 'K1-7 modified case'. Another value function sensitivity analysis was made using the heuristic rules of KIND-ET; the results were presented in the 'KIND-ET modified case'. The ranking results for the value function sensitivity analysis of the two modified cases were compared to the base case in Fig. 3.56.

TABLE 3.32. VALUE FUNCTION SENSITIVITY ON KEY INDICATOR 'KI-7 LUAC+LUOM'

	Value function change	KI-7 LUAC+LUOM [US $/kW·yr.]					
Case	EFR investment cost US $/kW(e)	NES-1	NES-2	NES-3	NES-4	NES-5	NES-6
Base case	3500	324.4	348.15	324.4	341.49	324.4	338.0
KI-7 modified	4000	324.4	362.33	324.4	354.67	324.4	352.36

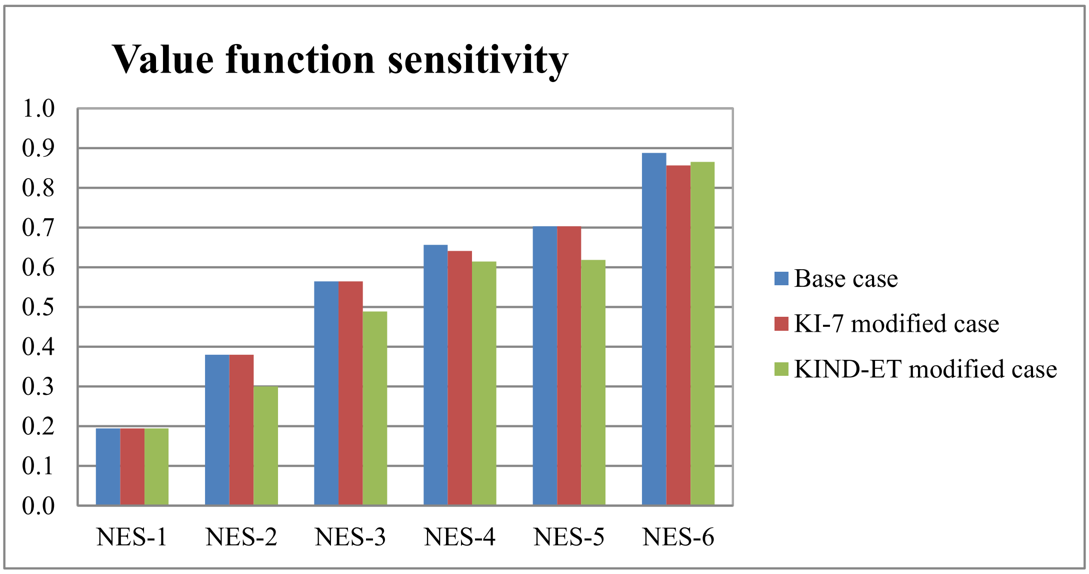


FIG. 3.56. Ranking results for value function sensitivity.

A complementary analysis is to prepare a graph of domination identifier. This analysis uses the values of the performance table as inputs, and through the heuristic rules, the graph helps to identify which NES dominates the others in each key indicator. Figure 3.57 shows the domination identifier graph. Other help to decision makers is to examine the dominating option chart. The input to obtain it is also the values of the performance table. Table 3.33 shows the results. It can be observed that NES-1 is dominated by NES 3 and NES-5; NES-2 is dominated by NES-4 and NES-6; NES-3 is dominated by NES-5; NES-4 is dominated by NES-6; NES-5 and NES-6 are not dominated by others.

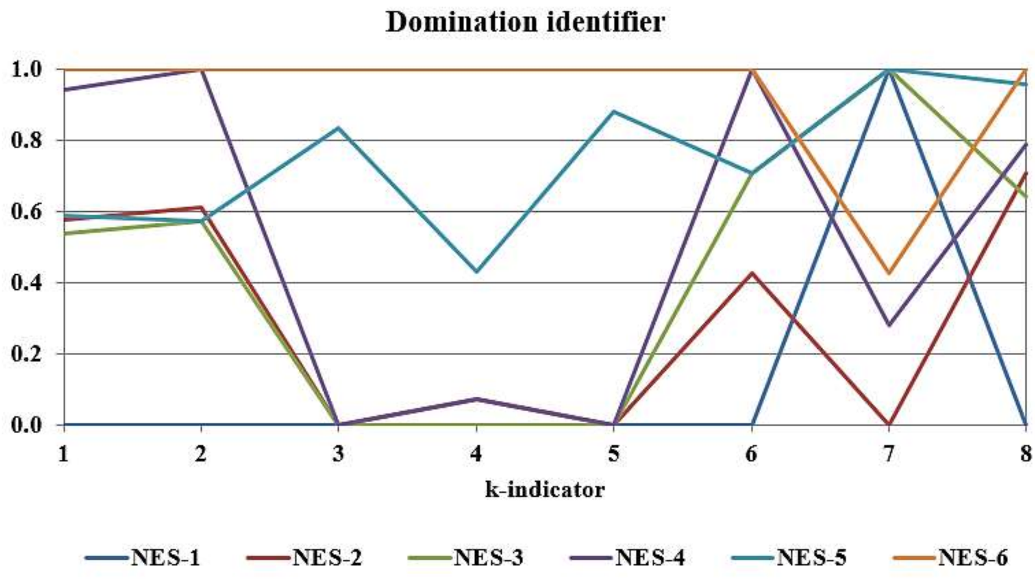


FIG. 3.57. Domination identifier results.

TABLE 3.33. DOMINATING OPTIONS TABLE

Domination table		Dominating options					
		NES-1	NES-2	NES-3	NES-4	NES-5	NES-6
Dominated options	NES-1		—	<	—	<	—
	NES-2	—		—	<	—	<
	NES-3	—	—		—	<	—
	NES-4	—	—	—		—	<
	NES-5	—	—	—	—		—
	NES-6	—	—	—	—	—	

The analysis includes the advanced uncertainty treatment regarding weighting factors and single attribute value functions using relevant tools developed within the CENESO collaborative project. Table 3.34 presents the results of the statistical characteristics of the probabilistic distributions of the global uncertainty analysis with respect to weights (Overall Score Spread Builder), and Fig. 3.58 shows the resulting scores when all weights are uncertain.

TABLE 3.34. PROBABILISTIC DISTRIBUTIONS.

	NES-1	NES-2	NES-3	NES-4	NES-5	NES-6
Mean	0.15656	0.30032	0.46752	0.47213	0.76768	0.84760
Standard deviation (SD)	0.25138	0.19783	0.23735	0.29642	0.12372	0.23831
Maximum value (Max)	0.99849	0.70677	0.99871	0.99988	0.99979	1.00000
Quartile (Q3, 75%)	0.20590	0.46003	0.62677	0.74069	0.86492	0.99781
Median	0.01924	0.29099	0.50867	0.47170	0.77645	0.97565
Quartile (Q1, 25%)	0.00114	0.11890	0.28597	0.19114	0.68086	0.79760
Minimum value (Min)	0.00000	0.00000	0.00006	0.00004	0.42656	0.05316

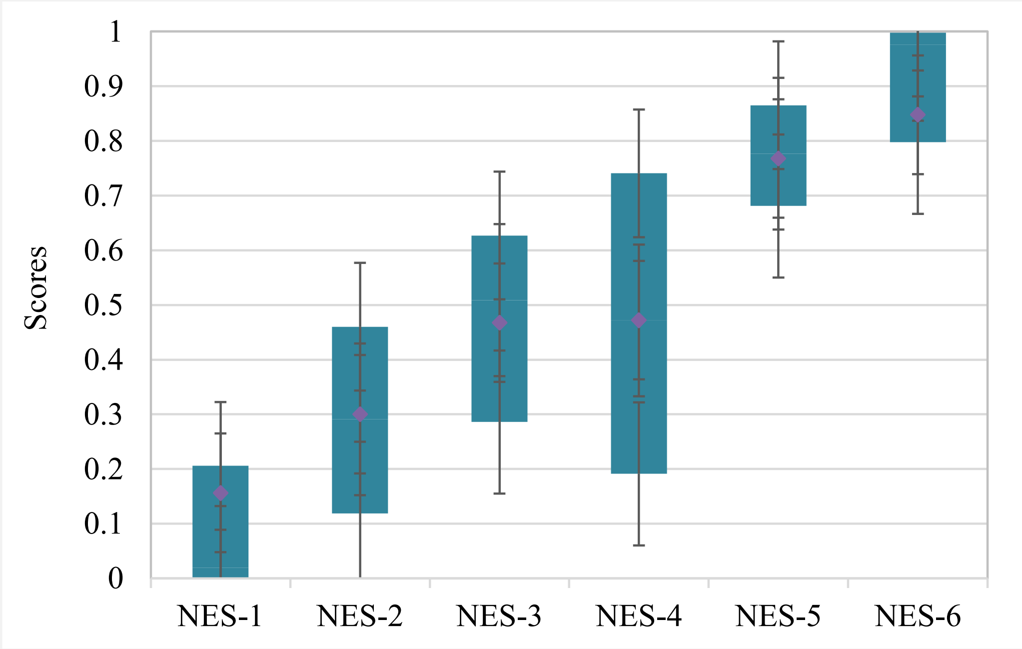


FIG. 3.58. The resulting diagram of Overall Score Spread Builder.

Ranks mapping tool was used to build the preferences map that indicates areas in the high-level objective weights space for which the corresponding option can take the first place in the ranking (See Fig. 3.59). Figure 3.60 presents the maximal overall scores for all NES options.

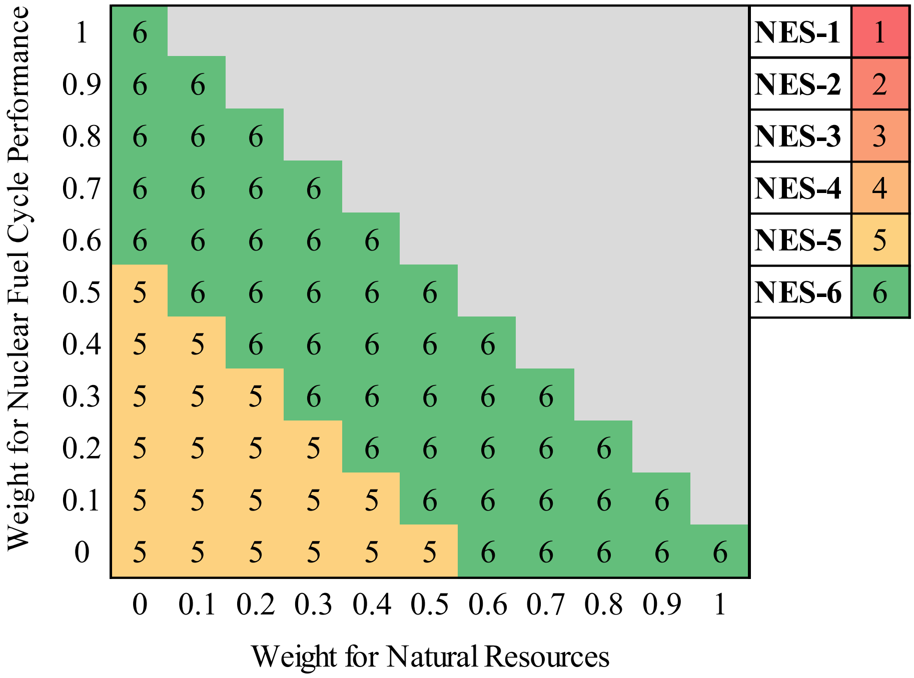


FIG. 3.59. NES options with the first rank.

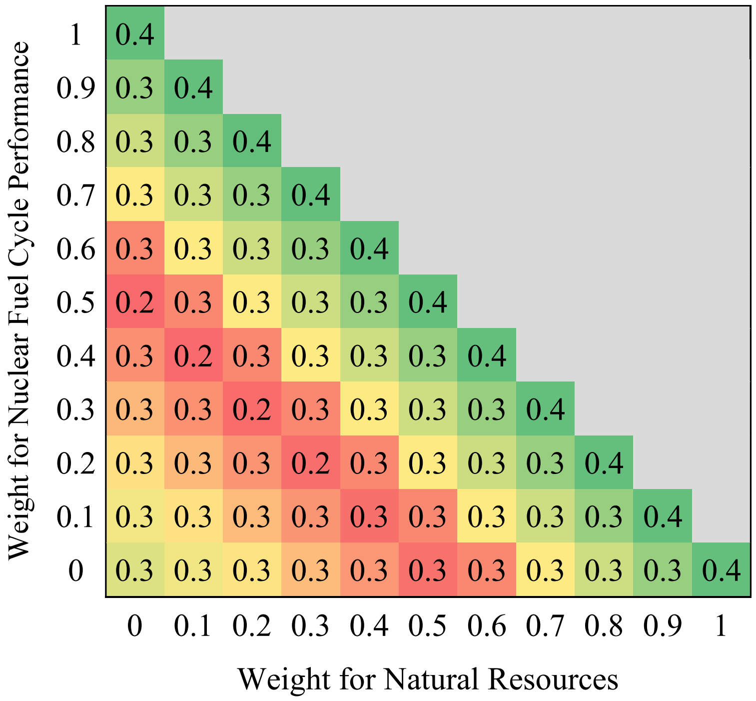


FIG. 3.60. Maximal overall scores for all NES options.

3.5.6. Discussion of results

The results of the multicriteria comparative assessment of the six NES examined show that NES-6 is the best scenario and NES-1 is the worst.

The focus on HLO-3 Economics reduces the attractiveness of the NES-6, however, it is absolutely the best in the two other high-level objectives, HLO-1 Natural resources and HLO-2 Nuclear Fuel Cycle Performance.

3.5.7. Conclusions

The objective of the Mexican case study was to apply a multicriteria decision analysis method using the INPRO/KIND approach to study long term scenarios of NES options in which a deployment of thermal reactors and fast reactors are combined in synergy to produce electricity. The study focuses on the technological level looking for long term sustainable systems in terms of the use of natural resources, nuclear fuel cycle performance and economics.

Six hypothetical NESs were compared in the study. The period of study is from 2030 to 2100. The main assumptions are as follows. The current two BWRs are in operation and will be retired by 2055; in the year 2030 new nuclear capacity is added progressively in such a way that nuclear energy will cover 10% of the total annual electricity demand expected for the country by 2100; only the generation of electricity from different nuclear technologies and its implications are investigated without any relationship to non-nuclear technologies.

The scenario NES-6, which uses fast reactors and a large recycling of plutonium in the NFC, resulted with the best score. It is important to mention that the results obtained in this report are indicative and more detailed analysis of parameters needs to be performed, specifically those corresponding to costs.

3.6. COMPARATIVE EVALUATION OF NUCLEAR AND OTHER THERMAL ELECTRICITY GENERATION OPTIONS IN PAKISTAN: AN APPLICATION OF THE IAEA INPRO EVALUATION TOOL "KIND-ET"

This chapter presents structured report of a case study done by experts from the Islamic Republic of Pakistan.

3.6.1. Introduction

Pakistan is the fifth most populous country in the world with a population of 211.17 Million in 2019 and a growth rate of 1.94 % per annum [3.21]. Around 65 percent of the total population lives in rural areas.

During 2018–19, Pakistan's economic growth remained at 1.91% with a major contribution from the services sector. Per capita income for 2018–19 remained at USD 1455 [3.21]. Like the other world economies, the country's economy is being affected by COVID-19. The provisional GDP for 2019-20 is estimated to be minus 0.38% due to the adverse impact witnessed by industrial and services sectors [3.21].

The total proven fossil fuel reserves of Pakistan as of June 2018 are 3,856 million tonnes of oil equivalent (TOE), comprising Gas: 331 million TOE, Oil: 47.0 million TOE and Coal: 3,478 million TOE. The total coal resources of Pakistan are about 186 billion tonnes of which measured reserves are 7.78 billion tonnes [3.22]. The hydro power potential of Pakistan is about 60,000 MW, of which only 9,769 MW (16.3%) could be exploited so far [3.23, 3.24]. The wind potential of Pakistan is about 43,000 MW, in Sindh coastal areas, mostly in the Gharo-Kati Bandar wind corridor. The exploitable electric power generation potential of this area is about 11000 MW[20]. Per capita primary commercial energy supply in Pakistan is 0.41 TOE that is supplied by oil, gas, coal, hydro, nuclear and renewable energy sources. Around 47% of energy is imported spending exports money and remittances.

As of June 2019, the installed electricity generation capacity was 39,145 MW comprising 25.0% hydro, 53.8% oil/gas, 11.9% coal fired power plants, 3.7% nuclear, and 5.6% renewable. During the financial year 2018–19, the grid supplied electricity was 137,039 million kWh comprising, hydro: 24.2%, oil & gas: 53.0%, coal: 12.2%, nuclear: 6.7%, renewable: 3.6% and import: 0.3% [3.25]. At present, the per capita annual electricity consumption is 532 kWh, which is around one-sixth of the world average of 3,152 kWh [3.26]. The residential sector, growing at a pace of 8.4% annually during the last five years, is the biggest consumer of electricity among all socioeconomic sectors.

The demand for electricity will continue to increase in the future due to increases in population and economic development, and the supplies for indigenous energy resources will remain inadequate to meet the projected demand. The future power generation system of the country is expected to expand using the technologies based on hydro, local coal, LNG, nuclear and renewable energy. There are many criteria and factors which may play roles for selection of technology. Assessment of technologies for all the criteria/ factors is required before deciding the most feasible option.

The collaborative project CENESO was preceded by the collaborative project KIND. The outcome of the KIND project was an approach and associated Microsoft Excel based tools to perform comparative evaluations of nuclear energy systems or scenario alternatives. The

[20] http://www.aedb.org/ae-technologies/wind-power

objective of the CENESO collaborative project was further extension of the KIND approach to enhance presentations of ranking and sensitivity/uncertainty analysis as well as to widen the scope of the approach application to new problems.

The Applied Systems Analysis Division (ASAD) of the Pakistan Atomic Energy Commission (PAEC) has carried out a case study for the trial application of the IAEA INPRO tool (KIND-ET) and its extensions to perform comparative evaluations of nuclear, coal and LNG based electricity generation options in Pakistan.

3.6.2. Methodology overview

KIND-ET is a multi attribute value theory (MAVT) based Excel-template developed for multi-criteria comparative evaluation. Following are the major steps involved in the KIND approach:

- Objective and problem formulation;
- Identification of high-level objectives (HLOs), evaluation areas and corresponding key indicators (KIs);
- Assigning of weights in a three level objective tree;
- Scoring of key indicators/ finalizing the performance table;
- Selection of single attribute value function (SAVF) form and domain;
- Calculation of SAVF;
- Calculation of multi attribute value function (MAVF)/ ranking results/ overall score;
- HLO weights' sensitivity and SAVF sensitivity;
- Application of KIND-ET extensions for screening of options, uncertainty analysis and illustration of results;
- Conclusions.

Application of the KIND-ET Excel based tool is described in the Final Report of the INPRO Collaborative Project KIND [3.1]. Some suggestions for comparative evaluation described in the report for nuclear energy systems (NES) are presented in Table 3.35.

TABLE 3.35. SUGGESTIONS FOR COMPARATIVE EVALUATION IN THE KIND APPROACH

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 used indicators in a comparative evaluation	
Fewer than 20	
Role of secondary indicators (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)
Objective tree and weighting factors	
Three level objective 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).	

3.6.3. Objective and problem formulation

The main objective of this study is the comparative evaluation of different electricity generation options with the help of the KIND-ET tool and its extensions. In particular, nuclear, local coal and LNG based electricity generation options will have significant contribution in the future generation mix of Pakistan as baseload electricity generation options. Therefore, a comparative evaluation among these electricity generation options has been performed. The activities being carried out in the country for electricity generation, in relation to the specific energy chain, have also been considered for the evaluation. Moreover, the plants considered in the study, for each technology, are assumed to be a typical representative of plants being deployed/ being planned in the country. Some parameters of typical plants based on the data from [3.27] are given in Table 3.36.

TABLE 3.36. SOME PARAMETERS OF TYPICAL PLANTS

	Unit	Nuclear	Local coal	Gas (LNG)	Gas (LNG)
	—	Steam Turbine	Steam Turbine	Combustion Turbine	Combined Cycle
Capacity	MW	1100	660	400	1263
Net capacity	MW	1017	607	396	1243
Life of plant	years	60	30	30	30
Minimum load	%	100	50	25	50
Scheduled outage	days/year	60	30	30	13
Initial investment	USD/kW	4,215	1,310	439	587
Fuel price	$/GJ	0.49	1.37	9.25	9.25
Lifetime average net heat rate at max load/ min load	GJ/MW·h	9.62/9.62	9.725/10.582	9.464/13.33	6.457/6.825

3.6.4. Identification of high-level objective and evaluation areas

The Government of Pakistan issued a "Power Generation Policy" in 2015 to overcome the shortfall in electricity supply[21]. The main objectives are:

- "Provide sufficient power generation capacity at the least cost;
- Encourage and ensure exploitation of indigenous resources;
- Ensure that all stakeholders are looked after in the process"[20];
- Be attuned to safeguarding the environment.

Considering these policy objectives, Economics, Performance and Environment have been identified as high-level objectives. Moreover, at the second level of the objective tree, these HLOs are divided into the corresponding evaluation areas. Costs and Employment are the most applicable/commonly considered areas of evaluation for the HLO of Economics. The Performance objective has been divided into three evaluation areas namely, Technical, Security of Fuel Supply and Safety. Security of fuel supply has been separately considered because of the government policy direction on the use of indigenous resources. For the Environment objective, in addition to Waste, Emissions and Public acceptance, Resource has been considered as an evaluation area, which is water requirement only, as Pakistan is water stressed and there are risks that country may become a water scarce country.

3.6.5. Identification of key indicators

For comparative evaluation, key indicators (KIs) are identified and defined at the third level of the three level objective tree corresponding to the evaluation areas and HLOs. Guidance on key indicator sets, to be used for comparative evaluation, is given in IAEA report [3.1]. Issues specific to the country also bring out some KIs to be considered for evaluation. Additionally, review of various studies on comparative evaluations for electricity generation options helps in identification of KIs. The KIND approach suggests the use of preferably 15 KIs. For the present analysis, the following 13 KIs have been selected considering their importance in electricity system of Pakistan.

[21] https://policy.asiapacificenergy.org/sites/default/files/Power%20Generation%20Policy%202015.pdf

i. Initial investment

This KI is the average specific capital cost (in USD/kW) of the projects for different technologies. In addition to the size of investment, there are other factors such as availability of financing sources, interest/discount rates, plant design/technology, construction time, plant life, plant factor, efficiency, etc. which may influence the decision making and need to be considered while evaluating this indicator.

Nuclear power is generally capital intensive and is financed by governments or with government guarantees. Also, for small economies with limited foreign reserves, financing/loan repayment may be increasingly difficult with the expansion of a nuclear power programme. For the LNG, cost of terminals, if a new terminal is required, may be considered for evaluation. Similarly, for local coal, mining cost may also be considered for evaluation.

ii. Levelized unit cost

The other KI commonly used for economics is the Levelized Unit Cost (LUEC) measured in terms of Pak Rupees per kWh (Rs./kWh). It is the total cost incurred over the lifetime of a plant divided by the total electricity produced over its lifetime while considering discounting. In the case of nuclear power, initial investment and its financing costs contribute more than 60 percent to LUEC. These costs are generally recovered in 12–15 years. The factors that may influence LUEC are changes in material prices, construction period, exchange rates, etc.

iii. Fuel price

Fuel price is the fuel cost per unit of electricity generated, Rs./kWh. The increase in electricity prices due to increase in fuel prices is also an important factor to consider for evaluation, as it has economic impact on individuals, businesses and the country.

Fuel cost is a major component of the price of electricity generated by coal and LNG based power plants. For nuclear power, the fuel cost component is low, and prices are more stable than fossil fuels which provides stability to nuclear electricity prices.

For imported fuel, like LNG, this cost puts pressure on foreign exchange reserves and also increases with weakening currency that leads to affordability issue. LNG import, in the long term, for large capacity additions may lead into a huge burden/import bill.

iv. Job creation

This is the number of jobs created by different technologies. The number of jobs is different for the construction phase and operation phase. The number of jobs also depends on energy chain activities being carried out indigenously in the country, e.g., mining of coal, LNG terminals operation, transportation of fuel, etc.

v. Load following

This indicator is related to the flexibility of generating electricity - that is how quickly can a plant ramp its electrical output up or down without violating operating parameters. Another important factor is the minimum stable operating level that a plant can maintain. This indicator is valuable to respond to temporal variations in demand and to complement intermittent renewable sources generation. Nuclear power is generally not considered to be a very flexible source of electricity generation.

vi. Distance from load centres

This can be described as the suitability of the plant to locate close to load centres and major cities. Remote sites incur additional infrastructure costs such as long transmission lines, road and/or rail networks for fuel transportation and communication, housing and medical facilities for manpower, etc. Long distances also result in higher transmission losses.

vii. Security of fuel supply

Security of fuel supply is basically reliable and continuous supply of fuel at a stable price. The factors important for this indicator include domestic or imported fuel, number of fuel suppliers, supply disruption possibilities due to some climate (floods, earthquake, etc.) or political events and the capacity of on-site storage. Moreover, price changes also affect the supply of fuel due to affordability issues. In case of gas (LNG), depleting domestic gas reserves and demand for gas by different end-use sectors, such as transport, fertilizer, commercial, domestic, etc., also effect security of supply, and in a high demand season it may result in shortage of supply.

viii. Safety risk

This is the risk and impact of accidents that might occur in the specific plant technology and its supply chain. Factors that may be considered for safety risk are frequency of accidents, cause of accidents (man-made, natural disaster, design related), number of fatalities (immediate and latent) and plant technologies (design, operation and emergency procedures).

ix. Waste generation

Waste generation by different electricity generation options considers both the volume of waste (solid and liquid) and its hazard. Nuclear power plants produce radioactive waste which requires long term management and disposal.

x. CO_2 emissions

Fossil fuel fired power plants emit CO_2 emission per unit of electricity generated, g/kWh, depending on fuel efficiency, and considering the full chain. CO_2 emissions are an indicator of global environmental impact owing to their role in global warming and climate change.

xi. SO_x, NO_x, PM, local pollutants and radiation emissions

There are SO_x, NO_x, particulate matter (PM) emissions per unit of electricity generated, g/kWh. These emissions depend on fuel composition and emission control measures and are important as these have local adverse impacts on health, agriculture and buildings. In the case of nuclear power plants, control of the radiation level within the regulatory limits in plant surroundings is ensured which is also very important.

xii. Water requirement

Water is used (consumptive and non-consumptive form) for electricity generation for cooling and other utility needs. Water requirement is important for water stressed countries. In this study, water consumption for nuclear power plants was assumed to correspond to a once-through water cycle, whereas for coal and liquified natural gas (LNG) plants, a closed water cycle has been considered. For coal, the water requirement for mining is also considered. Moreover, for local coal mining in Pakistan, availability of water at the site is an issue which needs to be considered during evaluation.

xiii. Public acceptance

This indicator refers to the public viewpoint/opinion about a specific electricity generation option. The public in the vicinity of power plants or energy chain are a major stakeholder as the plant affects them the most. There are benefits such as employment for local persons, health and education facilities, etc. Risks of accidents and health impacts associated with each option also influence the public acceptance. National standards/guidelines and international agreements/protocols to mitigate local adverse impacts and global warming also need to be considered while evaluating the options.

Table 3.37 presents the summary of factors to consider while scoring the selected KIs.

TABLE 3.37. SCORING CONSIDERATIONS FOR KEY INDICATORS

	Key indicators (KI)	KI scoring considerations
1.	Initial investment	Investment size, financing sources/ availability, interest/ discount rates, plant technology/ design, construction time etc.
2.	Levelized unit cost	Changes in material prices, construction time, exchange rate etc.
3.	Fuel price	Fuel import dependence, variation in fuel price
4.	Job creation	Plant construction and operation phase, mining of coal, fuel transportation, temporary shutdown jobs
5.	Load following	Flexibility of generation, minimum stable operation level
6.	Distance from load centres	Support infrastructure requirements, fuel transportation, transmission losses
7.	Security of fuel supply	Fuel supply vulnerabilities such as fuel price variations, exchange rate variations, supply disruptions due to political, economic and climate (floods/ earthquake) reasons etc., on-site storage, demand for end-use sectors
8.	Safety risk	Probability and impact of accidents
9.	Waste generation	Volume and hazard, waste disposal and management
10.	CO_2	Climate change issue
11.	SO_X, NO_X, PM, radiation	Health impacts due to these emissions
12.	Water requirement	Consumptive requirement for operation phase only, nuclear once-through, coal & gas cooling towers based, for coal water required for mining is also considered
13.	Public acceptance	Local population acceptance, National standards/ guidelines and international agreements related to environment

The three-level objective tree, finalized for this study after discussions with experts, with goals for each indicator is shown in Figure 3.61.

High-level objectives	Evaluation Areas	Key Indicators	Goal
Economics	Cost	*Initial Investment (E1)*	*min*
		Levelized Unit Cost (E2)	*min*
		Fuel Price (E3)	*min*
	Employment	*Job Creation (E4)*	*max*
Performance	Technical	*Load Following (P1)*	*max*
		Distance from Load Centers (P2)	*min*
	Fuel Supply	*Security of Fuel Supply (P3)*	*max*
	Safety	*Safety Risk (P4)*	*min*
Environment	*Waste*	*Waste Generation (EN1)*	*min*
	Emissions	CO_2 *(EN2)*	*min*
		SO_X, NO_X, *PM, Radiation (EN3)*	*min*
	Resource	*Water Requirement (EN4)*	*min*
	Social	*Public Acceptance (EN5)*	*max*

FIG. 3.61. Three-level objective tree with goals for each key indicator.

3.6.6. Assigning of weights in three-level objective tree

Key factors in the application of KIND-ET are: (i) defining high-level objectives and corresponding evaluation areas/ indicators considering national and international circumstances, and (ii) assigning weights to HLOs, evaluation areas and KIs. These weights need to be assigned accurately and as independent of any bias or current trends as possible. The weighting factors allow the relative importance of the indicators, evaluation areas, and high-level objectives to be considered and reflect national preferences.

The simplest and the most natural way to evaluate weighting factors is the direct method combined with a hierarchical weighting. To apply this method, weights need to be assigned to the three-level objective tree, separately at each level (high level objective, evaluation areas and key indicators).

The weighting factors for each indicator may be determined by soliciting input from subject matter experts in the corresponding fields. Experts set the weighting factors (real numbers from 0 to 1 at each hierarchy level) with the constraint that the sum of the weighting factors at each level of the objective tree needs to be equal to 1. Subsequently, the final weighting factor for each indicator is determined by multiplication of the corresponding weights mentioned above.

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. The evaluation method for weighting factors has been discussed in detail in [3.1].

For this case study, final weights were calculated by simple averaging the input from 10 experts including energy planners, economist and engineers, which were asked to assign weights to the three-level objective tree as per the requirements of KIND-ET. The average of weighting factors is given in Figure 3.62:

High-level objectives titles	High-level objectives weights	Areas titles	Areas weights	Indicators abbr.	Indicators weights	Final weights
Economics	0.50	*Cost*	0.78	*E1*	0.39	0.152
Economics	0.50	*Cost*	0.78	*E2*	0.33	0.129
Economics	0.50	*Cost*	0.78	*E3*	0.28	0.111
Economics	0.50	*Employment*	0.22	*E4*	1.00	0.108
Performance	0.30	*Technical*	0.38	*P1*	0.49	0.056
Performance	0.30	*Technical*	0.38	*P2*	0.51	0.057
Performance	0.30	*Fuel Supply*	0.38	*P3*	1.00	0.113
Performance	0.30	*Safety*	0.25	*P4*	1.00	0.075
Environment	0.20	*Waste*	0.24	*EN1*	1.00	0.047
Environment	0.20	*Emissions*	0.38	*EN2*	0.38	0.029
Environment	0.20	*Emissions*	0.38	*EN3*	0.62	0.047
Environment	0.20	*Resource*	0.21	*EN4*	1.00	0.042
Environment	0.20	*Social*	0.18	*EN5*	1.00	0.035

FIG. 3.62. Average of weighting factors for HLO, areas and key indicators (screenshot from KIND-ET).

3.6.7. Scoring scales for key indicators and finalizing the performance table

Scores for each of the key indicator can be given in a natural scale, if data is available, or on a scale as described in the KIND approach [3.1]. As suggested in the KIND approach, 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 [3.1]. For this study, because of the broad definition of KIs, limited availability of country specific data for some KIs and some KIs being qualitative, experts were required to score all the key indicators on a scale of 1 to 10. For evaluation of KIs, experts considered country specific/international techno-economic data. Moreover, for key indicators, where the goal is to minimize (“min’ in the Fig. 3.61), lower scores represent better scores; for key indicators where goal is to maximize, higher scores are better. The final scores, obtained by averaging the inputs from all the experts are given in Fig. 3.63.

High-level objectives titles	Areas titles	Indicators titles	Indicators abbr.	MIN score	MAX score	Nuclear	Local Coal	Gas (LNG)
Economics	*Cost*	*Initial Investment*	*E1*	1	10	8.75	5.00	3.50
Economics	*Cost*	*Levelized Unit Cost*	*E2*	1	10	7.00	5.50	6.50
Economics	*Cost*	*Fuel Price*	*E3*	1	10	2.00	5.25	8.50
Economics	*Employment*	*Job Creation*	*E4*	1	10	6.00	7.00	4.00
Performance	*Technical*	*Load Following*	*P1*	1	10	3.75	5.25	7.50
Performance	*Technical*	*Distance from Load Centers*	*P2*	1	10	6.00	7.50	3.50
Performance	*Fuel Supply*	*Security of Fuel Supply*	*P3*	1	10	7.00	9.00	3.50
Performance	*Safety*	*Safety Risk*	*P4*	1	10	4.75	5.50	3.50
Environment	*Waste*	*Waste Generation*	*EN1*	1	10	6.00	6.00	2.30
Environment	*Emissions*	CO_2	*EN2*	1	10	1.25	9.00	5.50
Environment	*Emissions*	SO_X NO_X. *PM, Radiation*	*EN3*	1	10	1.50	8.50	5.00
Environment	*Resource*	*Water requirement*	*EN4*	1	10	5.50	6.00	4.00
Environment	*Social*	*Public Acceptance*	*EN5*	1	10	6.50	7.00	7.50

FIG. 3.63. Performance table in KIND-ET (screenshot).

3.6.8. Single attribute value function form and domain

The next step in KIND-ET is the selection of a single attribute value function (SAVF), its form and domain. Some SAVF described in the KIND-ET report [3.1] are given in Table 3.38. The table includes the most common types of SAVF, which have found wide applications in various applied studies including nuclear engineering. These are mostly linear and exponential functions.

TABLE 3.38. SINGLE ATTRIBUTE VALUE FUNCTION FORMS

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 is reasonable to select as close to each other as reasonably possible to improve MAVT resolution.

Domain is the minimum and maximum value ($x^{\min}$ and $x^{\max}$) that can be given to a key indicator and are subsequently used for calculation of SAVF. Global domain means the minimum and maximum values of the defined scale are used for calculation of SAVF whereas in the local domain, the minimum and maximum values given by experts as shown in performance table (Fig. 3.63) are used.

For trial application only, linear form of value function with global domain is selected for all the key indicators. Also, for key indicators where the goal is 'min' decreasing SAVF is used and vice versa. The SAVF calculated by the KIND-ET is given in Fig. 3.64.

Indicators titles	Indicators abbr.	Goal	Form	Exponent power	VF domain	MIN VF domain	MAX VF domain	Nuclear	Local Coal	Gas (LNG)
Initial Investment	*E1*	min	lin	1	global	1	10	0.139	0.556	0.722
Levelized Unit Cost	*E2*	min	lin	1	global	1	10	0.333	0.500	0.389
Fuel Price	*E3*	min	lin	1	global	1	10	0.889	0.528	0.167
Job Creation	*E4*	max	lin	1	global	1	10	0.556	0.667	0.333
Load Following	*P1*	max	lin	1	global	1	10	0.306	0.472	0.722
Distance from Load Centers	*P2*	min	lin	1	global	1	10	0.444	0.278	0.722
Security of Fuel Supply	*P3*	max	lin	1	global	1	10	0.667	0.889	0.278
Safety Risk	*P4*	min	lin	1	global	1	10	0.583	0.500	0.722
Waste Generation	*EN1*	min	lin	1	global	1	10	0.444	0.444	0.856
CO_2	*EN2*	min	lin	1	global	1	10	0.972	0.111	0.500
SO_X NO_X. PM, Radiation	*EN3*	min	lin	1	global	1	10	0.944	0.167	0.556
Water requirement	*EN4*	min	lin	1	global	1	10	0.500	0.444	0.667
Public Acceptance	*EN5*	max	lin	1	global	1	10	0.611	0.667	0.722

FIG. 3.64. Single attribute value function for the base case (screenshot from KIND-ET).)

3.6.9. Ranking of energy options/overall score

The type of multi attribute value function (MAVF) widely applied in different studies (the so called 'additive model of multi attribute value function') and also suggested for the KIND approach has the following form:

$$U(x) = \sum_{i=1}^{n} w_i \, u_i(x_i), \text{ where } \sum_{i=1}^{n} w_i = 1 \quad (3.1)$$

In above expression $u_i(x_i)$ is the single attribute value function (as given in Figure 3.64) for the i-th indictor that is scaled from 0 to 1, w_i is the weight for *i-th* indicator as given in Fig. 3.62. The ranking result/overall score of the energy system options, calculated in KIND-ET using the above MAVF, are given in Fig. 3.65. Local coal comes out to be first viable option whereas nuclear power is better than the LNG option. The results show that Economics is the major contributor to coal's high score. It is observed that difference between scores for the three energy system options is very small, which may be due to global domains selected for single attribute value function.

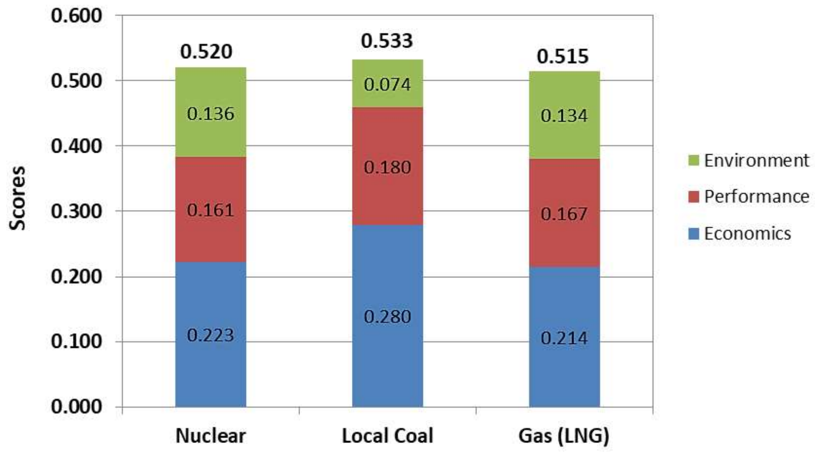


FIG. 3.65. Ranking results/ overall score calculated by KIND-ET.

Figure 3.66 shows the scores at HLO level for the compared options. In Economics, nuclear is slightly better than LNG whereas coal has the highest score in this HLO. Nuclear has the highest score in the Environment and lowest in Performance.

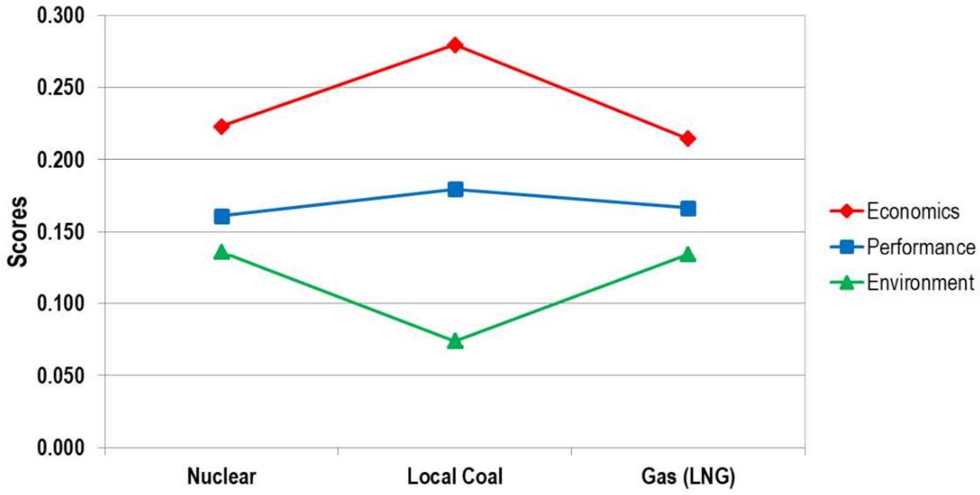


FIG. 3.66. HLO scores (base case).

To gain further insight, scores are also calculated at evaluation area level and are given in Fig. 3.67. It is evident from the table that out of the total nine evaluation areas, nuclear power has the highest rank in Emissions area, and has good scores in Employment, Security of Fuel Supply, Safety and Resource. Nuclear power is not a competitive option in the areas of Cost, Technical, Waste and Social.

In the Cost area, high initial investment is the major contributor to the lower score of nuclear compared to other options. Similarly, load following is the main contributor in the Technical area for lower scores. In the areas of Waste and Social, scores of nuclear power are also lowest due to radioactive waste generation and public acceptance respectively.

Nuclear power has better scores than LNG in the areas of Employment and Fuel Supply which solely represents security of fuel supply. Nuclear fuel is lowest in volume and cost component is small and can easily absorb fuel supply disruptions for significantly large period compared to fossil fuels. Also, nuclear power has better scores than local coal in the area of Resource (water requirement for energy generation; coal and LNG fired power plants in the country are assumed to be using closed cooling systems requiring more water) and Safety.

		Nuclear	Local Coal	Gas (LNG)
1	*Cost*	0.163	0.207	0.178
2	*Employment*	0.060	0.072	0.036
3	*Technical*	0.042	0.042	0.081
4	*Fuel Supply*	0.075	0.100	0.031
5	*Safety*	0.044	0.038	0.054
6	*Waste*	0.021	0.021	0.040
7	*Emissions*	0.073	0.011	0.041
8	*Resource*	0.021	0.019	0.028
9	*Social*	0.021	0.023	0.025

FIG. 3.67. Scores at evaluation area level for the base case (KIND-ET screenshot).

3.6.10. HLO weight sensitivity

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, i.e., scores and ranks of alternatives [3.1].

Two more cases, "High Env" and "High Econ", in addition to the Base Case were investigated by changing the weights of HLOs. The overall score with corresponding weights for the three cases are given in Fig. 3.68.

	HLO Weights			Ranking Results/ Overall Score		
	Economics	Performance	Environment	Nuclear	Local Coal	Gas (LNG)
Base Case	0.500	0.300	0.200	0.520	0.533	0.515
High Env	0.400	0.300	0.300	0.543	0.514	0.539
High Econ	0.600	0.300	0.100	0.497	0.552	0.491

FIG. 3.68. Ranking result/ overall score and HLO weights for three cases (screenshot from KIND-ET).

Figures 3.69 and 3.70 show the results of the weight sensitivity. It can be seen that in the High Env case, when weight of the Environment is increased by 0.1 and weight of Economics is decreased by 0.1, nuclear power comes out to be the first rank option and coal as the lowest rank. However, in High Econ case, as the weight of Economics is further increased by lowering the weight of Environment, the overall score of coal improves, but the ranking of options is the same as in the Base Case.

The impact of changes in weights on overall scores for the three options is given in Fig. 3.70. Overall scores for nuclear power and LNG are highest for the High Env case while coal has the highest score for High Econ case. Moreover, overall scores for nuclear power and LNG options drop significantly in the High Econ case.

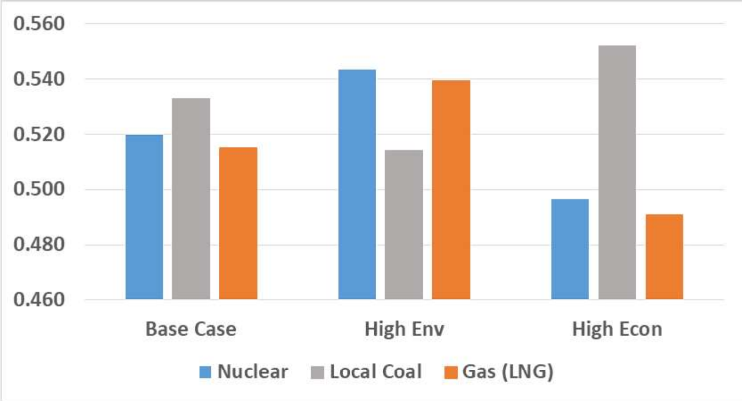


FIG. 3.69. Ranking results for three cases (sensitivity of weights).

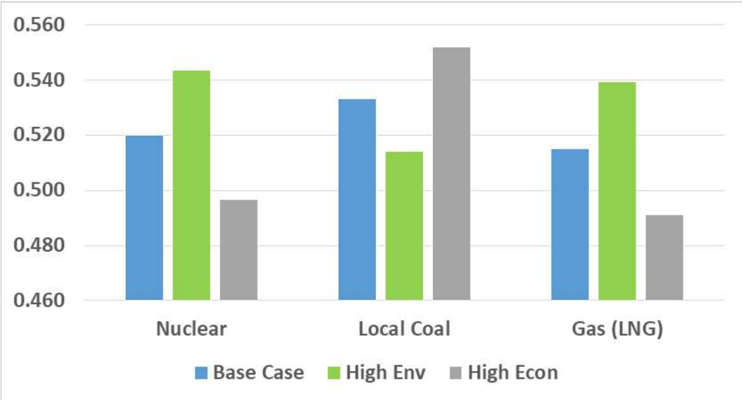


FIG. 3.70. Ranking results for three energy systems (sensitivity of weights).

3.6.11. KIND-ET extensions

The KIND-ET tool has been further extended in the CENESO collaborative project to include screening of options, uncertainty analysis and illustration of results. The extensions used in this study are described in the following sections.

3.6.11.1. Domination Identifier

The extension identifies the generation option (called the Dominated Option) which has worse values of SAVF for all the key indicators in comparison to some other generation options (called Dominating Options) under evaluation. The dominated option/energy system can then be omitted from further evaluation. Domination identifier is a very useful tool when a large number of options/energy systems are under evaluation because dominated options can be screened from analysis at the outset. Further details for this extension are given in User Instructions for Extensions of KIND-ET.

For identification of the dominated option in excel the major steps are:

- Populate the 'Performance Table' worksheet with same values as used in KIND-ET;
- In the 'Domination' worksheet, calculate normalized values of the KIs by calculating linear single attribute value functions specified at local domains for the whole set of KIs;
- Identify dominated and relevant dominating options from the domination table (in cells with the sign '<' one can find names of dominated and dominating options).

As discussed earlier, the Domination Identifier is more useful for cases with a large number of options. In this study there are only three options under evaluation, and none is being dominated by another. The results of the Domination Identifier are given in Fig. 3.71.

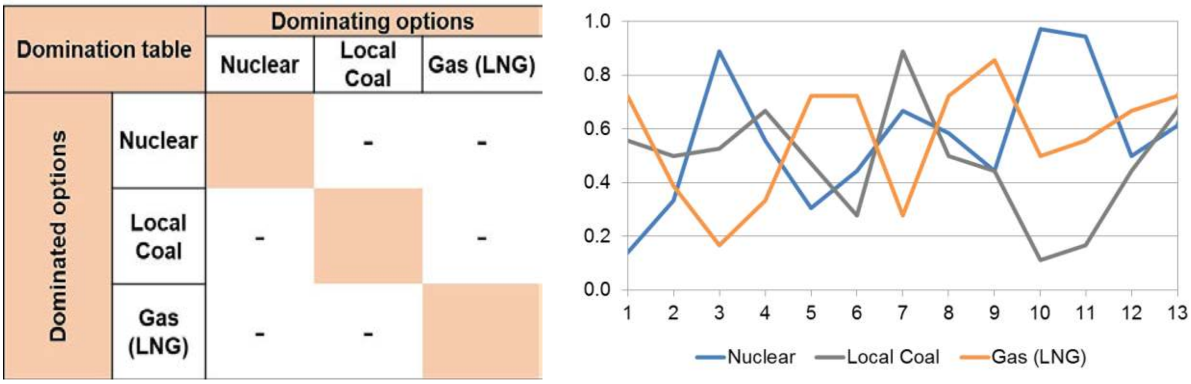


FIG. 3.71. Result of Domination Identifier (screenshot).

3.6.11.2. Overall score spread builder

Examination of the weighting factor uncertainty impact on ranking results may be performed using stochastic (probabilistic) variation of weights representing the individual indicator's relative significance that makes it possible to determine the probability distributions of options' scores and ranks, considering uncertainties in weighting factors. Such examination allows making overall judgments regarding ranking results in spite of the absence of final information usually gained by means of expert stakeholder elicitation in an iterative process. Further details for this extension are given in User Instructions for Extensions of KIND-ET.

Overall Score Spread Builder consists of three Excel files:

- Weight Generator (this component generates 10,000 combinations of weighting factors uniformly distributed in the range from 0 to 1, constrained only by normalization conditions, and provides the capability to select weight combinations satisfying some restrictions).
- Randomizer (this is an accessorial component of Overall Score Spread Builder allowing one to change conditions for weights randomizations).
- Score Evaluator (this component evaluates overall scores of options for each weight combination and build the resulting box and whisker chart, demonstrating the spread of overall scores for all options considered due to uncertainties in weighting factors).

Score Evaluator is the main component of Overall Score Spread Builder, which provides associated evaluations and builds box and whisker diagrams for the overall score spreads. The SAVF used in KIND-ET are first populated in the Score Evaluator sheet (see Fig. 3.72) and then Final (Randomized) Weights for 10,000 combinations are populated from weight generator sheet. The results of the Score Evaluator are shown in the Fig. 3.73.

Single-attr. value functions		KI-1	KI-2	KI-3	KI-4	KI-5	KI-6	KI-7	KI-8	KI-9	KI-10	KI-11	KI-12	KI-13
Please input here data rearding single-attr. value functions from the KIND-ET model	**Nuclear**	0.138889	0.333333	0.888889	0.555556	0.305556	0.444444	0.666667	0.583333	0.444444	0.972222	0.944444	0.5	0.611111
	Local Coal	0.555556	0.5	0.527778	0.666667	0.472222	0.277778	0.888889	0.5	0.444444	0.111111	0.166667	0.444444	0.666667
	Gas (LNG)	0.722222	0.388889	0.166667	0.333333	0.722222	0.722222	0.277778	0.722222	0.855556	0.5	0.555556	0.666667	0.722222

FIG. 3.72. SAVF (base case) used as input of score evaluator (screenshot of KIND-ET).

	Nuclear	Local Coal	Gas (LNG)
Mean	0.56701	0.47790	0.56801
Standart deviation (SD)	0.16402	0.13590	0.13781
Maximum value (Max)	0.97157	0.88827	0.85516
Quartile (Q3, 75%)	0.66276	0.55202	0.68155
Median	0.55461	0.48643	0.58901
Quartile (Q1, 25%)	0.45736	0.40639	0.47472
Minimum value (Min)	0.13935	0.11168	0.16690
Calculations for chart			
Bottom	0.45736	0.40639	0.47472
2 Q Box	0.09725	0.08004	0.11428
3 Q Box	0.10815	0.06559	0.09254
Whisker -	0.31801	0.29472	0.30783
Whisker +	0.30881	0.33625	0.17362

FIG. 3.73. Results of the Overall Score Spread Builder (screenshot).

The results in Fig. 3.73 show that the mean value for LNG is highest, followed by nuclear power with a small difference, whereas Local Coal has the lowest mean. The box and whisker plot for spread of overall scores for all options considered due to uncertainties in weighting factors is shown in Fig. 3.74.

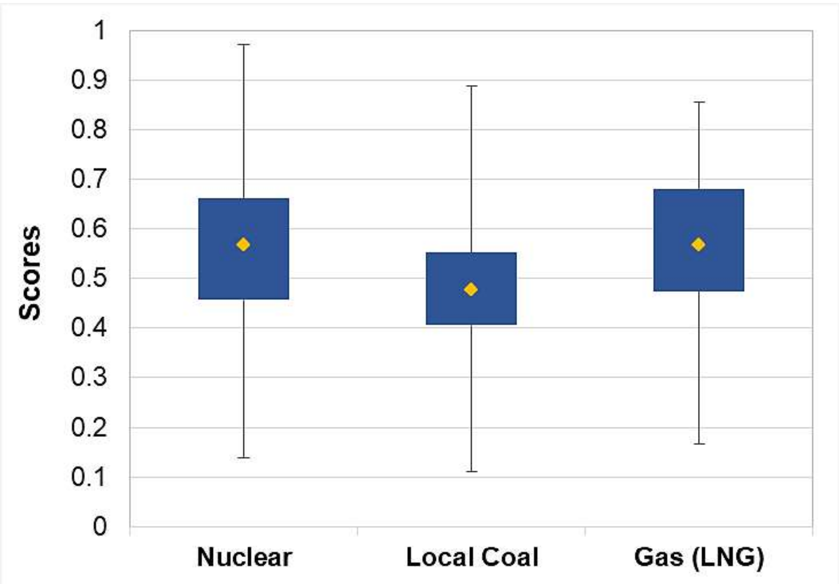


FIG. 3.74. Overall score spreads

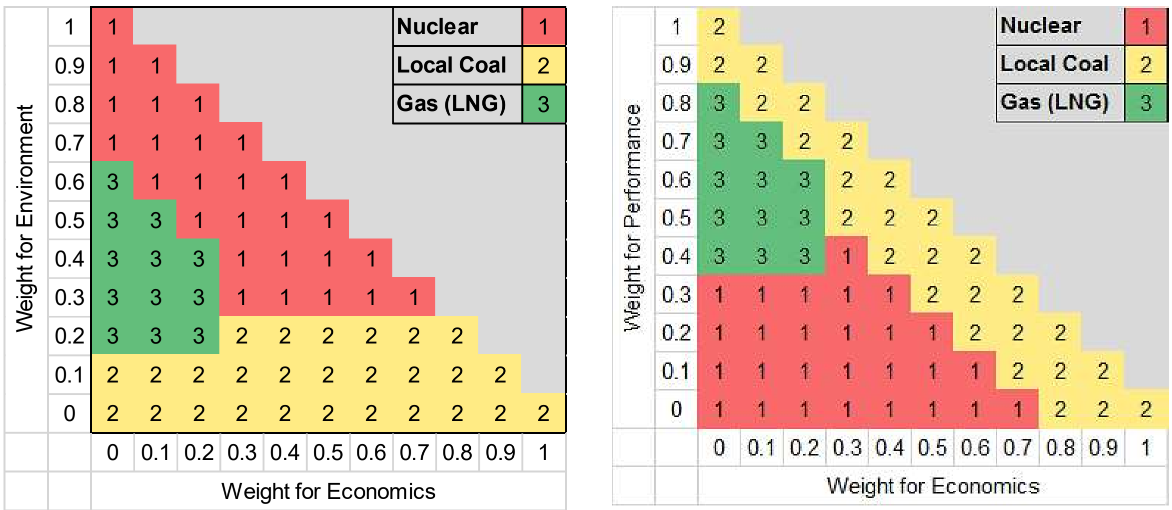
3.6.11.3. Ranks mapping tool

This extension is mainly a visualization tool that gives decision makers a complete view of which system is a first rank option for a set of weights of HLOs. Since it is a two-dimensional presentation, weights of two HLOs are assumed and third HLO weight is calculated by difference. The details for this extension are given in User Instructions for Extensions of KIND-ET.

The main steps involved in the Ranks Mapping Tool extension are as follows:

- Populate the ‘HLO scores’ worksheet of Ranks Mapping Tool by the data on high-level objective scores for the options under study. This data is calculated in the ‘Ranking results’ worksheet of the associated KIND-ET model by setting weights equal to unity for all HLOs.
- Calculate overall scores for options given for each weight combination.
- Evaluate and highlight the options taking the first rank and relevant areas in the high-level objective weight space.

Below are the results of the Ranks Mapping Tool. Figure 3.75(a) shows that local coal is the sole first rank option when Economics is given higher weight (above 0.7) and for lower weights of Environment (below 0.1). Nuclear power becomes the sole first rank option when environment has higher weight (above 0.7), Emissions being the differentiating area between nuclear and other options. LNG also occupies some area in the plot for certain weight options. Figure 3.75(b) shows the overall scores, by plotting weights for performance against economics. It is evident that nuclear occupies space in the graph for lower weights of performance this is mainly due to lower scores of the technology in the technical evaluation area.



(a) (b)

FIG. 3.75. Screenshot of ranks mapping tool, (a) Environment vs economy, (b) Performance vs economy.

3.6.12. Conclusions

Thermal generation options (Nuclear Power, Local Coal and LNG) will be a key component of capacity additions that are planned in the next few decades due to increased electricity demand mainly for growing population and expected economic growth of Pakistan. These options have been compared using IAEA KIND-ET and its extensions, MS Excel based tools. As reflected in the results of the Domination Identifier, it is observed that none of the evaluated options is superior to others in all the indicators. The best suited option for the country depends on its conditions and national policies/preferences. For the present application of KIND-ET, coal comes out to be first rank option in the Base Case. The main conclusions are as follows:

- In Pakistan, local coal is a good option mainly due to its economics and security of fuel supply. However, coal is not an attractive option if the weight of environment is set to be high due to increasing concern of global warming.
- Nuclear power is the cleanest of the compared options. Therefore, if the weight of environment is set to be high, it comes out to be first rank option. Also, nuclear power is good in employment generation and provides stability of electricity prices due to low and stable fuel costs. However, nuclear power has high capital cost which makes it unattractive especially for small/poor economies or large capacity additions in short time or operation at low plant factors. Inflexibility of generation, safe disposal of radioactive waste, and public acceptance are other weak areas/ concerns for nuclear energy.
- Imported LNG is good in load following and can be located near to load centres but is not a good option due to security of fuel supply and high fuel price. Furthermore, LNG, though a cleaner option, still has emissions which can be significant in the long term depending on consumption.

Energy systems option can be effectively and suitably compared in KIND-ET, and its extensions further enhance visualization of results. Some other conclusions are:

- Including detailed guidelines for scoring in the user manual of KIND-ET would be useful.
- Including detailed guidelines in the user manual on selection of SAVF (linear, exponential) would be useful.
- Providing a section on how to interpret results in the user manual would be useful.

3.7. BENEFITS VERSUS CHALLENGES COMPARATIVE EVALUATION OF INNOVATIVE AND EVOLUTIONARY NES TECHNOLOGIES (ROMANIA)

This chapter presents structured report of the first of the two case studies done by experts from Romania.

3.7.1. Introduction

Romania is a nuclear technology user country with a 70 years old nuclear programme, which benefits from successful operation of nuclear reactors (both research and commercial reactors) and nuclear installations, proven capabilities (infrastructure, industry, human resources, experienced specialists) and positive public acceptance towards nuclear energy. The Government’s long term commitment to nuclear power development is sustained not only by the strategic documents in force and official plans, but also by the increased participation in international R&D projects, including development of innovative technologies (European Lead Fast Reactor).

In the INPRO KIND Collaborative Project framework, the expert team from RATEN ICN Pitesti, Romania, performed a case study which sustained the national interest in supporting the nuclear energy development and continuing the nuclear programme envisaging its sustainability in the long term [3.1]. A comparative multicriteria analysis was conducted applying the KIND approach and the KIND-ET tool to evaluate evolutionary and innovative NES technologies based on specific key indicators and taking into consideration country specifics.

For the comparative multicriteria evaluation, three NES technologies were selected as follows: CANDU technology (already existing/operating NES technology); evolutionary technology (GenIII+ enhanced CANDU technology) – eNES; and innovative technology (GenIV LFR technology) – iNES.

The NES technologies have been assessed with the KIND-ET tool considering a 3-level objective tree composed by: three High Level Objectives, HLOs (Cost, Performance, and Acceptability); seven Areas of Evaluation, AEs (Economics, Waste Management, Environment, Proliferation Resistance, Safety, Maturity of technology, Country Specifics); and 18 Key Indicators, KIs (16 KIs developed in KIND CP and 2 KIs defined for Country Specifics area).

Considering Romania's potential interest for the nuclear technologies considered, the case study looks to offer an expert technical support for decision making based on the answers to several questions of interest regarding the investigated NES technologies, status for different weights assigned to HLOs and to specific AEs, and how much can country specifics effect on the analyses results.

Following a preliminary screening for realistic solutions to be further considered in objective tree elements weighting, 3 main working cases were considered in respect to the HLOs weights, namely: Best Cost case (Cost 50%, Performance 30%, Acceptability 20%), Best Performance case (Cost 30%, Performance 50%, Acceptability 20%), and Best Cost & Performance case (Cost 40%, Performance 40%, Acceptability 20%). The 'Country Specifics' AE has been included in the Acceptability HLO in order to avoid artificially increasing this area importance by using a higher HLO weight.

The overall scores obtained by the innovative technology promote it as more attractive (better in Performance HLO - in 'Safety', 'Waste Management' and 'Environment' AEs, and also for the 'Country Specifics' AE in Acceptability HLO). The evolutionary and CANDU technologies were better evaluated in Acceptability HLO, a realistic result considering the good scores obtained for the 'Maturity of technology' AE.

Some sensitivity analyses were performed by considering different weights for AEs in Performance HLO (where iNES has better ranking), and by selecting equal weights for 'Economics' KIs in Cost HLO (increasing therefore the importance of R&D costs and affecting the ranking of iNES with adverse scores for this KI). The ranking results proved the reliability and robustness of the assessment.

The KIND approach gives the possibility to communicate the potential of innovative technologies by creating their correct image if the approach is applied properly. For each case, country specific conditions need to be considered, as they can significantly impact the ranking of considered NES technologies.

3.7.2. Objective and problem formulation

The Romanian case study analyses performed in the KIND collaborative project could be refined and get more weight by including a 3-level objective tree analysis on Benefits versus Challenges for the considered NES technologies, as long as these important elements are always associated with a strategic importance, especially on the decision making level.

In this respect, a new case study was proposed by the RATEN ICN experts in the INPRO CENESO CP, whose main goal was to apply the KIND approach and the KIND-ET tool with new developed extensions, for the multicriteria comparative evaluation of evolutionary and innovative NES options.

As specific objectives of the case study, the following were addressed:

- To evaluate the considered NES technologies taking into consideration the benefits and challenges associated based on a 3-level objective tree including specific areas of evaluations and key indicators for the two HLOs considered (Benefits and Challenges);
- To take into consideration country specifics;
- To perform sensitivity analyses considering different weights for AEs in Benefits and/or Challenges HLOs;
- To improve the results illustration and to allow their better understanding and presentation based on the application of KIND-ET additional modules.

Compared with the case study previously performed in the INPRO KIND CP, new AEs have been considered (for example: Legal and political environment, Public Acceptance), as well as new KIs corresponding to already existing and new considered AEs (for example: Effectiveness of accident management - prevention and mitigation, National infrastructure, Competency creation, Early involvement of stakeholders in the nuclear decision making process).

In a national context and discussing a specific technology an individual AE may be a benefit, whilst in another context or technology it may be a challenge. Therefore, the assignation process of the AEs to the HLOs is technology and country dependent. Sometime even if the national context is clearly known, and the technology is already chosen, there are different arguments to assign an AE to the Benefits or contrarily to the Challenges. For example:

- 'Waste management' is generally considered as a challenge due to the insufficient long term experience for the spent fuel final disposal, and due to the apprehension of the public for the risks with long duration together with a transfer of the responsibility to future generations. But for a Generation IV fast reactor-based technology the reduction of the amount and the radiotoxicity of the generated wastes by a factor of ten is a clear benefit. At the same time the possibility of the technology to burn the minor actinides from the spent fuel accumulated after the operation of the current fleet of NPPs is a great advantage and provides sufficient reason to assign the WM as a benefit.
- 'Public acceptance' is generally a challenge for many national contexts, both for the newcomer countries and the nuclear programme experienced countries. However, in the case of an advanced technology there are arguments to improve the acceptance level. They are based on the great advantages of the new nuclear systems such as those of Generation IV: (1) better sustainability due to increasing of the efficiency in using the

natural resources and due to the drastic reduction of the long term waste amounts; (2) improved economics by increasing the overall plant efficiency, standardization, and limitation of the financial risks; (3) higher safety and reliability by achieving a "very low likelihood and degree of reactor core damage"[22], and by elimination of "the need for offsite emergency response"[21]; (4) better resistance to the proliferation by increasing "the assurance that they are very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism"[21]. In this case public acceptance may be transferred into the benefits category .

— 'Legal and political environment' is a benefit for an experienced nuclear programme country and a great challenge for a newcomer country since a lot of efforts during one or two decades are necessary to set up the needed infrastructure. For a new technology, the existing legal and political environment is important, but the novelty of the nuclear system may introduce relevant difficulties, including important changes in the procedures and legal framework.

Taking into consideration the above comments, the case study can offer an expert technical support for the decision making based on reasonable answers to several questions:

— What would be the NES technology rankings if 'Waste Management', 'Legal and political environment' and 'Public Acceptance' are considered as benefits for NES development?
— What would be NES technology rankings if 'Waste Management', 'Legal and political environment' and 'Public Acceptance' are considered as challenges for NES development?
— How would the NES technology rankings be affected by considering 'Waste Management' AE as a challenge for NES development?
— How would the NES technology rankings be affected by considering of 'Legal and political environment' AE as a challenge for NES development?
— How would the NES technology rankings be affected by considering of 'Public Acceptance' AE as a challenge for NES development?
— What would be the impact of HLO scores on the total scores of NES technologies?
— How much could the country specific conditions affect the analyses results?

3.7.3. Inputs, methods and assumptions used

<u>Formulation and description of NES options to be evaluated in the study</u>

The case study takes into consideration the same three NES technologies selected for multi-criteria comparative analysis in the KIND CP, namely: CANDU technology (at present Romania operates two CANDU6 reactors at Cernavoda NPP, whose contribution to the total electricity production is about 20%) – CANDU; evolutionary technology (GenIII+ Enhanced CANDU technology) – eNES; and innovative technology (GenIV Lead Fast Reactor technology) – iNES [3.1]. The main technical parameters characterizing the considered NES technologies are shown in Table 3.39.

[22] https://www.gen-4.org/gif/jcms/c_9502/generation-iv-goals

TABLE 3.39. MAIN TECHNICAL PARAMETERS OF NES TECHNOLOGIES [3.1]

Parameter	CANDU	eNES	iNES
Reactor type	HWR	HWR	LFR
Fuel type	Natural UO_2	Slightly enriched UO_2	MOX
Capacity [MWe]	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

Identification/Elaboration of a problem-specific Key Indicator set

The NES technologies have been evaluated with the KIND-ET tool defining a 3-level objective tree which includes:

— Two High Level Objectives (Benefits and Challenges);
— Nine Areas of Evaluation (Economics, Waste Management, Environment, Proliferation Resistance, Safety, Maturity of technology, Country Specifics, Legal and Political Environment, Public Acceptance);
— 20 Key Indicators.

In the following, the developed set of KIs will be briefly presented together with the corresponding areas of evaluation.

Area of 'Economics' represent one of the main factors to be considered in evaluation of a technology development, either conventional, nuclear or renewable. The two KIs selected developed and used in INPRO KIND CP were:

— Levelized energy product/service cost (E1);
— RD&D costs (E2).

Regarding the waste generated by nuclear reactors, the INPRO Methodology (Waste Management area, Basic Principle 1) states that it is very important to minimize the amount of generated waste in all stages of the nuclear fuel cycle, avoiding such way to transfer undue burdens to future generations [3.28]. For the 'Waste Management' area, two KIs developed and used in INPRO KIND CP were selected, namely:

— Specific radwaste inventory (WM1);
— Spent nuclear fuel costs (WM2).

The sustainable development is supported by nuclear power, which is able to provide energy with relatively low impact on the atmosphere, water, and land use, and efficient use of the natural resources is an important contributing factor to the NES increased performance. The evaluation in the 'Environment' area was done using the KI developed in the INPRO KIND CP - Amount of useful energy produced by NES from a unit of mined natural U (ENV1).

Two main aspects regarding the proliferation resistance are to be followed in order to have a sustainable NES, namely: the NES needs to be characterized by a low attractiveness of the nuclear materials including considerations on the overall technical difficulties to build a nuclear weapon; and Safeguards approach for the NES is to be identified and available, as stated by the INPRO methodology (Proliferation resistance area) [3.29]. The evaluation of considered NESs in 'Proliferation resistance' area was performed based on two KIs:

— Attractiveness of nuclear material and technology (PR1);
— Safeguard approach identified (PR2).

The 'Safety' area requires special attention being practically related to all the other areas of the INPRO Methodology and a main contributing factor to the political commitment and the society acceptance for nuclear power development in the country. After the Fukushima Daiichi NPP accident, the evaluation of NES safety features became very sensitive and under newly adopted strict regulations. The fundamental safety approach for NESs, either evolutionary or innovative, needs to include not only enhanced defence-in-depth features, but also increased inherent safety characteristics and passive safety systems. Four KIs were chosen for the evaluation of considered NES in the 'Safety' area, as follows:

— Design concept includes specific safety inherent and passive features/systems, including the potential to prevent release (S1);
— Core damage and large early release frequencies (S2);
— Source term (S3);
— Effectiveness of accident management (prevention and mitigation) (S4).

According to the INPRO methodology, [3.28] the assessment of a NES capability to fulfil criteria, user requirements and basic principles is to be completed by judgement on the level of maturity of technology, especially for innovative technologies. The higher the uncertainty, the greater are the risks that development goals will not be fully met and that the costs of development will exceed estimated costs. To perform the evaluation in the 'Maturity of technology' area, three KIs were used, namely:

— Design stage (M1);
— Time needed to mature the technology (M2);
— Competency creation (M3).

In addition to the first two KIs developed in the INPRO KIND CP, it is important to consider the competency creation aspect knowing that a NES development in a sustainable manner is possible with the support of existing capabilities (infrastructure, industry, human resources, qualified specialists, etc).

In Romania, special attention was devoted to the education and training of specialists to sustain the increasing workload associated with the advancement of the ALFRED project. A detailed plan was drafted (and is regularly reviewed) on the basis of a survey on the required and available competences, and corrective actions identified and deployed. Academic curricula, approved by the Ministry of Education and Research, have been adopted by the main Romanian universities (an engineering education programme on Energetic and Nuclear Technologies, with specific modules on Generation-IV systems and the LFR in particular, has been developed at the University of Pitesti and the Polytechnic University of Bucharest). A Memorandum of Understanding (MoU) among the key national R&D and E&T (Education and Training) actors was also signed to facilitate lecturing by renowned experts and training stages at appropriate infrastructures.

A significant and increasing number of specialists will be required for Research, Development and Qualification (RD&Q), design, licensing and operation, as soon as the activities move from the preparatory phase to the implementation of the Project and the associated demonstration programme. The timely planning of the need for such qualified human resources is among the crucial aspects determining the success of the Project.

A dedicated survey was conducted on the resources required to cover all areas and phases of the ALFRED implementation, in terms of competences and skills, and predicted effort, and successively compared with the European landscape of E&T capabilities. The comparison led to the identification of gaps potentially impairing the smooth and timely execution of the Project, so that a dedicated strategy was established also considering the existing education programmes, schemes and best practices available at a European (such as ENEN programs) and international (as those elaborated, e.g., by the IAEA) level. The strategy clearly identifies priority actions, which have been planned and deployed.

The signature of the CESINA partnership in 2017, strengthening the cooperation between the main Romanian E&T and R&D actors, was dictated by the will to further enhance the effectiveness of the E&T strategy. Among the key objectives appears the extension of the process of updating the curricula, and the practical organization of agreements – among the CESINA partners and with European organizations – facilitating lecturing by renown experts and training stages at appropriate infrastructures.

At the same time, dedicated agreements were signed by RATEN ICN with relevant organizations in the field of LFR and heavy liquid metal (HLM) technology, such as ENEA (Italy) and SCK•CEN (Belgium), for ad-hoc trainings dedicated to experts on specific aspects, or to future operators of the planned facilities.

The ‘Country Specifics’ area was included in the Romanian study performed in the INPRO KIND CP in order to address the importance of the local considerations in the multi-criteria comparative evaluation of the NES technologies. The justification of such AE was based on the nuclear technology potential contribution to the development of the country on multiple levels (economy, society, infrastructure, R&D, human resources, education, culture, etc) [3.1]. As a brief argumentation, some major aspects are highlighted in the following:

— “Stimulation of the national research by active involvement of the R&D organizations and industry in programmes of international interest” [3.1];
— Improvement of the experimental and testing infrastructure and reinforcement of the R&D groups by adding relevant experimental facilities, specific methods and tools;
— Increasing the innovation spirit and the quality of the research;
— Stimulation of the national, regional and local development by creating new jobs and keeping high expertise position jobs;
— Stimulation of E&T efforts and reduction of the loss of high qualified specialists and young professionals;
— Stimulation of stakeholders to get involved and invest in the community, in terms of education, health or infrastructure development;
— Better support for the use of natural resources.

For the evaluation of selected NESs, the following two KIs were chosen [3.1]:

— Socioeconomic impact (CS1);
— Technological impact on national R&D (CS2).

For the socioeconomic impact [3.1], the evaluation of NESs is performed in terms of: new jobs created, and jobs maintained by implementation of the technology; stimulation of the national and local economy; impact on the consolidation of the national nuclear sector; and attractiveness of the nuclear field in the country, especially for young talents.

Regarding the technological impact on the national R&D, the following elements are considered [3.1] for the evaluation of NESs: number of new research themes, projects, or national programmes generated; number of publications and patents generated; number of new international collaborations; capacity to stimulate the development of new RDI infrastructure; and the impact on the quality of the human resources and knowledge capital.

The following two AEs were newly considered and included in the objective tree structure developed for multi-criteria evaluation of NES technologies of interest in Romania: *'Legal and Political Environment'* and *'Public Acceptance'*.

In the *'Legal and Political Environment'* area, two KIs were chosen for the evaluation of NESs, namely:

— National infrastructure (institutions, laws and regulations) (LP1);
— National commitment for nuclear programme development (LP2).

Romania has a well-developed infrastructure for nuclear energy consisting of institutions, legal framework and regulations.

CNCAN (National Commission for Nuclear Activities Control) is the national "authority responsible for the regulation, licensing and control" in the nuclear field, for all the activities and installations[23]. Romania has an adequate legal infrastructure to fulfil its commitments to all relevant international nuclear safety conventions and obligations. The regulations developed are based on relevant international standards and good practices (e.g., IAEA Safety Standards, WENRA Safety Reference Levels, regulatory requirements of other countries, and licensing and regulatory framework inspired by Canadian and US regulations).

The promotion, development and implementation of the National Nuclear Programme and Nuclear Strategy is in the responsibility of ANDR (Nuclear and Radioactive Waste Agency), the structure of which is directly coordinated by the Ministry of the Economy, Energy and Business Environment. The Radioactive Waste Strategy is also in the responsibility of ANDR.

Romania, with its long and successful record of nuclear energy use and nuclear industry, has an extensive set of national laws and regulations in the field of peaceful use of the atomic energy[24]. However, none of these regulations still include the specificities associated with SMRs.

[23] https://www.cncan.ro/main-page/
[24] http://www.cncan.ro/legislatie/; http://andr.ro/en/category/radioactive-waste-management/

Romania implemented the Aarhus Convention on promoting effective public participation in decision making in environmental matters, and the Espoo Convention on environmental impact assessment in a transboundary context [3.30]. Other information regarding the environmental impact assessment (EIA) are available on the Ministry of Environment website.

RATEN (Technologies for nuclear energy state owned company) is one of the major organizations providing the technical support for nuclear activities. It coordinates the R&D activities in the nuclear energy field, which maintain and develop the scientific and technologic support for the national nuclear energy programme.

According to the National Energy Strategy in force, nuclear energy is a strategic option for Romania and the construction of new nuclear capacities represents a strategic decision, with a significant impact on the electric energy exports (increasing from 7 up to 11 TW·h per year) in the region [3.31]. The following elements represent the current priorities for the nuclear programme development: extension of the lifetime for Unit 1 at Cernavoda NPP (including decision for refurbishment programme starting from 2026); continuation of the construction of Units 3 and 4 at Cernavoda NPP; operational safety of nuclear installations; implementation of ALFRED demonstrator of LFR technology; completion the construction of the national repository for low and intermediate radioactive waste; and finalizing the strategy for geological disposal.

From the point of view of medium term development and also from the Research, Development and Innovation (RDI) infrastructure perspective, the Romanian efforts in the field of Lead Fast Reactors (LFR) technology have to be noted. As a result of the research activities performed in the last decades at national and international level, some decisions were agreed at the Romanian national level [3.32, 3.33] such as: MoU regarding the availability for hosting GenIV LFR demonstrator ALFRED in Romania (MoU, 2011), FALCON Consortium Agreement devoted to the co-operation on the development of ALFRED (signed by Ansaldo Nucleare, ENEA and RATEN ICN, 2013), and preparatory actions for the implementation of ALFRED demonstrator in Romania (MoU, 2014).

Presently, ALFRED is included as a key element of innovation in the Governmental Programme, in the National Energy Strategy and in the National Plan for Research, Development and Innovation. Following the inclusion of ALFRED both in the Smart Specialization Strategy of the South-Muntenia region (where the selected site for the demonstrator is located) and in the National Roadmap for Major Research Infrastructures, actions are being organized for appointing ALFRED as a major project of strategic relevance within the Programme for Operational Competitiveness [3.33].

A general roadmap was elaborated for the ALFRED Project, complying with the achievement of the end of construction for the demonstrator in 2028. The roadmap is structured into four main phases – Viability, Preparation, Construction and Operation – and further detailed into five areas of intervention: Management, RD&Q, Licensing, Engineering and Human Resources. Project and quality management tools typical of large projects are implemented, relying on the capabilities of FALCON members in timely delivery of complex nuclear projects worldwide [3.33].

The means of financial support, required for the execution of the Project, are being secured on the basis of the Governmental commitment of Romania and the support of Italy. A regular, dedicated budget of about 4.5 M€/year ensures the smooth execution of the activities. Extraordinary investments are required to cover special actions planned in the roadmap [3.33].

In 2019, the implementation of ATHENA and ChemLAb (two of the six supporting research infrastructures) was approved to be financed based on structural funds (total value 22 mil. Euro). A national project (2 mil Euro) is in the implementation phase to produce the technical documentation necessary for the application for the other 4 research infrastructures [3.34].
For the evaluation of NES in the 'Public Acceptance' area, two KIs were chosen:

— Public perception on operational safety of the nuclear technology (A1);
— Early involvement of stakeholders in nuclear decision making process (A2).

There are no major concerns on safety and security, except those formulated by some small groups or NGOs, often influenced by the international groups such as Greenpeace.

A public information process is defined by the existing legislation. The nuclear topics are dealt with in conjunction with the Aarhus Convention, Espoo Convention and relevant rules reflected in national laws (Law 86/2000, and Law 22/2001). The environmental impact assessment requirements are included in the Government Decision (GD) no. 918/2002. The GD no. 1115/2002 stipulates obligations of owners and operators to assure free access to environmental information. The national laws and regulations are in full conformity with the EU directives and recommendations of IAEA. Information on existing and planned nuclear facilities is available to the general public mainly on the website of national organizations and national authorities [3.34].

Information for all stakeholders, including for the general public, is available and appropriate to the existing knowledge. The public can introduce observations, suggestions, questions, and concerns by internet, by petitions or during public meetings. Generally, the public meetings are organized such as to allow a large participation of the affected public, like the local communities. The tasks in which the public is being asked to participate are clearly formulated both as nature and scope. The decision making process is in an incipient stage from the point of view of the public contribution, taking into consideration that the public is involved in a late stage of decision making in order to formulate suggestions to improve the final decision. It seems that not enough practice has been accumulated at the level of the decision-makers and the public to understand the crucial importance of public participation. Resources are allocated and evaluation of cost effectiveness is done for the consultation process according with the existing level of participation of the public [3.34].

Related to the representativeness of the participants in the process, the openness of participation is ensured and also a large dissemination for the public meetings. Invitations are generally sent to the NGOs, associations or other representatives of the public. A general participation of the stakeholders is possible, but not always reached due to the relatively low level of interest for public debates.

In connection with radioactive waste management (RWM) issues, a National Stakeholder Group for RWM was formed in the frame of Euratom FP7-IPPA project[25]. Some methods were practiced including the moderation of the process by experienced mediators. However, such treatment of the public participation needs to be consolidated and improved, especially by stimulation of the public participation. The influence in the final policy is not evident for the public. Generally, there is a feeling of distrust in the results of the public participation in the decision making process.

[25] https://cordis.europa.eu/project/id/269849

An example of early participation of the public in decision making process is the Local Dialogue Group (LDG) set up in 2015 to act as an interface between the implementer of ALFRED demonstrator of LFR technology (FALCON Consortium) and the local community of the town of Mioveni, the shortest distance between the proposed reference site for ALFRED and the town being 2.5 km [3.35]. The LDG is composed of 13 persons: 5 elected among the members of the Local Council, 5 representing the citizenship and nominated by the Mayor and Local Council, and 3 technicians from RATEN ICN as permanent representatives of the FALCON Consortium. During the meetings, the evolution of the implementation, the sustainability aspects, the existing knowledge about the ALFRED Project, the perceived benefits for the local community and the potential concerns in relation with the investment, the public participation in the process of implementing a nuclear project, and the socioeconomic impact of ALFRED at local and regional levels were discussed [3.35]. The evolution of the LDG – whose role is mainly informative – towards a Local Committee, invested with an actual participation to the decision making process, is being discussed.

Determination of key indicator values for each of the NES options studied

The values for each KI corresponding to the considered NES technologies were established using a 10 point scoring scale, in accordance with the assumptions regarding the goals to be achieved by each KI. Therefore, as a rule, if the KI goal is to be maximized, 8 is better than 2, and if the KI goal is to be minimized, 3 is better than 9.

Table 3.40 presents some elements from the performance table prepared by Romanian experts for the case study; HLOs were not included as they include different AEs for each case study considered. For a clear understanding, additional to information provided in the performance table constructed in KIND-ET, the goals for each KI were included. The scores for considered NES technologies are representing the experts' opinion, not any officially planning or documents being involved. As was previously mentioned, the following acronyms were used for NES technologies: CANDU (existing CANDU NES), eNES (evolutionary NES), and iNES (innovative NES).

TABLE 3.40. PERFORMANCE TABLE PREPARED FOR THE CASE STUDY

Evaluation areas	Key indicators	KIs abbr.	Goals	eNES	iNES	CANDU
Waste management	Specific radwaste inventory	WM1	Min	6	2	7
	Spent nuclear fuel cost	WM2	Min	6	2	5
Environment	Amount of useful energy produced by NES from a unit of mined nat. U	ENV1	Max	4	7	2
Safety	Design concept specific safety inherent and passive features/ systems, including the potential to prevent release	S1	Max	5	8	3
	Core damage and large early release frequencies	S2	Min	4	2	5
	Source term	S3	Min	4	2	4
	Effectiveness of accident management (prevention & mitigation)	S4	Max	5	7	5
Country specifics	Socioeconomic impact	CS1	Max	6	8	3
	Technological impact on national R&D	CS2	Max	4	8	2
Legal and political environment	National infrastructure (institutions, laws and regulations)	LP1	Max	7	6	9
	National commitment for nuclear programme development	LP2	Max	4	7	9
Public acceptance	Public perception on operational safety of the nuclear technology	A1	Max	8	8	7
	Early involvement of stakeholders in nuclear decision making process	A2	Max	5	8	2
Economics	Levelized energy product/service cost	E1	Min	5	3	6
	RD&D costs	E2	Min	4	6	2
Proliferation resistance	Attractiveness of nuclear material and technology	PR1	Min	3	4	2
	Safeguard approach identified	PR2	Max	7	4	9
Maturity of technology	Design stage	M1	Max	8	4	9
	Time needed to mature the technology	M2	Min	3	6	2

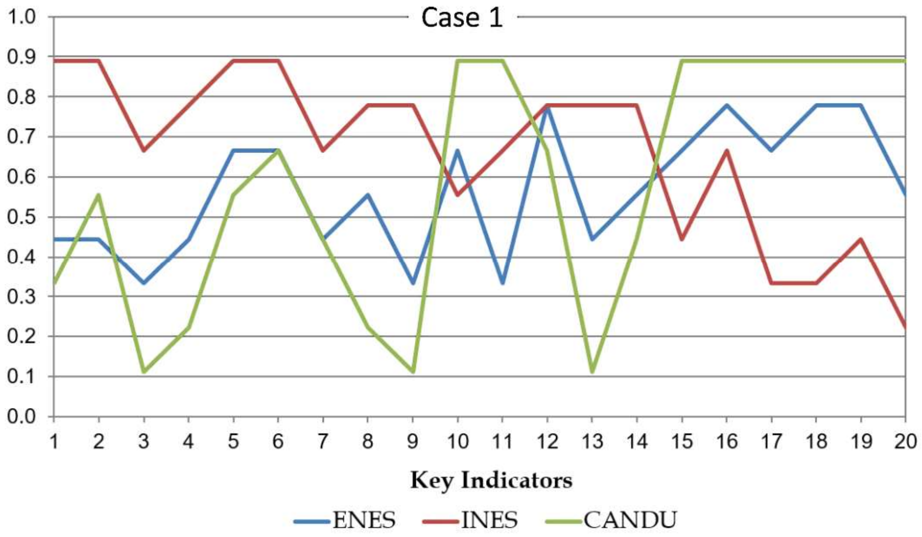
KIND-ET extensions have been applied to multi-criteria comparative analysis of the selected NES technologies in different stages, not only to improve the results presentation but also for an oriented selection of the working cases.

For the comparative evaluation of NES options some preliminary analysis (screening) was performed assuming equal weights for elements at each level of the objective tree. In order to perform the sensitivity analyses, three sub-cases for each main working case were constructed considering: different weights for the AEs in Benefits HLO or Challenges HLO, and different weights for the KIs selected for the ‘Economics’ AE. Some uncertainty analyses were also performed considering a 10% uncertainty in KIs, the value of single attribute value functions (SAVF), and weights. A brief description of the working cases and corresponding sensitivity and uncertainty sub-cases is given in Table 3.41.

TABLE 3.41. WORKING CASES PERFORMED FOR THE CASE STUDY

Steps	Working case	Short description (weights for HLOs, AEs or KIs)
NES options analysis	Case 1	Benefits HLO: WM, ENV, S, CS, LP, A (16.66% each) Challenges HLO: E, PR, M (33.33% each) Equal weights for HLOs; equal weights for KIs in each AE.
	Case 2	Benefits HLO: ENV, S, CS, LP, A (20% each) Challenges HLO: WM, E, PR, M (25% each) Equal weights for HLOs; equal weights for KIs in each AE.
	Case 3	Benefits HLO: WM, ENV, S, CS, A (20% each) Challenges HLO: E, PR, M, LP (25% each) Equal weights for HLOs; equal weights for KIs in each AE.
	Case 4	Benefits HLO: WM, ENV, S, CS, LP (20% each) Challenges HLO: E, PR, M, A (25% each) Equal weights for HLOs; equal weights for KIs in each AE.
	Case 5	Benefits HLO: ENV, S, CS (33.33% each) Challenges HLO: WM, LP, A, E, PR, M (16.66% each) Equal weights for HLOs; equal weights for KIs in each AE.
Sensitivity analysis	Sub-cases 1a, 2a, 3a, 4a, 5a	Different weights for AEs in Benefits HLO (according to their importance – expert opinion); equal weights for AEs in Challenges HLO. Equal weights for HLOs; equal weights for KIs in each AE.
	Sub-cases 1b, 2b, 3b, 4b, 5b	Different weights for AEs in Challenges HLO (according to their importance – expert opinion); equal weights for AEs under Benefits HLO. Equal weights for HLOs; equal weights for KIs in each AE.
	Sub-cases 1c, 2c, 3c, 4c, 5c	Similar with corresponding main working cases. Different weights for KIs in 'Economics' AE: E1 70%, E2 30%.
Uncertainty analysis	Sub-cases 1d, 2d, 3d, 4d, 5d	10% uncertainty in KIs, SAVF, and weights.

A screening for the dominant option among the considered NESs was also performed after the performance table was established and KI goals were defined. In the considered working cases, no dominant option was found (as can be seen in Fig. 3.76 for Case1 and Case2), all five cases being kept for the final analysis.



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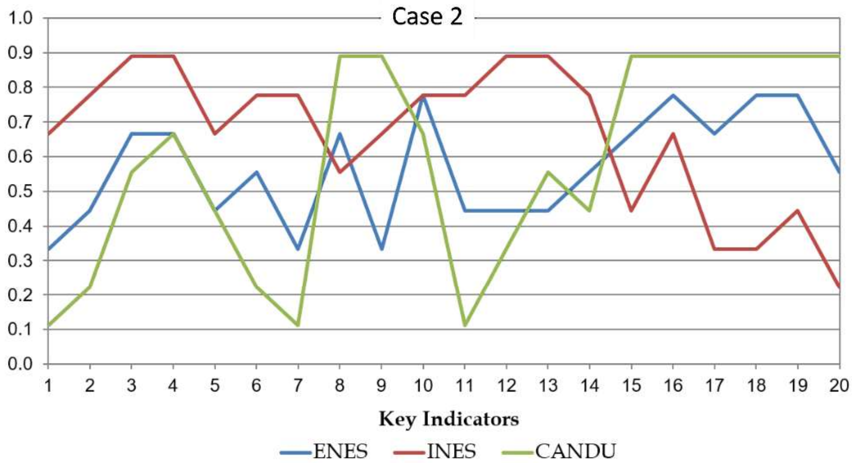


(b)

FIG. 3.76. Dominance screening results for Case 1 (a) and Case 2 (b).

Figure 3.77 shows the 3-level objective tree structure for Case 1, as an example; the other main working cases can be described by similar structures according to the AEs included in each HLO.

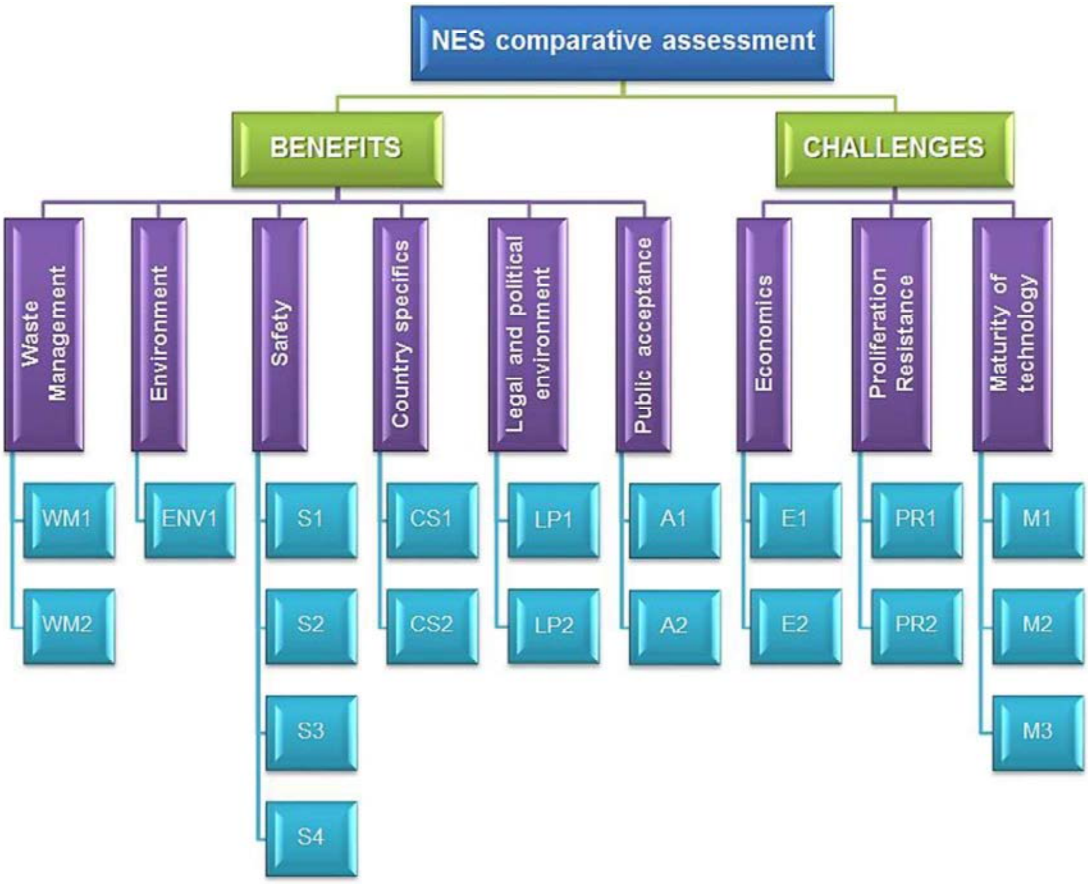


FIG. 3.77. 3-level objective tree structure for Case 1.

Selection of a Multi-Criteria Decision Analysis method

The multi-criteria comparative evaluation of the considered NES technologies has been performed by applying the KIND approach in which a Multi-Criteria Decision Analysis (MCDA) framework is considered, the main MCDA method to be used being the Multi Attribute Value Theory (MAVT). The case study multi-criteria analyses are not looking for a 'right solution' or 'perfect answer', the goal being to find the 'best alternative' for a decision maker, based on the multi-criteria evaluation of defined key indicators in specific conditions and considering the country specifics.

In a preliminary phase of the case study, some analyses were performed by assuming equal importance for HLOs, Areas of evaluation 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 were given considering both a 2 point and a 10 point scoring scale, using local or global domain for SAVF values, and the linear or exponential form of the SAVF. For the final analysis, a 10 point scoring scale for KIs, global domain for SAVF values, and linear form of the SAVF were used, to assure the consistency with the case study previously performed in the INPRO KIND CP.

The weights for each hierarchical level were specified according to the experts' preferences/opinion related to the objective tree elements' relative importance/significance, then they were multiplied down to get the final lower-level weights. Due to normalization constraints at each branch of the objective tree the sum of involved weighting factors is to be equal to 1.

The final weights calculated with KIND-ET for the main working cases and the corresponding sensitivity cases are comparatively presented in the following tables (Tables 3.42- 3.46). As was mentioned before in cases description, for the first two sensitivity analyses the AEs weighting factors for Benefits HLO or Challenges HLO were modified according to expert opinion regarding their importance in the specific country conditions. For the last sensitivity analysis, only the weighting factors considered for the two KIs in the 'Economics' AE were modified, giving 70% for E1 and 30% for E2.

TABLE 3.42. FINAL WEIGHTING FACTORS FOR CASE 1 AND SENSITIVITY CASES

High-level objectives	Evaluation areas	KIs abbr.	Final weights			
			Case1	Case1a	Case1b	Case1c
Benefits	Waste management	WM1	0.042	0.075	0.042	0.042
		WM2	0.042	0.075	0.042	0.042
	Environment	ENV1	0.083	0.025	0.083	0.083
	Safety	S1	0.021	0.038	0.021	0.021
		S2	0.021	0.038	0.021	0.021
		S3	0.021	0.038	0.021	0.021
		S4	0.021	0.038	0.021	0.021
	Country specifics	CS1	0.042	0.038	0.042	0.042
		CS2	0.042	0.038	0.042	0.042
	Legal and political environment	LP1	0.042	0.025	0.042	0.042
		LP2	0.042	0.025	0.042	0.042
	Public acceptance	A1	0.042	0.025	0.042	0.042
		A2	0.042	0.025	0.042	0.042
Challenges	Economics	E1	0.084	0.084	0.125	0.117
		E2	0.084	0.084	0.125	0.050
	Proliferation resistance	PR1	0.083	0.083	0.063	0.083
		PR2	0.083	0.083	0.063	0.083
	Maturity of technology	M1	0.055	0.055	0.042	0.055
		M2	0.055	0.055	0.042	0.055
		M3	0.055	0.055	0.042	0.055

TABLE 3.43. FINAL WEIGHTING FACTORS FOR CASE 2 AND SENSITIVITY CASES

High-level objectives	Evaluation areas	KIs abbr.	Final weights			
			Case2	Case2a	Case2b	Case2c
Benefits	Environment	ENV1	0.100	0.025	0.100	0.100
	Safety	S1	0.025	0.044	0.025	0.025
		S2	0.025	0.044	0.025	0.025
		S3	0.025	0.044	0.025	0.025
		S4	0.025	0.044	0.025	0.025
	Country specifics	CS1	0.050	0.038	0.050	0.050
		CS2	0.050	0.038	0.050	0.050
	Legal and political environment	LP1	0.050	0.050	0.050	0.050
		LP2	0.050	0.050	0.050	0.050
	Public acceptance	A1	0.050	0.023	0.030	0.030
		A2	0.050	0.053	0.070	0.070
Challenges	Waste management	WM1	0.063	0.063	0.075	0.063
		WM2	0.063	0.063	0.075	0.063
	Economics	E1	0.063	0.063	0.100	0.088
		E2	0.063	0.063	0.100	0.038
	Proliferation resistance	PR1	0.063	0.063	0.038	0.063
		PR2	0.063	0.063	0.038	0.063
	Maturity of technology	M1	0.042	0.042	0.025	0.042
		M2	0.042	0.042	0.025	0.042
		M3	0.042	0.042	0.025	0.042

TABLE 3.44. FINAL WEIGHTING FACTORS FOR CASE 3 AND SENSITIVITY CASES

High-level objectives	Evaluation areas	KIs abbr.	Final weights			
			Case3	Case3a	Case3b	Case3c
Benefits	Waste management	WM1	0.050	0.075	0.050	0.050
		WM2	0.050	0.075	0.050	0.050
	Environment	ENV1	0.100	0.025	0.100	0.100
	Safety	S1	0.025	0.044	0.025	0.025
		S2	0.025	0.044	0.025	0.025
		S3	0.025	0.044	0.025	0.025
		S4	0.025	0.044	0.025	0.025
	Country specifics	CS1	0.050	0.038	0.050	0.050
		CS2	0.050	0.038	0.050	0.050
	Public acceptance	A1	0.050	0.038	0.050	0.050
		A2	0.050	0.038	0.050	0.050
Challenges	Economics	E1	0.063	0.063	0.125	0.088
		E2	0.063	0.063	0.125	0.038
	Proliferation resistance	PR1	0.063	0.063	0.038	0.063
		PR2	0.063	0.063	0.038	0.063
	Maturity of technology	M1	0.042	0.042	0.033	0.042
		M2	0.042	0.042	0.033	0.042
		M3	0.042	0.042	0.033	0.042
	Legal and political environment	LP1	0.063	0.063	0.038	0.063
		LP2	0.063	0.063	0.038	0.063

TABLE 3.45. FINAL WEIGHTING FACTORS FOR CASE 4 AND SENSITIVITY CASES

High-level objectives	Evaluation areas	KIs abbr.	Final weights			
			Case4	Case4a	Case4b	Case4c
Benefits	Waste management	WM1	0.050	0.075	0.050	0.050
		WM2	0.050	0.075	0.050	0.050
	Environment	ENV1	0.100	0.025	0.100	0.100
	Safety	S1	0.025	0.044	0.025	0.025
		S2	0.025	0.044	0.025	0.025
		S3	0.025	0.044	0.025	0.025
		S4	0.025	0.044	0.025	0.025
	Country specifics	CS1	0.050	0.038	0.050	0.050
		CS2	0.050	0.038	0.050	0.050
	Legal and political environment	LP1	0.050	0.038	0.050	0.050
		LP2	0.050	0.038	0.050	0.050
Challenges	Economics	E1	0.063	0.063	0.125	0.088
		E2	0.063	0.063	0.125	0.038
	Proliferation resistance	PR1	0.063	0.063	0.038	0.063
		PR2	0.063	0.063	0.038	0.063
	Maturity of technology	M1	0.042	0.042	0.033	0.042
		M2	0.042	0.042	0.033	0.042
		M3	0.042	0.042	0.033	0.042
	Public acceptance	A1	0.063	0.063	0.038	0.063
		A2	0.063	0.063	0.038	0.063

TABLE 3.46. FINAL WEIGHTING FACTORS FOR CASE 5 AND SENSITIVITY CASES

High-level objectives	Evaluation areas	KIs abbr.	Final weights			
			Case5	Case5a	Case5b	Case5c
Benefits	Environment	ENV1	0.167	0.050	0.167	0.167
	Safety	S1	0.042	0.063	0.042	0.042
		S2	0.042	0.063	0.042	0.042
		S3	0.042	0.063	0.042	0.042
		S4	0.042	0.063	0.042	0.042
	Country specifics	CS1	0.083	0.088	0.083	0.083
		CS2	0.083	0.088	0.083	0.083
Challenges	Waste management	WM1	0.042	0.042	0.050	0.042
		WM2	0.042	0.042	0.050	0.042
	Economics	E1	0.042	0.042	0.075	0.058
		E2	0.042	0.042	0.075	0.025
	Proliferation resistance	PR1	0.042	0.042	0.025	0.042
		PR2	0.042	0.042	0.025	0.042
	Maturity of technology	M1	0.028	0.028	0.025	0.028
		M2	0.028	0.028	0.025	0.028
		M3	0.028	0.028	0.025	0.028
	Legal and political environment	LP1	0.042	0.042	0.038	0.042
		LP2	0.042	0.042	0.038	0.042
	Public acceptance	A1	0.042	0.042	0.025	0.042
		A2	0.042	0.042	0.025	0.042

3.7.4. Ranking result and its analysis

Ranking alternatives (NES options) with the selected MCDA method

The results obtained for the multi-criteria comparative evaluation of evolutionary and innovative NES technologies from the perspective of the associated Benefits and Challenges are presented in the following.

Table 3.47 presents the multi attribute value function values (total scores) calculated for the main working cases.

TABLE 3.47. TOTAL SCORES OF NES TECHNOLOGIES FOR MAIN WORKING CASES

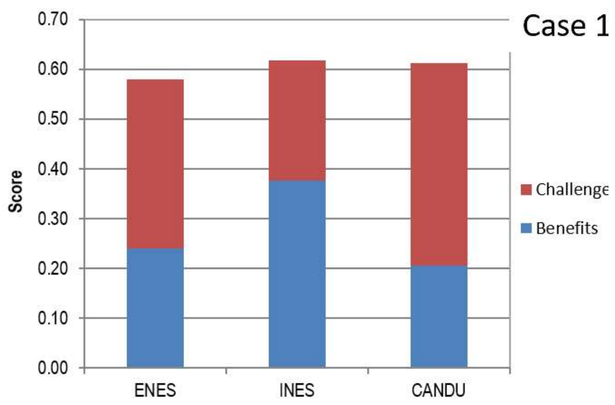
Working case	eNES	iNES	CANDU
Case 1	0.580	0.618	0.613
Case 2	0.555	0.656	0.564
Case 3	0.556	0.649	0.575
Case 4	0.559	0.653	0.562
Case 5	0.522	0.685	0.472

As can be seen from the MAVF values, the innovative technology seems to be more attractive than the evolutionary one, eNES MAVF values being lower than those for iNES (by 6% in Case 1, 15% in Case 2, 23% in Case 3, 14% in Case 4 and by 24% in Case 5, respectively). CANDU technology has the lowest MAVF values in Case 3 and Case 5, but the CANDU total score is only 0.8% lower than the iNES one in Case 1, being also higher than the one for eNES in Case 2 and 4.

Decomposition of MAVF in components ($score_{HLOs}$ and $score_{AEs}$) can offer a clearer image on each of the objective tree levels where technologies get better or lower scores, corresponding to how closer they succeeded to be of the declared goals for the specific KIs. Tables 3.48 contains the HLOs scores obtained by the evolutionary, innovative and CANDU technologies for the main working cases; the scores for HLOs and AEs are illustrated in Fig. 3.78 and 3.79.

TABLE 3.48. HIGH-LEVEL OBJECTIVE SCORES FOR NES TECHNOLOGIES

NES	Benefits					Challenges				
	Case1	Case2	Case3	Case4	Case5	Case1	Case2	Case3	Case4	Case5
eNES	0.241	0.244	0.239	0.228	0.222	0.339	0.310	0.317	0.331	0.299
iNES	0.377	0.364	0.392	0.375	0.375	0.241	0.292	0.257	0.278	0.310
CANDU	0.206	0.203	0.158	0.208	0.125	0.407	0.361	0.417	0.354	0.347



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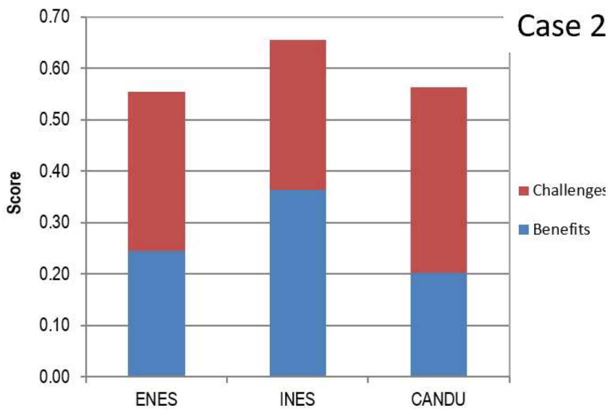

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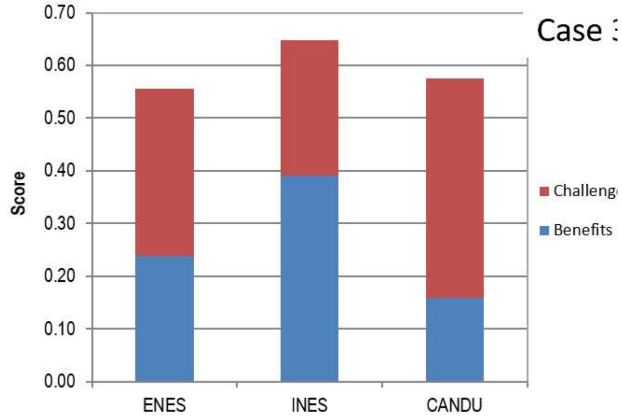

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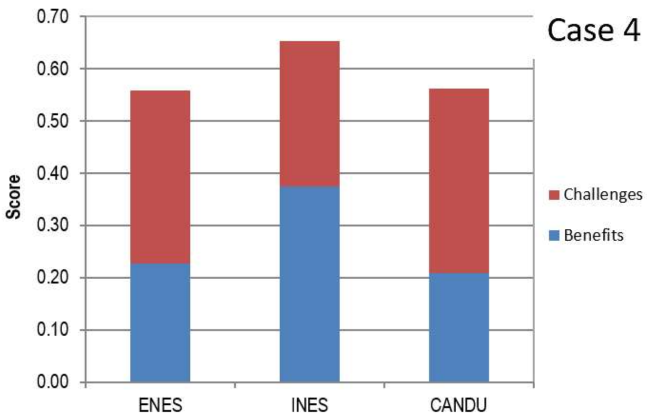

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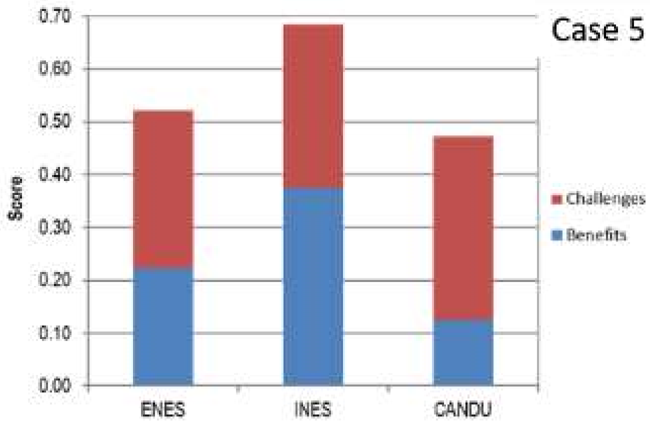


(e)

FIG. 3.78. HLOs scores for the main working cases: Case 1(a), Case 2(b), Case 3(c), Case 4(d), and Case 5 (e).

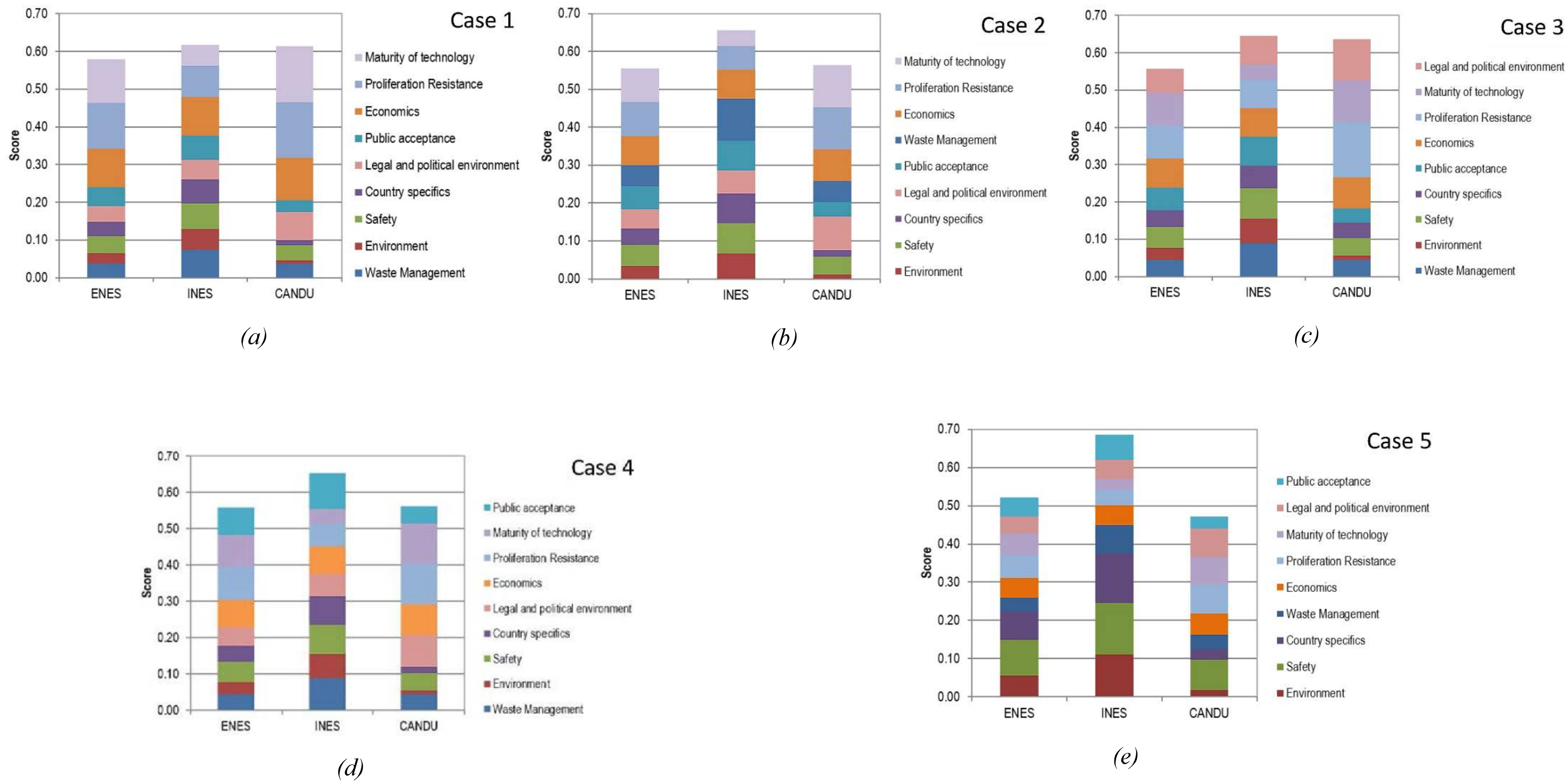


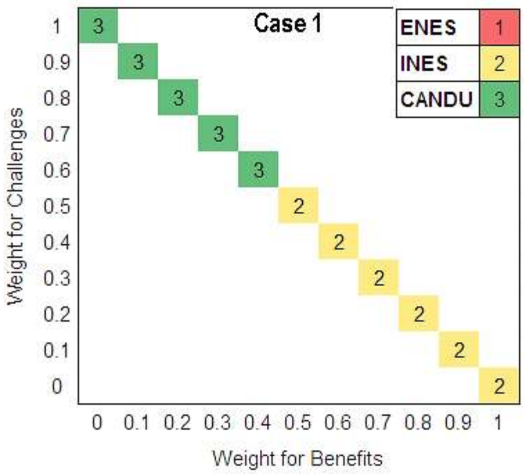
FIG. 3.79. Scores of AEs for the main working cases: Case 1(a), Case 2(b), Case 3(c), Case 4(d), and Case 5 (e).

By considering the ‘Waste Management’, ‘Legal and political environment’ and ‘Public acceptance’ areas of evaluation in Benefits HLO or Challenges HLO, the total scores and HLO scores obtained by the evolutionary, innovative and CANDU technologies change.

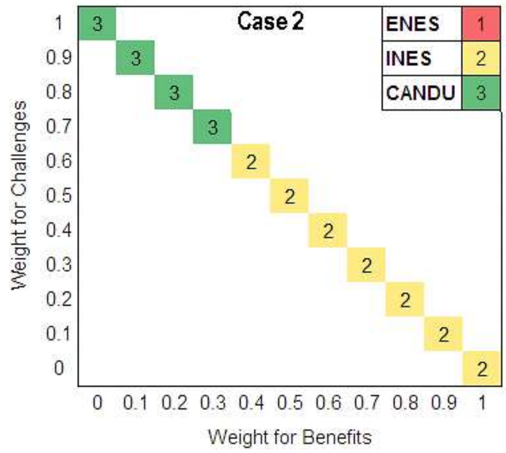
The evolutionary technology has better scores comparatively with the innovative technology for ‘Proliferation resistance’ and ‘Maturity of technology’ AEs. The innovative technology has the leading position for ‘Waste management’, ‘Environment’, ‘Safety’, ‘Country specifics’, and ‘Public acceptance’ areas. The better scoring of the innovative technology seems realistic considering the associated improvements and perspectives. Generally, the scores obtained by the evolutionary technology in ‘Waste management’, ‘Environment’, ‘Safety’, and ‘Country specifics’ areas are about 50% lower than the ones corresponding to the innovative technology. The very good scores obtained by the innovative technology in ‘Public acceptance’ area comparatively with the evolutionary one is mainly due to the early involvement of stakeholders in the nuclear decision making process. The low score obtained by iNES in the ‘Maturity of technology’ area, is due to the technological and institutional difficulties that need to be overcome.

As regarding the evaluation in ‘Economics’ and ‘Legal and political environment’ areas, both the evolutionary and the innovative technologies scores were lower than the scores obtained by the CANDU technology (by 10% lower in ‘Economics’ area, and by 30% lower in ‘Legal and political environment’ area, respectively).

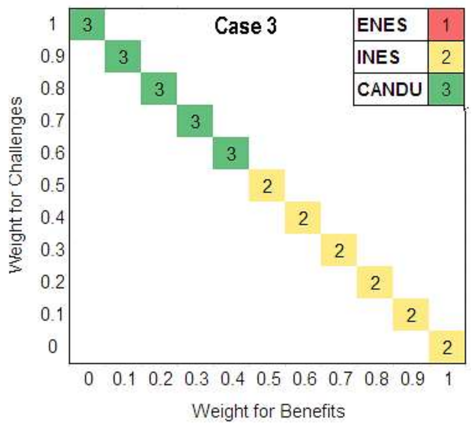
The KIND-ET ‘Ranks mapping tool’ extension [3.1] was applied to the results obtained for the considered working cases, the main goal being to reach a better understanding of the most preferable options for different HLOs weights. Figures 3.80–3.82 shows the NES options with the first ranks, and the eNES, iNES and CANDU technologies overall scores evolution when modifying the HLOs importance for Case1 and Case5, respectively. These last two figures show clearly how the selection of first ranks technologies (iNES and CANDU, respectively) was made according to the HLOs considered importance.



(a)



(b)



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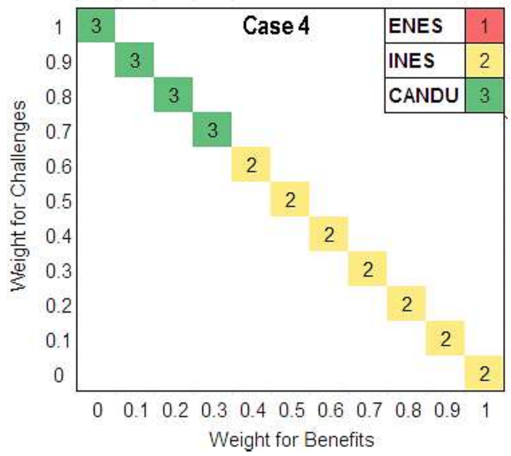

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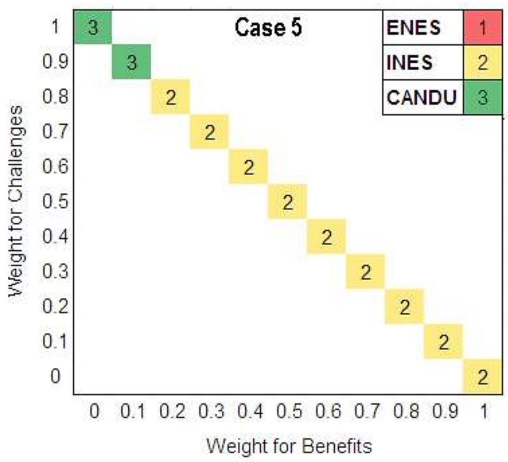
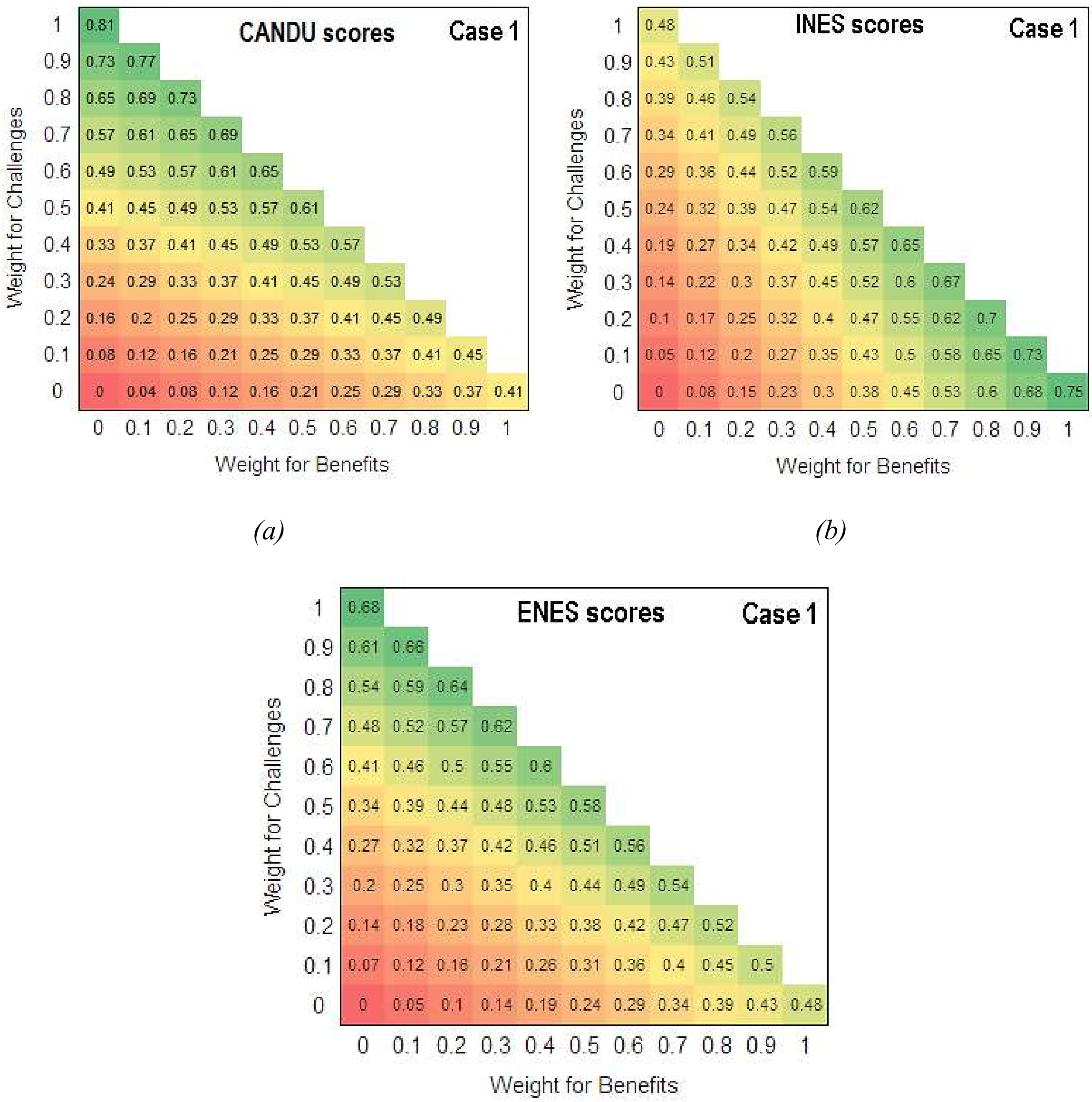


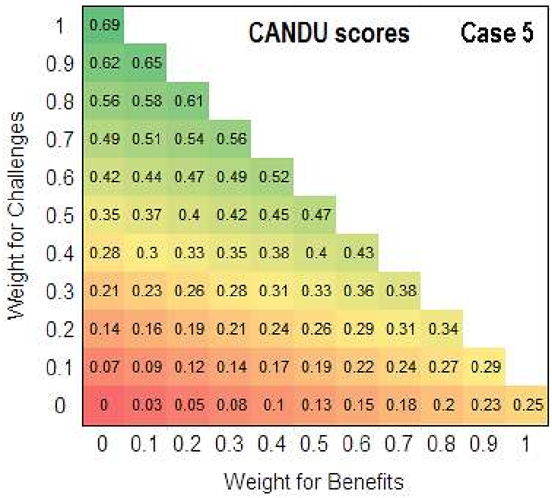
(e)

FIG. 3.80. NES options with the first ranks for the main working cases: Case 1(a), Case 2(b), Case 3(c), Case 4(d), and Case 5 (e).

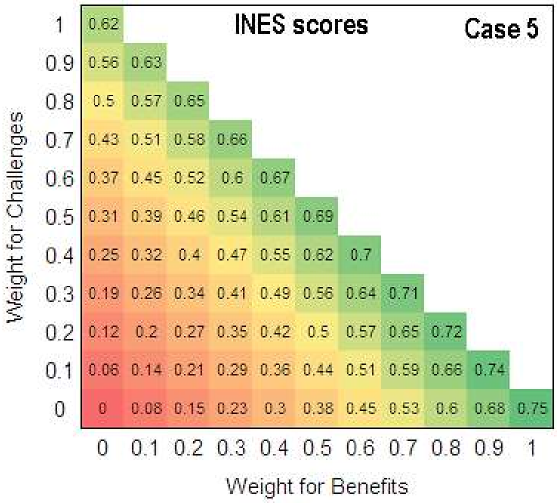


(c)

FIG. 3.81. Evolution of considered technologies overall scores with HLOs importance variation for Case1: CANDU (a), iNES (b), and eNES (c).



(a)



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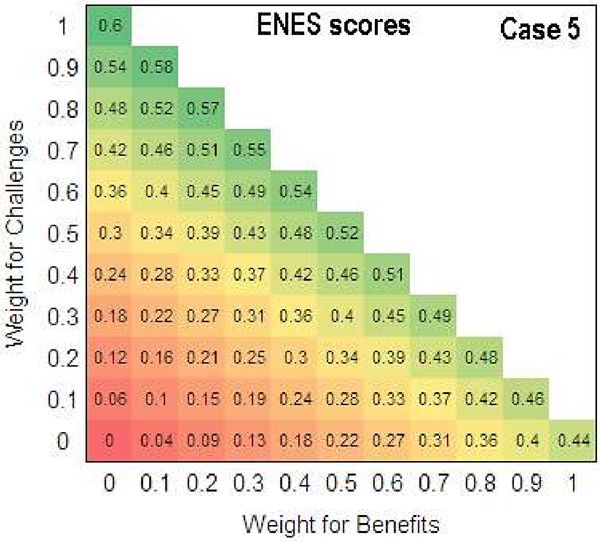


(c)

FIG. 3.82. Evolution of considered technologies overall scores with HLOs importance variation for Case5: CANDU (a), iNES (b), and eNES (c).

In the multi-criteria comparative analysis proposed by the case study, it is interesting to notice and discuss the impact of the HLO scores on the total scores obtained by the considered NES technologies. This aspect is treated by means of the diagrams presented in Figs. 3.83 and 3.84 for the considered working cases. The main difference in these two representations consists in selecting the global or local domain (the differences between the HLO scores obtained by the nuclear technologies are more visible) for the corresponding SAVF.

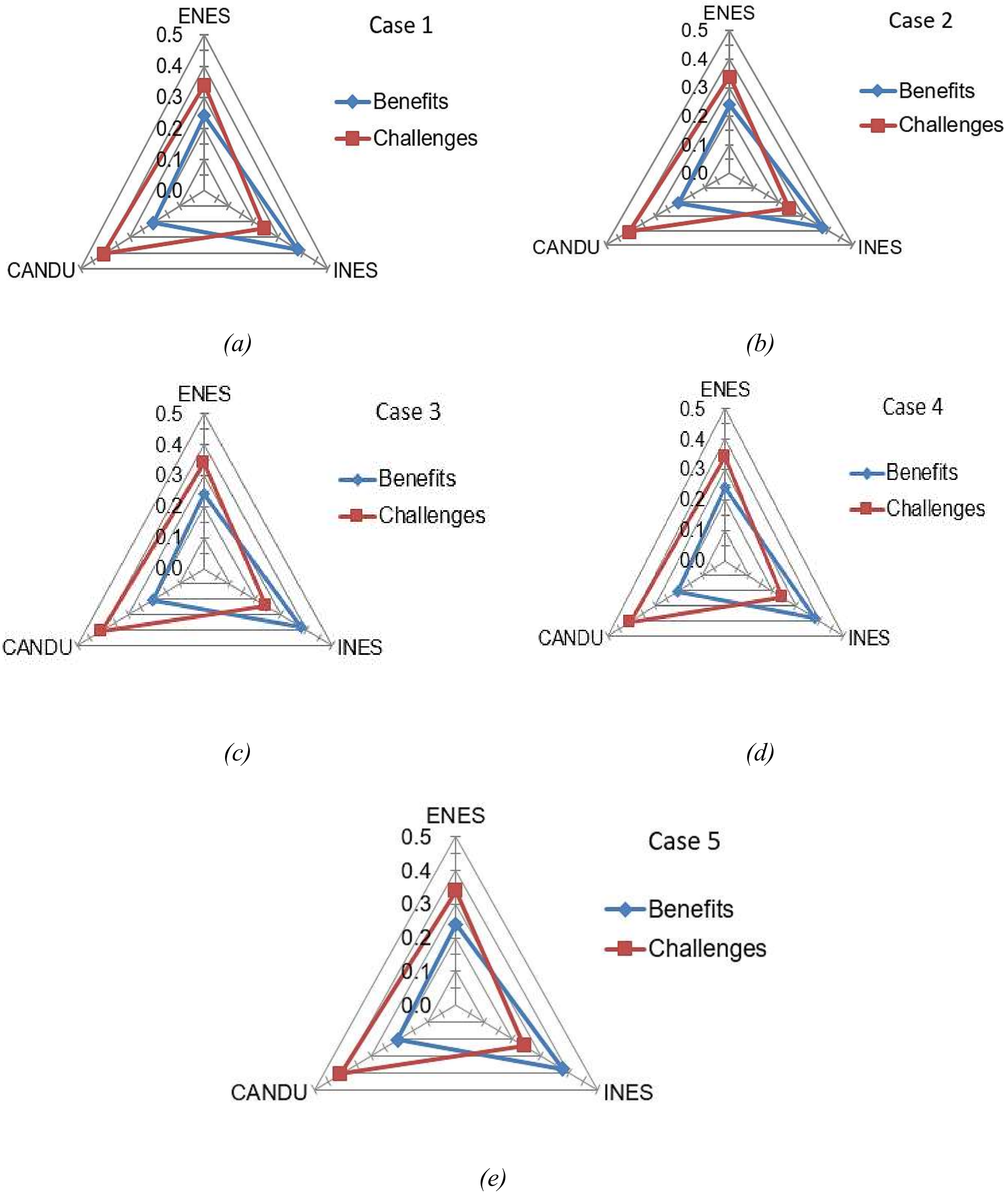


FIG. 3.83. The impact of HLO scores on the MAVF values for SAVF global domain selection: (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5.

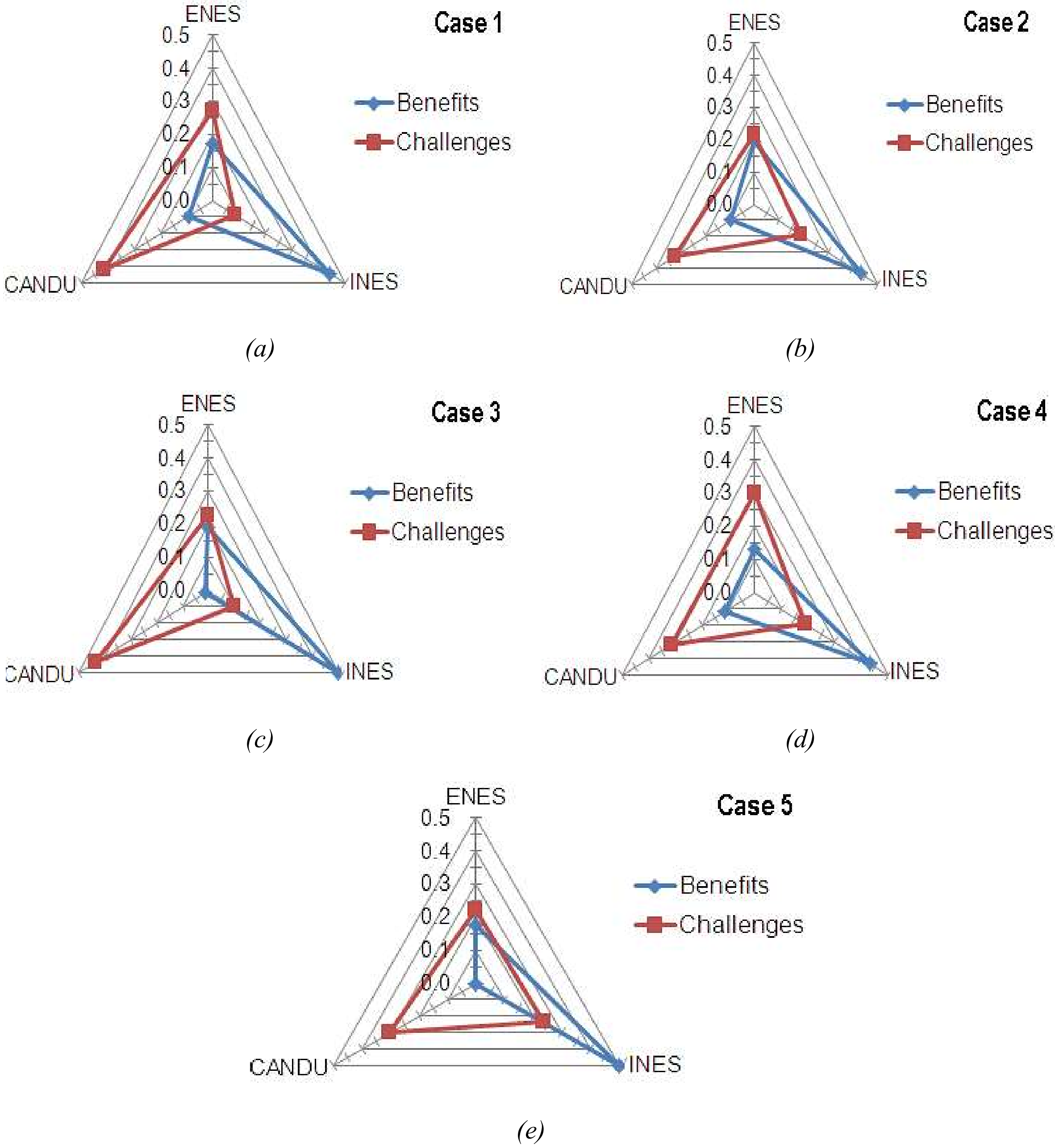


FIG. 3.84. The impact of HLO scores on the MAVF values for SAVF local domain selection: (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5.

In all considered cases, the innovative technology total scores are mainly due to the scores obtained in the Benefits HLO (around 0.4); meantime the scores for Challenges HLO are lower (around 0.25). For the evolutionary technology, the scores in the Benefits HLO (around 0.25) are lower than the ones in the Challenges HLO (around 0.35). The innovative technology gets the leading position based mainly on its benefits, which is a very important observation for the multi-criteria comparative analysis proposed by the case study.

<u>Performance of sensitivity/uncertainty analyses regarding weights, utility/value functions and Key Indicators</u>

For the defined working cases, the sensitivity analysis was performed based on a set of three sub-cases constructed as follows: two sub-cases considering different weights for the areas in Benefits HLO or Challenges HLO (see Tables 3.49–3.53), and one sub-case considering different weights for the KIs in 'Economics' area of evaluation, namely 70% for KI1 and 30% for KI2.

TABLE 3.49. AREAS OF EVALUATION RATINGS FOR CASE 1 AND ITS SUB-CASES

High-level objectives	— Evaluation areas	AEs weights [%]		
		Case 1	Case 1a	Case 1b
Benefits	Waste management	16.67	30	16.67
	Environment	16.66	5	16.66
	Safety	16.66	30	16.66
	Country specifics	16.67	15	16.67
	Legal and political environment	16.67	10	16.67
	Public acceptance	16.67	10	16.67
Challenges	Economics	33.34	33.34	50
	Proliferation resistance	33.33	33.33	25
	Maturity of technology	33.33	33.33	25

TABLE 3.50. AREAS OF EVALUATION RATINGS FOR CASE 2 AND ITS SUB-CASES

High-level objectives	— Evaluation areas	AEs weights [%]		
		Case 2	Case 2a	Case 2b
Benefits	Environment	20	5	20
	Safety	20	40	20
	Country specifics	20	20	20
	Legal and political environment	20	20	20
	Public acceptance	20	15	20
Challenges	Waste management	25	25	30
	Economics	25	25	40
	Proliferation resistance	25	25	15
	Maturity of technology	25	25	15

TABLE 3.51. AREAS OF EVALUATION RATINGS FOR CASE 3 AND ITS SUB-CASES

High-level objectives	Evaluation areas	AEs weights [%]		
		Case 3	Case 3a	Case 3b
Benefits	Waste management	20	30	20
	Environment	20	5	20
	Safety	20	35	20
	Country specifics	20	15	20
	Public acceptance	20	15	20
Challenges	Economics	25	25	50
	Proliferation resistance	25	25	15
	Maturity of technology	25	25	20
	Legal and political environment	25	25	15

TABLE 3.52. AREAS OF EVALUATION RATINGS FOR CASE 4 AND ITS SUB-CASES

High-level objectives	Evaluation areas	AEs weights [%]		
		Case 4	Case 4a	Case 4b
Benefits	Waste management	20	30	20
	Environment	20	5	20
	Safety	20	35	20
	Country specifics	20	15	20
	Legal and political environment	20	15	20
Challenges	Economics	25	25	50
	Proliferation resistance	25	25	15
	Maturity of technology	25	25	20
	Public acceptance	25	25	15

TABLE 3.53. AREAS OF EVALUATION RATINGS FOR CASE 5 AND ITS SUB-CASES

High-level objectives	Evaluation areas	AEs weights [%]		
		Case 5	Case 5a	Case 5b
Benefits	Environment	33.33	15	33.33
	Safety	33.34	50	33.34
	Country specifics	33.33	35	33.33
Challenges	Waste management	16.67	16.67	20
	Economics	16.67	16.67	30
	Proliferation resistance	16.67	16.67	10
	Maturity of technology	16.67	16.67	15
	Legal and political environment	16.66	16.66	15
	Public acceptance	16.66	16.66	10

Considering different weights for the AEs in the Benefits or Challenges HLOs didn't lead to the change of the leading position in the NES technologies ranking. The innovative technology succeeded to be more attractive than the evolutionary and CANDU ones in all sensitivity cases. The total scores characterizing the investigated NES technologies are given in the following tables (Tables 3.54–3.55).

TABLE 3.54. TOTAL SCORES OF NES TECHNOLOGIES FOR MAIN WORKING CASES AND THEIR SENSITIVITY SUB-CASES (AREAS DIFFERENT WEIGHTS)

Working case	eNES	iNES	CANDU
Case 1 (reference)	0.580	0.618	0.613
Case 1a	0.587	0.639	0.624
Case 1b	0.572	0.634	0.595
Case 2 (reference)	0.555	0.656	0.564
Case 2a	0.570	0.667	0.593
Case 2b	0.540	0.682	0.536
Case 3 (reference)	0.556	0.649	0.575

TABLE 3.54. TOTAL SCORES OF NES TECHNOLOGIES FOR MAIN WORKING CASES AND THEIR SENSITIVITY SUB-CASES (AREAS DIFFERENT WEIGHTS) (cont.)

Working case	eNES	iNES	CANDU
Case 3a	0.568	0.665	0.610
Case 3b	0.554	0.669	0.547
Case 4 (reference)	0.559	0.653	0.562
Case 4a	0.574	0.673	0.585
Case 4b	0.551	0.657	0.560
Case 5 (reference)	0.522	0.685	0.472
Case 5a	0.541	0.698	0.503
Case 5b	0.515	0.690	0.467

TABLE 3.55. TOTAL SCORES OF NES TECHNOLOGIES FOR MAIN WORKING CASES AND THEIR SENSITIVITY SUB-CASES (KIS DIFFERENT WEIGHTS)

Working case	eNES	iNES	CANDU
Case 1 (reference)	0.580	0.618	0.613
Case 1c	0.576	0.629	0.598
Case 2 (reference)	0.555	0.656	0.564
Case 2c	0.545	0.664	0.542
Case 3 (reference)	0.556	0.649	0.575
Case 3c	0.553	0.657	0.564
Case 4 (reference)	0.559	0.653	0.562
Case 4c	0.556	0.661	0.551
Case 5 (reference)	0.522	0.685	0.472
Case 5c	0.520	0.691	0.465

Taking into consideration more realistic weighting factors for the areas of evaluation according to experts' opinion regarding their importance in country specific conditions (see Tables 3.49–3.53), the following observations can be made:

- ***Case 1***: The new AEs weights in Benefits HLO brought increased MAVF values for all technologies, the new total scores obtained by eNES, iNES, and CANDU being higher by 1.1%, 3.3% and 1.7%, respectively. The new AEs weights in Challenges HLO brought an increasing of the iNES MAVF (by 2.5%) and a decreasing in MAVF value for eNES (by 1.5%) and CANDU (by 3.1%).

- ***Case 2***: The new AEs weights in Benefits HLO were reflected in lower MAVF values both for eNES (by 2.7%) and iNES (by 4.5%) technologies, and a quite small increase in CANDU technology total score (by 0.9%). The new AEs weights in Challenges HLO led to higher iNES total score (by 3.8%), and lower MAVF values for eNES (by 3.9%) and CANDU (by 7.4%).

- ***Case 3***: The new AEs weights in Benefits HLO led to higher total scores for all technologies eNES (by about 2% for eNES and iNES, and by 6% for CANDU). The new AEs weights in Challenges HLO were reflected by a higher iNES total score (by 2%), and lower MAVF values for eNES (by 0.4%) and CANDU (by 5.1%).

- ***Case 4***: The new AEs weights in Benefits HLO brought increased MAVF values for all technologies, the new total scores obtained by eNES, iNES, and CANDU being higher by about

3–4%. The new AEs weights in Challenges HLO brought a quite small increase of the iNES MAVF (by 0.6%) and a decreasing in MAVF value for eNES (by 1.4%) and CANDU (by 0.5%).

- ***Case 5***: The new AEs weights in Benefits HLO were reflected in a lower total score for iNES technology (by 0.6%) and higher MAVF values for eNES (by 2.1%) and CANDU (by 5.5%) technologies. The new AEs weights in Challenges HLO led to higher total score for iNES (by 0.8%), and lower total scores for eNES and CANDU (by 1.2%).

Considering the different weighting for the KIs in the 'Economics' area, namely 70% for KI1 (Levelized energy product/service cost) and 30% for KI2 (RD&D costs), the total scores obtained by the innovative technology increased by about 1–2% compared to the results in the reference cases (main working cases); for the evolutionary and CANDU technologies the total scores decreased by 1% and 2–4%, respectively. The case study also included the uncertainty analysis of the results obtained by the NES technologies of interest. As long as the KIs or the single attribute value function parameter were evaluated qualitatively (based on expert judgments), the uncertainty in their values may be caused by the ambiguity of reflecting expert qualitative judgments in a scoring scale. Thus, it may be important to analyse the ranking results' sensitivity to a scatter in possible values of indicators or parameters of single attribute value functions. To perform this task, the KIND-ET 'Uncertainty propagator' extension [3.1] was applied considering a 10% uncertainty in KIs, the value of single attribute value functions, and weights. Figures 3.85–3.89 present the overall scores and uncertainties for the NES technologies in selected working cases.

Overall scores and uncertainties	ENES	INES	CANDU
Best estimate	**0.580**	**0.618**	**0.613**
Absolute uncertainties	**0.029**	**0.029**	**0.033**
contribution due to uncertainties in key indicators	0.014	0.015	0.016
contribution due to uncertainties in s.a. value functions	0.020	0.020	0.024
contribution due to uncertainties in weights	0.015	0.015	0.017

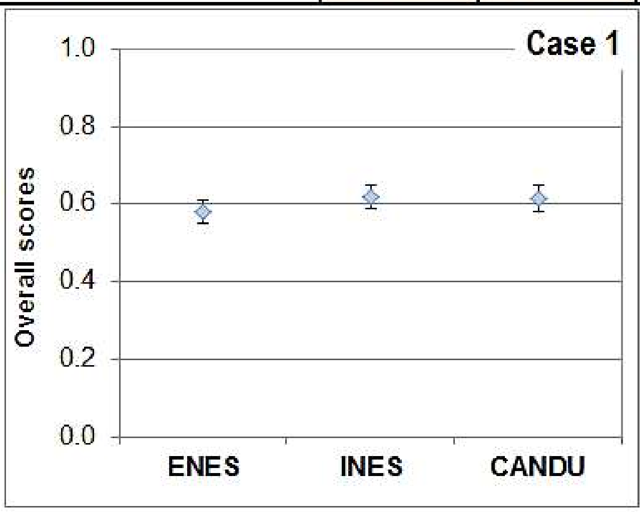


FIG. 3.85. The overall scores and uncertainties for Case 1 (screenshot from Uncertainly Propagator).

Overall scores and uncertainties	ENES	INES	CANDU
Best estimate	**0.555**	**0.656**	**0.564**
Absolute uncertainties	**0.027**	**0.032**	**0.030**
contribution due to uncertainties in key indicators	0.014	0.015	0.015
contribution due to uncertainties in s.a. value functions	0.019	0.023	0.021
contribution due to uncertainties in weights	0.013	0.016	0.015

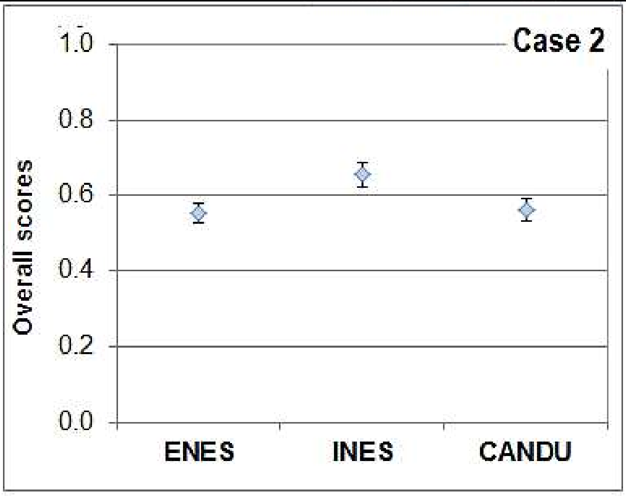


FIG. 3.86. The overall scores and uncertainties for Case 2 (screenshot from Uncertainty Propagator).

Overall scores and uncertainties	ENES	INES	CANDU
Best estimate	**0.556**	**0.649**	**0.575**
Absolute uncertainties	**0.028**	**0.033**	**0.032**
contribution due to uncertainties in key indicators	0.014	0.016	0.015
contribution due to uncertainties in s.a. value functions	0.020	0.024	0.023
contribution due to uncertainties in weights	0.013	0.016	0.015

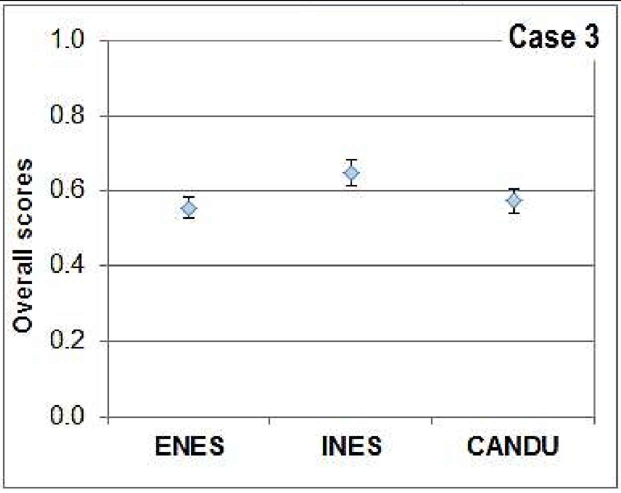


FIG. 3.87. The overall scores and uncertainties for Case 3(screenshot from Uncertainty Propagator) .

Overall scores and uncertainties	ENES	INES	CANDU
Best estimate	**0.559**	**0.653**	**0.562**
Absolute uncertainties	**0.028**	**0.034**	**0.030**
contribution due to uncertainties in key indicators	0.014	0.016	0.014
contribution due to uncertainties in s.a. value functions	0.020	0.025	0.022
contribution due to uncertainties in weights	0.013	0.016	0.015

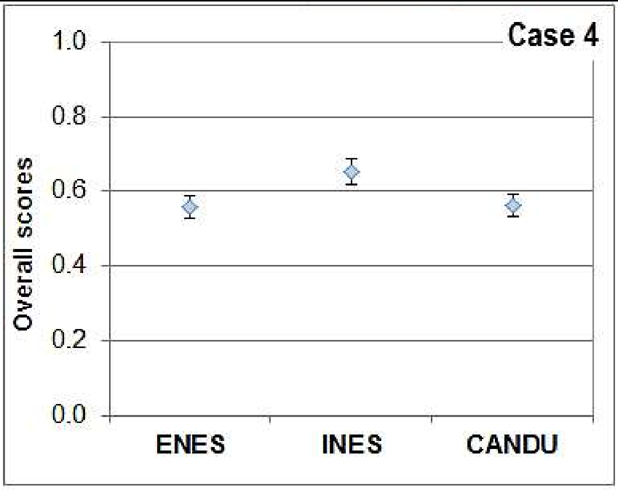


FIG. 3.88. The overall scores and uncertainties for Case 4 (screenshot from Uncertainty Propagator).

Overall scores and uncertainties	ENES	INES	CANDU
Best estimate	**0.522**	**0.685**	**0.472**
Absolute uncertainties	**0.028**	**0.042**	**0.024**
contribution due to uncertainties in key indicators	0.014	0.019	0.012
contribution due to uncertainties in s.a. value functions	0.020	0.032	0.017
contribution due to uncertainties in weights	0.012	0.018	0.011

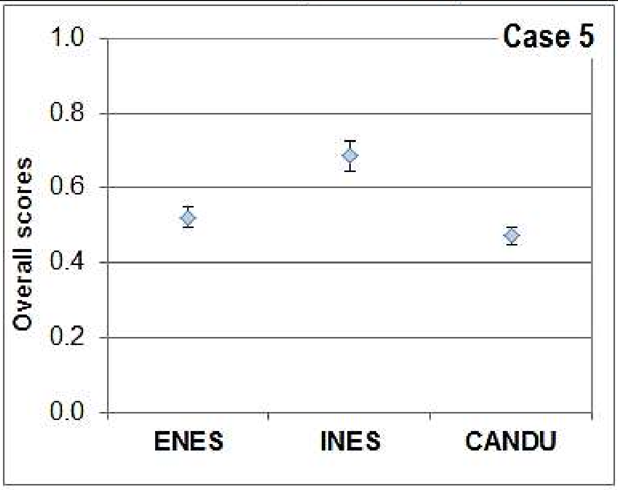


FIG. 3.89. The overall scores and uncertainties for Case 4 (screenshot from Uncertainty Propagator).

3.7.5. Conclusions

The case study aims were the multi-criteria comparative evaluation of the evolutionary (Enhanced CANDU) and innovative (Gen IV LFR) nuclear technologies applying the KIND approach and the KIND-ET evaluation tool developed in the INPRO KIND and CENESO CPs. As reference, the CANDU6 nuclear technology successfully operating in Romania at Cernavoda NPP, Units 1 and 2, was considered in the multi-criteria comparative evaluation.

For the proposed analysis, the KIND approach based on the multi attribute value function method (MAVT) was used for the nuclear technologies ranking. A 3-level objective tree was constructed, which includes the following elements: two High-Level Objectives (Benefits and Challenges); nine Areas of Evaluation ('Waste management', 'Environment', 'Safety', 'Country specifics', 'Legal and political environment', 'Public acceptance', 'Economics', 'Proliferation resistance' and 'Maturity of technology'); and 20 specific Key indicators to evaluate the nuclear technologies performance.

The main assumption was to consider equal importance for the elements at each level of the objective tree. For the analysis, five main working cases were selected according to consideration of the areas of evaluation with a 'dual potential' in one of the HLOs, Benefits or Challenges, as follows:

- Case 1: Benefits HLO includes 6 areas ('Waste management', 'Environment', 'Safety', 'Country specifics', 'Legal and political environment', and 'Public acceptance'); Challenges HLO includes 3 areas ('Economics', 'Proliferation resistance', and 'Maturity of technology').
- Case 2: Benefits HLO includes 5 areas ('Environment', 'Safety', 'Country specifics', 'Legal and political environment', and 'Public acceptance'); Challenges HLO includes 4 areas ('Waste management', 'Economics', 'Proliferation resistance', and 'Maturity of technology').
- Case 3: Benefits HLO includes 5 areas ('Waste management', 'Environment', 'Safety', 'Country specifics', and 'Public acceptance'); Challenges HLO includes 4 areas ('Economics', 'Proliferation resistance', 'Maturity of technology' and 'Legal and political environment').
- Case 4: Benefits HLO includes 5 areas ('Waste management', 'Environment', 'Safety', 'Country specifics', and 'Legal and political environment'); Challenges HLO includes 4 areas ('Economics', 'Proliferation resistance', 'Maturity of technology' and 'Public acceptance').
- Case 5: Benefits HLO includes 3 areas ('Environment', 'Safety', and 'Country specifics'); Challenges HLO includes 6 areas ('Waste management', 'Economics', 'Proliferation resistance', 'Maturity of technology', 'Legal and political environment', and 'Public acceptance').

The innovative technology seems to be more attractive than the evolutionary technology for all the considered working cases, obtaining the best scores for the following areas: 'Waste management', 'Environment; 'Safety', 'Country specifics' and 'Public acceptance'.

The evolutionary technology obtained the best scores for the areas of 'Proliferation resistance' and 'Maturity of technology' comparatively with the innovative technology.

The scores obtained by the innovative and evolutionary technologies for the areas of ‘Economics’ and ‘Legal and political environment’ were similar and slightly higher, respectively, for the innovative technology.

The total scores (MAVF values) obtained by the innovative and evolutionary technologies for the considered working cases sustain the leading position of the innovative technology, $MAVF_{INES}$ being higher than $MAVF_{ENES}$ by 6% (Case 1), 15.4% (Case 2), 14.3% (Case 3), 14.4% (Case 4), and 23.8% (Case 5), respectively.

In all considered cases, the innovative technology total scores are mainly due to the scores obtained in the Benefits HLO (around 0.4); meantime the scores for Challenges HLO are lower (around 0.25). For the evolutionary technology, the scores in the Benefits HLO (around 0.25) are lower than the ones in the Challenges HLO (around 0.35). The innovative technology gets the leading position based mainly on its benefits, which is a very important observation for the multi-criteria comparative analysis proposed by the case study.

iNES, eNES and CANDU are non-dominated options for all the main working cases considered in the screening process (preliminary analysis).

The multi-criteria comparative analysis included some sensitivity and uncertainty analyses. For the sensitivity analyses, three sub-cases were considered, namely: different weights for the areas in Benefits HLO; different weights for the areas in Challenges HLO; and different weights for the two KIs in areas of ‘Economics’. The innovative technology succeeded in all sub-cases to keep its leading position and even to increase the relative difference against the evolutionary technology total scores.

The uncertainty propagator module reproduced the overall scores obtained by the iNES, eNES and CANDU technologies using the KIND-ET tool. The absolute uncertainties were calculated, based on the contributions due to uncertainties in KIs, in single attribute value functions, and in weights.

3.8. APPLICATION OF COMPARATIVE MULTI-CRITERIA KIND APPROACH AS SUPPORT FOR NESA IN ROMANIA (ROMANIA)

This chapter presents structured report of the second of the two case studies done by experts from Romania.

3.8.1. Introduction

The “Nuclear Energy System Assessment (NESA) in Romania” was launched in 2013 in the framework of the International Project on Nuclear Reactors and Fuel Cycles (INPRO) to define the Most Probable Scenarios for the Long Term Nuclear Energy System (NES) contribution in the National Energy Mix (NEMix), and to apply the INPRO Methodology to assess the status of the Romanian NES sustainability in areas of Economics, Radioactive Waste Management and Infrastructure, and to prepare some suggestion related to each representative scenario.

The first report titled “The potential role of the nuclear power in the national mix of energy supply: Romanian case study – Preliminary Report”, was completed by the national expert team in October 2015 using the Model for the Analysis of Energy Demand (MAED)[26] and the Model

[26] https://www.iaea.org/publications/7430/model-for-analysis-of-energy-demand-maed-2

for Energy Supply Strategy Alternative and their General Environment Impacts (MESSAGE)[27]. The Nuclear Agency and Radioactive Waste (AN&DR) provided the report to the INPRO secretariat in 2016.

The second report titled "NESA Romanian Case Study – Second Report, Assessment of the long term options for the NES development, using the INPRO Methodology in the areas of Economics, Infrastructure and Radioactive Waste Management" was completed in the middle of 2018. Some of the data used to perform the radioactive waste management assessment were provided only in contractual regime and the preliminary advice from experts was formulated to be agreed in-house. This was discussed and then considered in-house to be implemented at the institutional level in the short and medium term.

3.8.2. Objective and problem formulation

The main objective of this case study is to explore the KIND-ET applicability to support new expert analysis related to the global and specific effect of the political decisions in developing a NEMix including conventional nuclear and renewable technologies.

In the first NESA report previously mentioned a General Case Study matrix of the available technologies in the combined power and district heat system to provide the energy demand in Romania until 2070 was established using the MAED tool, from 2010 to 2070. All the data used to this General Case Study matrix were publicly available data in the world until the year 2012.

All conventional and renewable technologies are considered to be selected in the optimistic assumption (only solar capacity was limited to about 1/3 of maximal resources availability).

Three nuclear scenarios (Reference, Low and High) were defined as options, in order to select the optimal contribution of the nuclear technologies in the NEMix to ensure its sustainability until 2070:

- S1 (Low): only 2 CANDU units (the existing ones, considering their life extensions);
- S2 (Reference): 4 CANDU units – based on national energy strategy in force 2013–2020 (the existing plants and those in construction, considering their life extensions);
- S3 (High): 4 CANDU units + New NPP installed capacities (Gen III+ after 2035: PWR/HWR), not limited capacities until 2070.

The life extension for CANDU units was considered in a conservative mode in relation with their high-capacity factor (over 85%) reported after 2010.

Other non-proven technologies, including SMR, GenIV reactors and CO_2 capture technologies are included together as additional technologies with a very high cost for the whole modelling period. These are in development status and the industrial use will be considered as very costly. These technologies were considered to be developed and used into the system only when the energy demand will exceed the proven technology capacity associated to each selected scenario.

In the first report, four principles are proposed to discuss the scenarios selection:

[27] https://www.iaea.org/publications/10861/modelling-nuclear-energy-systems-with-message-a-users-guide

— P1: The sustainability of the National Energy Mix (NEMix) is ensured by its Proven Technologies' components capability to meet associated sustainable demand.
— P2: The security of energy supply of the National Energy Mix (NEMix) is ensured by their structural components capability to meet associated sustainable demand.
— P3: The “MESSAGE case study” performed for this report is considering the Combined Electricity and District Heat national mix (EDHMix) - composed by 3 main competitor components at minimal total costs of energy production [Objective function=MESSAGE optimisation criteria]: Conventional Renewables and Nuclear; Non-Proven (additional) technologies are also considered in competition in order to assure matching of the considered demand.
— P4: NEMix security of energy supply can be ensured if all its subsystems contribute to the security of energy supply, in compliance with EU requirements on minimising the CO_2 emissions – but is sustainable and secured if the additional technologies are not selected.

For the medium demand increase of energy, a discount rate of 8% per year and with a 10 USD/tCO_2 penalty, the MESSAGE optimal solution for the “security of energy supply” was analysed for each nuclear scenario considered. In this approach there was no need to install additional technologies until 2070 for the High Nuclear Scenario, but these technologies were used in the Low Nuclear Scenario after 2045 and in the Reference Scenario, after 2065.

The principles [P1], [P2] and [P4] were not used in the framework of a multi-criteria analysis and all the discussion about the results were limited to ranking the scenarios and to identify some additional indicators which can be evaluated in the future as opportunities for the decision makers to support the security of the energy supply by the development of the recovered energy technologies (Hot Water Boilers and Hydro Pumping Storage Systems) in the combined heat and power grid.

The overall cost of the technologies, and the associated resources used in NEMix to satisfy the long term national energy demand for each considered load region, is the main indicator in the MESSAGE objective function in order to provide the optimal contribution for each of the available technologies for all the period of modelling considered in the system.

The basic matrix (General Case Study used in the first report titled ‘The potential role of the nuclear power in the national mix of energy supply. Romanian case study – Preliminary Report’), includes:

— 32 energy forms organized on five levels;
— 24 load regions (for demand and for Hydro, Solar PV and Wind Farm production, respectively);
— two demands (electricity and heat);
— seven relations (for CO_2 production, for processed water and wind and solar production);
— 60 technologies, including classical coal, lignite and gas power plants to produce electricity and combined heat and power plants (CHP) with two or three alternate regimes, hydro power plants (run on rivers and with storage dams), nuclear technologies (CANDU, advanced HWRs and advanced PWRs), renewable technologies (solar PV and wind farms), transport and distribution technologies for electricity and heat including district heat accumulators and hot water boilers (HWB), a hydro pumping–storage system, spent fuel storages and transport spent fuel technologies, import and export technologies, and additional technologies (in the first year of the modelling period, the non-proven technologies are in development status, are very costly for an

industrial production and their installation in the system will be the last solution to meet increasing of the energy demand over the proven technologies installed capacity);
— four domestic resources (for coal, lignite, gas and uranium).

The period of modelling is considered between 2010 and 2070, the steps of optimization being annual until 2024, biannual until 2040 and at 5 years until 2070.

Linear programming is applied in MESSAGE for each scenario, taking into consideration the restrictions for the technologies' availability in time and their technical and economics performances (investment costs, fixed and variable costs, efficiency, plant factor, plant life, unit capacity, construction time, etc.). Some bounds (limits and penalties) are used to include the country commitment to EU policy to mitigate CO_2 emissions.

The objective function in MESSAGE is the total cost of the energy system, over the entire study periods, which is to be minimized. Relations between the different components of the energy system are defined as constraints, which need to be satisfied, but an optimal solution cannot be selected if the technical and economic parameters for the used technologies are very close to each other; and/or if more than one additional type of technologies are used without an option to prioritize them in a hierarchy; and/or if too many restrictions are imposed. In these cases, MESSAGE can stop (after several days of continuous running) with an error indicating that the optimal solution cannot be found.

In reality, the objective function, defined only on the technical and economic parameters (used in classical business models, in order minimize the overall costs and to maximize the internal rate of return) is not enough to estimate for the long term the society evolution. Some social, environmental and country specific indicators can and will affect the public acceptance, and the ad-hoc actions taken by the political decision makers in very short time will also affect the public acceptance.

In this respect, the performance of KIND-ET and KIND-ET extensions to provide consistent results was tested using an input matrix of 15 values associated with 15 key indicators for 12 different scenarios, generated both in quantitative values, resulting from the MESSAGES optimization, as well as after an additional qualitative ranking of the initial quantitative values into the integers numbers area from 1 to 12, according to the decision of an expert. The conclusions about the obtained results were discussed versus the options of the decision makers and in correlation with the experts' approach in the case studies analyse.

In order to save time to find an optimal solution in MESSAGE, MESSAGE was run with a limited set of restrictions for several scenarios to collect more quantitative information from the system, related to environmental effect and country specifics parameters, that can be saved as new indicators to be used in a performance table (technology support activities, country specifics, acceptability of the risks, etc) as input data for a comparative multi-criteria analysis.

3.8.3. Specific objective of the case study

The specific objective of this case study in the CENESO project is to explore the sensitivity of the Multi Attribute Value Theory (MAVT) and the KIND approach, and their capability to provide support for the political short term decisions in a (hypothetical) country that has decided to use an intelligent system for energy management (including advanced solutions for the maintenance of the old district heat systems and the hydro pumping-storage development) in order to select the optimal long term acceptable contribution for nuclear and non-nuclear technologies, including renewable technologies, in a diverse national energy mix (NEMix) with respect to the European Union policy to mitigate overall CO_2 emissions.

In the present study, the same general matrix as in the first NESA report was used, limited only to the medium (reference) demand of energy established in 2012 for Romania's evolution until 2070 (starting year 2010) from the three demand options provided by the MAED model. For the MESSAGE optimisation only the 8% per year discount rate (medium discount rate) and 10 USD/tonne of the CO_2 emissions as penalty (medium penalty) for the classic fossil fuel technologies was selected (in the first NESA report, three discount rates and three values for the CO_2 emissions penalties are used).

The three nuclear development scenarios were still considered, but in S1 the extended life was from 210,000 effective full power hours (EFPH) to approximately 245,000 EFPH (expected as a result of the international experience), and in S3 the number of advanced PWRs and/or advanced HWRs was limited to two units each.

For the renewable technologies, it was decided to study the political decisions to allow their full development until a hypothetical maximum capacity of the national resources is established, or to bound their development to approximately 1/3 of these hypothetical availability of national resources in the renewable resources area.

In support of the decision makers political approaches, three possibilities to use subventions in district heat rehabilitation were considered in order to replace the old hot water boilers and the old heat distribution system. Also, the effect of 90% subvention in the refurbishment investment costs of the nuclear installed units in the first year of the modelling period (unit 1 and unit 2 at Cernavoda site, in this hypothetical system) was investigated versus a multi criteria ranking results obtained by KIND-ET.

3.8.4. Inputs, methods and assumptions used

Twelve hypothetical scenarios were prepared for assessment and ranking using the KIND-ET:

— No.1: NES300xy70 – S3 (4 CANDU units + 2 advanced PWR + 2 advanced HWR) with 90% subvention for the investment in the refurbishment of the nuclear installed units in the first year of the modelling period (U1 & U2 at Cernavoda); maximal capacity of renewable (Hydro, Wind and Solar); maximal capacity of classic fossil fuel technologies and 100% subvention in District Heat Grid Rehabilitation;
— No.2: NES200xy70 – S2 (4 CANDU units) with 90% subvention for the investment in the refurbishment of U1 & U2 at Cernavoda; maximal capacity of renewable (Hydro, Wind and Solar); maximal capacity of classic fossil fuel technologies and 100% subvention in District Heat Grid Rehabilitation;
— No.3: NES300ccy70 – S3 (4 CANDU units + 2 advanced PWR + 2 advanced HWR) with 90% subvention for the investment in the refurbishment of U1 & U2 at Cernavoda; maximal capacity of renewable (Hydro, Wind and Solar); maximal capacity of classic fossil fuel technologies and no subvention in District Heat Grid Rehabilitation;
— No.4: NESc200ccy70 – S2 (4 CANDU units) with 90% subvention for the investment in the refurbishment of U1 & U2 at Cernavoda; maximal capacity of renewable (Hydro, Wind and Solar); maximal capacity of classic fossil fuel technologies and no subvention in District Heat Grid Rehabilitation;
— No.5: NES301cy70 – S3 (4 CANDU units + 2 advanced PWR + 2 advanced HWR) with 90% subvention for the investment in the refurbishment of U1 & U2 at Cernavoda; maximal capacity of Hydro, 1/3 capacity of Wind and 1/3 capacity Solar; maximal

capacity of classic fossil fuel technologies and 50% subvention in District Heat Grid Rehabilitation;

- No.6: NES201cy70 – S2 (4 CANDU units) with 90% subvention for the investment in the refurbishment of U1 & U2 at Cernavoda; maximal capacity of Hydro, 1/3 capacity of Wind and 1/3 capacity of Solar; maximal capacity of classic fossil fuel technologies and 50% subvention in District Heat Grid Rehabilitation;
- No.7: NES301ccy70 – S3 (4 CANDU units + 2 advanced PWR + 2 advanced HWR) with 90% subvention for the investment in the refurbishment of U1 & U2 at Cernavoda; maximal capacity of Hydro, 1/3 capacity of Wind and 1/3 capacity Solar; maximal capacity of classic fossil fuel technologies and no subvention in District Heat Grid Rehabilitation;
- No.8: NES303ccy70 – S3 (4 CANDU units + 2 advanced PWR + 2 advanced HWR) with 90% subvention for the investment in the refurbishment of U1 & U2 at Cernavoda; maximal capacity of Hydro and Wind and 1/3 capacity of Solar; maximal capacity of classic fossil fuel technologies and no subvention in District Heat Grid Rehabilitation;
- No.9: NES201ccy70 – S2 (4 CANDU units) with 90% subvention for the investment in the refurbishment of U1 & U2 at Cernavoda; maximal capacity of renewable (Hydro, Wind and Solar); maximal capacity of classic fossil fuel technologies and no subvention in District Heat Grid Rehabilitation;
- No.10: NESc101ccy70 – S1 (only 2 CANDU units - the MESSAGE Matrix with no other nuclear technologies) with 90% subvention for the investment in the refurbishment of U1 & U2 at Cernavoda; maximal capacity of Hydro, 1/3 capacity of Wind and 1/3 capacity Solar; maximal capacity of classic fossil fuel technologies and no subvention in District Heat Grid Rehabilitation;
- No.11: NESc101cy70 – S1 (only 2 CANDU units - the MESSAGE Matrix with no other nuclear technologies) with 90% subvention for the investment in the refurbishment of U1 & U2 at Cernavoda; maximal capacity of Hydro, 1/3 capacity of Wind and 1/3 capacity Solar; maximal capacity of classic fossil fuel technologies and 50% subvention in District Heat Grid Rehabilitation;
- No.12: NESz300xy70 – S3 (4 CANDU units + 2 advanced PWR + 2 advanced HWR) no subventions for the investment in the refurbishment of U1 & U2 at Cernavoda; maximal capacity of renewable (Hydro, Wind and Solar); maximal capacity of classic fossil fuel technologies and 100% subvention in District Heat Grid Rehabilitation.

Based on the MESSAGE quantitative results, 15 Key Indicators were selected, aggregated in seven Areas of Evaluation and three High Level Objective. The objective tree structure is shown in Fig. 3.90.

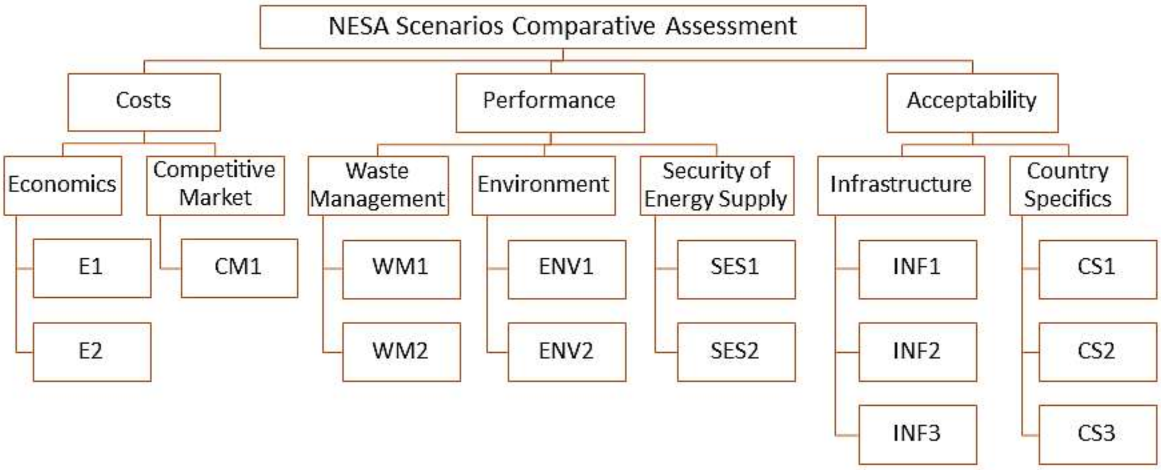


FIG. 3.90. The objective tree structure for comparative assessment of NESA scenarios.

The three High Level Objectives are:

— Costs;
— Performance;
— Acceptability.

The seven Evaluation areas are:

— Economics (E);
— Competitive market (CM);
— Waste management (WM);
— Environment (ENV);
— Security of energy supply (SES);
— Infrastructure (INF);
— Country specific (CS).

The 15 Key Indicators and their ranking goals {min/max} are distributed under the evaluation areas as following:

— Technologies' total levelized energy cost (E1), {min};
— R&D and licensing costs (E2), {min};
— Objective function of the NEMix (CM1), {min};
— NES radwaste activity (WM1), {min};
— Costs of spent nuclear fuel management (WM2), {min};
— Amount of useful NES energy produced by unit of conv. Fuel (ENV1), {max};
— Amount of CO_2 emissions (ENV2), {min};
— Need for additional and import technologies (SES1), {min};
— Need of recovery energy systems (SES2), {min};
— New investments_ in nuclear (INV1), {min};
— New investments in solar, photovoltaic and wind farms (INF2), {min};
— New investments in hot water boilers (INF3), {min};
— Energy produced by combined heat and power (CHP) system (CS1), {min};
— Energy recovered by hydro-PS system (CS2), {min};
— Energy recovered by heat accumulators (CS3), {min}.

Only the indicator related to the R&D and/or Licensed Needs was defined as a qualitative indicator (between 1 and 4) based on the experts' judgement versus the R&D status (max 2 points demerit ranking) and Licensing Needs status (max 2 points demerit ranking).

3.8.5. Selection of a key indicator set and determination of their values

Two methods were proposed to study the performance of the INPRO KIND Evaluation Tool (KIND-ET) based on Multi Attribute Value Theory (MAVT) with the additive aggregation model and taking into consideration the country specifics for Romania (nuclear technologies are integrated into a diverse and well-balanced national energy system):

- To use the MESSAGE quantitative values in physical integer significant units (Fig. 3.91);
- To use also qualitative indicators and expert's judgement to rank the 12 hypothetical scenarios quantitative value provided by the MESSAGE optimal solution found (Fig. 3.92).

The discussions of the obtained results selectivity are examined for the first step versus the user instructions for the extensions of KIND-ET (Domination Identifier, Overall Score Spread Builder, Ranks Mapping Tools and Uncertainty Propagator).

Two sets of data were prepared for the Performance table, a quantitative set and a qualitative one. In each set the possibilities of dominant/ dominated scenarios were examined. For each of them NES301ccy70 (with no subvention in District Heat Grid Rehabilitation), the 7th scenario, was determined to be a dominant scenario for NES301cy70 (with 50% subvention in District Heat Grid Rehabilitation), the 5th scenario. The two scenarios are identical in all the other considered assumptions (see Figs 3.92 and 3.94).

This result can be discussed later, considering that there is no benefit for the system to allow government subventions in District Heat Grid Rehabilitation.

At this step of the study, the analysis of relative differences in the score for each of the scenarios as performed by the two methods (see Figs 3.91 and 3.93) has revealed that no preference can be given to any of the methods in terms of discriminative power.

Indicators abbr.	MIN score	MAX score	NES300x y70	NES200x y70	NES300c cy70	NESc200 ccy70	NES301c y70	NES201c y70	NES301c cy70	NES303c cy70	NES201c cy70	NESc101 ccy70	NESc101 cy70	NESz300 xy70	Goal
E1	291	447	374	443	374	443	402	441	402	401	447	291	291	372	min
E2	2	4	3	2	3	2	3	4	3	3	2	4	4	3	min
CM1	519	5929	519	531	520	528	556	2107	538	527	2108	5929	5927	526	min
WM1	502	1165	980	827	980	827	1165	796	1165	1117	822	502	502	980	min
WM2	13	42	34	26	34	26	42	26	42	40	26	13	13	34	min
ENV1	443	566	546	446	546	446	566	449	566	542	446	443	443	546	max
ENV2	1444	1567	1449	1555	1463	1556	1499	1562	1483	1474	1558	1561	1567	1444	min
SES1	0	5956	0	0	0	0	0	2541	0	0	2541	5956	5915	0	min
SES2	97	7122	876	1324	273	793	1152	1170	97	223	451	1343	583	7122	min
INF1	283	2233	1814	283	1814	283	2233	1121	2233	2233	1121	283	283	1814	min
INF2	41	171	170	170	170	171	48	41	48	116	41	47	47	169	min
INF3	0	205	14	160	0	205	39	41	0	0	115	40	20	120	min
CS1	258	357	258	311	271	304	318	357	310	271	349	351	357	272	min
CS2	0	319	216	0	253	198	319	38	77	203	14	14	14	276	min
CS3	2	132	66	132	2	59	83	113	2	2	44	12	57	44	min

FIG. 3.91. KIND-ET performance table for the MESSAGE quantitative values in physical integer significant units (screenshot from KIND-ET).

Domination table		Dominating options											
		NES300xy70	NES200xy70	NES300ccy70	NESc200ccy70	NES301cy70	NES201cy70	NES301ccy70	NES303ccy70	NES201ccy70	NESc101ccy70	NESc101cy70	NESz300xy70
Dominated options	NES300xy70		-	-	-	-	-	-	-	-	-	-	-
	NES200xy70	-		-	-	-	-	-	-	-	-	-	-
	NES300ccy70	-	-		-	-	-	-	-	-	-	-	-
	NESc200ccy70	-	-	-		-	-	-	-	-	-	-	-
	NES301cy70	-	-	-	-		-	<	-	-	-	-	-
	NES201cy70	-	-	-	-	-		-	-	-	-	-	-
	NES301ccy70	-	-	-	-	-	-		-	-	-	-	-
	NES303ccy70	-	-	-	-	-	-	-		-	-	-	-
	NES201ccy70	-	-	-	-	-	-	-	-		-	-	-
	NESc101ccy70	-	-	-	-	-	-	-	-	-		-	-
	NESc101cy70	-	-	-	-	-	-	-	-	-	-		-
	NESz300xy70	-	-	-	-	-	-	-	-	-	-	-	

FIG. 3.92. Domination Identifier screenshot for the MESSAGE quantitative values in physical integer significant units: NES301ccy70 is a dominating option for NES301cy70.

			1	2	3	4	5	6	7	8	9	10	11	12	
Indicators abbr.	**MIN score**	**MAX score**	**NES300 xy70**	**NES200 xy70**	**NES300 ccy70**	**NESc200 ccy70**	**NES301 cy70**	**NES201 cy70**	**NES301 ccy70**	**NES303cc y70**	**NES201 ccy70**	**NESc101 ccy70**	**NESc101 cy70**	**NESz300 xy70**	**Goal**
E1	6	12	7	9	7	10	9	11	9	8	12	6	6	7	min
E2	2	4	3	2	3	2	3	4	3	3	2	4	4	3	min
CM1	1	12	1	6	2	5	8	9	7	4	10	12	11	3	min
WM1	6	12	12	9	12	9	11	7	11	10	8	6	6	12	min
WM2	6	12	10	7	9	7	12	7	12	9	8	6	6	10	min
ENV1	5	12	11	6	11	6	12	7	12	9	8	5	5	10	max
ENV2	1	12	2	7	3	8	6	11	5	4	9	10	12	1	min
SES1	1	12	1	1	1	1	1	10	1	1	9	12	11	1	min
SES2	2	12	10	12	5	9	12	11	2	4	6	3	7	8	min
INF1	9	12	11	9	10	9	12	9	12	12	9	9	9	10	min
INF2	4	12	10	11	9	12	6	4	6	7	4	5	5	8	min
INF3	1	12	4	11	1	12	6	8	1	1	9	7	5	10	min
CS1	1	12	1	7	2	5	8	11	6	3	9	10	12	4	min
CS2	1	12	9	1	10	7	12	12	6	8	5	4	4	11	min
CS3	3	12	9	12	3	8	10	11	3	3	6	4	7	5	min

FIG. 3.93. KIND-ET performance table for the MESSAGE qualitative indicators (screenshot).

Domination table		Dominating options											
		NES300xy70	NES200xy70	NES300ccy70	NESc200ccy70	NES301cy70	NES201cy70	NES301ccy70	NES303ccy70	NES201ccy70	NESc101ccy70	NESc101cy70	NESz300xy70
Dominated options	NES300xy70		-	-	-	-	-	-	-	-	-	-	-
	NES200xy70	-		-	-	-	-	-	-	-	-	-	-
	NES300ccy70	-	-		-	-	-	-	-	-	-	-	-
	NESc200ccy70	-	-	-		-	-	-	-	-	-	-	-
	NES301cy70	-	-	-	-		-	<	-	-	-	-	-
	NES201cy70	-	-	-	-	-		-	-	-	-	-	-
	NES301ccy70	-	-	-	-	-	-		-	-	-	-	-
	NES303ccy70	-	-	-	-	-	-	-		-	-	-	-
	NES201ccy70	-	-	-	-	-	-	-	-		-	-	-
	NESc101ccy70	-	-	-	-	-	-	-	-	-		-	-
	NESc101cy70	-	-	-	-	-	-	-	-	-	-		-
	NESz300xy70	-	-	-	-	-	-	-	-	-	-	-	

FIG. 3.94. Domination Identifier screenshot for the MESSAGE qualitative indicators: NES301ccy70 is a dominating option for NES301cy70.

3.8.6. Selection of the working cases' attributes

For the next step of this study, four 'Base cases' were considered to examine the effect of multi attribute value theory method (local /global domain and linear /exponential approach for single attribute value functions, SAVF) versus the format of input data (quantitative /qualitative):

- Base case 1 – quantitative values in 'Performance table', local domain selected for the value function (VF);
- Base case 2 – quantitative values in 'Performance table', global domain selected for VF;
- Base case 3 – qualitative values in 'Performance table', local domain selected for VF;
- Base case 4 – qualitative values in 'Performance table', global domain selected for VF.

The total scores obtained in the above-mentioned Base cases are represented at the level of High-Level Objectives and Assessment areas in Figs 3.95(a)–3.98(a) and Figs 3.95(b)– 3.98(b), respectively. The sensitivity analyses were also performed for these cases, both for SAVF and weights sensitivity. It needs to be mentioned that the weights sensitivity analysis was performed considering only the linear form for SAVF. Figs 3.95(c)–3.98(c), respectively show the total scores variation when the HLOs weight changes from equal weights to 40%-40%-20% weights sensitivity. The total scores variation when the SAVF form changes from linear to exponential value function sensitivity, is represented in Figs 3.95(d)–3.98(d).

The sensitivity analyses provide the following observations:

- For both value function and weights sensitivity analyses, when quantitative values are used, the best scenario (with the highest total score MAVF in 'Ranking results' worksheet) is the 7th one, regardless of whether local or global domain for VF is selected.
- For both value function and weights sensitivity analyses, when qualitative values are used, the best scenario (with the highest total score MAVF in 'Ranking results' worksheet) is the 3rd one, regardless of whether local or global domain for VF is selected.
- The last selected scenario (with the lowest total score MAVF in 'Ranking results' worksheet) is varying from the 6th one (most of the Base cases, for both types of sensitivity analyses) to the 12th one (in Base case 2, for quantitative values).

This first result can be understood by noting that different input data were used for the same group of scenarios, respectively, quantitative value given by the MESSAGE optimization, and qualitative data resulted from a formal expert judgement using an integer equal difference (1) for ordering the quantitative values given by MESSAGE, for each of the 12 hypothetical scenarios, from 1 to 12.

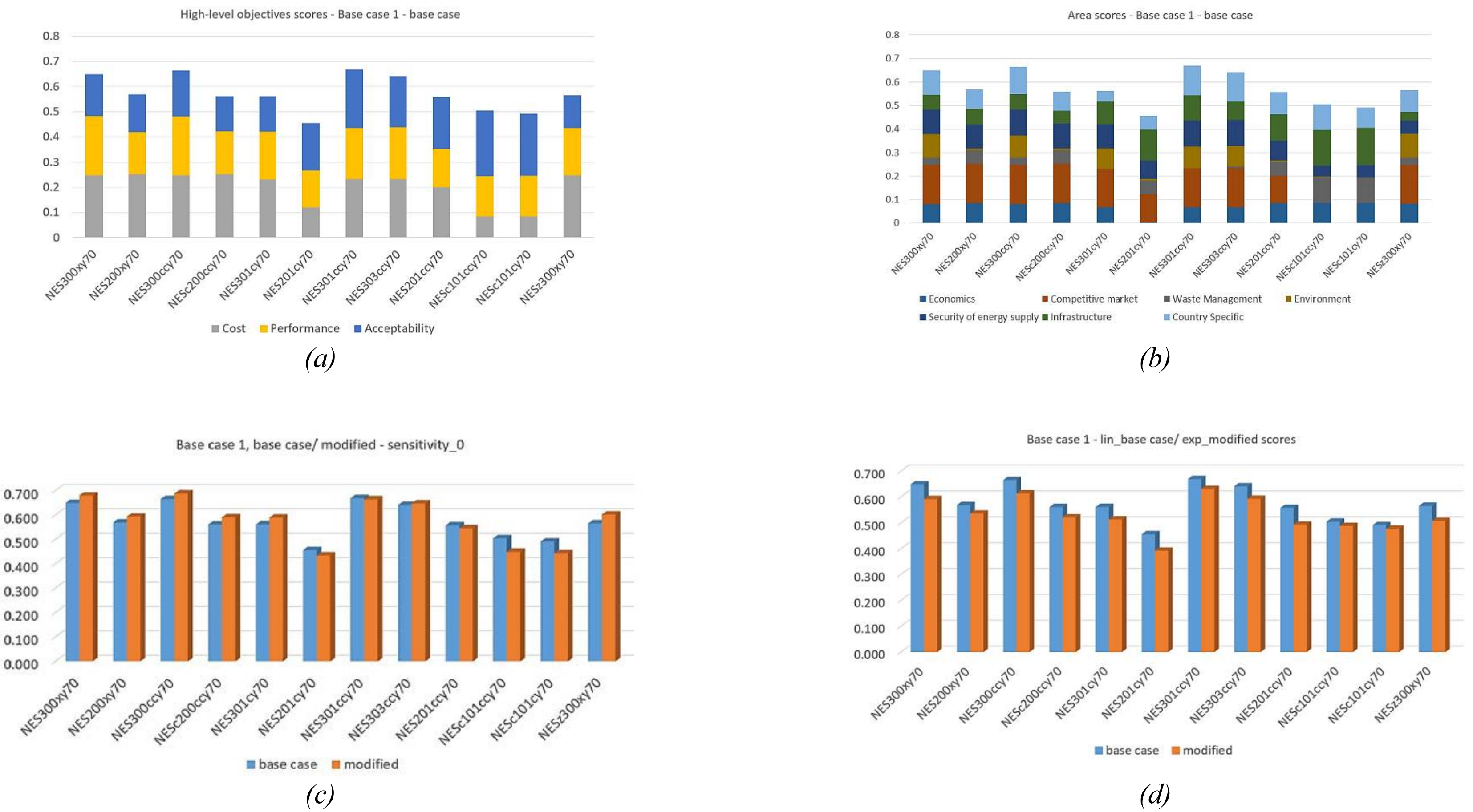


FIG. 3.95. KIND-ET MAVF scores in base case 1 (local domain, quantitative input data) for: (a) high-level objectives, (b) areas, (c) weight sensitivity analysis, (d) sensitivity analysis for SAVF form change.

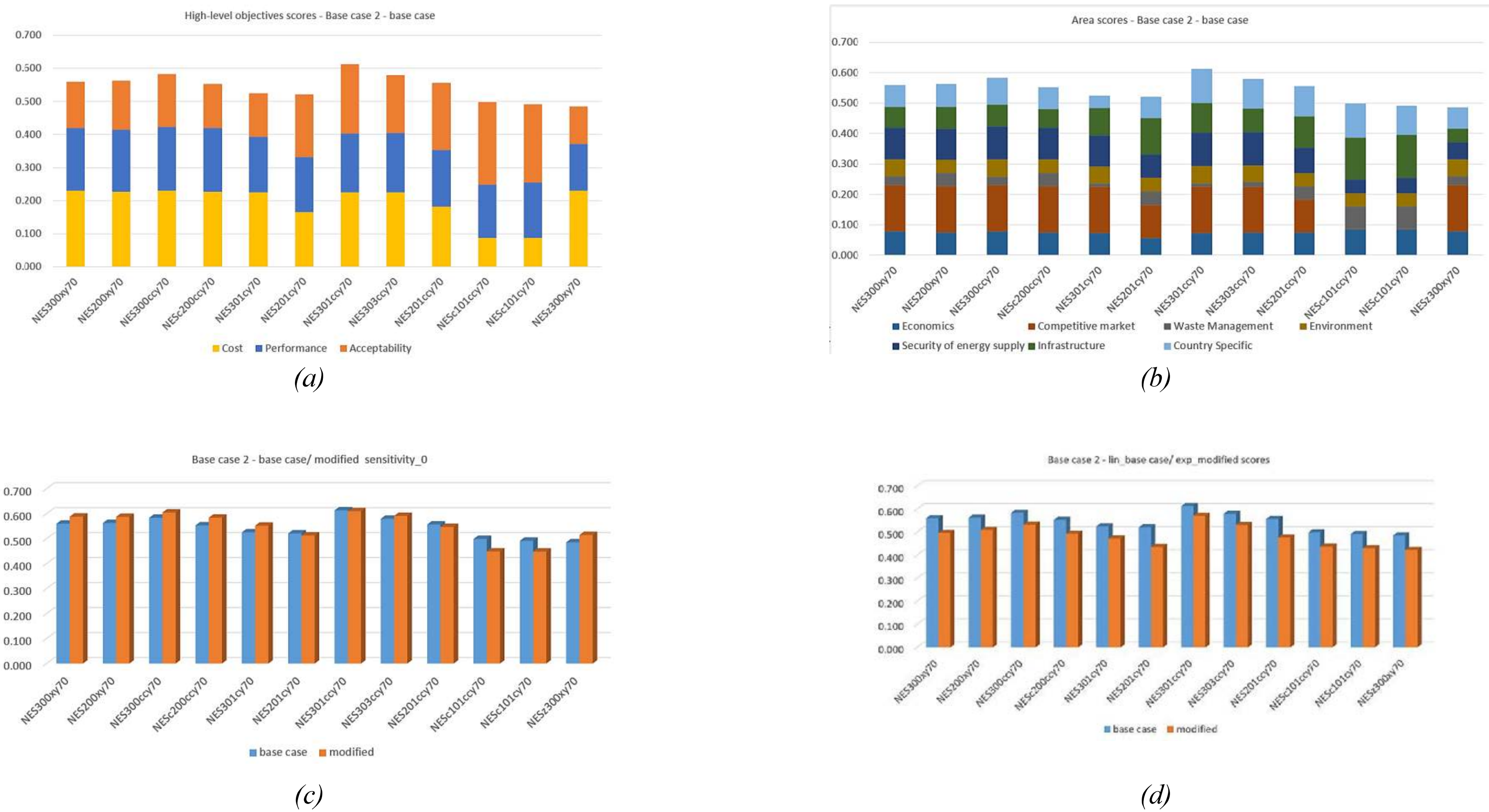


FIG. 3.96. KIND-ET MAVF scores in base case 2 (global domain, quantitative input data) for: (a) high-level objectives, (b) areas, (c) weight sensitivity analysis, (d) sensitivity analysis for SAVF form change.

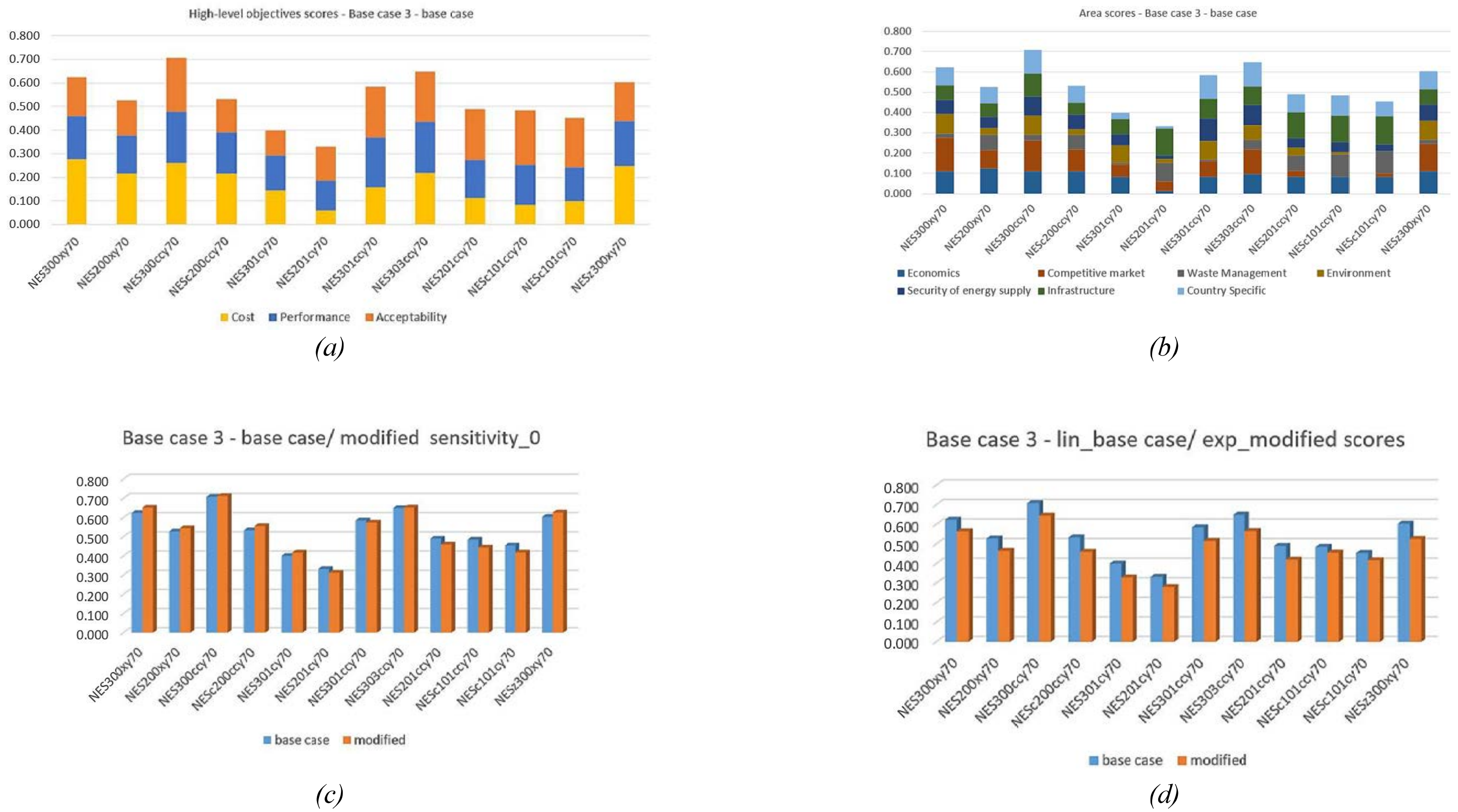


FIG. 3.97. KIND-ET MAVF scores in base case 3 (local domain, qualitative input data) for: (a) high-level objectives, (b) areas, (c) weight sensitivity analysis, (d) sensitivity analysis for SAVF form change.

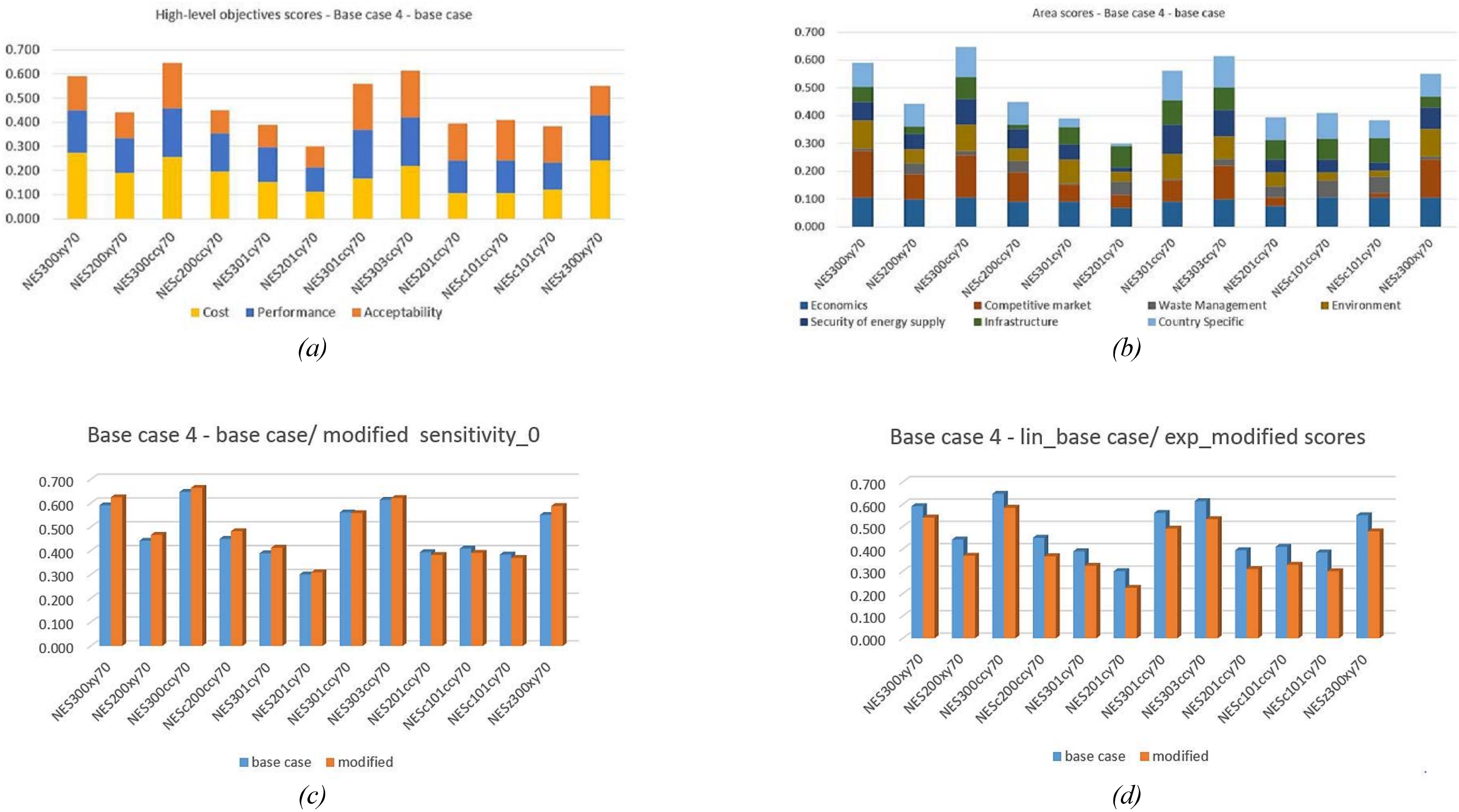


FIG. 3.98. KIND-ET MAVF scores in base case 4 (global domain, quantitative input data) for: (a) high-level objectives, (b) areas, (c) weight sensitivity analysis, (d) sensitivity analysis for SAVF form change.

In the sensitivity analyses, for the modified case (different weights for considered HLOs -40%-40%-20% instead of equals weights, and exponential SAVF instead of the linear one, respectively) a certain pattern can be noticed, as follows:

- Weights' sensitivity: MAVF values in the modified case are greater or equal with the base cases total scores, except for the 6th, 9th, 10th and 11th scenarios, in which base cases MAVF values are greater than the modified cases ones. In Base case 4, only for the 9th, 10th and 11th scenarios, MAVF values are greater in the base case comparatively with the modified one, but the differences decreased.
- Value function sensitivity: For all considered Base cases, the MAVF values obtained in the modified case (exponential SAVF) are lower than the ones characterizing the linear SAVF.

As was mentioned before, the first selected (the preferred option) scenario is different depending on the type of input data (quantitative or qualitative data) and depending on which global/local domain of VF or linear/exponential form of SAVF were selected.

If the scenarios selection in the linear approach for SAVF and different weights for HLOs are studied, it can be observed that only for Base case 1, the best scenario selected is different in the modified case versus the base case. The rest of the considered Base cases preserve the preferred scenario both in the modified case and the base case. Supplementary, it can be observed that in Base case 3, the scenarios selection order when different weights of HLOs (modified case) are used is the same with the case when equal weighting is used.

In this respect, it can be concluded that the more stable case is Base case 3 (for qualitative input data in local domain approach for SAVF) and the more sensitive case is Base case 1 (for quantitative input data in local domain approach for SAVF).

For this reason, the more sensitive case (for quantitative input data in local domain) considering the linear form for SAVF was selected to perform the next step of the analysis.

3.8.7. Application of the KIND software – derive aggregated indicators at different levels of aggregation

The next step of the study is dedicated to analysing how political decisions in prioritizing differently the HLOs, Areas of Evaluation (AEs) and Key Indicators (KIs) can and will affect mathematically the final optimal scenarios selected.

Based on the preliminary conclusions of the last step, only quantitative values were considered in the 'Performance table', and only the local domain and the linear form for SAVF, defining 4 Final cases to study as following:

(1) Final case 1 - HLOs - Costs dominant weights (Costs - 80%, Performance - 10%, Acceptability -10%) and Areas of Evaluation and KIs equal weights for the 'base case' (HLOs scores and MAVT total scores in Fig. 3.99), and:

- Equal weights for all the AEs, with different weights for the KIs E1 and E2 (E1 - 70%, E2 - 30%) and equal weights for the rest of the KIs, for 'sensitivity_1' analyse (Fig. 3.100 a);

- Different weights for the ‘Economics’ and ‘Competitive Market’ Areas of Evaluation (E – 30%, CM – 70%) and equal weights for the rest of the AEs and for all the KIs, for ‘sensitivity_2’ analyse (Fig. 3.100 b.);
- Different weights for the ‘Economics’, ‘Competitive Market’ Areas of Evaluation (E – 30%, CM – 70%) and for the KIs E1 and E2 (E1 – 70%, E2 – 30%), and equal weights for the rest of the AEs and KIs, for ‘sensitivity_2’ analyse (Fig. 3.100 c).

(2) Final case 2 - HLOs - Performance dominant weights (Costs - 10%, Performance - 80%, Acceptability -10%), Areas of Evaluation and KIs equal weights for the ‘base case’ (HLOs scores and MAVT total scores in Fig. 3.101), and:

- Equal weights for all the AEs, with different weights for the KIs SES1 and SES2 (SES1 - 80%, SES 2 - 20%) and equal weights for the rest of the KIs, for ‘sensitivity_1’ analyse (Fig. 3.102 a);
- Different weights for the ‘Waste Management’, ‘Environment’, and ‘Security of energy supply’ Areas of Evaluation (WM – 10%, E – 10%, SES – 80%) and equal weights for the rest of the AES and for all the KIs, for ‘sensitivity_2’ analyse (Fig. 3.102 b);
- Different weights for the ‘Waste Management’, ‘Environment’, and ‘Security of energy supply’ Areas of Evaluation (WM – 10%, E – 10%, SES – 80%), different weights for the KIs SES1 and SES2 (SES1 – 80%, SES2 – 20%) and equal weights for the rest of the AEs and KIs, for ‘sensitivity_3’ analyse (Fig. 3.102 c).

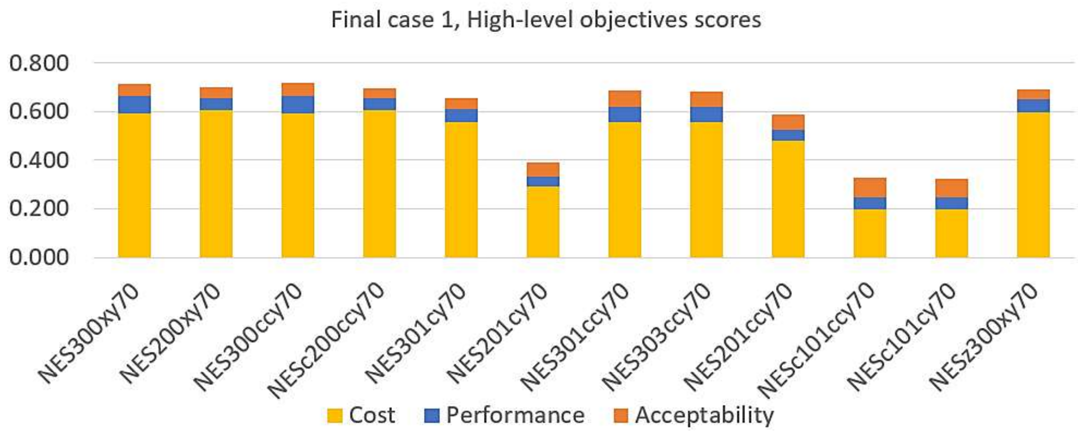
(3) Final case 3 - HLOs – Costs and Performance equal dominant weights (Costs - 45%, Performance - 45%, Acceptability -10%), Areas of Evaluation and Key Indicators equal weights for the ‘base case’ (HLOs scores and MAVT total scores in Fig. 3.103), and:

- Equal weights for all the AEs and KIs, the KIs corresponding HLO1 and HLO2 (E1/ 70%, E2 - 30%; SES1 – 80%, SES2 – 20%), and equal weights for the rest of the KIs, for ‘sensitivity_1’ analyse (Fig. 3.104 a);
- Different weights for the ‘Economics’, ‘Competitive Market’, ‘Waste Management’, ‘Environment’ and ‘Security of Energy Supply’ AEs (E – 30%, CM – 70%; WM – 10%, ENV – 10%, SES – 80%) and equal weights for the rest of the AEs and for all the KIs, for ‘sensitivity_2’ analyse (Fig. 3.104 b);
- Different weights for the ‘Economics’, ‘Competitive Market’, ‘Waste Management’, ‘Environment’, and ‘Security of Energy Supply’ AEs (E – 30%, CM – 70%; WM – 10%, ENV – 10%, SES – 80%), different weights for the E1, E2, SES1 and SES2 KIs (E1 – 70%, E2 – 30%; SES1 – 80%, SES2 – 20%), and equal weights for the rest of the AEs and KIs, for ‘sensitivity_3’ analyse (Fig. 3.104 c).

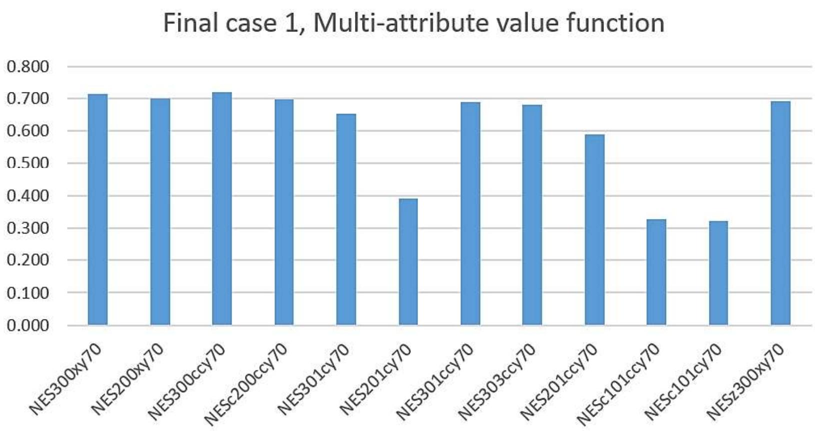
(4) Final case 4 - HLOs – Cost, Performance, Acceptability, different weights (Costs – 50%, Performance – 35%, Acceptability – 15%), Areas of Evaluation and Key Indicators equal weights for the ‘base case’ (HLOs scores and MAVT total scores in Fig. 3.105), and:

- Equal weights for all the AEs, with different weights for the E1, E2, SES1 and SES2 KIs (E1 – 70%, E2 – 30%; SES1 – 80%, SES2 – 20%) and equal weights for the rest of the KIs, for ‘sensitivity_1’ analyse (Fig. 3.111 a);
- Different weights for the ‘Economics’ and ‘Competitive Market’ AEs (E – 30%, CM – 70%) and equal weights for the rest of the AEs and for all the KIs, for ‘sensitivity_2’ analyse (Fig.3.111. b);

- Different weights for the 'Economics' and 'Competitive Market' AEs (E – 30%, CM – 70%), and for the E1 and E2 KIs (E1 – 70%, E2 – 30%), and equal weights for the rest of the AEs and KIs, for 'sensitivity_3' analyse (Fig.3.106 c.).

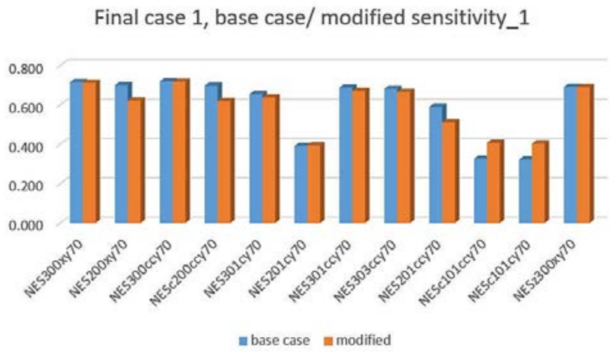


(a)

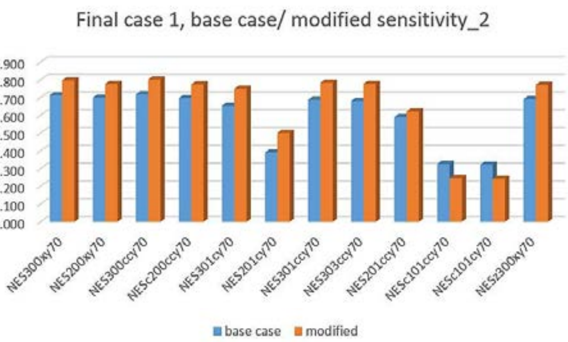


(b)

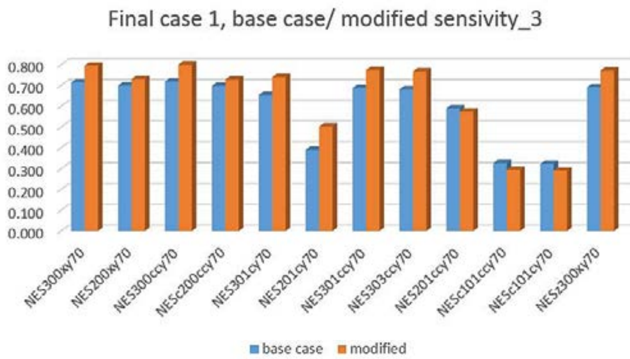
FIG. 3.99. KIND-ET scores in final case 1 (base case, cost – 80%, performance – 10%, acceptability – 10%) for: (a) high level objectives, (b) MAVF.



(a)



(b)



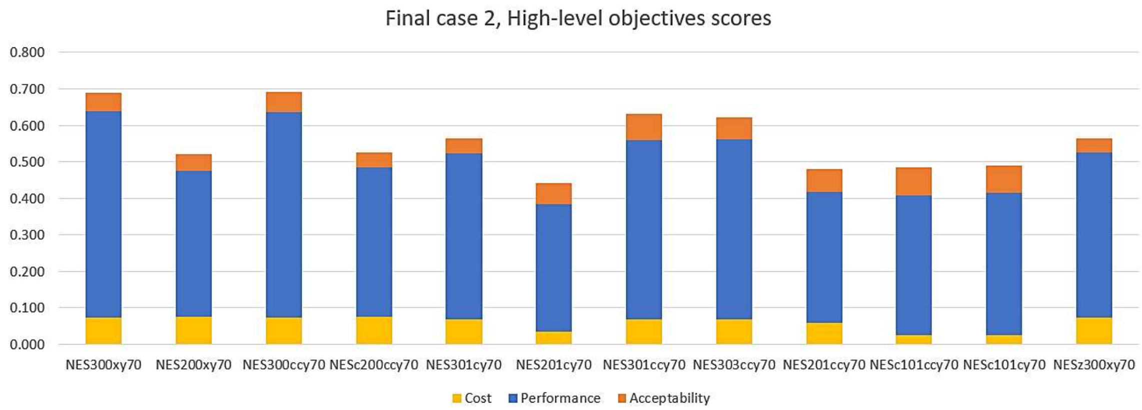
(c)

	1	2	3	4	5	6	7	8	9	10	11	12
base case	2.000	3.000	1.000	4.000	8.000	10.000	6.000	7.000	9.000	11.000	12.000	5.000
Weights sensitivity 1	2.000	7.000	1.000	8.000	6.000	12.000	4.000	5.000	9.000	10.000	11.000	3.000
Weights sensitivity 2	2.000	5.000	1.000	6.000	8.000	10.000	3.000	4.000	9.000	11.000	12.000	7.000
Weights sensitivity 3	2.000	7.000	1.000	8.000	6.000	10.000	3.000	5.000	9.000	11.000	12.000	4.000

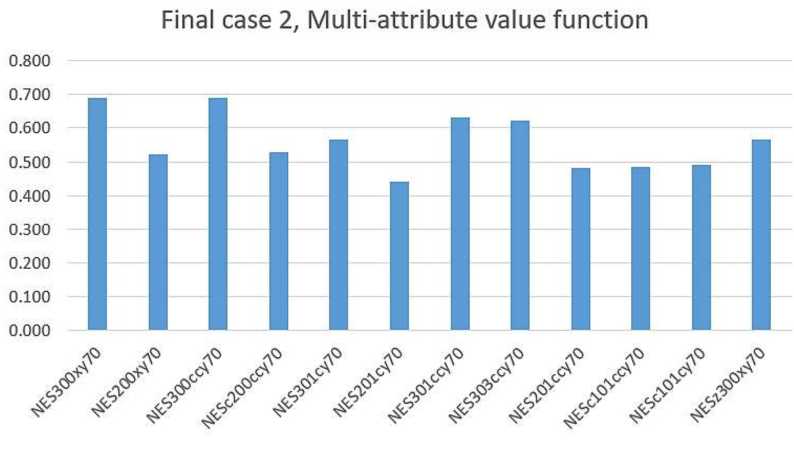
(d)

FIG. 3.100. KIND-ET scores in final case 1 (base case, cost – 80%, performance – 10%, acceptability – 10%): (a) base case/ modified sensitivity_1,(b) sensitivity_2, (c) sensitivity_3, (d) screenshot of weight sensitivity table from KIND-ET.

In all base cases considered for the four ‘final cases’ the best scenario selected is the 3rd one. This option is the same for all sensitivity analysis in the Final case 1, but it is different only for the ‘sensitivity_1’ analyse in the Final case 2, Final case 3 and Final Case 4. The 'sensitivity_1' analysis kept the equal weighting in all the AEs and prioritize some KIs in one or more AEs. The ‘sensitivity_2’ and ‘sensitivity_3’ analyses prioritize the AEs first and then, if they are selected, the KIs in the correspondent AEs.

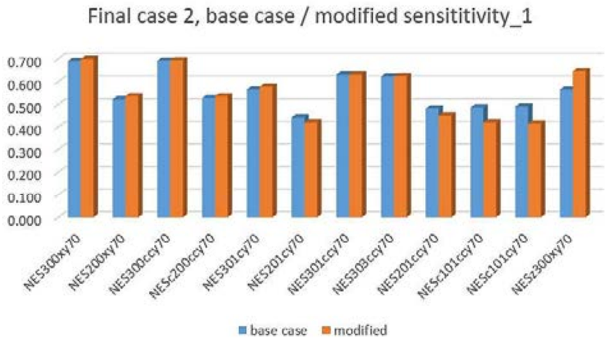


(a)

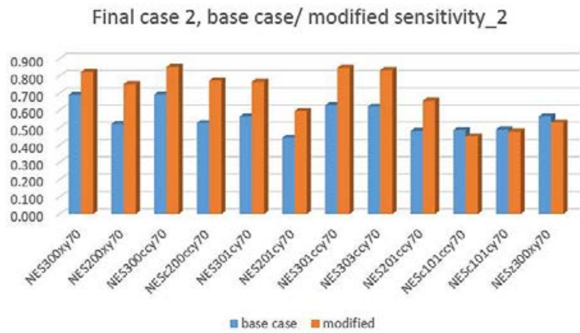


(b)

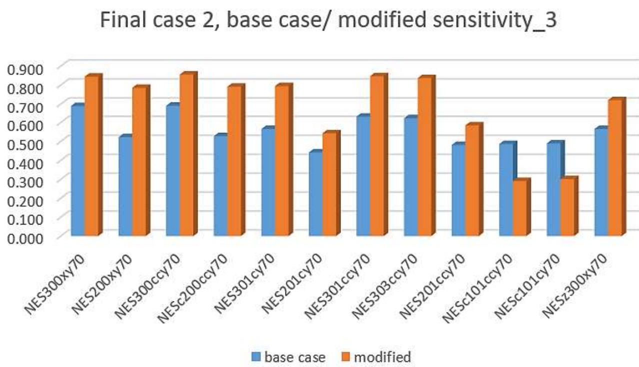
FIG. 3.101. KIND-ET scores in final case 2 (base case, cost - 10%, performance - 80%, acceptability -10%) for: (a) high-level objectives, (b) MAVF.



(a)



(b)

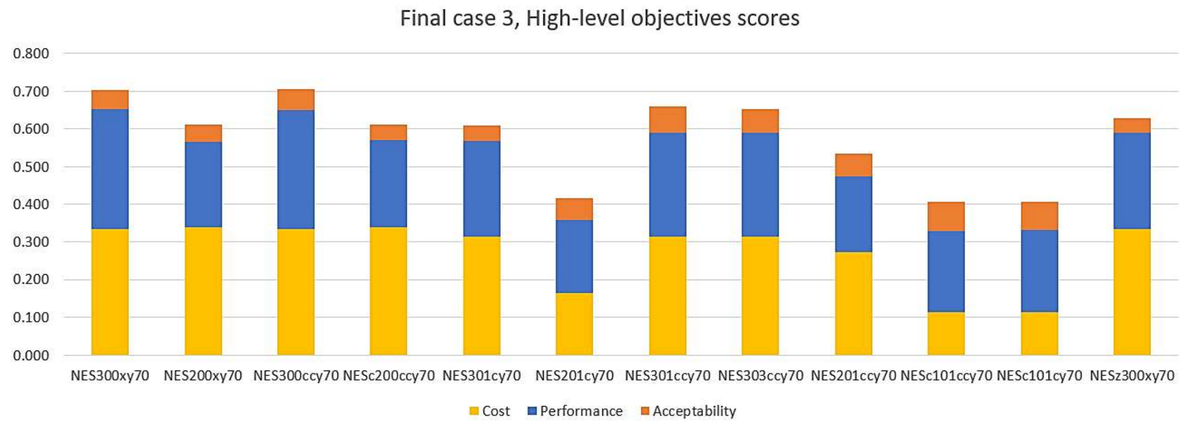


(c)

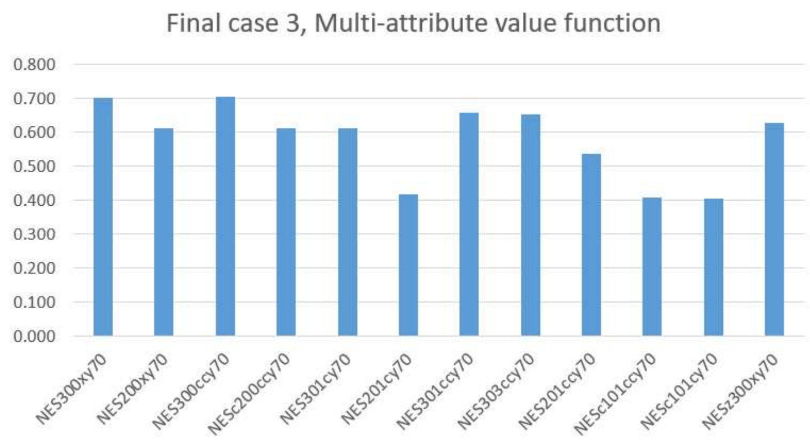
	1	2	3	4	5	6	7	8	9	10	11	12
base case	2.0000	8.0000	1.0000	7.0000	5.0000	12.0000	3.0000	4.0000	11.0000	10.0000	9.0000	6.0000
Weights sesitivity 1	1.0000	7.0000	2.0000	8.0000	6.0000	11.0000	4.0000	5.0000	9.0000	10.0000	12.0000	3.0000
Weights sensitivity 2	4.0000	7.0000	1.0000	5.0000	6.0000	9.0000	2.0000	3.0000	8.0000	12.0000	11.0000	10.0000
Weights sensitivity 3	3.0000	7.0000	1.0000	6.0000	5.0000	10.0000	2.0000	4.0000	9.0000	12.0000	11.0000	8.0000

(d)

FIG. 3.102. KIND-ET scores in final case 2 (base case, cost – 10%, performance – 80%, acceptability – 10%): (a) base case/ modified sensitivity_1, (b) sensitivity_2, (c) sensitivity_3, (d) screenshot of weight sensitivity table from KIND-ET.

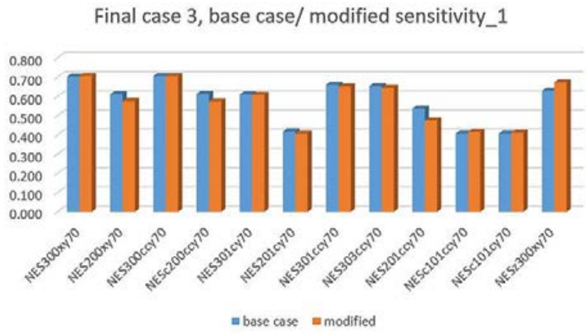


(a)

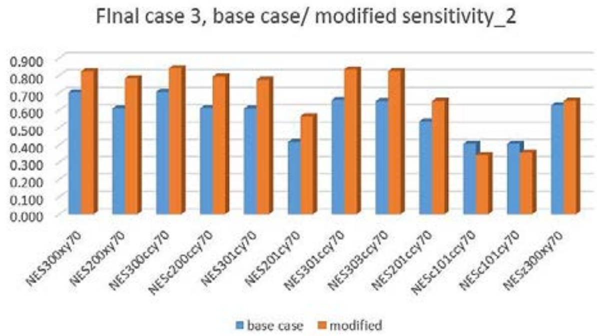


(b)

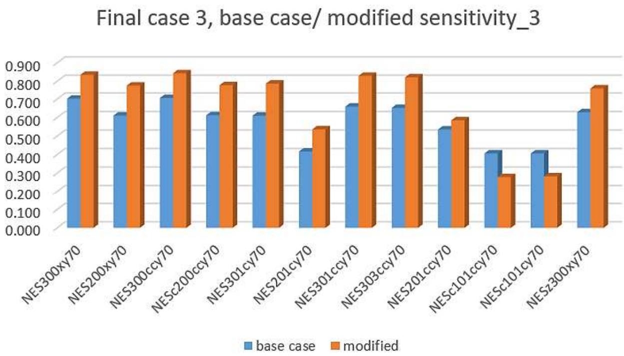
FIG. 3.103. KIND-ET scores in final case 3 (base case, cost and performance both 45%; acceptability 10%) for: (a) high-level objectives, (b) MAVF.



(a)



(b)

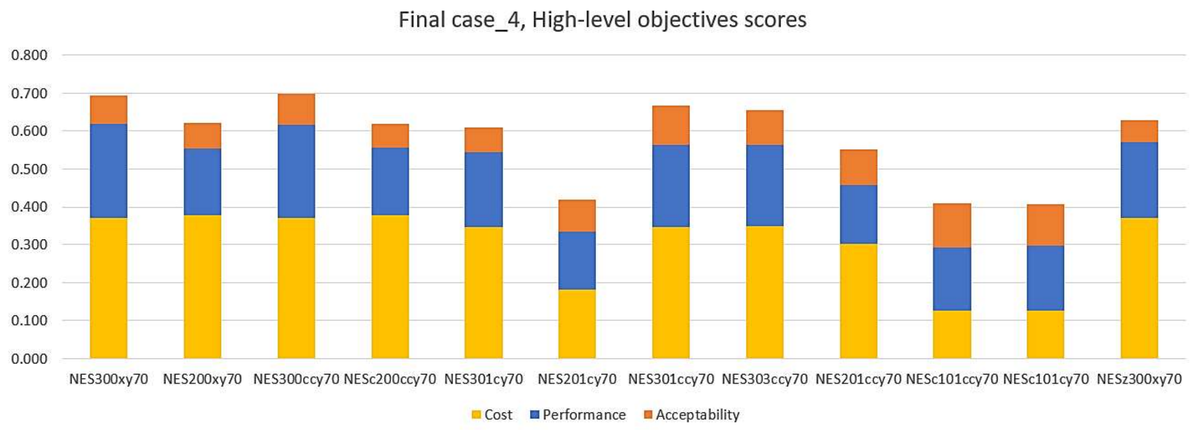


(c)

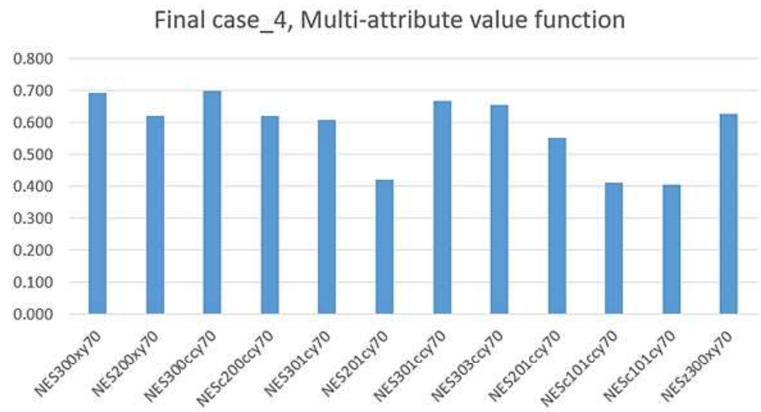
	1	2	3	4	5	6	7	8	9	10	11	12
base case	2.00000	7.00000	1.00000	6.00000	8.00000	10.00000	3.00000	4.00000	9.00000	11.00000	12.00000	5.00000
Weights sesitivity 1	1.00000	7.00000	2.00000	8.00000	6.00000	12.00000	4.00000	5.00000	9.00000	10.00000	11.00000	3.00000
Weights sensitivity 2	4.00000	6.00000	1.00000	5.00000	7.00000	10.00000	2.00000	3.00000	9.00000	12.00000	11.00000	8.00000
Weights sensitivity 3	2.00000	7.00000	1.00000	6.00000	5.00000	10.00000	3.00000	4.00000	9.00000	12.00000	11.00000	8.00000

(d)

FIG. 3.104. KIND-ET scores in final case 3 (cost and performance both 45%, acceptability – 10%): (a) base case/ modified sensitivity_1, (b) sensitivity_2, (c) sensitivity_3, (d) screenshot of weight sensitivity table from KIND-ET.

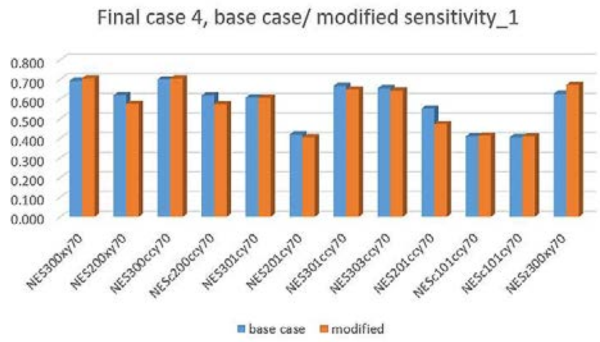


(a)

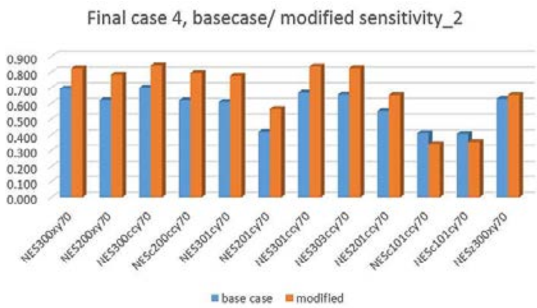


(b)

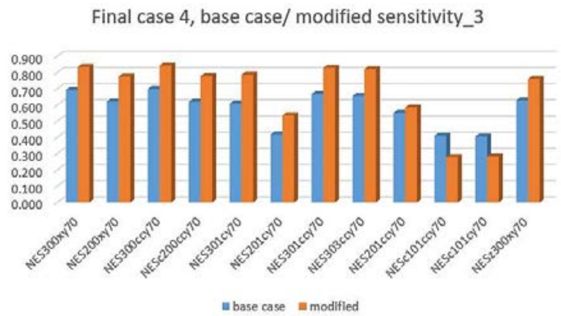
FIG. 3.105. Scores in KIND-ET final case 4 (base case, cost - 50%, performance - 35%, acceptability -15%) for: (a) high-level objectives, (b) MAVF.



(a)



(b)



(c)

	1	2	3	4	5	6	7	8	9	10	11	12
base case	2.00000	6.00000	1.00000	7.00000	8.00000	10.00000	3.00000	4.00000	9.00000	11.00000	12.00000	5.00000
Weights sesitivity 1	1.00000	7.00000	2.00000	8.00000	6.00000	12.00000	4.00000	5.00000	9.00000	10.00000	11.00000	3.00000
Weights sensitivity 2	4.00000	6.00000	1.00000	5.00000	7.00000	10.00000	2.00000	3.00000	9.00000	12.00000	11.00000	8.00000
Weights sensitivity 3	2.00000	7.00000	1.00000	6.00000	5.00000	10.00000	4.00000	3.00000	9.00000	11.00000	12.00000	8.00000

(d)

FIG. 3.106. KIND-ET scores in final case 4 (base case, cost - 50%, performance - 35%, acceptability -15%): (a) base case/ modified sensitivity_1, (b) sensitivity_2, (c) sensitivity_3, (d) screenshot of weight sensitivity table from KIND-ET.

This result can be explained considering the ‘Key Indicators Tree Structure’ (Fig. 3.90) in which more 'Indicators' values generate a multi attribute score in an 'Area' of assessment and more 'Areas' scores generate a multi attribute score in a HLO (the multi attribute value function is generated by the sum of the products between the particular weights and KIs in the corresponding Areas of evaluation). In this respect, it is logical that if a KI is prioritized into the local domain approach, it is necessary to also prioritize the corresponding AE and the HLO in the Objective Tree Structure. Otherwise, the result is confusing.

In this respect, the coherence in the Final case 1 is realized by including the KI E1 into the ‘Economics’ AE that is included under the ‘Costs’ HLO, prioritized with 80% comparatively with the other two HLOs.

3.8.8. Application of the KIND-ET extensions – performance of sensitivity/ uncertainty analysis

In the next step the objective tree structure effect in the resulted options in the base case of KIND-ET versus the case of using the mean value of more than 10,000 different weighting spread of the KIs normalized values provided by the table of ‘Single attribute functions’ from KIND-ET is examined.

In order to perform this study, the ‘Overall Score Spread Builder – Score Evaluator’ is applied. That is an express Excel-based tool extending the KIND-ET functionality for evaluations of option overall score spreads caused by uncertainties in weighting factors of the KIs' normalized values, provided in KIND-ET from the ‘Single attribute value functions’ worksheet, both for the ‘MESSAGE quantitative values’ and for the ‘qualitative indicators’ used as input data in the ‘Performance table’ of KIND-ET.

The results for ‘MESSAGE quantitative values’ are shown in Figs 3.107 and 3.108 and for ‘qualitative indicators’ are shown in Figs 3.109 and 3.110.

	NES300xy70	NES200xy70	NES300ccy70	NESc200ccy7(	NES301cy70	NES201cy70	NES301ccy70	NES303ccy70	NES201ccy70	NESc101ccy7(	NESc101cy70	NESz300xy70
Mean	0.60102	0.50679	0.63405	0.49275	0.48536	0.46205	0.67226	0.62702	0.56306	0.60879	0.57798	0.49871
Standart deviation (SD	0.22385	0.28453	0.2474	0.24767	0.25628	0.24913	0.25036	0.24526	0.23236	0.29614	0.30024	0.23364
Maximum value (Max	0.94656	0.96468	0.97415	0.91673	0.90701	0.84516	0.98531	0.97358	0.92765	0.96152	0.96071	0.88306
Quartile (Q3, 75%)	0.79315	0.74869	0.84851	0.657	0.68809	0.66188	0.87972	0.83489	0.72308	0.86783	0.85317	0.67876
Median	0.58732	0.49736	0.66883	0.50353	0.47641	0.48066	0.72132	0.65235	0.5807	0.688	0.62143	0.48863
Quartile (Q1, 25%)	0.43502	0.26528	0.43344	0.31738	0.3042	0.24218	0.51246	0.43952	0.41906	0.3673	0.33308	0.31391
Minimum value (Min)	0.25112	0.06071	0.22462	0.07569	0.05261	0.06336	0.16148	0.17951	0.12625	0.07024	0.04319	0.13447
Calculations for chart					Base case 1 and Base case 2							
Bottom	0.43502	0.26528	0.43344	0.31738	0.3042	0.24218	0.51246	0.43952	0.41906	0.3673	0.33308	0.31391
2 Q Box	0.15229	0.23208	0.23538	0.18615	0.17222	0.23849	0.20886	0.21283	0.16163	0.32071	0.28835	0.17472
3 Q Box	0.20583	0.25133	0.17968	0.15347	0.21168	0.18122	0.1584	0.18254	0.14239	0.17982	0.23174	0.19013
Whisker -	0.1839	0.20457	0.20882	0.24169	0.25158	0.17881	0.35098	0.26001	0.29281	0.29705	0.28988	0.17944
Whisker +	0.15341	0.21599	0.12564	0.25973	0.21892	0.18327	0.10559	0.13869	0.20457	0.09369	0.10753	0.20431

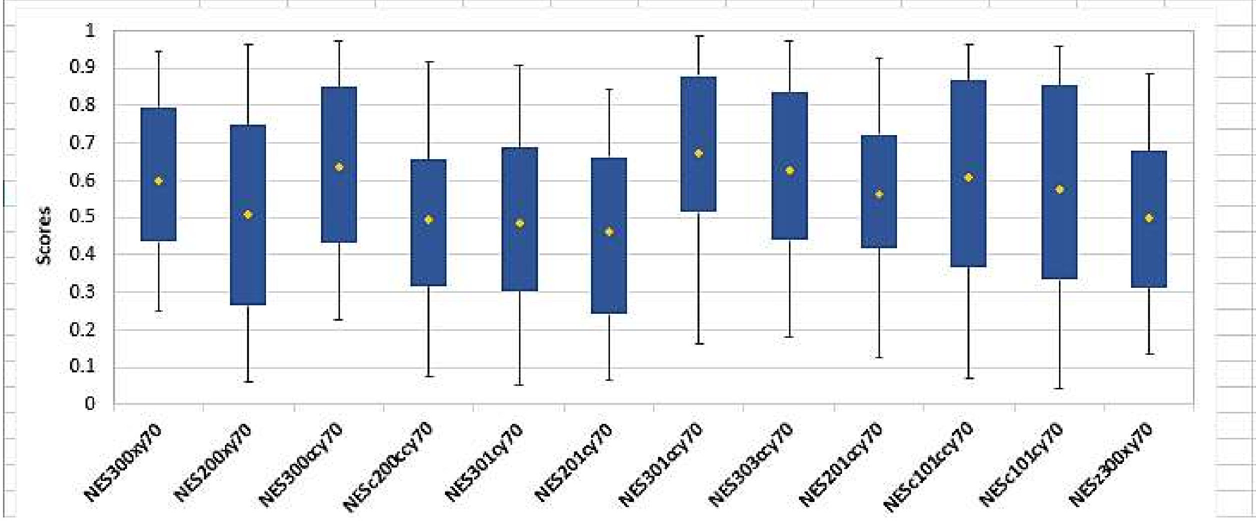


FIG. 3.107. Screenshot from the Overall Score Spread Builder: score evaluator results for base cases 1 and 2 and final cases 1 to 4 (MESSAGE quantitative values).

		NES300xy70	NES200xy70	NES300ccy70	NESc200ccy70	NES301cy70	NES201cy70	NES301ccy70	NES303ccy70	NES201ccy70	NESc101ccy70	NESc101cy70	NESz300xy70
1st - sel.	Final case 1 to 4	2	3	1	4	8	10	6	7	9	11	12	5
	Mean	5	8	2	10	11	12	1	3	7	4	6	9
	Base case 1 and 2	3	5	2	8	7	12	1	4	9	10	11	6
values	Final case 1 to 4	0.648754	0.568375	0.664702	0.560284	0.560682	0.455323	0.668847	0.640651	0.557457	0.504169	0.490689	0.565117
	Mean	0.601024	0.506789	0.634054	0.492747	0.485358	0.462052	0.672262	0.627023	0.563061	0.608789	0.57798	0.498712
	Base case 1 and 2	0.714062	0.699259	0.718771	0.697035	0.653834	0.390559	0.687397	0.68079	0.589418	0.326167	0.322264	0.690771
	Standart deviation (SD)	0.223846	0.284533	0.247395	0.247674	0.256285	0.249131	0.250357	0.245264	0.232362	0.296137	0.300241	0.233645

FIG. 3.108. Screenshot from the Overall Score Spread Builder: score evaluator results for base cases 1 and 2 and final cases 1 to 4 (MESSAGE quantitative values).

In the construction of the ‘Overall Score Spreading – Score Evaluator’ Excel file, the 'User Instructions for Extensions of KIND-ET' were used, including the tables provided by the ‘Overall Score Spreading – Weight Generator’ to generate the 10,000 weightings values matrix corresponding to the 15 KIs considered in this study. The ‘Overall Score Spreading – Score Evaluator’ excel files were extended to include the data provided by KIND-ET ‘Single attribute functions’ table for each of the 12 scenarios considered in the study, both for the ‘MESSAGE quantitative values’ and for the ‘qualitative indicators’ used as input data in the ‘Performance table’ worksheet of KIND-ET.

	NES300xy70	NES200xy70	NES300ccy70	NESc200ccy7	NES301cy70	NES201cy70	NES301ccy70	NES303ccy70	NES201ccy70	NESc101ccy7	NESc101cy70	NESz300xy70
Mean	0.54985	0.49661	0.68263	0.49384	0.36773	0.32703	0.62979	0.65334	0.5392	0.57171	0.50952	0.55293
Standart deviation (SD)	0.21995	0.26548	0.21549	0.21182	0.2163	0.23625	0.22631	0.19308	0.19579	0.26687	0.26157	0.21129
Maximum value (Max)	0.92523	0.94822	0.96527	0.88107	0.76054	0.8231	0.97357	0.95236	0.903	0.94088	0.91929	0.85421
Quartile (Q3, 75%)	0.72889	0.70288	0.85473	0.62496	0.50429	0.45652	0.80232	0.78999	0.6584	0.80314	0.70909	0.71708
Median	0.52509	0.4829	0.72426	0.47922	0.35632	0.25682	0.62944	0.66831	0.54864	0.60739	0.5394	0.58159
Quartile (Q1, 25%)	0.36136	0.28198	0.5406	0.36409	0.20856	0.14601	0.50699	0.53187	0.38756	0.35931	0.30548	0.4041
Minimum value (Min)	0.25078	0.08872	0.25942	0.12483	0.03432	0.05731	0.1965	0.33629	0.24902	0.1038	0.06016	0.16771
Calculations for chart					Base case 3 and Base case 4							
Bottom	0.36136	0.28198	0.5406	0.36409	0.20856	0.14601	0.50699	0.53187	0.38756	0.35931	0.30548	0.4041
2 Q Box	0.16372	0.20092	0.18365	0.11513	0.14776	0.11081	0.12245	0.13644	0.16108	0.24808	0.23392	0.17749
3 Q Box	0.20381	0.21999	0.13047	0.14574	0.14797	0.19969	0.17288	0.12168	0.10976	0.19574	0.16969	0.1355
Whisker -	0.11059	0.19327	0.28119	0.23927	0.17423	0.0887	0.3105	0.19557	0.13854	0.25551	0.24532	0.23638
Whisker +	0.19634	0.24534	0.11054	0.2561	0.25624	0.36658	0.17125	0.16237	0.2446	0.13774	0.2102	0.13712

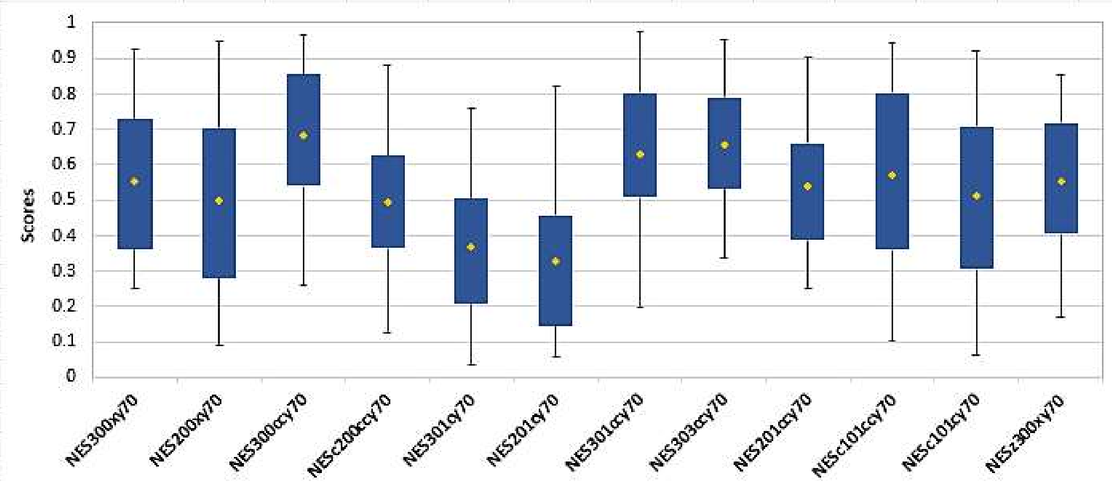


FIG. 3.109. Screenshot from the Overall Score Spread Builder: score evaluator results for base cases 3 and 4 (qualitative values).

		NES300xy70	NES200xy70	NES300ccy70	NESc200ccy70	NES301cy70	NES201cy70	NES301ccy70	NES303ccy70	NES201ccy70	NESc101ccy70	NESc101cy70	NESz300xy70
	Mean	6	9	1	10	11	12	3	2	7	4	8	5
1st - sel.	Base case 3 and 4	3	7	1	6	11	12	5	2	8	9	10	4
values	Mean	0.549853	0.496605	0.682632	0.493839	0.367728	0.327033	0.629788	0.65334	0.539203	0.571712	0.509525	0.552933
	Base case 3 and 4	0.623019	0.526875	0.707663	0.532325	0.399084	0.331003	0.584053	0.64856	0.48904	0.48403	0.453334	0.602516
	Standart deviation (SD)	0.223846	0.284533	0.247395	0.247674	0.256285	0.249131	0.250357	0.245264	0.232362	0.296137	0.300241	0.233645

FIG. 3.110. Screenshot from the Overall Score Spread Builder: score evaluator results for base cases 3 and 4 (qualitative values).

A short analysis of the results for this step shows that the ranks of the mean value of all 10,000 weighting values provided by the weight generator for the 12 scenarios considered is coherent with the results from the previous step which considered also the 15 Key Indicators into a tree structure aggregated in seven area of evaluation and three High Level Objectives only for the Base cases 1 to 4, and is totally different from the results provided for the Final cases 1 to 4:

- The first selected scenario is the same for Base case 1 to 4 (respectively the 7th scenario for Base case 1 and 2 and the 3rd scenario for Base case 3 and 4), and all the MAVF values for the considered scenarios are covered by the standard deviation for the correspondent mean values.
- The MAVF values of the first selected scenario are different for Final cases 1 to 4 (respectively 3rd scenario) and the scenarios standard deviation for the correspondent mean values do not cover all correspondent functions MAVF values.

In the next step of this study, it was proposed to examine the performance of the KIND-ET extension ‘Ranks Mapping Tool’ and the resulting information which can be useful for the expert specific study in order to provide the best selection approach to the decision makers.

As is specified in the 'User Instructions for Extensions of KIND-ET', the ‘Ranks Mapping Tool’ module/extension provides a map of the first options regarding the first scenario selected in the study, with respect to the results obtained by modifying the HLOs weights under an established objective tree structure with equal weights for the AEs and KIs.

For this step it is necessary to populate in the ‘HLO scores’ worksheet of 'Ranks Mapping Tool' with the data provided by the KIND-ET model on the ‘Ranking results’ worksheet for each HLO in maximal weighting (1) and in neglecting the others (weighting 0).

It is important to also observe that in this approach the obtained input matrix of HLOs is the same if the same input data (qualitative or quantitative) in the same approach (local or global) is used. Base case 1 and the Final cases 1 to 4 are conducted in the local approach and they have identical quantitative input data.

Base case 3 - NES options with the first rank

Weight for HLO-2 \ Weight for HLO-1	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
1	8										
0.9	8	3									
0.8	3	3	3								
0.7	3	3	3	3							
0.6	3	3	3	3	3						
0.5	3	3	3	3	3	3					
0.4	3	3	3	3	3	3	3				
0.3	3	3	3	3	3	3	3	1			
0.2	3	3	3	3	3	3	3	3	1		
0.1	3	3	3	3	3	3	3	3	1	1	
0	3	3	3	3	3	3	3	3	3	1	1

NES300xy70	1
NES200xy70	2
NES300ccy70	3
NESc200ccy70	4
NES301cy70	5
NES201cy70	6
NES301ccy70	7
NES303ccy70	8
NES201ccy70	9
NESc101ccy70	10
NESc101cy70	11
NESz300xy70	12

(a)

Base case 4 - NES options with the first rank

Weight for HLO-2 \ Weight for HLO-1	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
1	7										
0.9	7	3									
0.8	7	3	3								
0.7	7	3	3	3							
0.6	7	3	3	3	3						
0.5	7	3	3	3	3	3					
0.4	7	3	3	3	3	3	3				
0.3	7	3	3	3	3	3	3	1			
0.2	7	3	3	3	3	3	3	1	1		
0.1	7	8	3	3	3	3	3	3	1	1	
0	7	8	3	3	3	3	3	3	1	1	1

NES300xy70	1
NES200xy70	2
NES300ccy70	3
NESc200ccy70	4
NES301cy70	5
NES201cy70	6
NES301ccy70	7
NES303ccy70	8
NES201ccy70	9
NESc101ccy70	10
NESc101cy70	11
NESz300xy70	12

(b)

	1	2	3	4	5	6	7	8	9	10	11	12		
base case	3.000	5.000	2.000	8.000	7.000	12.000	1.000	4.000	9.000	10.000	11.000	6.000	(lin)	Base case 1
modified	4.000	5.000	2.000	6.000	7.000	12.000	1.000	3.000	9.000	10.000	11.000	8.000	(exp)	(local)
1st rank options	3.000	4.000	2.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	5.000	0.000	(lin)	Base case 1
assoc. ap. no.	10	1	23	0	0	0	25	0	0	0	6	0		(local)

(c)

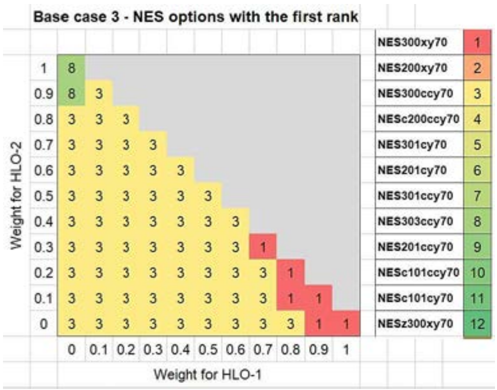
	1	2	3	4	5	6	7	8	9	10	11	12		
base case	5.000	4.000	2.000	7.000	8.000	9.000	1.000	3.000	6.000	10.000	11.000	12.000	(lin)	Base case 2
modified	5.000	4.000	2.000	6.000	8.000	10.000	1.000	3.000	7.000	9.000	11.000	12.000	(exp)	(local)
1st rank options	3.000	4.000	2.000	0.000	0.000	0.000	1.000	0.000	0.000	3.000	4.000	4.000	(lin)	Base case 2
assoc. ap. no.	0	0	23	0	0	0	29	0	0	12	1	1		(local)

(d)

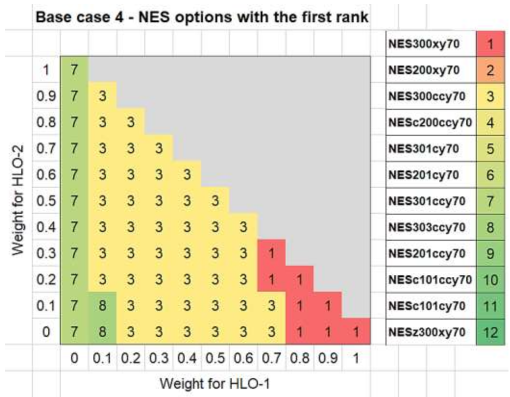
FIG. 3.111. Effect of supplementary HLO ranking into the high-level objective weight space for the same input data: (a) base cases 1 and final cases 1 to 4 (linear approach), (b) base case 2, (exponential approach), (c) screenshot from KIND-ET corresponding to case (a), (d) screenshot from KIND-ET corresponding to case (b).

With this important comment, the coherence between the KIND-ET results and the 'Ranks Mapping Tool' extension scores can be tested:

— First of all, if another set of input data in 'Ranks Mapping Tool' extension is used, different results are expected, but these results need to be coherent with the KIND-ET result for equal HLOs weighting; in this respect Fig. 3.112 analyses the results provided by KIND-ET and the 'Ranks Mapping Tool' extension for the Base case 3 and Base Case 4; the first selected scenario is the same (the 3rd scenario in Fig. 3.112), but different of the result provided by the Base case 1 and 2 and the Final cases 1 to 4 (the 7th scenario in Fig. 3.111).
— Second, for the first rank option provided by the KIND-ET base cases for KIs and AEs equal ranking and by the 'Ranks Mapping Tool' extension using the same input data, only the results obtained by Final case 1 and 2, including 10 % differences in HLOs ranking, can be compared (Fig. 3.113).
— Third, the MAVF results and the corresponding 'Ranks Mapping Tool' extension scores considering linear or exponential SAVF form can be compared (Fig. 3.112).



(a)



(b)

	1	2	3	4	5	6	7	8	9	10	11	12		
base case	3.000	7.000	1.000	6.000	11.000	12.000	5.000	2.000	8.000	9.000	10.000	4.000	(lin)	Base case 3
modified	3.000	6.000	1.000	7.000	11.000	12.000	5.000	2.000	9.000	8.000	10.000	4.000	(exp)	(local)
1st rank options	3.000	0.000	1.000	0.000	0.000	0.000	0.000	3.000	0.000	0.000	0.000	0.000	(lin)	Base case 3
assoc. ap. no.	6	0	55	0	0	0	0	2	0	0	0	0		(local)

(c)

base case	3.000	7.000	1.000	6.000	10.000	12.000	4.000	2.000	9.000	8.000	11.000	5.000	(lin)	Base case 4
modified	2.000	6.000	1.000	7.000	9.000	12.000	4.000	3.000	10.000	8.000	11.000	5.000	(exp)	(local)
1st rank options	3.000	0.000	1.000	0.000	0.000	0.000	2.000	4.000	0.000	0.000	0.000	0.000	(lin)	Base case 4
assoc. ap. no.	8	0	45	0	0	0	2	2	0	0	0	0		(local)

(d)

FIG. 3.112. Effect of supplementary HLOs ranking into the high-level objective weight space for: (a) base case 3, (b) base case 4 (both using linear and exponential form of SAVF), (c) screenshot of KIND-ET table corresponding to case (a), (d) screenshot of KIND-ET table corresponding to case (b).

Base case 3 - NES options with the first rank

Weight for HLO-2 \ Weight for HLO-1	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
1	8										
0.9	8	3									
0.8	3	3	3								
0.7	3	3	3	3							
0.6	3	3	3	3	3						
0.5	3	3	3	3	3	3					
0.4	3	3	3	3	3	3	3				
0.3	3	3	3	3	3	3	3	1			
0.2	3	3	3	3	3	3	3	3	1		
0.1	3	3	3	3	3	3	3	3	1	1	
0	3	3	3	3	3	3	3	3	3	1	1

NES300xy70	1
NES200xy70	2
NES300ccy70	3
NESc200ccy70	4
NES301cy70	5
NES201cy70	6
NES301ccy70	7
NES303ccy70	8
NES201ccy70	9
NESc101ccy70	10
NESc101cy70	11
NESz300xy70	12

(a)

Base case 4 - NES options with the first rank

Weight for HLO-2 \ Weight for HLO-1	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
1	7										
0.9	7	3									
0.8	7	3	3								
0.7	7	3	3	3							
0.6	7	3	3	3	3						
0.5	7	3	3	3	3	3					
0.4	7	3	3	3	3	3	3				
0.3	7	3	3	3	3	3	3	1			
0.2	7	3	3	3	3	3	3	1	1		
0.1	7	8	3	3	3	3	3	3	1	1	
0	7	8	3	3	3	3	3	3	1	1	1

NES300xy70	1
NES200xy70	2
NES300ccy70	3
NESc200ccy70	4
NES301cy70	5
NES201cy70	6
NES301ccy70	7
NES303ccy70	8
NES201ccy70	9
NESc101ccy70	10
NESc101cy70	11
NESz300xy70	12

(b)

	1	2	3	4	5	6	7	8	9	10	11	12		
base case	3.000	7.000	1.000	6.000	11.000	12.000	5.000	2.000	8.000	9.000	10.000	4.000	(lin)	Base case 3
modified	3.000	6.000	1.000	7.000	11.000	12.000	5.000	2.000	9.000	8.000	10.000	4.000	(exp)	(local)
1st rank options	3.000	0.000	1.000	0.000	0.000	0.000	0.000	3.000	0.000	0.000	0.000	0.000	(lin)	Base case 3
assoc. ap. no.	6	0	55	0	0	0	0	2	0	0	0	0		(local)

(c)

base case	3.000	7.000	1.000	6.000	10.000	12.000	4.000	2.000	9.000	8.000	11.000	5.000	(lin)	Base case 4
modified	2.000	6.000	1.000	7.000	9.000	12.000	4.000	3.000	10.000	8.000	11.000	5.000	(exp)	(local)
1st rank options	3.000	0.000	1.000	0.000	0.000	0.000	2.000	4.000	0.000	0.000	0.000	0.000	(lin)	Base case 4
assoc. ap. no.	8	0	45	0	0	0	2	2	0	0	0	0		(local)

(d)

FIG. 3.113. Ranks Mapping Tool presentation for all scenarios: (a) base case 3, (b) base case 4; KIND_ET tables for: (c) MAVF for the final case 1, (d) MAVF for the final case 2, screenshots from KIND-ET.

3.8.9. Conclusions

This case study was prepared to explore the KIND-ET tool's capabilities to support the expert analysis related to the global and specific effect of the political decisions in the best scenario selected for developing a NEMix that include traditional nuclear and renewable technologies in order to fit with the long term national energy demand (electricity and heat), established by using the MAED tool. The annual demand curve is divided in 32 load regions in order to take into consideration the variable production evolution for electricity provided by the Hydro, Solar PV and Wind Farm technologies.

Twelve different scenarios were prepared using the optimal solution found by using the MESSAGE tool for different options related to a defined basic matrix of technical and economic parameters for a diverse, well-balanced NEMix (National Energy Mix) including 60 technologies, as follows:

- Classical coal, lignite and gas power plants to produce electricity and combined heat and power plants (CHP);
- Hydro power plants;
- Nuclear technologies (CANDU, advanced HWRs and advanced PWRs);
- Renewable technologies (solar PV and wind farms);
- Transport and distribution technologies for electricity and heat including district heat accumulators and hot water boilers (HWB);
- A hydro pumping-storage system, spent fuel storages and transport;
- Spent fuel technologies, import and export technologies, and additional technologies.

Based on quantitative technical and economic data and on the INPRO NESA basic principles, MESSAGE optimal solutions were used by the experts to provide a quantitative set of values associated with 15 KIs. This set of indicators was structured also by the expert judgement in a quantitative matrix that ordered the indicator values for each of the 12 scenarios in the scale of 1 to 12. The two sets of indicators were used as different inputs in the KIND-ET analysis for the first selected scenario, based on an Objective Tree Structure composed by three HLOs, seven Areas of Evaluation and 15 KIs. Equal or different weights for the 'HLOs', 'AEs' and 'KIs' were considered according to potential political decisions.

The KIND-ET extension Domination Identifier was used first to identify if there is a scenario which can be considered dominant or dominated in the system. For both sets of input data (quantitative and qualitative) it was found that NES301ccy70 (with no subvention in District Heat Grid Rehabilitation), the 7th scenario, is a dominant scenario for NES301cy70 (with 50% subvention in District Heat Grid Rehabilitation), the 5th scenario.

The first conclusion is for the decision makers: in this specific NEMix government subventions in District Heat Grid Rehabilitation are not a benefit for the system.

In the next steps of the study, the best approach to use the KIND-ET tool and other 2 extensions (Overall Score Spread Builder – Score Evaluator and Ranks Mapping Tool) was identified in order to provide the best advice to the decision makers.

Four 'Base cases' (1 to 4) were conducted in order to identify the sensitivity of the scenario selection into the KIND-ET setting (local and global domain and linear and exponential form of SAVF approaches) versus the format of input data (quantitative or qualitative values).

The second conclusion is for the experts: in this specific NEMix, the sensitivity is the highest for the MESSAGE calculated quantitative parameters in the local domain approach. The linear or exponential form of SAVF does not change the first and the last scenario selected. This observation can be extended to all types of input data generated by an optimization modelling procedure based on logical correlation with technical, economic, technological and environmental restrictions.

In the third step of the study the best approach to prioritize the HLOs, Areas of Evaluation and Key Indicators in the KIND-ET tool as support of expert advice given to the political decision makers was examined. Four 'Final cases' (1 to 4) were used considering the quantitative set of input data and the specific base cases with different weights for HLOs using local domain and linear form of SAVF, and with equal and different weights in 'Areas of Evaluation' and 'Key Indicators'.

The third conclusion is for the experts: into the local domain approach of SAVF, the coherence of all 'case studies' will be done only if, in the 'Objective Tree Structure', all the 'Key Indicators' and the correspondent 'Areas of Evaluation' and HLOs are prioritized. Otherwise, the result is confusing. Different options on the HLOs, Areas and Key Indicators weighting can be used in KIND-ET to provide to the decision makers the best advice on the first scenario selected.

In the fourth step of the study, the objective tree structure effect was investigated regarding the resulted options in ranking the resulting the scenarios scores provided into the base case by KIND-ET versus the ranking of mean values of the scenarios scores provided by the 'Overall Score Spread Builder – Score Evaluator' of KIND-ET extension, for the same established matrix for the input data.

The fourth conclusion is for the experts: the standard deviation (SD) of the main values from the 'Overall Score Spread Builder – Score Evaluator' covers all the 'Multi attribute value functions' (MAVF) provided by KIND-ET in the base case with equal weights for HLOs, AEs and KIs. In these cases, the first scenario selected (with the maximal value of MAVF) is the same for all cases that used the same set of input data. The first scenario selected will be different if a different set of input data (the 7th scenario for MESSAGE quantitative values and the 3rd scenario for qualitative values, respectively) is used. The 'Overall Score Spread Builder – Score Evaluator' main values standard deviation (SD) do not cover all the 'Multi attribute value functions' provided by KIND-ET in the base case with different weights for HLOs, AEs and KIs. In these cases, the first scenario selected is not the same for the same set of input data.

In the fifth step of the study, the performance of the KIND-ET extension 'Ranks Mapping Tool', and which information can be useful for the expert specific study in order to provide the best selection approach to the decision makers, were studied.

The fifth conclusion is for the experts: the 'Rank Mapping Tool' provides an easy understandable graphic chart regarding the first scenario selected considering the specific Objective Tree structure with different weights for the HLOs, and equal weights for the AEs and KIs. The scenarios with the best associated apparition number (assoc. ap. no.) in 'The first rank option' of 'Rank Mapping Tool' excel sheet is the same with the first selected scenario in the 'Multi attribute value functions' (MAVF) provided by KIND-ET in base case with equal weights for HLOs, AEs and KI.

The sixth conclusion is for experts: If there are only 10 % differences in HLOs ranking and if equal weightings for AEs and KIs are used, the coherence between the result provided by

KIND-ET MAVF and the ‘The Rank Mapping Tool’ scenarios scores is verified. This coherence is verified for two different HLOs, in linear approach, respectively for 80/10/10 (Final case 1) and 10/80/10 (Final case 2); remembering that the first scenario selected is the same for the same input data and for relatively large differences in HLOs ranking, but the last scenario selected is more sensitive and can be different for different HLOs ranking. In all the cases the coherence between KIND-ET MAVF and the ‘The Rank Mapping Tool’ scenarios scores are fully verified.

The seventh conclusion is for the decision makers: in this specific NEMix, the most preferred scenario is different if different input data in KIND-ET ‘Performance table’ is used. These data generate corresponding also different inputs for the KIND-ET extensions, but the result provided by the KIND-ET and their extensions are coherent if the same weightings in the tree structure for HLOs, AEs and KIs are used.

For this reason, the most preferred scenario can be affected by the political option in the weighting HLOs, AEs and KIs but the stability of the result is done by the MAVT in the KIs tree structure. After using in Overall Score Spread Builder – Score Evaluator 10,000 HLOs different weightings, the analysis of the inputs provided by KIND-ET Single Attribute Value Function (SAVF) table can begin; these inputs are different for the same ‘Performance table’ in same approach for the Base case 1 and 2 (that used equal HLOs weightings) versus all the Final cases 1 to 4 that used different HLOs weightings).

The main values provided by Overall Score Spread Builder – Score Evaluator are affected by the HLOs initial different weightings. In this respect it can be concluded that the most neutral approach is to use the Base case 1 and Base case 2 input data. In this neutral approach the 7th scenario is the best.

The differences between Performance table value from Base cases 1 and 2 and Base cases 3 and 4 are generated by a supplementary expert ranking of the KIs value provided quantitative by the MESSAGE optimisation. The final ‘neutral’ results approach provided for the best scenario by Overall Score Spread Builder – Score Evaluator, respectively the 3rd scenario, is not so ‘neutral’ because it includes an initial qualitative expert ranking.

It is also important to remember that the 7th scenario is different to the 3rd scenario only in the limit of the maximal contribution of the solar and wind farm technologies to 1/3 of the total availability of the country resource until the final year of the modelling period (2070). Therefore, the selected final energy mix cannot be substantially different for the 2 scenarios.

This is the reason why the selection between the two scenarios will be different using different weighting in the HLOs; this affirmation is sustained by the results provided by Ranks Mapping Tool extensions in ‘The first rank option’ table: only for equal weighting of HLOs the 7th scenario is preferred; all different raking for Economics and Performance HLOs will provide the 3rd scenario as winner; This scenario will be also preferred for a large area of HLOs weightings in the HLOs (20% to 80%) if the qualitative ranking of MESSAGE quantitative optimal values for KIs are used as input. After consideration by the experts, the final option to select the most suitable scenario (7th or 3rd from the 12 scenarios proposed) will be only the political makers’ decision.

3.9. COMPARATIVE EVALUATION OF RUSSIAN NUCLEAR ENERGY DEPLOYMENT SCENARIOS WITH FAST AND THERMAL REACTORS IN CLOSED NUCLEAR FUEL CYCLE (RUSSIAN FEDERATION)

This chapter presents structured report of the first of the four case studies done by experts from the Russian Federation.

3.9.1. Introduction

This section provides the results of a case study on a comparative evaluation of Russian nuclear energy deployment scenarios with water cooled thermal reactors and sodium-cooled fast reactors in the closed nuclear fuel cycle (the so-called ‘two-component NES’). The performed analysis is based on the extensively utilized IAEA/INPRO approach for carrying out comparative evaluations of NES options, including advanced uncertainty treatment in regard to weighing factors. The comparative analysis considered 10 possible Russian nuclear energy deployment scenarios with different shares of water cooled thermal reactors and sodium-cooled fast reactors, including options involving the use of MOX fuel in VVERs. The scenario analyses involved eight key indicators arranged in a three-level objective tree and were conducted to the year 2100. The comparative evaluations and rankings were carried out based on the multi attribute value theory according to the KIND approach and utilizing the KIND-ET tool and its extensions. The model for assessing the key indicators was elaborated using the IAEA/INPRO nuclear energy planning tool – MESSAGE-NES. The information base of the study was formed by publications of experts from the Joint Stock Company ‘State Scientific Centre of Russian Federation Institute of Physics and Power Engineering’ (JSC SSC RF-IPPE), National Research Centre ‘Kurchatov Institute (NRC Kurchatov Institute) and National Research Nuclear University Moscow Engineering Physics Institute (NRNU MEPhI). The presented results suggest that the Russian NES sustainability can be substantially enhanced by the intensive deployment of sodium-cooled fast reactors and transition to the closed nuclear fuel cycle. Some problems are also outlined for further considerations with a view to obtaining more rigorous conclusions about preferred options for the national two-component NES development.

3.9.2. Objective and problem formulation

The starting point in discussing possible ways of developing nuclear energy is usually the option of extensive development of the existing NES with thermal reactors and a once-through nuclear fuel cycle as the most mature and affordable technology for the moment. There are several reasons to believe that thermal reactors will retain a significant share in the national nuclear energy sector at least until the end of this century. This is due to the fact that the lifetime of the present nuclear power units with thermal reactors reaches 60 years and, in the future, through the use of new materials, it can be extended to 100 years. However, the implementation of a NES with only thermal reactors and a once-through nuclear fuel cycle does not solve the problems associated with the nuclear energy supply, accumulated and expected in the next decades. In the future, this will worsen the overall situation in the nuclear industry due to the growing problems with the resource supply, spent nuclear fuel, radioactive waste management, economics and some others, which will inevitably lead to a deterioration in public attitudes to nuclear technologies. The combination of these factors has already led to the fact that some countries have significantly limited their nuclear power programmes, and some others have completely abandoned the use of nuclear energy.

In the Russian Federation, the deployment of a two-component NES is considered as one of the possible ways to solve the problems of nuclear power. This two-component NES is based on the joint operation of pressurized light water reactors and sodium-cooled fast reactors in one system (see, Fig.3.114–3.115). Possible configurations of this NES are widely discussed. Two-component NESs at various stages of their development may include thermal reactors with uranium oxide fuel, thermal reactors with partial or full loading of mixed uranium-plutonium oxide fuel (MOX) and sodium-cooled fast reactors with MOX fuel [3.36–3.39]. All reactors in the system can be linked by a single closed nuclear fuel cycle in which the processed spent fuel products from some reactors are used to produce fresh fuel for other reactors.

The various possible configurations of a two-component NES have certain similarities and differences, advantages and disadvantages, quantified through key performance indicators and characterized by resource consumption, economics, material flows in the nuclear fuel cycle, etc. In this context, it becomes an urgent task to carry out a comparative analysis and ranking of the most representative and probable scenarios for developing the national two-component NES with thermal and fast reactors using the multi-criteria decision analysis framework. It will make it possible to compare costs, risks and benefits associated with each option on the quantitative basis and provide advice regarding the most effective ways to enhance the national nuclear energy sustainability. This study presents the results of such a trial analysis using the IAEA/INPRO tools and elaborates suggestions for carrying out scenario analyses and comparative evaluations of the NES development options.

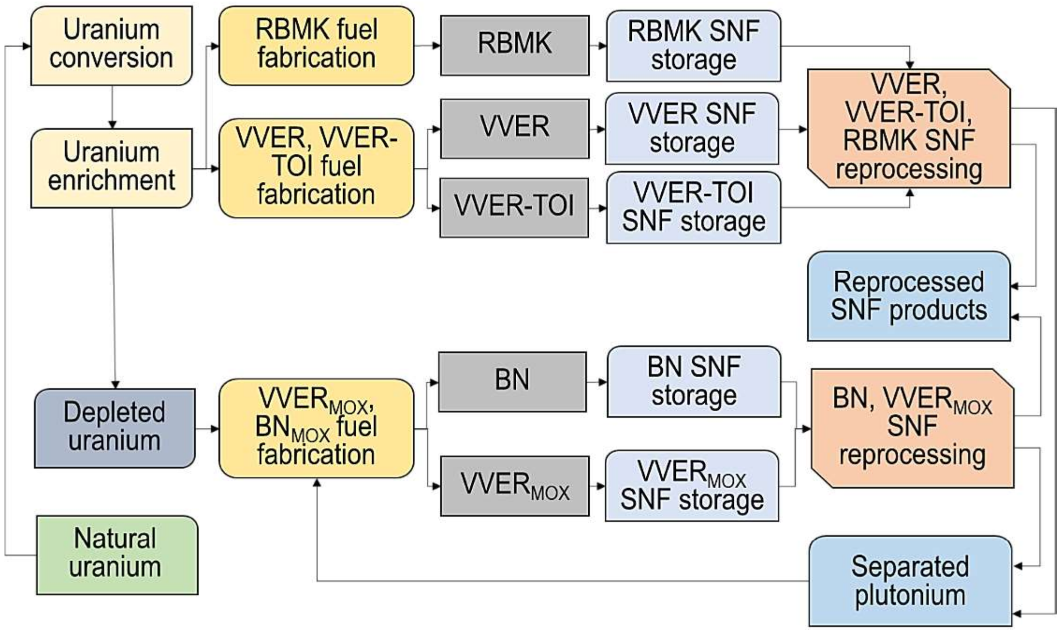


FIG. 3.114. A two-component NES and relevant nuclear fuel cycle.

While performing a comparative analysis and ranking of NES deployment scenarios within the multi-criteria decision analysis framework, it is necessary to solve these three main problems [3.3, 3.7, 3.40, 3.41]:

- To develop and implement a NES model that would consider the expected growth rates of electricity production and describe the main elements of the industrial infrastructure, including nuclear reactors and fuel cycle facilities with specified technical and economic parameters;
- To propose and evaluate key performance indicators characterizing the economics, uranium consumption, required capacities of fuel cycle facilities, amounts of spent fuel and radioactive waste, secondary fissile materials in the fuel cycle, etc.;

– To develop and implement a decision support model including an uncertainty/sensitivity analysis.

The decision support model can be based, for example, on the multi-criteria decision analysis methods, where the initial data are the scenario analysis results, i.e., values of the key indicators for each of the considered NES options. Using this model, supplemented with data on the experts/decision makers' preferences, it is possible to perform a comparative analysis and ranking of the options under consideration. Considering the results of the sensitivity/uncertainty analysis of the main factors, this model can also help to identify the most effective directions to enhance the national nuclear energy sustainability.

In this case study, eight key performance indicators were calculated for 10 possible scenarios that were selected by experts for the national two-component NES deployment (see Table 3.56 and Fig.3.115). These scenarios include, in various proportions, thermal reactors (both with uranium fuel and with partial loading of MOX fuel) and sodium-cooled fast reactors with MOX fuel (Fig. 3.114). The calculations were performed using the IAEA/INPRO optimization nuclear energy planning tool – MESSAGE-NES [3.3, 3.7, 3.23, 3.40–3.44]. The IAEA/INPRO tools for carrying out comparative evaluations of NES options and sensitivity/uncertainty analyses with regard to weighting factors [3.3, 3.7, 3.43] were adapted for comparisons and rankings of the considered scenarios (namely, the KIND-ET tool and its extensions).

3.9.3. Inputs, methods and assumptions used

The following assumptions were considered as the expected growth of overall NES capacities: 35 GW in 2030, 55 GW in 2050 and 103 GW in 2100 [3.44]. The following reactor types were considered as candidates for the integration into the future national NES: VVER, VVER-TOI (modified VVER reactor with increased burnup), VVER-TOI MOX (modified VVER reactor with partial loading of MOX fuel) and BN-1200 (sodium-cooled fast reactor with MOX fuel). It was assumed that VVER and VVER-TOI could be commissioned from the first year of the forecast period, BN-1200 – from 2030 and VVERmox – from 2040. Table 3.56 presents 10 possible national NES deployment scenarios considered in this study, which can be divided into 3 groups according to the implemented fuel cycle strategies: once-through, partially closed and full closed fuel cycles.

TABLE 3.56. CONSIDERED SCENARIOS OF THE NATIONAL NES DEPLOYMENT.

Scenarios	Abbreviation	Comments
		Once-through NFC
Scenario 1	VVER (100%)	Share of VVER-TOI in the NES structure in 2100 – 100%
		Partly closed NFC
Scenario 2	VVERmox (10%)	Shares of VVER-TOI and VVERmox in the NES structure in 2100 – 90 and 10%, respectively
Scenario 3	VVERmox (30%)	Shares of VVER-TOI and VVERmox in the NES structure in 2100 – 70 and 30%, respectively
Scenario 4	VVERmox (50%)	Shares of VVER-TOI and VVERmox in the NES structure in 2100 – 50 and 50%, respectively
		Fully closed NFC
Scenario 5	BN (20%)	Shares of VVER-TOI and BN in the NES structure in 2100 – 80 and 20%, respectively
Scenario 6	BN (50%)	Shares of VVER-TOI and BN in the NES structure in 2100 – 50 and 50%, respectively
Scenario 7	BN (90%)	Shares of VVER-TOI and BN in the NES structure in 2100 – 10 and 90%, respectively
Scenario 8	VVERmox (10%) BN (20%)	Shares of VVER-TOI, VVERmox and BN in the NES structure in 2100 – 70, 10 and 20%, respectively
Scenario 9	VVERmox (50%) BN (20%)	Shares of VVER-TOI, VVERmox and BN in the NES structure in 2100 – 30, 50 and 20%, respectively
Scenario 10	VVERmox (10%) BN (50%)	Shares of VVER-TOI, VVERmox and BN in the NES structure in 2100 – 40, 10 and 50%, respectively

The features of the NES model are described in [3.44]. The service unit costs of fuel cycle services were taken from [3.36] (average values). Regarding the overnight cost of reactor installations, a conservative assumption has been made that the specific overnight capital cost of BN-1200 is 10% higher than that of VVER, the specific overnight capital cost of which is 4 000 $/kW. The discount rate was assumed to be 5% [3.36]. The calculations were carried out with due account for the history of nuclear power deployment in the Russian Federation and on the assumption that there are not any resource and infrastructure restrictions. The loads of fuel cycle facilities were determined based on the solution of the optimization problem (minimization of the total discounted costs for the whole deployment programme) on the condition that the NES structure reaches the target values specified in Table 3.56. The spent fuel cooling time for all reactor types before reprocessing is assumed to be 5 years, and the spent fuel reprocessing is to be realized in a centralized manner. The separated plutonium accumulated by 2015 (ex-weapon and reactor-grade plutonium) and plutonium contained in spent fuel are resources for producing nuclear fuel for fast reactors (the data were taken from [3.45]).

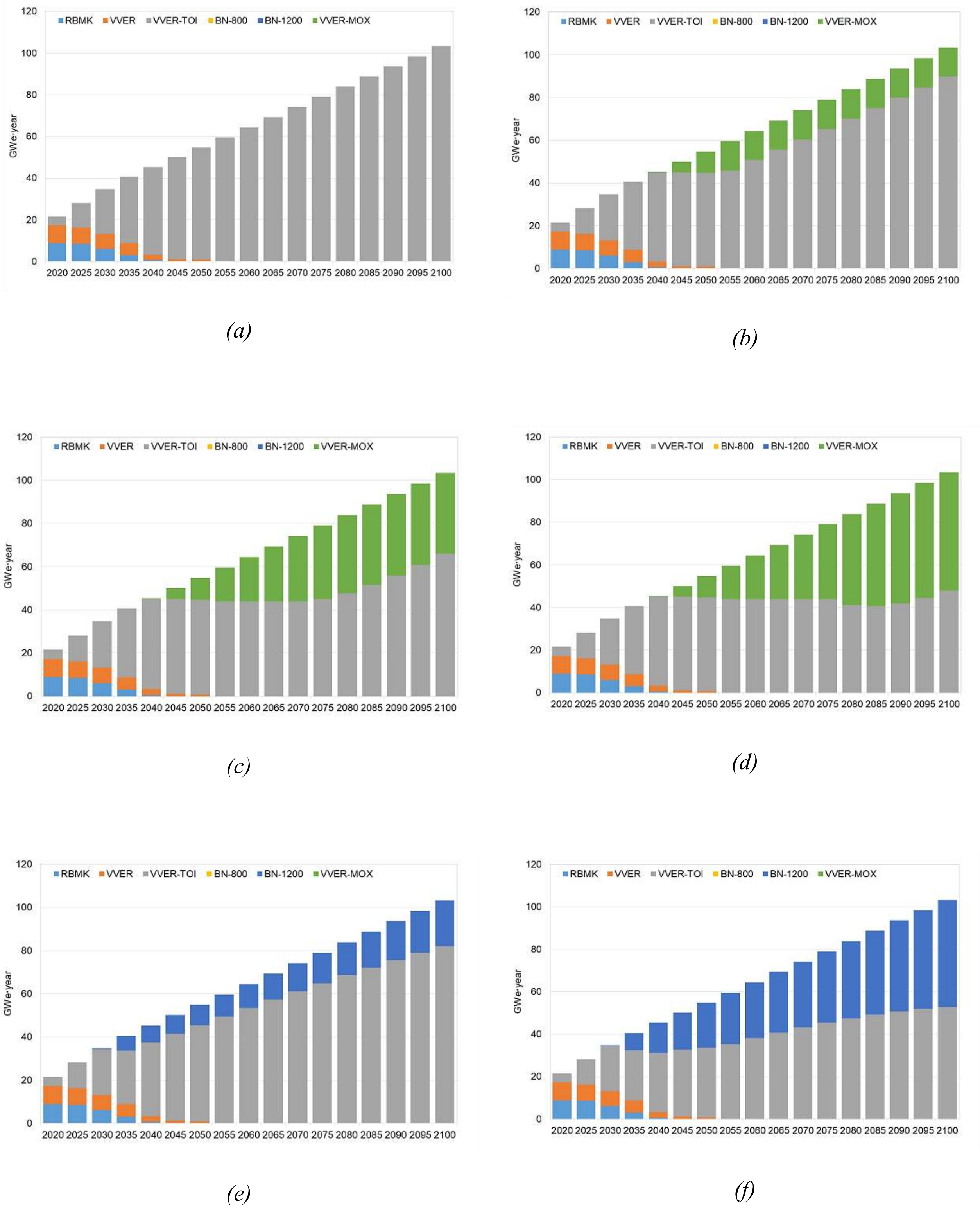
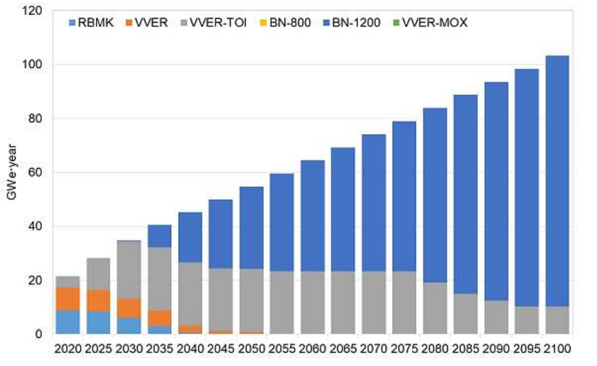
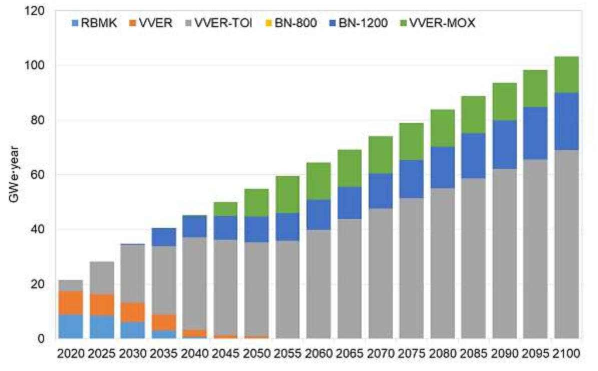


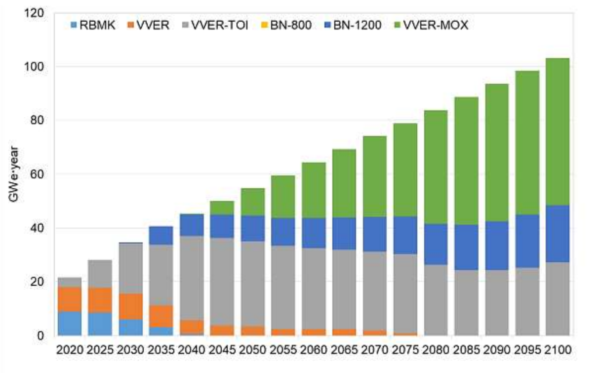
FIG. 3.115. NES options: (a) scenario 1 – VVER (100%), (b) scenario 2 – VVERmox (10%), (c) scenario 3 – VVERmox (30%), (d) scenario 4 – VVERmox (50%), (e) scenario 5 – FR (20%), (f) scenario 6 – FR (50%).



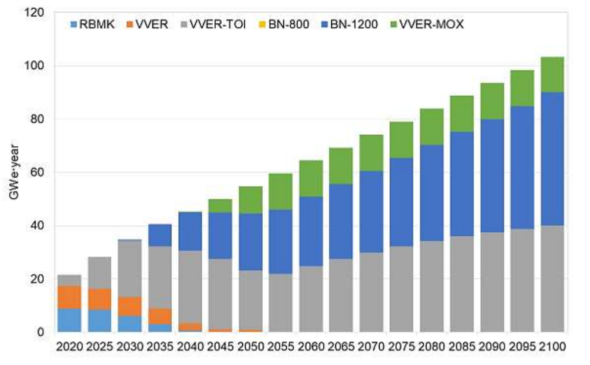
(g)



(h)



(i)



(j)

FIG. 3.116. NES options: (g) scenario 7 – FR (90%), (h) scenario 8 – VVERmox (10%) FR (20%), (i) scenario 9 – VVERmox (50%) FR (20%), (j) scenario 10 – VVERmox (10%) FR (50%).

Eight key indicators, estimated as of 2100, were used for the comparative evaluation, including cumulative natural uranium consumption, cumulative enrichment capacities, cumulative reprocessing capacities, spent fuel stocks, radioactive wastes, the amount of plutonium in the nuclear fuel cycle, the amount of accumulated depleted uranium, and the levelized generation cost (LGC). All the key indicators are to be minimized in order to obtain a higher overall score for the NES. All the key indicators were combined in five evaluation areas (resources, fuel cycle capacities, waste management, nuclear materials stocks, and economics) which belong to the three high-level objectives (resources, performance and economics) (see Fig. 3.117). The values of the indicators for the considered scenarios are given in Table 3.57 (all the scenarios are non-dominated, i.e., among the entire set of scenarios, there are no options that would be worse for at least one of the remaining scenarios for all indicators).

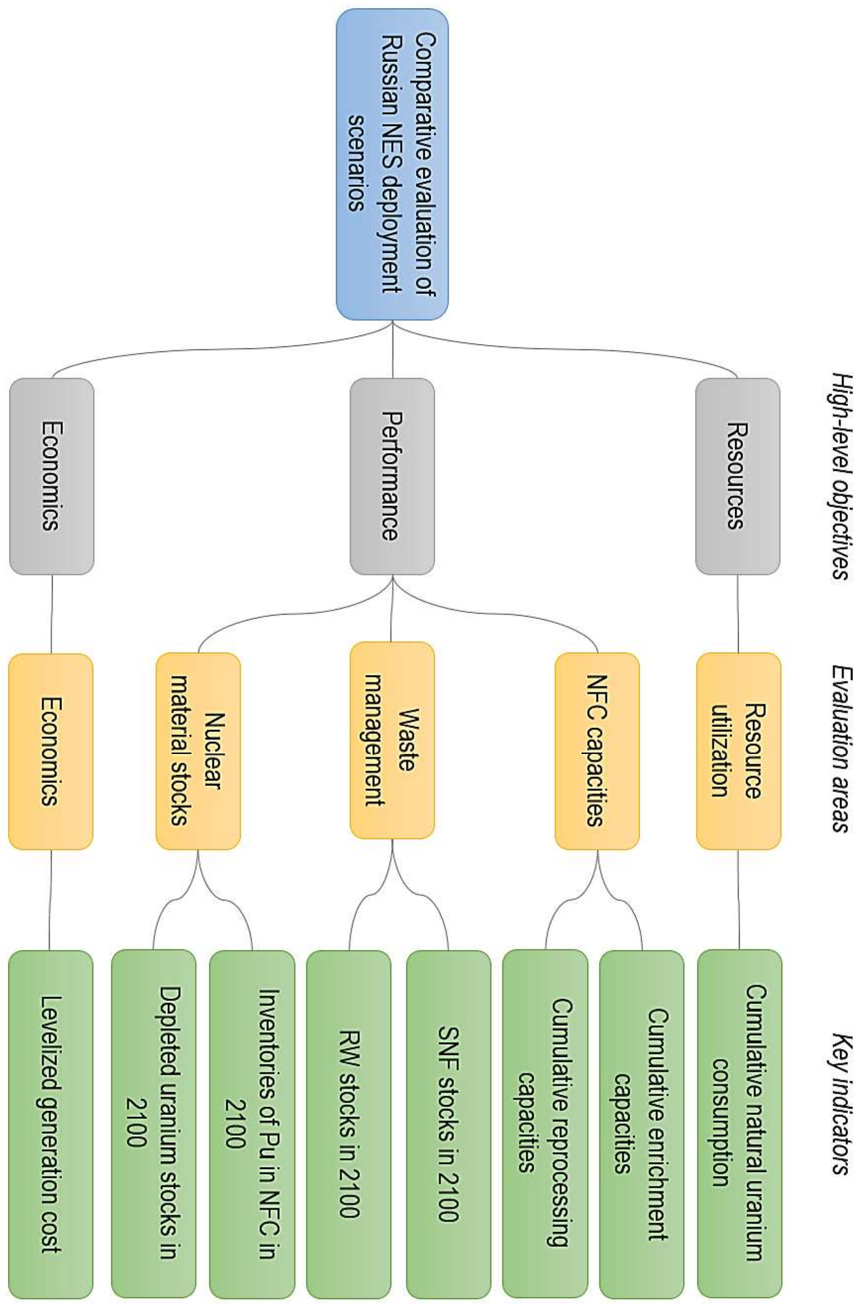


FIG. 3.117. Objective tree.

TABLE 3.57. PERFORMANCE TABLE

Scenarios/Key indicators	Cumulative uranium consumption, kt	Cumulative enrichment capacities, ktSWU	Cumulative reprocessing capacities, kt HM	Spent fuel stocks in 2100, kt HM	Rad waste stocks in 2100, kt	Inventories of Pu in NFC in 2100, kt	Depleted uranium stocks in 2100, kt	LGC, mills/kW·h
VVER (100%)	787.65	666.75	0	126.98	0	1.09	1669.03	29.48
$VVER_{MOX}$ (10%)	782.92	662.72	27.36	106.12	26.92	0.84	1658.34	29.89
$VVER_{MOX}$ (30%)	776.18	656.97	71.81	69.11	70.76	0.54	1644.80	30.40
$VVER_{MOX}$ (50%)	772.07	653.46	92.71	51.06	91.42	0.41	1638.11	30.57
BN (20%)	658.10	556.25	12.15	111.54	10.96	1.02	1544.24	29.53
BN (50%)	492.27	414.81	41.77	77.70	38.93	0.91	1384.26	30.22
BN (90%)	284.97	237.99	100.28	13.96	95.37	0.76	1184.07	31.09
$VVER_{MOX}$ (10%) BN(20%)	651.51	550.63	346.08	81.58	46.76	0.77	1531.93	30.29
$VVER_{MOX}$ (50%) BN (20%)	640.97	541.64	126.27	14.46	123.68	0.34	1511.78	31.57
$VVER_{MOX}$ (10%) BN (50%)	470.99	396.66	79.63	44.59	76.26	0.65	1359.36	31.70

The comparative evaluation and ranking of the considered scenarios were carried out using the Multi attribute Value Theory implemented in KIND-ET: it involved the additive form of the multi attribute value function and decreasing linear functions for single attribute value functions for all performance indicators [3.3, 3.40, 3.41].

The ‘equal weights’ option was used as a starting point for the analysis, assuming that all the performance indicators had the same importance (see Table 3.58). This approach can be applied when there is no information from experts and decision makers or when the available information about the relative importance of the performance indicators is insufficient [3.39, 3.41, 3.45]. However, even if there is no detailed information from experts for weights, the ‘equal weights’ evaluation approach, combined with a detailed sensitivity/uncertainty analysis regarding the weights, makes it possible to conclude about the attractiveness of the considered options from different perspectives.

TABLE 3.58. BASE CASE WEIGHTING FACTORS

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

3.9.4. Ranking result and its analysis

Figure 3.117 and Table 3.59 show the ranking results, including the decomposition of overall scores for all NES options according to the structure of the objective tree for the ‘equal weights’ weighting option. As can be seen from these figures, the BN (90%) option, assuming that the share of sodium-cooled fast reactors with MOX fuel in the NES structure in 2100 is about 90%, has the highest overall score for the base case of the weights, followed by the BN (50%), VVERmox (10%) BN (50%), BN (20%), and VVERmox (50%) BN (20%) options with significant lags in their overall scores. The VVERmox (50%), VVERmox (30%), VVERmox (10%), VVER (100%) and VVERmox (10%) BN (20%) scenarios have the lowest overall scores with a slight difference between them.

Scenario scores for high-level objectives are shown in Table 3.59. For the ‘Resources’ area, the BN (90%) scenario has the best score and the VVER (100%) and VVERmox (10, 30, 50%) scenarios have the lowest scores. For the ‘Performance’ high-level objective, the largest score is also given to the BN (90%) scenario while the VVER (100%) and VVERmox (10%) BN (20%) options receive the lowest scores. The VVER (100%) and BN (20%) options have the most attractive scores for the ‘Economics’ high-level objective, whereas the VVERmox (10%) BN (50%) and VVERmox (50%) BN (20%) scenarios receive the lowest overall scores. The best high-level objectives’ scores of the BN (90%) scenario for the ‘Resources’ and ‘Performance’ areas allowed this option to take the first place in the ranking and this option can be considered the most attractive for the ‘equal weights’ weighting option, notwithstanding that this option did not obtain any high scores for the ‘Economics’ high-level objective. The VVERmox (10%) BN (50%) option, involving the use of approximately 20% of MOX fuel in the VVER reactors, reached the third place in the ranking (despite a slight reduction in the volume of consumed uranium, an increase in the cost of NFC will be observed due to the production and processing of MOX fuel for thermal reactors). The characteristic feature of this option, as well as other options using MOX fuel in VVERs, is the possibility of reducing the plutonium amount circulating in the fuel cycle (see Table 3.57).

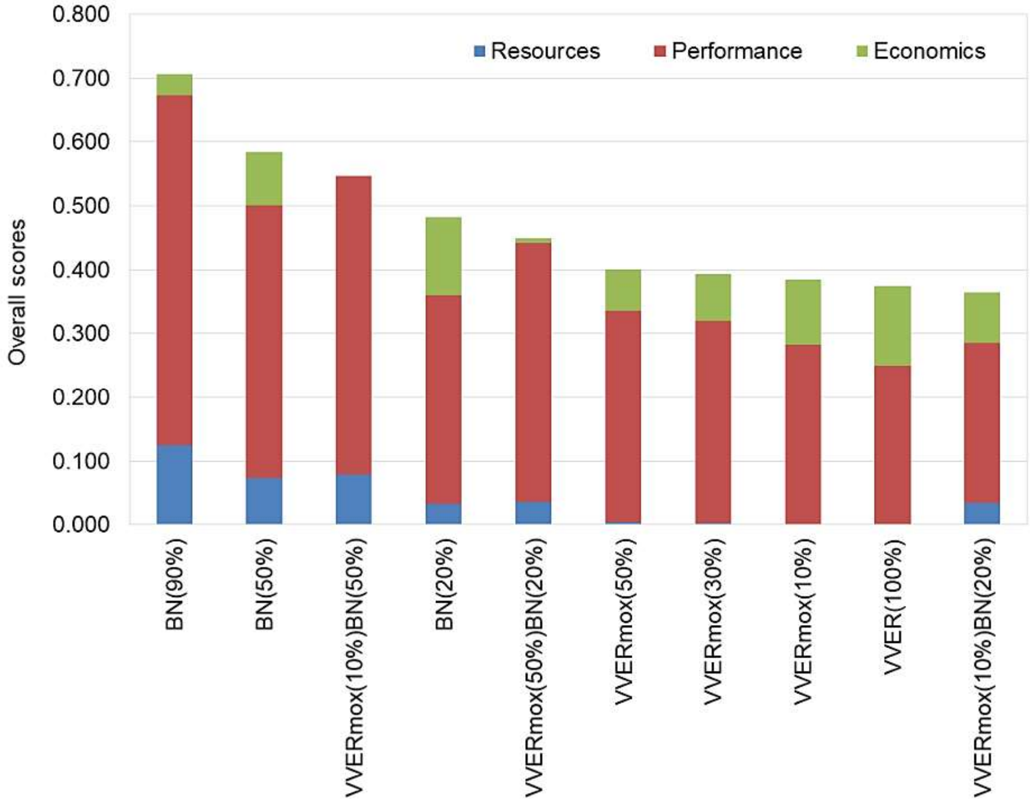


FIG. 3.118. Ranking results for the base case weighting option.

TABLE 3.59. SCORES FOR HIGH-LEVEL OBJECTIVES AND OVERALL SCORES

Scenarios	Resources	Performance	Economics	Overall score
VVER (100%)	0.000	0.250	0.125	0.375
$VVER_{MOX}$ (10%)	0.001	0.281	0.102	0.384
$VVER_{MOX}$ (30%)	0.003	0.317	0.073	0.393
$VVER_{MOX}$ (50%)	0.004	0.332	0.064	0.400
BN (20%)	0.032	0.328	0.122	0.483
BN (50%)	0.073	0.427	0.083	0.583
BN (90%)	0.125	0.548	0.034	0.707
$VVER_{MOX}$ (10%) BN (20%)	0.034	0.251	0.079	0.364
$VVER_{MOX}$ (50%) BN (20%)	0.036	0.406	0.007	0.449
$VVER_{MOX}$ (10%) BN (50%)	0.079	0.468	0.000	0.546

These ranking results were obtained for the ‘equal weights’ weighting option. At the same time, it is obvious that there is considerable uncertainty in the priorities of the NES deployment in the long term, and, as a result, the weighting factors are characterized by considerable uncertainty if the long term perspective is considered. Therefore, examining how the uncertainties in the weights will affect the overall scores of the options under consideration is of high interest. Evaluations of the overall score spreads due to the uncertainties in the weights were carried out in accordance with the methodology proposed in one of the studies carried out under the programme of the U.S. Department of Energy [3.46]. Using this method, it is possible to rank scenarios in the absence of information regarding the significance of key indicators and determine the probability of a certain scenario preference. This approach simulates how different expert groups with different views on the significance of key indicators would rank the scenarios in the absence of any information on development priorities (weights of key indicators). This information can be presented in the form of statistical distributions (for example, using box and whiskers plot). Based on this information, it is possible to identify the most promising scenario, assess its stability and the probability for its preference.

The overall score spreads for the scenarios considered due to the uncertainties in the weights are shown in Fig.3.118 (the number of examined weight combinations were 10 000 and it was assumed that all the weights are uniformly distributed within (0,1), provided that the sum of the weights for each combination is unity). The BN (90%) scenario is characterized by the most attractive spread in the overall score among all the other options. The BN (20%) scenario can also become attractive when some relevant conditions/requirements are met regarding the long term priorities for the nuclear energy deployment in the Russian Federation (see below). In general, this scenario will be even more attractive than all the scenarios involving the joint operation of the BN and VVER reactors with MOX fuel. The VVER (100%) and VVERmox (10, 30, 50%) scenarios can be considered statistically indistinguishable. The BN (50%) scenario has the smallest spread in the overall scores, but this spread is completely overlapped by the overall scores spreads for the BN (20%) and BN (90%) scenarios.

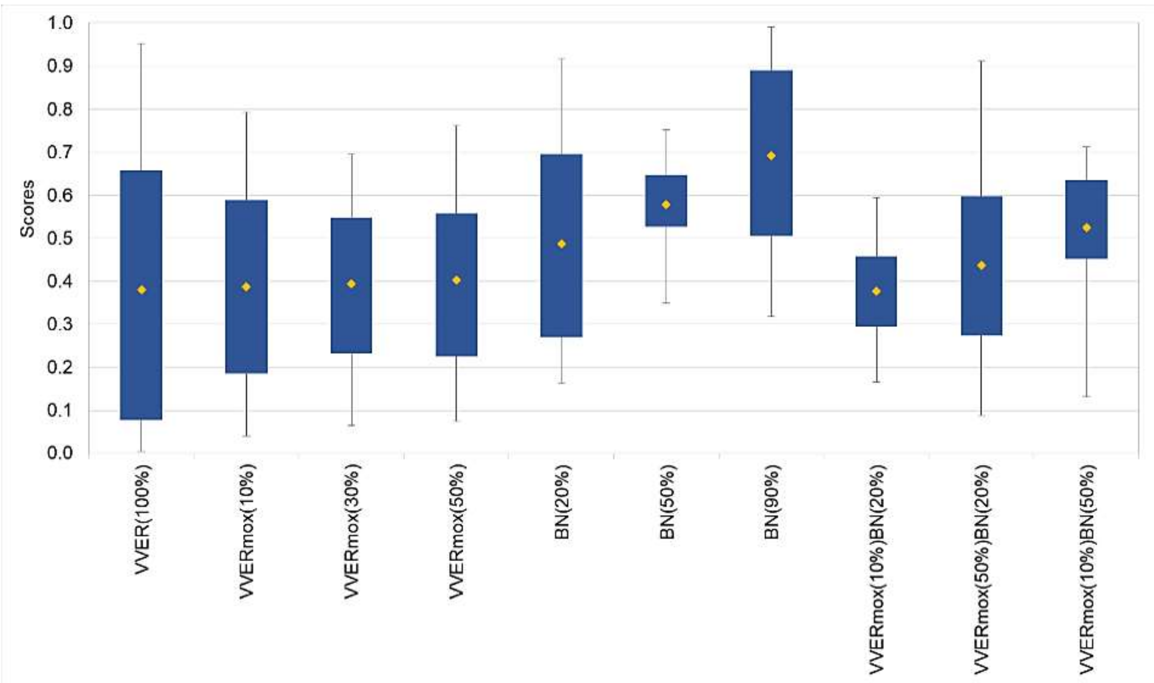


FIG. 3.119. Spreads in overall scores.

Additionally, another uncertainty analysis was performed with regard to the weights of the high-level objectives (assuming the equal weights at the lower levels of the objective tree) in order to identify scenarios that could potentially have the first rank. The performed analysis indicates areas of the weights of the high-level objectives for which the corresponding option can take the first place in the ranking (see Fig. 3.120: the abscissa axis demonstrates the possible weight values for the 'Resources' high-level objective; the ordinate axis shows the possible values for the 'Performance' high-level objective weight; the applique axis corresponds to the possible values for the 'Economics' high-level objective weight; the sum of these weights is equal to unity).

Figure 3.119 delineates preliminary conclusions about the most effective ways to enhance the national NES sustainability based on the multi-criteria evaluation paradigm. The BN (90%) scenario is the most attractive among all the considered options if the importance of meeting the ‘Resources’ and ‘Performance’ high-level objectives is predominant. The BN (20%) scenario becomes the most attractive if the importance of improving the ‘Economics’ high-level objective and, at the same time, the relevance of keeping the improved nuclear fuel cycle efficiency and the resources utilization still remain. The VVER (100%) scenario, which implies the commissioning of only VVER-TOI reactors with uranium oxide fuel in a once-through fuel cycle, can take the first place if there are no intentions to enhance the fuel cycle performance (including minimization of the amounts of spent fuel and plutonium in the nuclear fuel cycle, etc.) and resources utilization. This option can be considered extreme and unstable.

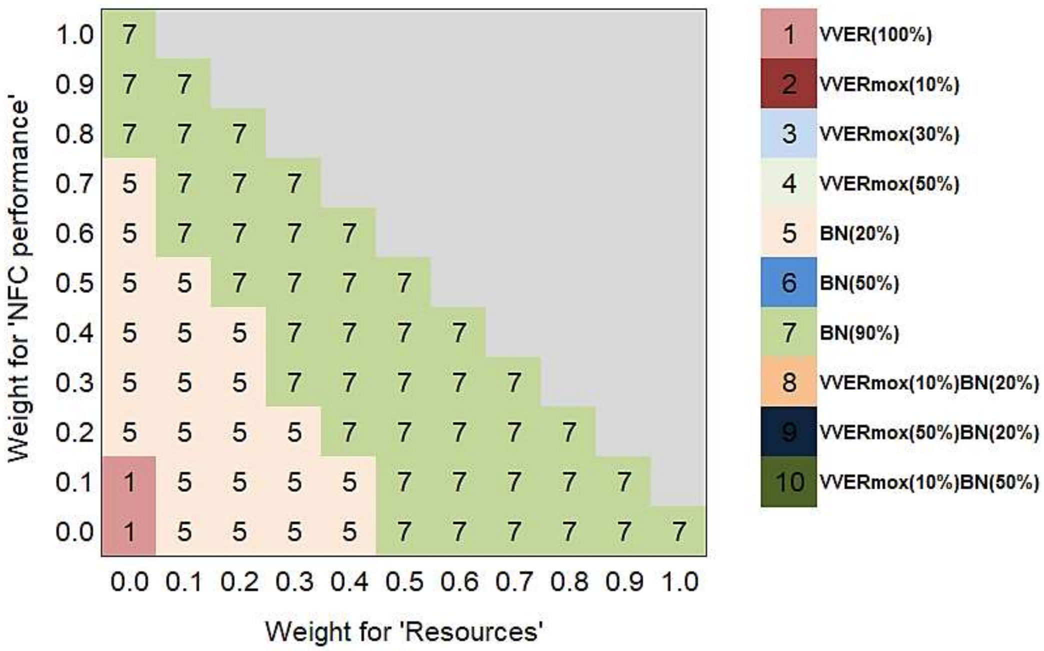


FIG. 3.120. Mapping of the first-rank options.

3.9.5. Results and discussion

The performed evaluation clearly indicates significant advantages of the scenarios with a large proportion of the BN-type reactors compared to the VVER (100%) scenario, but the role of thermal reactors with MOX fuel in the two-component NES was not clearly manifested. In particular, the scenarios involving the use of MOX fuel in thermal reactors did not obtain, as shown in Fig. 3.120, the first rank in the space of the high-level objective weights. At the same time, the VVERmox (10%) BN (50%) scenario took the third place in the overall ranking presented in Fig. 3.118. This shows the need for further studies on the role of MOX-fuelled thermal reactors in the two-component NESs.

The results of the evaluations indicate that the comparison of the NES deployment scenarios on the basis of only economic indicators without considering the rational use of resources, effective nuclear fuel cycle organization, and radioactive waste management objectives, show a one-sided picture giving preference to the NES option based on thermal reactors and a once-through fuel cycle. The multi-criteria decision analysis framework for comparing and ranking alternatives offers solutions different from those obtained by using the approaches based on economic decisions: preferences are given to energy production options which have the highest system efficiency considering the requirements of the sustainable development concept.

Certainly, the results obtained within this study are illustrative: it would make sense to consider much more possible configurations of the two-component NES, different growth rates of installed NES capacities and other sets of performance indicators. It needs also be considered that sodium-cooled fast reactors can be used not only for commercial production of electricity but due to an excess of neutrons in them, for burning off minor actinides and producing isotopes for their subsequent use in medicine and industry. Important for future studies may be, in particular, the tasks of considering the possibility of plutonium multi-recycling in thermal reactors after ‘improving’ the quality of plutonium in BN-type reactors [3.39] and assessing the impact of exported reactors and fuel cycle services on the Russian two-component NES structure.

3.9.6. Conclusions

The presented results of a multi-criteria comparative evaluation of the 10 possible Russian NES development scenarios characterized by various proportions of thermal and sodium-cooled fast reactors, including options for using MOX fuel in VVER reactors, allow drawing preliminary conclusions about the development of a national NES as a sustainable energy supply option providing a harmonious combination of technical, economic and environmental factors. In particular, it is shown that the Russian NES sustainability can be substantially enhanced by the intensive and large-scale deployment of sodium-cooled fast reactors and gradual transition to the closed nuclear fuel cycle. The performed analysis has demonstrated the need for further detailed studies on the possible role of MOX-fuelled thermal reactors in the two-component NES, since this commercially mature technology can burn excessive plutonium, thereby providing a plutonium balance (i.e., plutonium production equal to its consumption) in the system.

3.10. COMPARATIVE EVALUATION OF SCENARIOS WITH FAST AND THERMAL REACTORS WITH DETAILED MODELLING OF THE NUCLIDE COMPOSITION OF NUCLEAR MATERIAL FLOWS (RUSSIAN FEDERATION)

This chapter presents a structured report of the second of the four case studies done by experts from the Russian Federation.

3.10.1. Introduction

When modelling a closed nuclear fuel cycle, a rather complicated problem arises of how to consider changes in the nuclide composition of fuel materials in detail. Of particular difficulty is the simulation of fast-neutron reactors operating using plutonium in the fuel composition. The errors of approximate models in such simulations can become large, and therefore lead to incorrect conclusions when modelling complex development scenarios for two-component nuclear power plants with thermal and fast reactors. At the previous stage of the study, the MESSAGE code was used to study the material balances of fuel materials in modelling scenarios for the development of nuclear energy. The disadvantage of the code MESSAGE can be attributed to the lack of calculation of the change in the nuclide composition of the fuel during the operation of a nuclear reactor, which can lead to serious errors in the material flows when modelling complex development scenarios of two-component nuclear power plants with thermal and fast reactors.

Therefore, in this part of the work, when modelling the scenarios of developing nuclear power, special software based on a detailed description of the processes occurring in nuclear reactors of various types that are part of the scenario was used. Such software is implemented in the CYCLE code [3.47].

3.10.2. The CYCLE code for the system analysis of the nuclear fuel cycle

The CYCLE code is used for mathematical modelling of nuclear fuel cycles, development of scenarios for the effective development of nuclear power in Russia, and analysis of trends in the global nuclear energy industry. Special attention in the CYCLE code was given to the description and consideration of the features inherent in modelling a closed nuclear fuel cycle (NFC) with fast and thermal reactors.

Currently, the CYCLE code allows experts to simulate a two-component nuclear energy system (NES), the model of which, in addition to thermal reactors with fuel based on uranium oxide (UOX), includes fast reactors and provides multiple reprocessing of plutonium, uranium and minor actinides (MA). It is also possible to use mixed uranium-plutonium oxide (MOX) fuel or nitride fuel with a variable content of uranium and plutonium for thermal reactors. A fuel cycle is considered with the possibility of processing fuel, including the use of reserves of natural, depleted and reprocessed uranium, plutonium, neptunium, americium and curium.

The simulation results for the fuel cycle of thermal reactors with UOX-fuel (TR UOX), including the accumulation of uranium, plutonium and MA, are used as the input to simulate the operation of a reactor using plutonium fuel as part of a nuclear power system. Plutonium fuelled reactors are deployed using both plutonium generated in power reactors and plutonium obtained from other sources. The latter suggests that the initial characteristics of a given plutonium stockpile are to be indicated, not calculated. Various physical and logical topologies of plutonium storage facilities are possible. Thus, it is possible to simulate the development of nuclear energy through the joint operation of TR UOX, thermal reactors with partial loading of MOX fuel (TR MOX) and fast reactors. Thermal reactors with a partial MOX load are assigned the role of plutonium burners, while fast reactors (FR) can produce plutonium and thereby limit the build-up of higher plutonium isotopes during recycled plutonium burning in thermal reactors. A simplified block diagram of the NFC modelled in the CYCLE code is shown in Fig. 3.121.

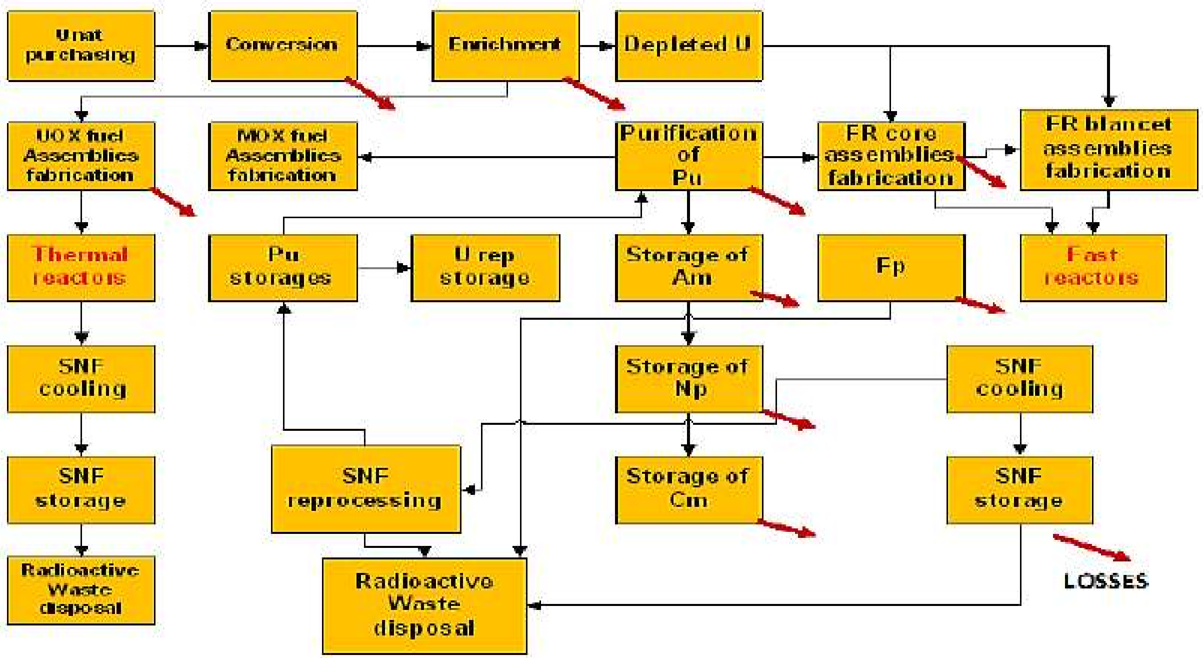


FIG. 3.121. The interaction scheme of the modules in the CYCLE code.

The first stage of plutonium use (or involvement in the nuclear fuel cycle) is advisable to start when the first BN-1200 reactor is put into operation [3.48] and the infrastructure providing the MOX fuel for reactors with BN-1200 will have been already created. As has been discussed, the Russian nuclear power complex has all the necessary prerequisites for launching a two-component NES.

The initial configuration of a nuclear power plant can consist of two types of connected reactor units: thermal reactor (TR) and sodium cooled fast reactor (SFR)(Fig. 3.122).

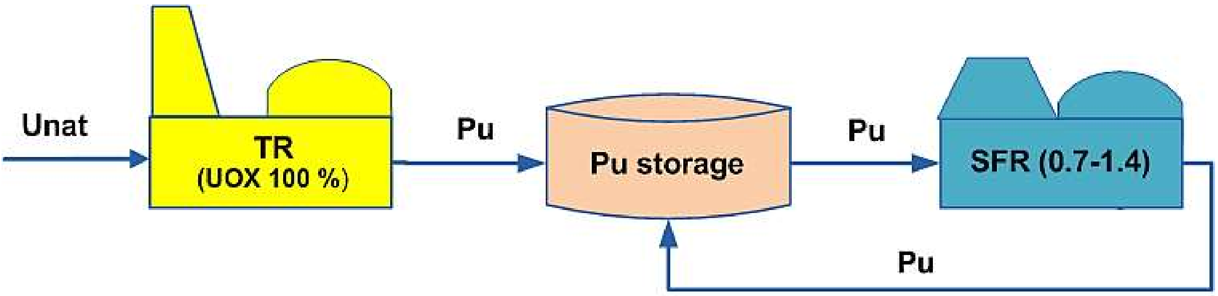


FIG. 3.122. The first phase of transition to a closed NFC.

Reactors of the BN-1200 type are put into operation sequentially, so as to form a small series of three reactors [3.49]. The source of plutonium for initial loading of fast reactors in this scheme is plutonium separated from the spent fuel produced by the operation of VVER-1200 reactors.

At the second stage of solving the problem of SNF management, if it is necessary to ensure high rates of development of plutonium NES from MOX BN-1200, it is advisable to send the reprocessed SNF to the loading of fast reactors for its multiple recycling (Fig. 3.123). The requirements for BN reactors in this version are high energy intensity; high breeding ratio (BR); and minimum time of the off-reactor fuel cycle (SNF exposure, reprocessing, storage and manufacturing).

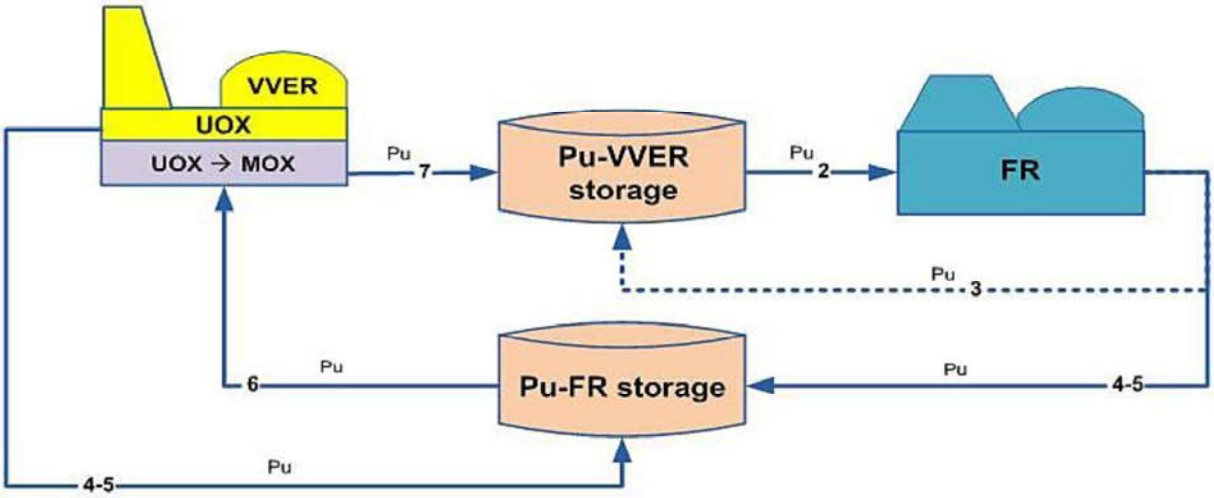


FIG. 3.123. The second phase of transition to a closed NFC with high demand for nuclear energy.

3.10.3. Inputs, methods and assumptions used

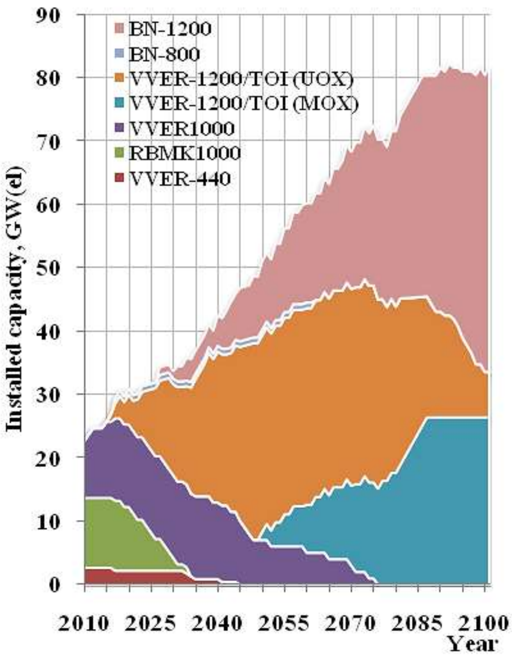
For the current case study, a two-component scenario for the development of nuclear power was used with achievement of a total installed capacity of about 50 GW by 2050 and development up to 2100 from the plutonium balance condition given in [3.50, 3.51]. The scenario designation by text is "50–50". Beside the two-component scenario, the reference scenario was additionally 'built', which implements an open NFC in VVER-type thermal reactors without reprocessing irradiated fuel, except for VVER-440 SNF.

The conditions of this scenario were as follows:

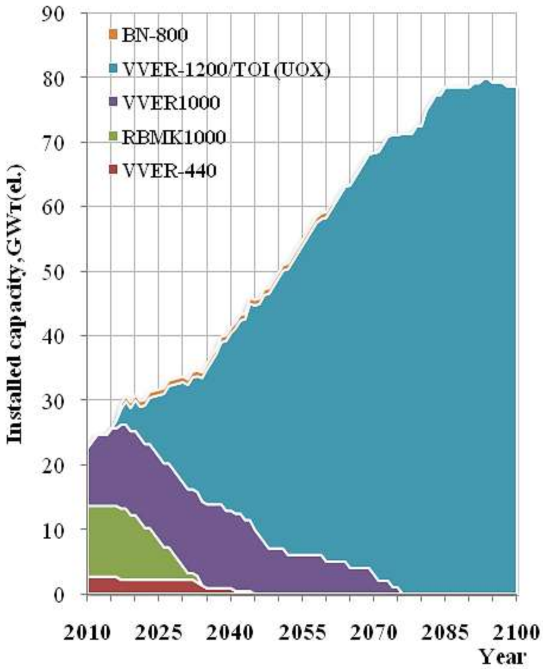
- 43 serial units of the BN-1200 are put into operation before the year 2100.
- Except for the loadings of the BN-800 reactor, natural uranium is not used in the BN reactors[28].
- Commission into operation of thermal reactors VVER-1200 / TOI (UOX) was made until 2048.
- In the period from 2050 to 2100, for the disposal of excess plutonium, 21 units VVER-1200 / TOI (41% MOX) are commission into the system. Reactors BN-1200 play the role of plutonium purifier with respect to the plutonium produced in thermal reactors.
- SNF of VVER reactors is reprocessed at RT-1 and at experimental and demonstration centre (ODC) of the RT-2 Russian reprocessing plants for the purpose of its disposal by ~ 2045.
- SNF of BN reactors is reprocessed from 2040–2041.
- SNF of RBMK-1000 is reprocessed from 2080.
- By 2050, the total need for reprocessing reaches ~ 900 tons of HM / year, and by 2100, the total need for reprocessing reaches ~ 2.300 tons of HM / year.

Figure 3.124 shows the installed powers in the two-component and reference scenarios 50–50. In the reference scenario BN-1200 and VVER (MOX) are replaced with the VVER (UOX).

[28] The reactors of BN type can use both reprocessed and depleted uranium. In this study the use of depleted uranium was considered.



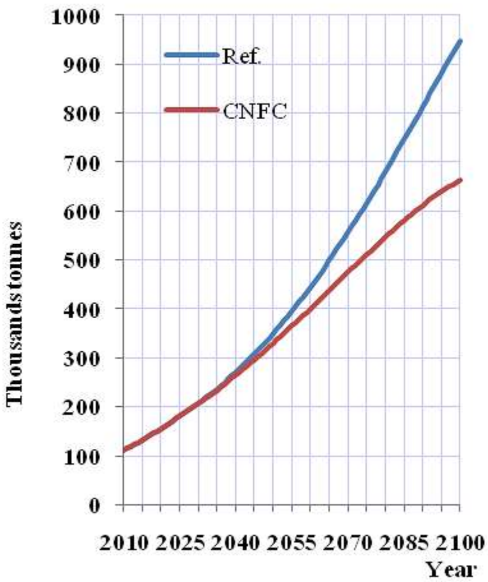
(a)



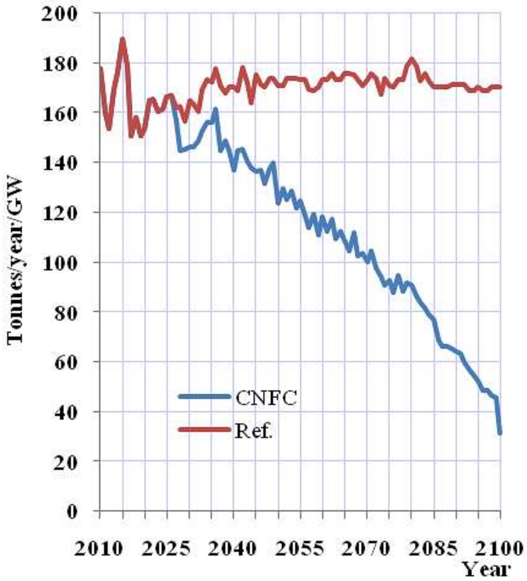
(b)

FIG. 3.124. Installed capacities in the two-component (a) and reference (b) scenarios 50–50.

Figure 3.125 shows a comparison of natural uranium consumption, integral and specific, in reference and two-component scenarios. The integral and specific consumption of natural uranium is significantly reduced in the two-component scenario compared with the reference one. Figure 3.126 shows a comparison of the changes over time in the quantities of SNF for a given pair of scenarios. In the reference scenario, the amount of SNF by the end of the century reaches almost one hundred thousand tons. In a two-component SNF quantity is reduced to zero.



(a)



(b)

FIG. 3.125. Integral (a) and specific (b) uranium consumption in two-component and reference scenarios 50–50. Legend: CNFC – closed nuclear fuel cycle.

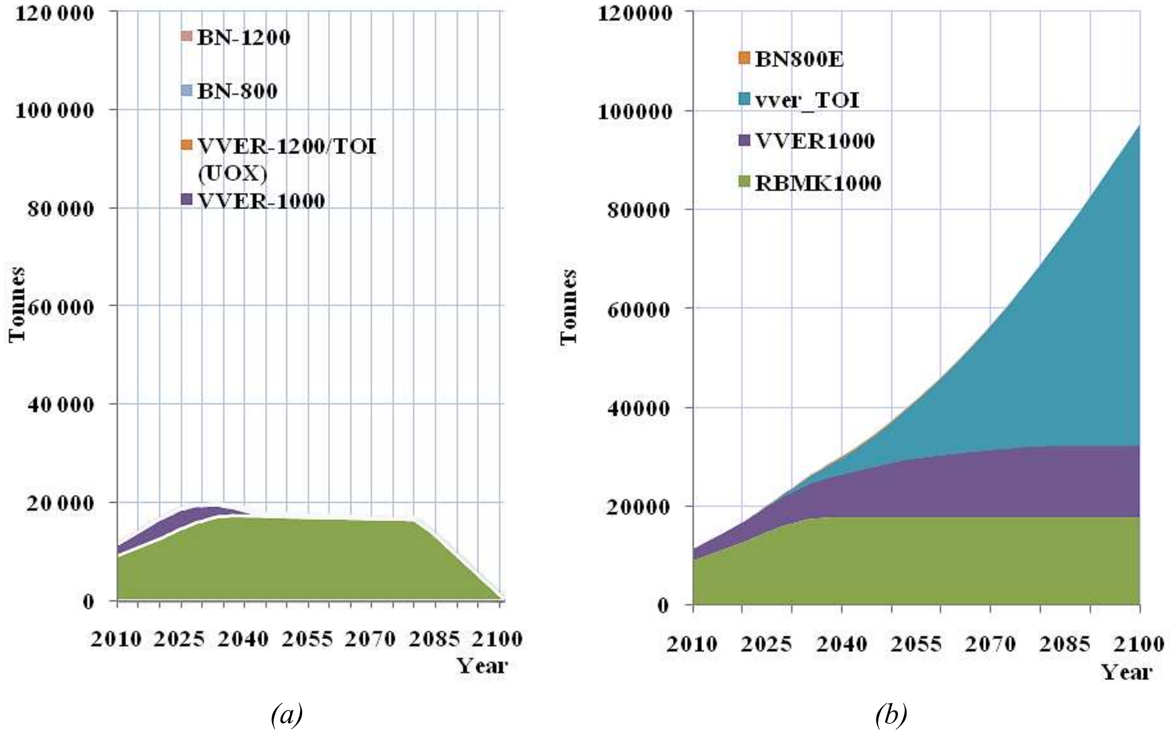


FIG. 3.126. Comparison of the rate of the SNF accumulation in the reference (a) and two-component (b) scenarios 50–50.

Figures 3.127 and 3.128 show the change in amounts of plutonium for the two scenarios. For an open fuel cycle, the amount of plutonium by the end of the century is slightly more than 1000 tons. In a two-component scenario, by the end of the century the amount of plutonium will reach approximately 25 tons. This quantity is needed as an operational stock.

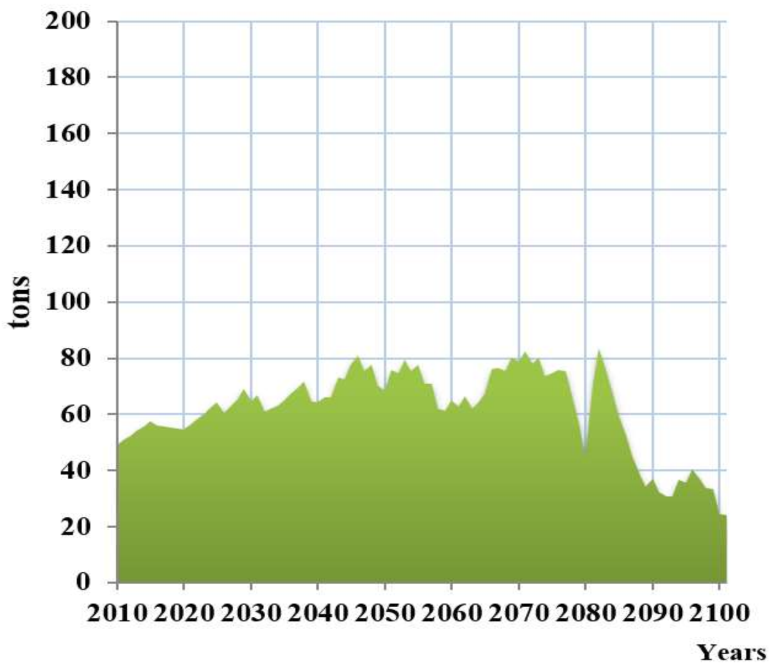


FIG. 3.127. Plutonium stock in a two-component scenario 50–50.

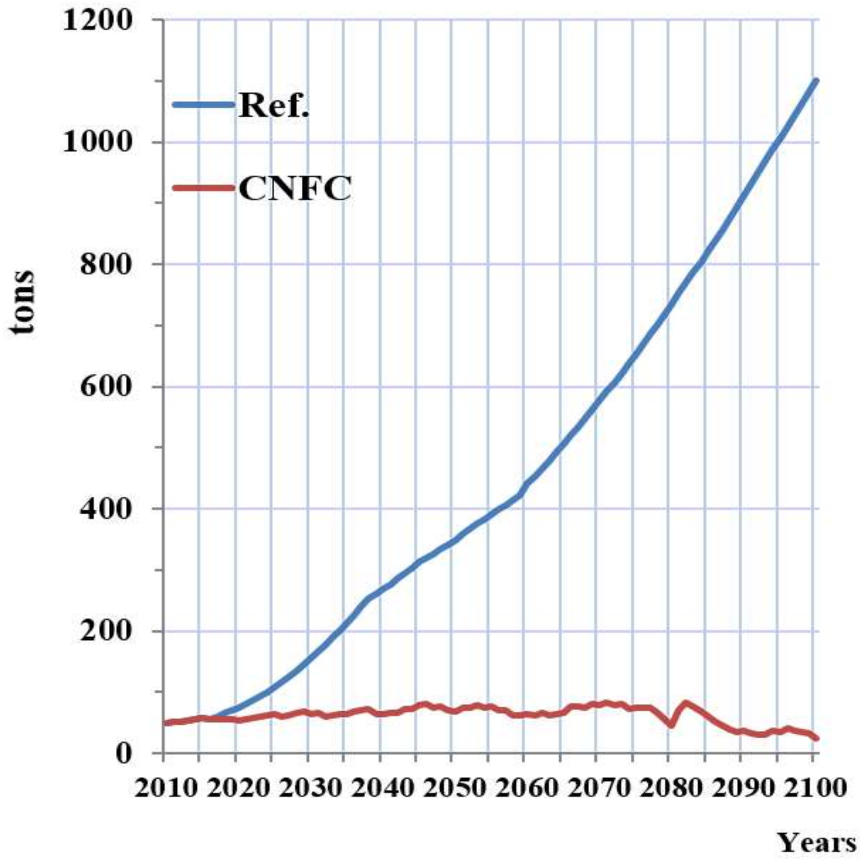


FIG. 3.128. Comparison of plutonium accumulation rates in reference and two-component scenarios 50–50. Legend: CNFC – closed nuclear fuel cycle.

The scores of the selected key indicators at the end of the period (year 2100) are given in Table 3.60.

TABLE 3.60. A SET OF USED KEY INDICATORS AND THEIR SCORES

#	Criteria	VVER	VVER+FR
1	LCOE – economy	1	0.9
2	SNF and RW management	0.32	0.97
3	Natural uranium consumption	0.32	0.97
4	Plutonium accumulation	0.32	0.97
5	Export potential	0.35	0.97

For the case study conducted within this work, a three-level objective tree was developed (see Fig 3.129).

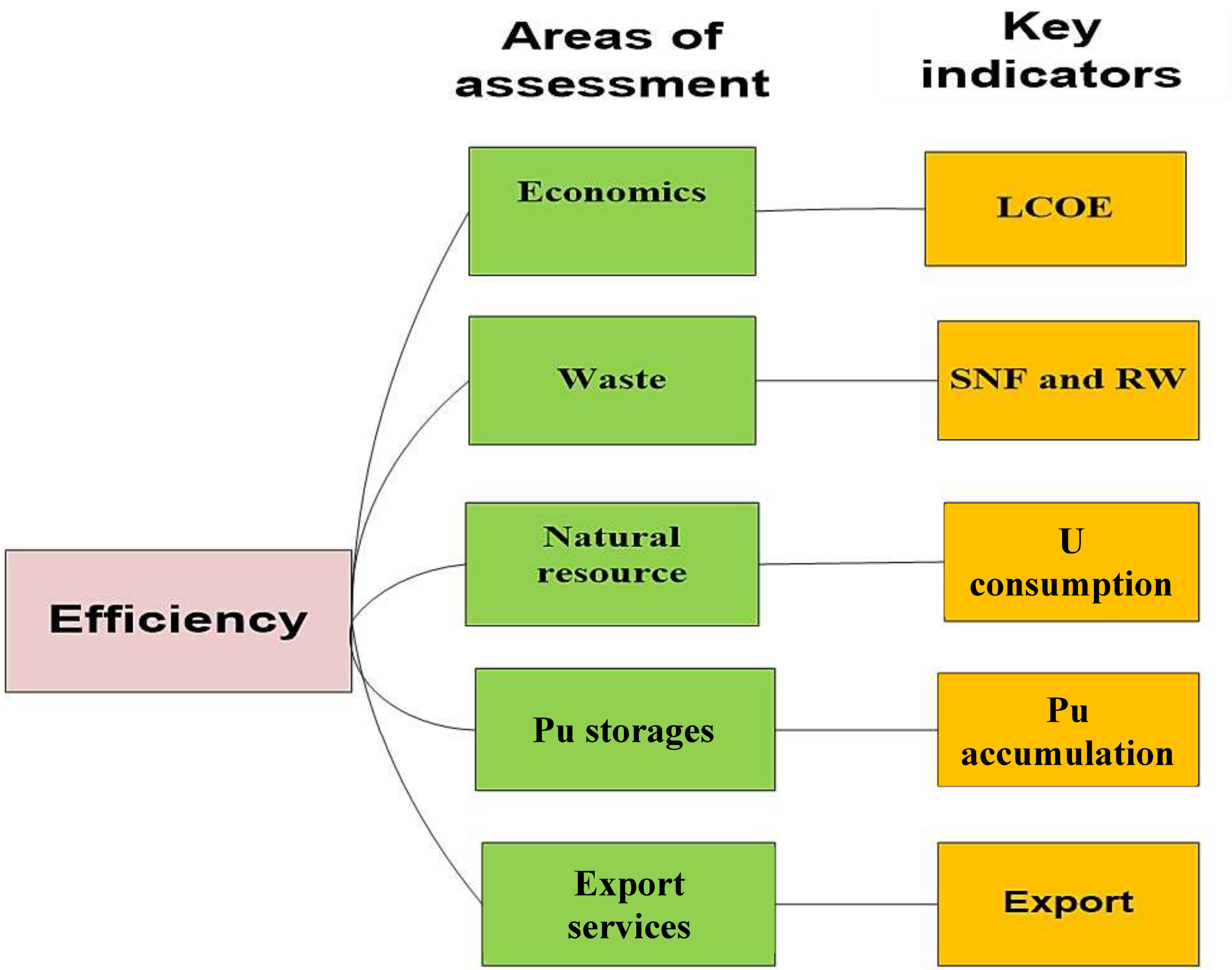


FIG. 3.129. Objective tree.

The high-level goal can be formulated as a comparison of the effectiveness of deployment scenarios. This structure is based on five key indicators, summarized in five evaluation areas. Both NES options under consideration are evaluated for each of the key indicators to year 2100. Figure 3.129 shows the results of the assessment for each criterion and the final assessment. The abscissa axis represents the option rating. The first two bars represent the ratings of the options by the economic criterion. It can be seen that, according to this criterion, a two-component system with a closed cycle is 'inferior' to a single-component one. According to the criterion 'handling of SNF and RW', the rating of the two-component scenario with closed NFC is significantly higher than the one-component scenario with open NFC. This follows from the results of the comparison of the rate of accumulation of SNF presented in Figure 3.129. According to the 'uranium consumption' criterion, the two-component scenario rating also significantly exceeds the rating of the single-component NES. The results of the comparison of uranium consumption rates in two scenarios are shown in Figure 3.130. By the criterion of 'export' of technologies, the rating of the 'two-component' scenario is also higher, which is connected with the provision of a more complete package of the associated fuel cycle services in a two-component scenario. According to the 'plutonium accumulation' criterion which defined development potential, the two-component scenario is also better since development in it will continue even after reasonably priced natural uranium is depleted. The result column provides the scores aggregated at the top level.

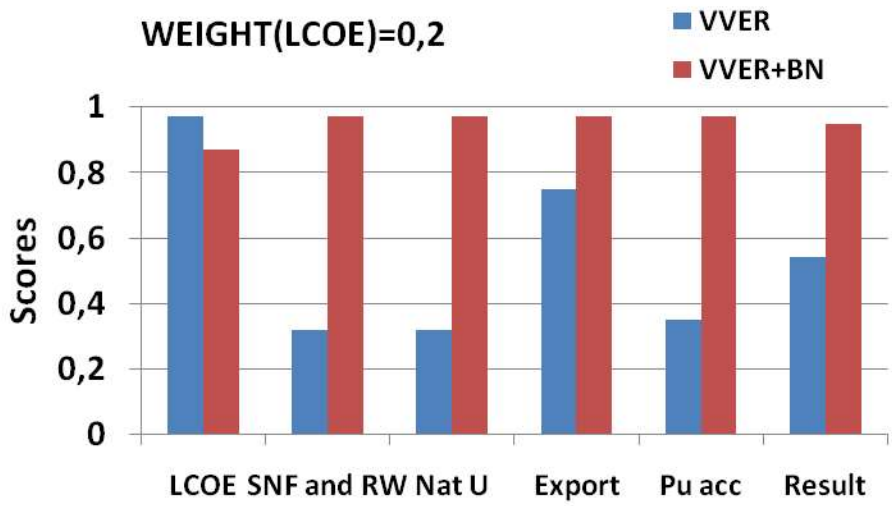


FIG. 3.130. Equilibrium option by key criteria.

The results of the final assessment show that a two-component system is the best alternative. Once again, it is noted that the studies assumed the same significance of all the criteria.

3.10.4. Uncertainty and sensitivity analysis for decision support

Difficulties in determining sensitivity to selected weights and criteria when conducting a multi-criteria analysis of nuclear power development scenarios consist primarily in the absence of complete information on uncertainties in the values of the criteria used, not to mention statistics, which are widely used, for example, in nuclear data. Thus, the techniques used in the analysis of calculations of nuclear reactors, in our task are quite difficult to use. In order to account for the uncertainties in research on the use of multi-criteria analysis in justifying the strategy of developing nuclear power, a 'deterministic' approach is proposed.

In the framework of this approach, it is proposed to carry out a change in the values of weights and criteria in a 'manual' mode using expert groups. To facilitate this work, special software was developed with the goal to quickly allow the user to determine how the change in weight or criteria will affect the value of the result of a multi-criteria analysis.

At this stage, the change in weight for the economic criterion is considered. It was assumed that the 'importance' of the economic criterion is equal to half of the sum of the importance of the other criteria. The remaining four criteria had weights (importance) of 0.125. The results presented in Figure 3.131 showed that in this case the two-component system has a higher rating.

The next option was to increase the significance of the economic criterion to 60 percent. The weights of the remaining criteria are therefore set to 0.1. The resulting rating of the two-component variant is also much higher than the single-component one. The results of the calculations are shown in Fig. 3.132.

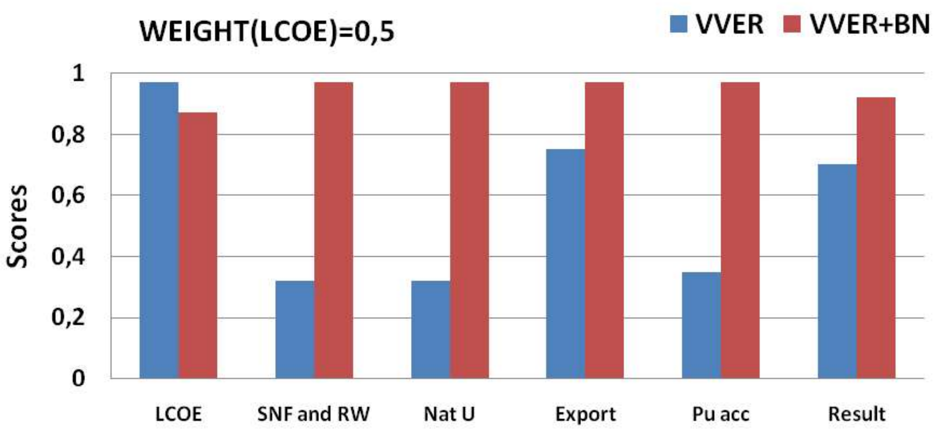


FIG. 3.131. Change in weight of LCOE to 0.5.

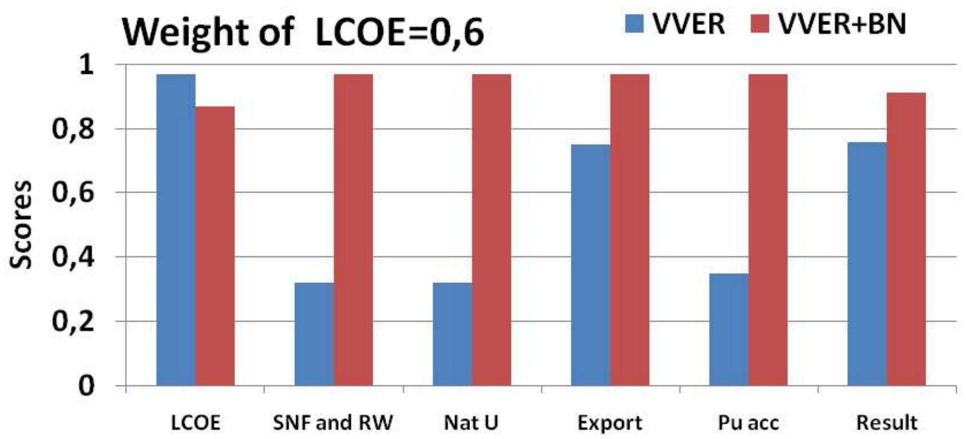
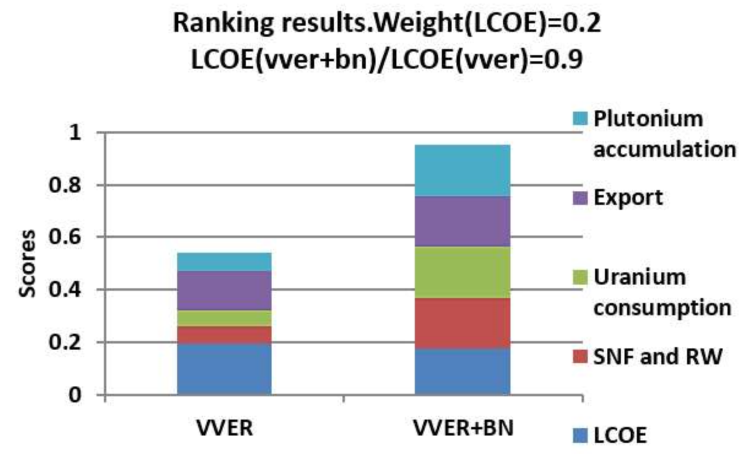
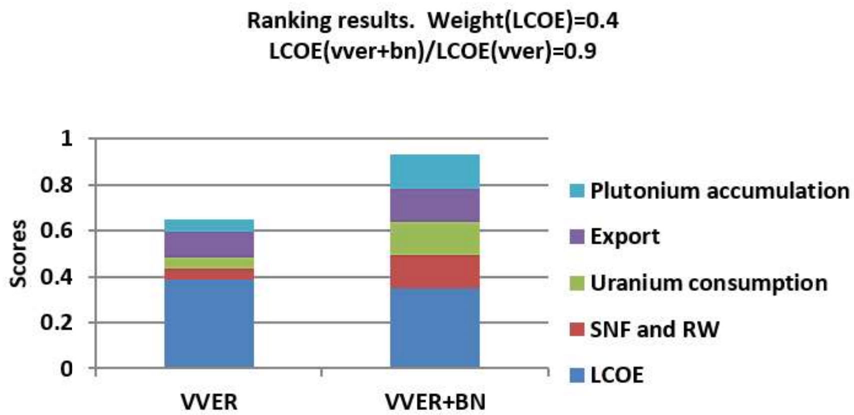


FIG. 3.132. Change in weight of LCOE to 0.6.

Further, not only the weight of the economic criterion by also its value was altered.

№	Criteria	Weights 1	Weights 2	Weights 3
1	LCOE - economy	0.2	0.4	0.8
2	Handling of SNF and RW	0.2	0.15	0.05
3	Natural uranium consumption	0.2	0.15	0.05
4	Plutonium accumulation	0.2	0.15	0.05
5	Export potential	0.2	0.15	0.05





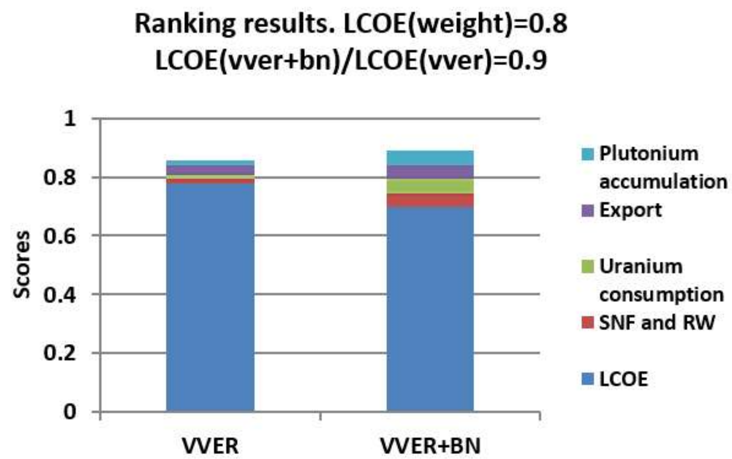
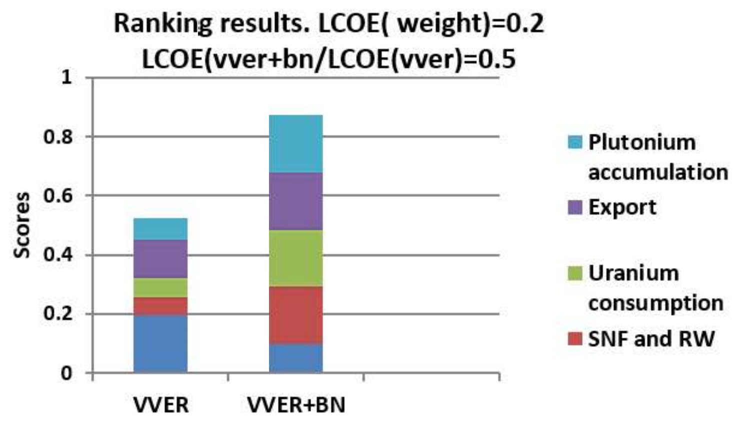
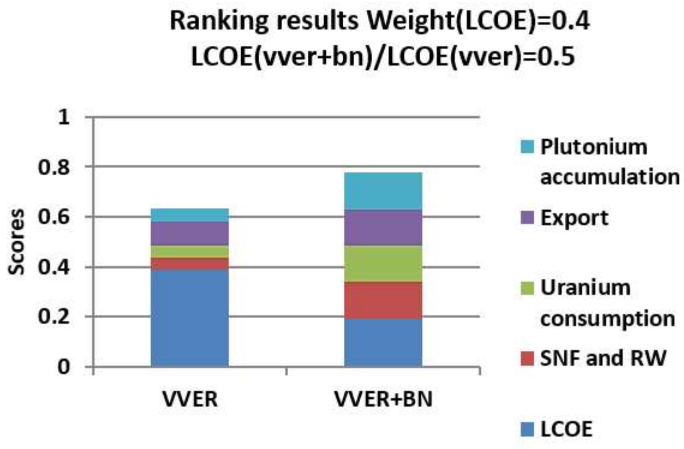


FIG. 3.133. Ranking results LCOE(BN+VVER)/ LCOE(VVER)=0.9.

Figure 3.133 shows the results of comparing the ratings of a single-component scenario with thermal neutron reactors (VVER) and a two-component scenario with fast and thermal neutron reactors (VVER + BN) while changing the weights and values of the economic criterion (LCOE). The results show that when the weight of the economic criterion changes to almost 0.7, the rating of a two-component system is higher than a one-component system. Moreover, the value of the economic criterion is worse for a two-component system by 10%.

№	Criteria	Weights 1	Weights 2	Weights 3
1	LCOE - economy	0.2	0.4	0.6
2	Handling of SNF and RW	0.2	0.15	0.1
3	Natural uranium consumption	0.2	0.15	0.1
4	Plutonium accumulation	0.2	0.15	0.1
5	Export potential	0.2	0.15	0.1





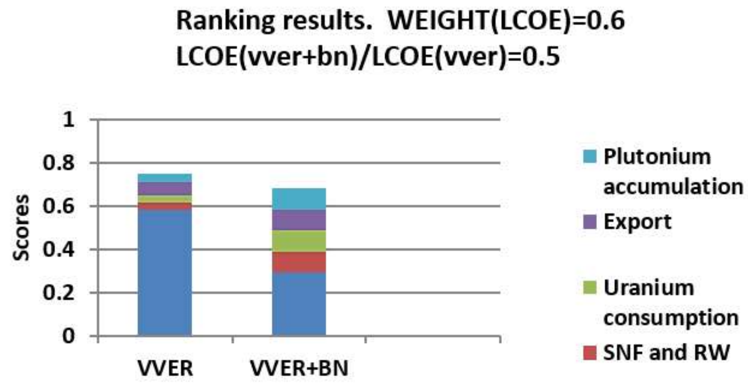


FIG. 3.134. Ranking results LCOE(BN+VVER)/ LCOE(VVER)=0.5.

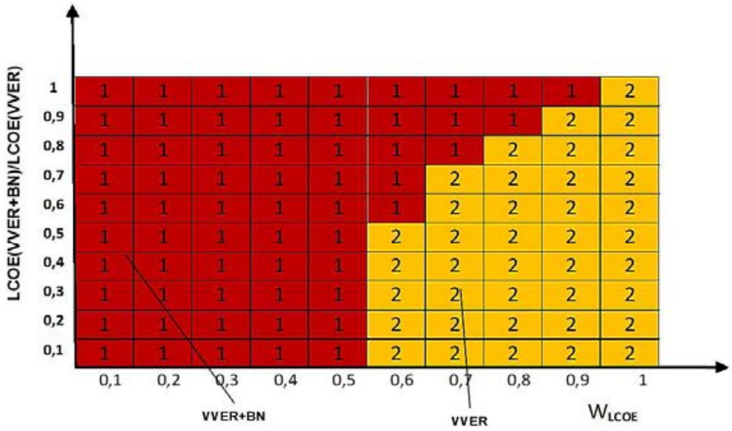


FIG. 3.135. Uncertainty analysis with respect to weight and criterion. Legend: LCOE – levelized cost of electricity, W_{LCOE} – LCOE weight.

Figure 3.134 shows the results of comparing the ratings of a single-component scenario with thermal neutron reactors (VVER) and a two-component scenario with fast and thermal neutron reactors (VVER + BN) while changing the weights and values of the economic criterion (LCOE). In this variant, the value of the economic criterion is already 50% worse for a two-component system. The results show that when the weight of the economic criterion changes to almost 0.5, the rating of a two-component system is higher than a one-component system.

Figure 3.135 shows the results of comparing ratings of nuclear power systems with a wider change in weights and values of the economic criterion. The abscissa axis is the value of the weights for LCOE, the ordinate axis is the values of LCOE (VVER+BN)/LCOE(VVER). The rating of the two-component system turned out to be quite stable against changes in the weights and values of the economic criterion.

3.10.5. Conclusions

The presented case study makes it possible to draw preliminary conclusions about the best ways to deploy a future two-component NES on the basis of the existing Russian nuclear energy technologies. In the case of the equally important development priorities or when the efficiency of natural uranium use, the reduction of accumulated SNF and the minimum of the required capacities in the 'front-' and 'back end' of the nuclear fuel cycle are selected as the priority, the future NES might need to move to a closed nuclear fuel cycle and increase the proportion of fast reactors up to full replacement of thermal reactors. If the main priority for the deployment of NES will be the economic efficiency of nuclear energy considering the needs for closure of the NFC, then the main share would be occupied by thermal reactors with uranium oxide fuel, and the share of fast reactors would be limited to 20–30% of the total installed capacity. The growth rate of the national NES up to 2100 which was used in the study limits the use of MOX fuel in thermal reactors as a more expensive option and the one that does not lead to significant resource savings.

It needs to be noted that the results of scenario evaluation obtained in the presented case study were obtained only for the purpose of method approbation and are based on expert opinions.

In the previous studies, the MESSAGE model was used to study the material balances of fuel materials in modelling of nuclear energy evolution scenarios. The disadvantage of MESSAGE can be attributed to the lack of detailed calculation of the changes in the nuclide composition of the fuel during operation of a nuclear reactor, which inevitably leads to some errors in the material flows when modelling scenarios for a two-component NES with thermal and fast reactors. Therefore, in the present study a special software incorporating detailed description of the processes occurring in nuclear reactors of various types was used.

A multi-criteria comparative analysis of the development scenarios of a single-component and two-component NESs has shown that using the selected set of key criteria, the rating of a two-component scenario with a closed NFC is significantly higher than that of a single-component one with an open NFC. Studies of sensitivity to the uncertainty of the values of criteria and their weights have shown that the rating value of the two-component system is quite resilient to changes in the values of weights and criteria.

3.11. COMPARATIVE EVALUATION OF RUSSIAN FEDERATION ENERGY DEVELOPMENT STRATEGIES USING THE KIND APPROACH (RUSSIAN FEDERATION)

This chapter presents structured report of the third of the four case studies done by experts from the Russian Federation.

3.11.1. Introduction

Today there are various kinds of power generation technologies offering different advantages and disadvantages to potential consumers. Energy policy is an important aspect of national economic development for any country and suboptimal solutions could potentially hamper the sustainability of an energy system in the long term. Although it is generally preferable for countries to diversify their energy supply, it is not always possible due to geographic, political or economic circumstances. In addition, the benefits of transferring to more advanced technologies might not always seem tangible in light of higher investment costs or the requirement for building supplementary infrastructure. To overcome these issues, simulation modelling and comparative evaluation tools can provide credible information for decision makers that would be otherwise forced to rely exclusively on expert opinion. Considering the fact that Russia is a key player in the global energy market with limited resources and an ever-growing climate change threat, an optimal strategy aimed at providing electricity at affordable prices without compromising sustainable development goals is a national priority.

3.11.1.1. Background

This case study presents the results of a comparative evaluation of Russian energy development strategies using the KIND approach. While working together with members of the CENESO project it was established that studies conducted within the ‘Proryv’ project (conducted at the Innovation and Technology Centre (ITC) Proryv) on closed fuel cycle transition scenarios could be enhanced by applying the KIND approach for comparative analysis of several Russian energy development strategies with a different mix of nuclear and non-nuclear options. The following sections present a general description of how system modelling tools developed at the ITC Proryv institution as well as the KIND approach and software developed at IAEA were utilized to compare a set of scenarios for the Russian power sector in the twenty-first century.

3.11.1.2. Objective

Two main objectives were set for this Russian Federation case study:

- Compare several plausible energy development scenarios in Russia from different aspects regarding economic performance, waste management, resource and environmental sustainability using the KIND approach;
- Apply additional modules of the KIND-ET tool for comparative evaluation of NES options within the CENESO collaborative project.

3.11.1.3. Scope

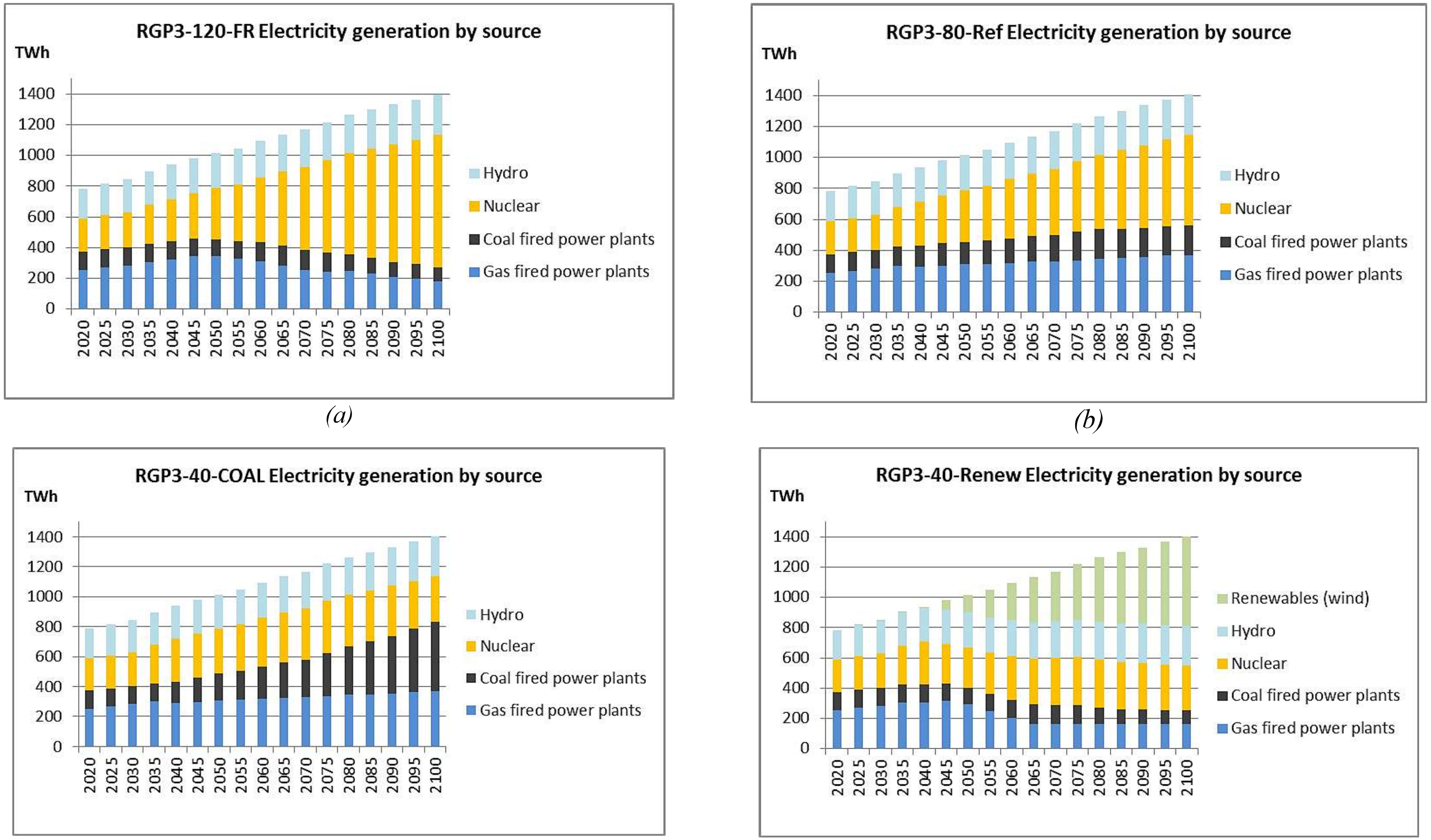
Seven scenarios (see Table 3.61) were developed with various generation capacity mixes and fossil fuel, nuclear and renewable development assumptions. The modelling time frame was set to 1970–2100. The base year for calculating discounted cash flows was set to 2020. The study was focused primarily on those power generating technologies that are expected to aggressively compete for future power market share, namely those that apply to fossil fuel, nuclear and renewable industries. All non-hydro renewable generation was modelled by using wind turbine technology parameters as a proxy, since this type of renewable power is expected to increase in scale the fastest in Russia in the far future.

TABLE 3.61. ASSUMPTIONS REGARDING INSTALLED CAPACITY ATTAINED IN YEAR 2100 FOR DIFFERENT SCENARIOS

Scenario ID:	120_FR	120_TR	80_REF	80_TR	40_Gas	40_Coal	40_Renew
FR installed cap.*, GWe	120	0	80	0	0	0	0
TR installed cap.*, GWe	0	120	0	80	40	40	40
Coal PP installed cap.**, GWe	13	13	27	27	13	66	13
Gas PP installed cap.**, GWe	21	21	49	49	97	49	21
Renewable installed cap., GWe	—	—	—	—	—	—	148

The scenarios were developed using energy outlook data obtained from latest available publications from the Energy Research Institute of the Russian Academy of Sciences (ERIRAS) albeit with different assumptions regarding capacity additions starting from the year 2050. Table 3.61 shows which specific technology is prioritized in the second half of the 21st century for each given scenario. Figure 3.136 illustrates how these assumptions affect electricity generation from different sources up to the year 2100 for some of the scenarios.

* – excluding exports.
** – excluding CHP plants.



(a) *(b)*

(c) *(d)*

FIG. 3.136. Electricity generation from different sources up to the year 2100 for some of the scenarios: (a) 120_FR, (b) 80_REF, (c) 40_Coal, (d) 40_Renew.

Different assumptions regarding the future generation mix will result in different advantages and disadvantages to the overall power system. By analysing the power mix using the KIND approach and diligently selecting indicators that could highlight the differences between the scenarios the decision maker will be able to identify the option that best suits his or her preferences.

3.11.2. Methodological framework

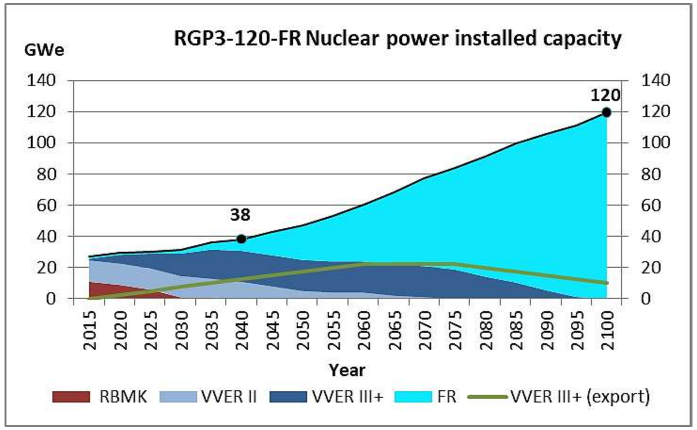
Calculations for the Russian case study were obtained by applying system modelling tools developed at the ITC Proryv institution and the KIND approach and software packages developed by the IAEA. The primary software application used for nuclear fuel cycle (NFC) modelling and energy systems scenario analysis at the ITC Proryv Analytics department is the USM-1 System Model Generator developed by Dr. Evgeni Muraviev [3.52]. This Excel-based tool can be used to generate models that simulate specific features inherent to production facilities or entire industries. The models themselves are dynamic and describe studied objects respective of their state in time allowing the user to control, explore and optimize how changes in their characteristics, whether technical or economic, affect the system as a whole. As a result, the data contained in these models are presented in the form of balanced, self-consistent scenarios. The models can describe the following characteristics for any energy or production systems:

- Power production development, balance of materials and resources;
- Infrastructure needed for construction and decommissioning (including personnel training, R&D, design, equipment procurement, assembly services, etc.);
- Transportation of input/output products;
- Cost structure, financing, profitability;
- Non-economic criteria: safety, ecological acceptability, non-proliferation.

Using the RGP3 (Russian Group Power) model a specific set of key indicators was calculated which served as input data for the KIND-ET tool for this case study.

3.11.3. RGP3 model

The RGP3 model and its corresponding scenarios use different assumptions regarding the scale of nuclear power development and type of reactor technology used which results in alternate fuel requirements, NFC infrastructure capacity (reprocessing, fuel fabrication facilities, etc.), SNF and HLW inventories. Figure 3.137 demonstrates the how installed power capacity changes over time in several selected scenarios.



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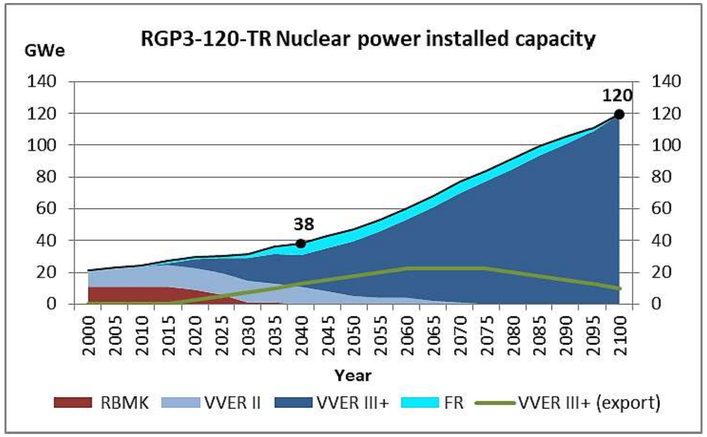

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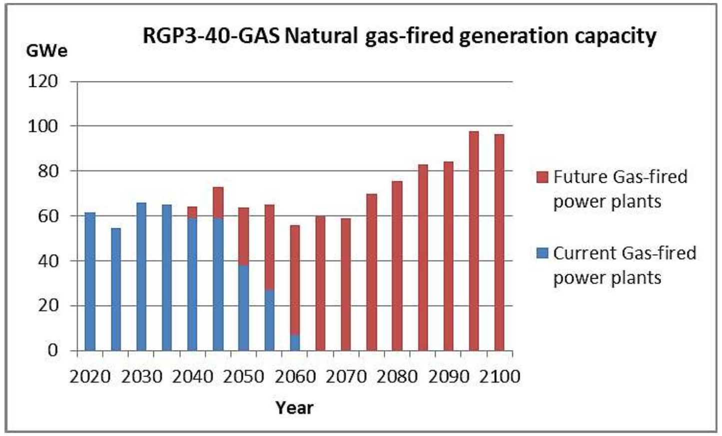

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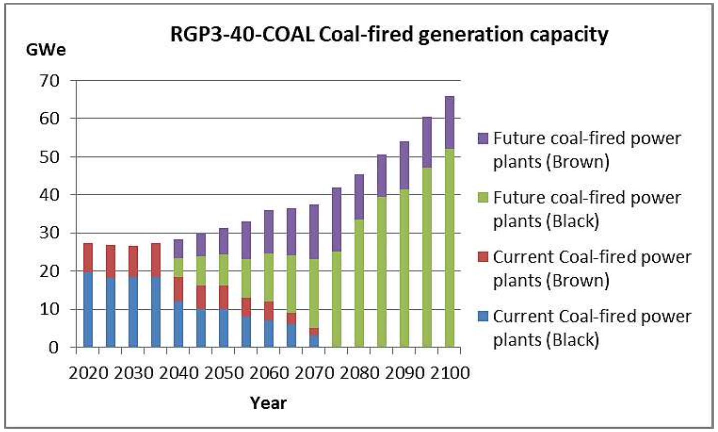


(d)

FIG. 3.137. Changes in installed capacity of technologies for selected scenarios: (a) RGP2-120-FR, (b) RGP3-120-TR, (c) RGP3-40-GAS, (d) RGP3-40-COAL.

The fuel balances for the developing a two-component NES with Fast Reactors and a closed NFC are defined by the following factors:

- UOX fuel requirements for thermal reactors;
- The requirement to recycle Pu as a product of reprocessing thermal reactor SNF with eventual fabrication of uranium-plutonium nitride fuel (MNUP fuel) fuel for FR;
- Utilization of recycled MNUP fuel with CR ~1.05;
- The amount of VVER SNF available for reprocessing (SNF from NPPs in Russia);
- U-Pu-MA recycling time frame.

Each RGP3 scenario has an underlying assumption that a certain type of power generating technology will be prioritized before others, be it thermal reactors, fast reactors, coal or gas-fired power plants. These assumptions have a discernible impact on product inventories for the entire system. Quantifying such aspects of the system as fuel requirements, resource depletion, CO_2 emission levels, SNF and Pu accumulation for each given scenario is important, as these parameters will affect performance and the overall scenario score. Figure 3.138, for example, illustrates how the share of fast reactors in the NES affects SNF inventory for two scenarios where nuclear power reaches 120 GWe in 2100.

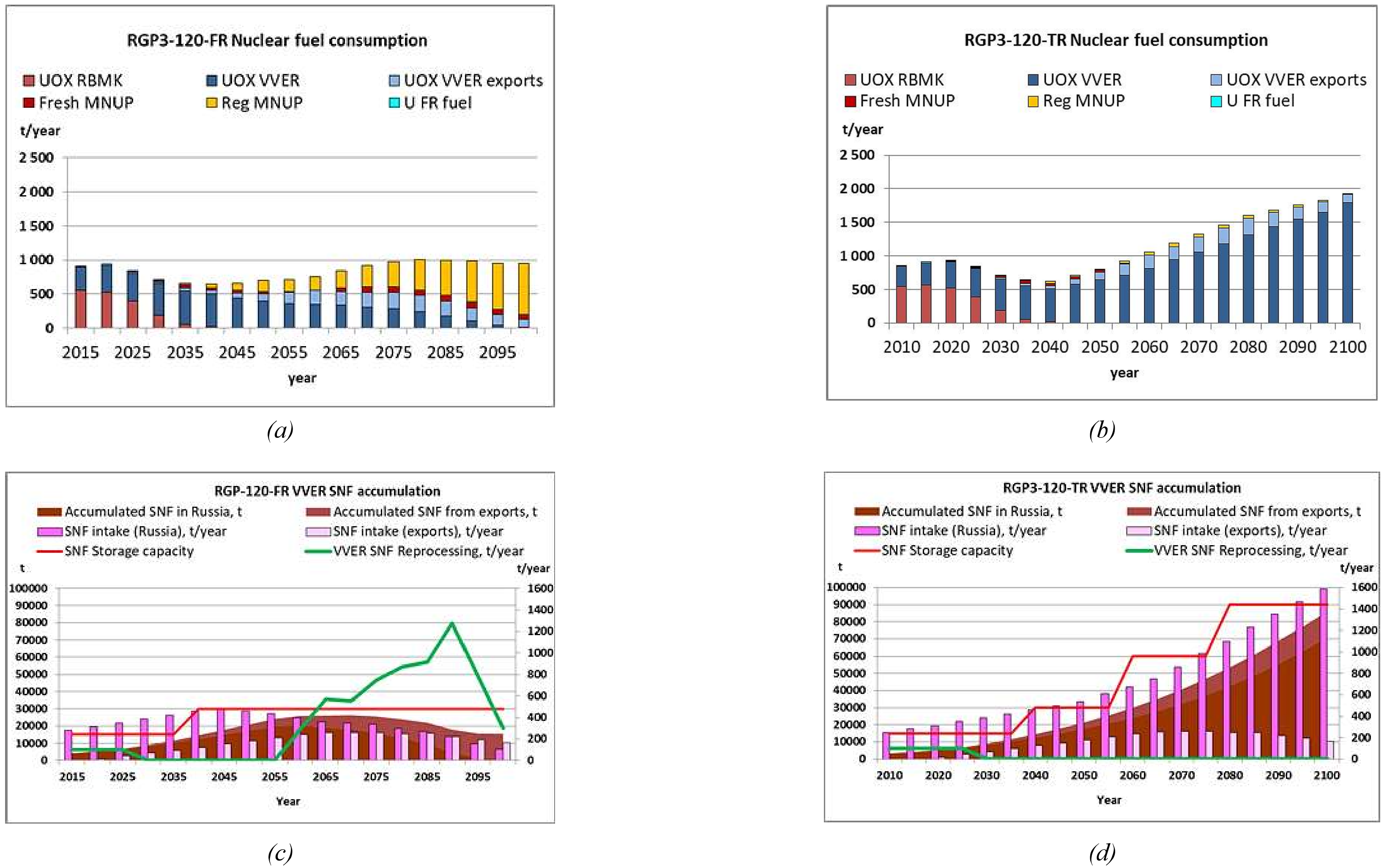


FIG. 3.138. *Fuel requirements and SNF inventory in scenarios: (a) RGP3-120-FR nuclear fuel consumption, (b) RGP3-120-TR nuclear fuel consumption, (c) RGP3-120-FR VVER spent nuclear fuel accumulation, (d) RGP3-120-TR VVER spent nuclear fuel accumulation.*

3.11.4. Assumptions used for RGP3 input data

The RGP3 model incorporates data from several sources of information to model the mass balance for each fuel cycle component and related cost data:

- Economic and NFC data for FR taken from recent project ‘Proryv’ publications [3.52];
- Russian Energy Outlook projections (the Energy research institute of the Russian academy of sciences (ERIRAS) for fossil fuel technology input data regarding fuel requirements, environmental impact and economics [3.53];
- Uranium 2018: Resources, Production and Demand (NEA, IAEA) [3.54];
- World Energy Outlook 2018 (International Energy Agency) [3.55].

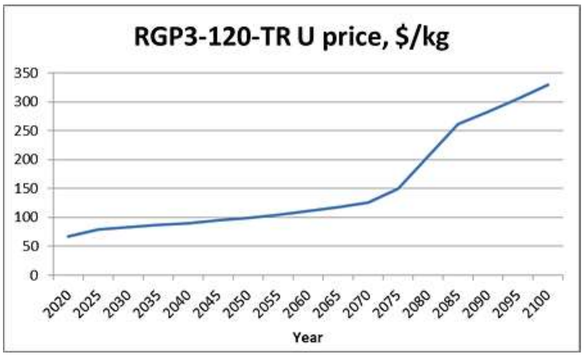
Price trends for natural gas and coal were derived from latest ERIRAS projections. Natural uranium prices were based on data published in the IAEA/NEA Red Book Uranium 2018: Resources, Production and Demand (NEA, IAEA) and are dependent on a cost/availability function that uses the price ranges contained in the Red Book. Key input data related to performance and cost characteristics for nuclear, gas and coal power used in the RGP3 model is given in Table 3.62. Cost data is given in 2016 US dollars.

TABLE 3.62. MAJOR COST AND PERFORMANCE ASSUMPTIONS FOR THE RGP3 POWER GENERATION TECHNOLOGIES

Parameter		Unit measure	Value
Overnight capital costs:			
	- VVER	US $/kWe	3160
	- FR*		2500
	- Coal-fired plant		1400-1650
	- Gas-fired plant		800
	-Wind power plant		650
Power unit operating life:			
	- VVER	years	60
	- FR		60
	- Coal-fired plant		40
	- Gas-fired plant		30
	-Wind turbines		25
Average burnup:			
	- VVER	GW·d/t HM	40-60
	- FR		62-115
CO_2 emissions:			
	- Old coal-fired power (black)	g/kW·h	0.960
	- Old coal-fired power (brown)		1.240
	- Old gas-fired power		0.600
	- New coal-fired power (black)		0.680
	- New coal-fired power (brown)		0.730
	- New gas-fired power		0.360

* This cost value is based on assuming that costs will be in this range if there is a mass-produced FR fleet

In contrast to natural gas and coal prices, which follow the same upward trend throughout every scenario, natural uranium prices are dependent on resource availability in Russia. Therefore, as is shown in Fig. 3.139, scenarios with a larger thermal reactor fleet will eventually be forced to buy more expensive uranium in the future due to earlier depletion of the less expensive resource category.



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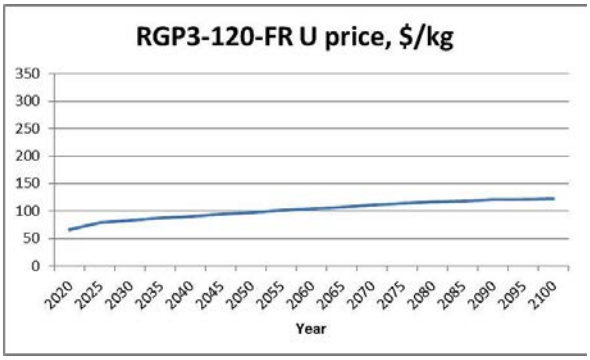
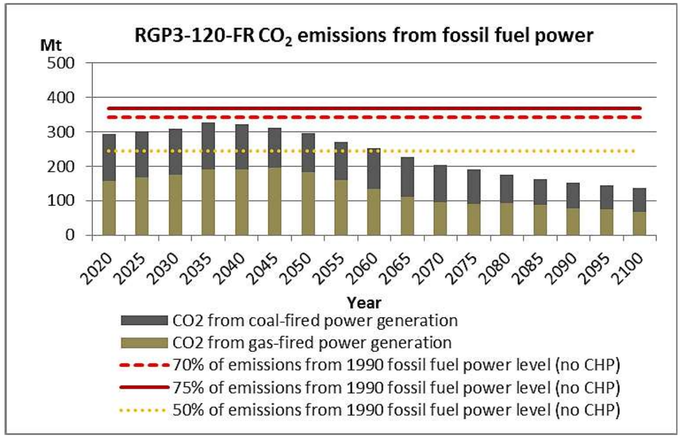


(b)

FIG. 3.139. Natural U prices in scenarios: (a) RGP3-120-TR, (b) RGP3-120-FR.

Another parameter, which will play a very important role in the overall score assessment for the selected scenarios, is CO_2 emission levels. This metric is dependent on how much and what kind of fossil fuel generation technology is deployed for any given scenario. In this case study Russia's Paris Climate Agreement intended nationally determined contribution is used as a benchmark for examining whether a scenario meets or fails to meet the sustainable development goal for mitigating climate change. The benchmark used in this study relates to 75%, 70% or 50% of the CO_2 emission level of the coal and gas-fired power generating plants in 1990. If any particular scenario fails to keep its emission levels below the 75% mark, then it is to be considered unsustainable from the point of view of mitigating climate change (Fig. 3.140).



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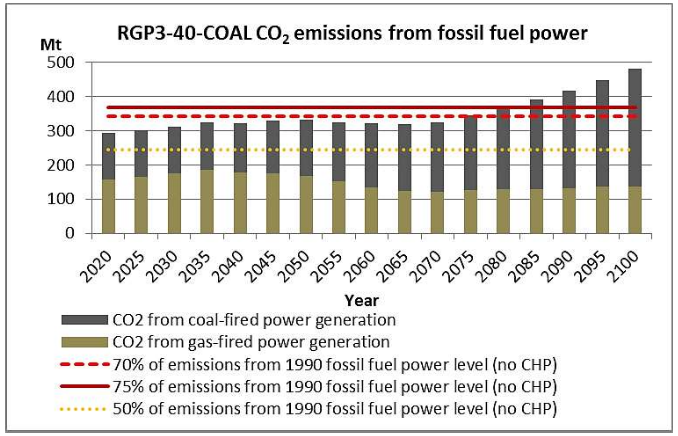

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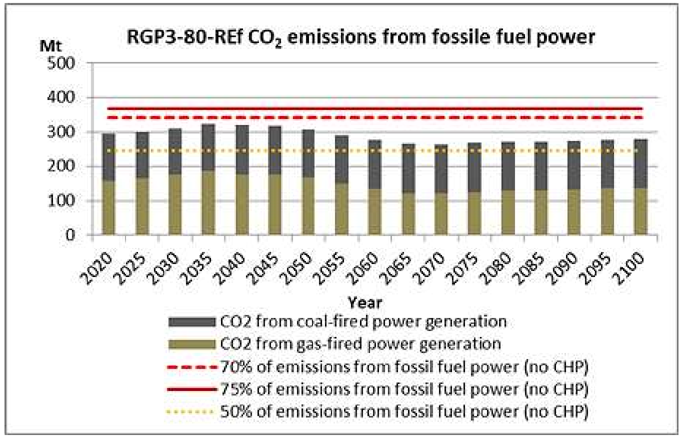

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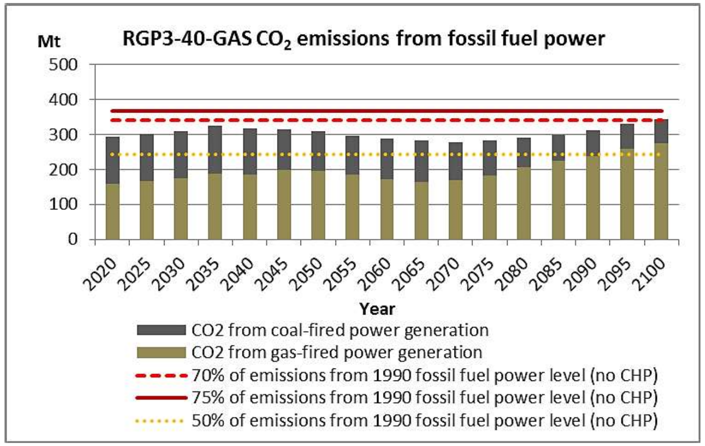


(d)

FIG. 3.140. CO_2 emission levels for RGP3 scenarios: (a) 120-FR, (b) 40-COAL, (c) 80-REf, (d) 40-GAS.

It needs also be noted that scenario 40_Renew which assumes a hypothetical massive transition to renewable energy sources (namely wind power in this study) in Russia has the same emissions profile as scenario 120_FR. Despite having the same effect on the environment regarding GHG emissions from directly generating electricity these scenarios are nevertheless expected to vary drastically in terms of material and land requirements and economics as well.

In terms of resource sustainability, three additional categories were selected for measuring resource requirements besides the traditional power station fuel needs: concrete, metals/alloys and land use. The discount rate for calculating the system LCOE was set at 2% to consider any long term effects on the energy system (even a 5% discount rate would make any cash flow beyond the 30-year time period practically irrelevant). Table 3.63 summaries the assumptions regarding material and land use requirements regarding different generating technologies selected for this study.

TABLE 3.63. ASSUMED MATERIAL AND LAND REQUIREMENTS FOR SELECTED POWER TECHNOLOGIES [3.56, 3.57]

Indicator:	Coal*	NGCC*	Nuclear*	Wind turbine
Metals and alloys, t/TW·h	310	170	160	2600
Concrete, m^3/TW·h	366	168	319	3000
Land use, ha/MWe	0.5	0.1	0.03	25

* - generator only

3.11.5. Key indicators

Table 3.64 contains the considered objective tree and the key indicator set selected for the study.

TABLE 3.64. RGP3 OBJECTIVE TREE

High-level objective titles	Areas titles	Indicators titles	Indicators abbr.
Cost	Economics	System LCOE, cents/kWh	E.1
Performance	Waste management	VVER SNF in 2100, t	WM.1
	Waste management	RBMK SNF in 2100, t	WM.2
	Resource sustainability	Cumulative U consumption since 2020, kt	RS.1
	Resource sustainability	Cumulative natural gas consumption since 2020, billion m^3	RS.2
	Resource sustainability	Metals and alloys requirements, million t	RS.4
	Resource sustainability	Concrete requirements, million m^3	RS.5
	Resource sustainability	Land use, ha	RS.6
	Maturity of technology	Time to commercial deployment	M.1
Environment	CO_2 reduction capability	CO_2 emissions in 2100, M_t	En.1

In this Russian case study, five areas were selected to adequately group the resulting KI set: economics, waste management, resource sustainability, maturity of technology and CO_2 reduction capability.

3.11.6. Ranking results

Table 3.65 contains the RGP3 scenario performance table, which was used for obtaining ranking results following the KIND approach.

TABLE 3.65. RGP3 PERFORMANCE TABLE

Indicator titles	Indicators	MIN score	MAX score	120_FR	120_TR	80_REF	80_TR	40_Gas	40_Coal	40_Renew
System LCOE, cents/kWh	E.1	0	10	3.87	4.05	3.87	3.96	4.03	3.90	4.57
VVER SNF in 2100, t	WM.1	0	100000	0	76058	15461	61134	48187	48187	48187
RBMK SNF in 2100, t	WM.2	0	25364	25364	25364	25364	25364	25364	25364	25364
Cumulative U consumption since 2015, kt	RS.1	0	1000	452	998	452	812	648	648	648
Cumulative natural gas consumption since 2020, billion m^3	RS.2	0	10000	4843	4843	5628	5628	7827	5628	4843
Metals and alloys requirements, million t	RS.3	10	70	13.4	13.4	14	14	13.5	15	64
Concrete requirements, million m^3	RS.4	15	80	20	20	19.9	19.9	18	21.1	76
Land use, ha	RS.5	10000	4000000	12200	12200	20800	20800	17400	39000	3709800
Time to commercial deployment	M.1	0	1	0	1	0	1	1	1	1
CO_2 emissions in 2100, M_t	En.1	0	500	136	136	280	280	345	482	136

Table 3.66 contains the base case weighting factors used for the assessment. The weighting factors were derived by means of using expert opinion.

TABLE 3.66. RGP3 – WEIGHTING FACTORS

High-level objective titles	High-level objective weights	Area titles	Area weights	Indicator abbr.	Indicator weights	Final weights
Cost	0.5	Economics	1	E.1	1	0.5
Performance	0.25	Waste management	0.35	WM.1	0.5	0.044
Performance	0.25	Waste management	0.35	WM.2	0.5	0.044
Performance	0.25	Resource sustainability	0.35	RS.1	0.2	0.018
Performance	0.25	Resource sustainability	0.35	RS.2	0.2	0.018
Performance	0.25	Resource sustainability	0.35	RS.3	0.2	0.018
Performance	0.25	Resource sustainability	0.35	RS.4	0.2	0.018
Performance	0.25	Resource sustainability	0.35	RS.5	0.2	0.018
Performance	0.25	Maturity of technology	0.3	M.1	1	0.075
Environment	0.25	CO_2 reduction capability	1	En.1	1	0.25

Several findings could be derived from studying the performance of the selected scenarios of this case study. Regardless of fossil fuel plant efficiency upgrades, scenarios that rely heavily on gas or coal-fired generation are unsustainable from an environmental perspective. Currently available Russian natural uranium resource deposits (although vast) will be unable to support a NES with a large fleet of thermal reactors being used for supplying power stateside and abroad, unless nuclear power capacity is limited to ~40 GWe in Russia or a closed fuel cycle is implemented. The 40_Renew scenario with a large share of wind generation seems uncompetitive in terms of economics and resource sustainability, although CO_2 reduction capability is on par with alternative options emphasizing large-scale nuclear build (120_FR and 120_TR).

The following ranking results were obtained by using the data contained in Table 3.63 and the KIND-ET tool (Fig. 3.141):

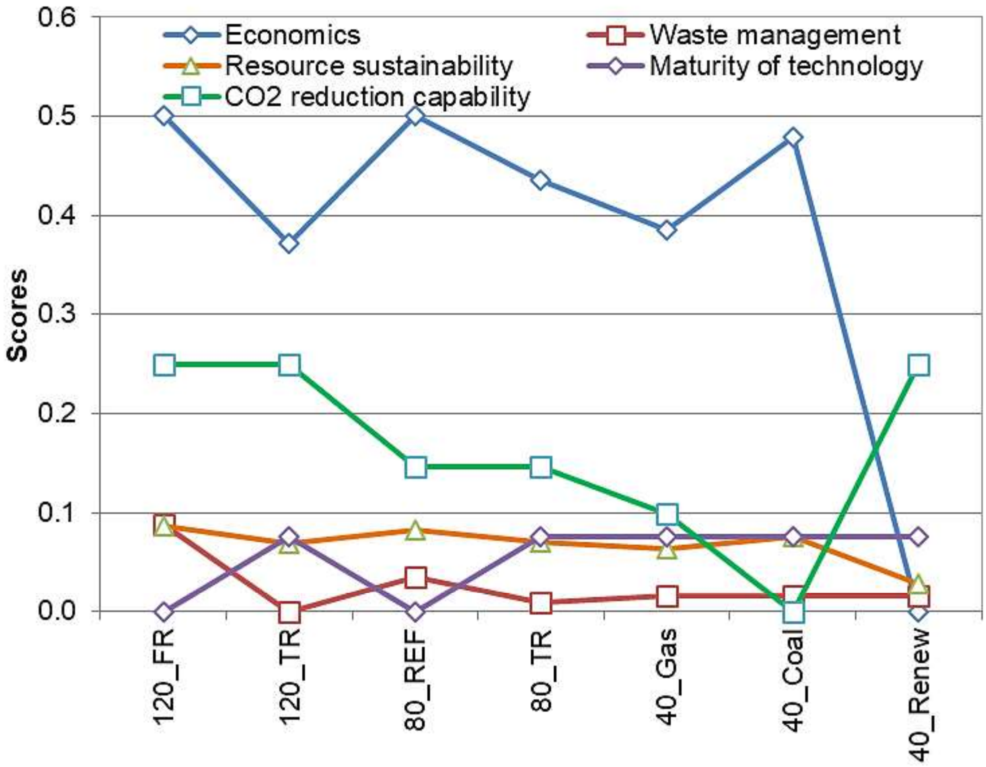


FIG. 3.141. Ranking results (evaluation areas).

By examining ranking results through evaluation areas, it can be seen that scenarios 120_FR, 120_TR and 40Renew are the most environmentally friendly scenarios out of the alternatives. The scenarios 40_Gas and 40_Coal received lowest scores on CO_2 reduction capability. Scenarios with the highest FR share in the energy mix, namely 120_FR and 80_REF, were best in terms of resource sustainability. Paradoxically, the 40_Renew scenario has the lowest resource sustainability score (for the given KI set) due to the colossal amount of material throughput and land use needed for its realization. Figure 3.142 highlights how all of these scores factor into the overall score for each scenario for the base case weighting factors.

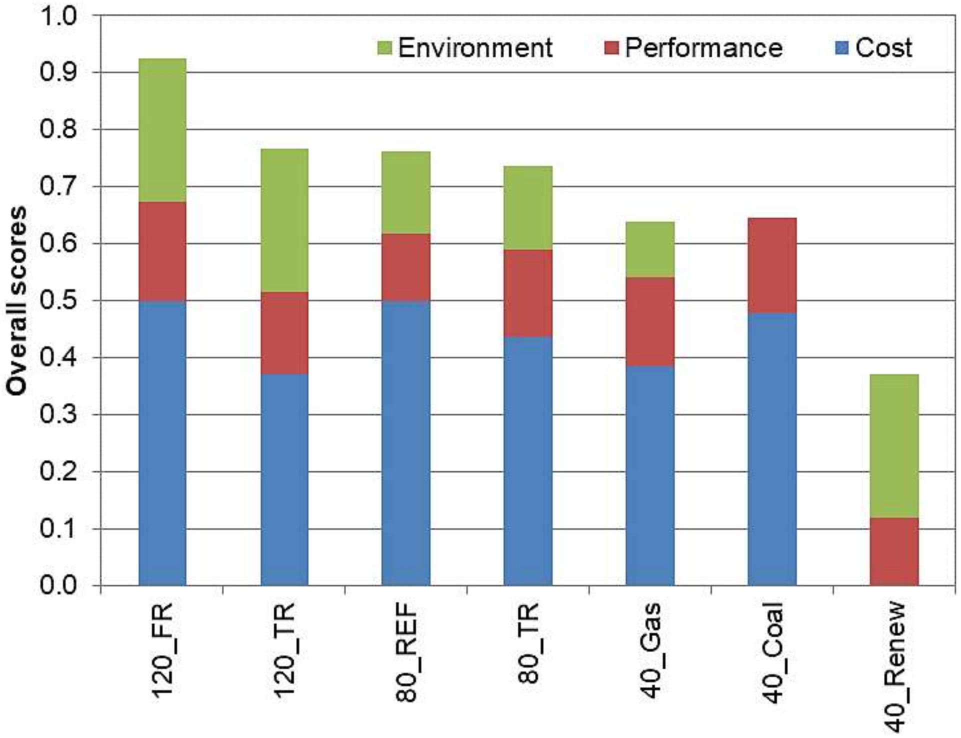


FIG. 3.142. High level objective scores for the base case weighting factors.

Weights' sensitivity analysis was also carried out in order to illustrate how sensitive the outcome variables are to variation of individual weights.

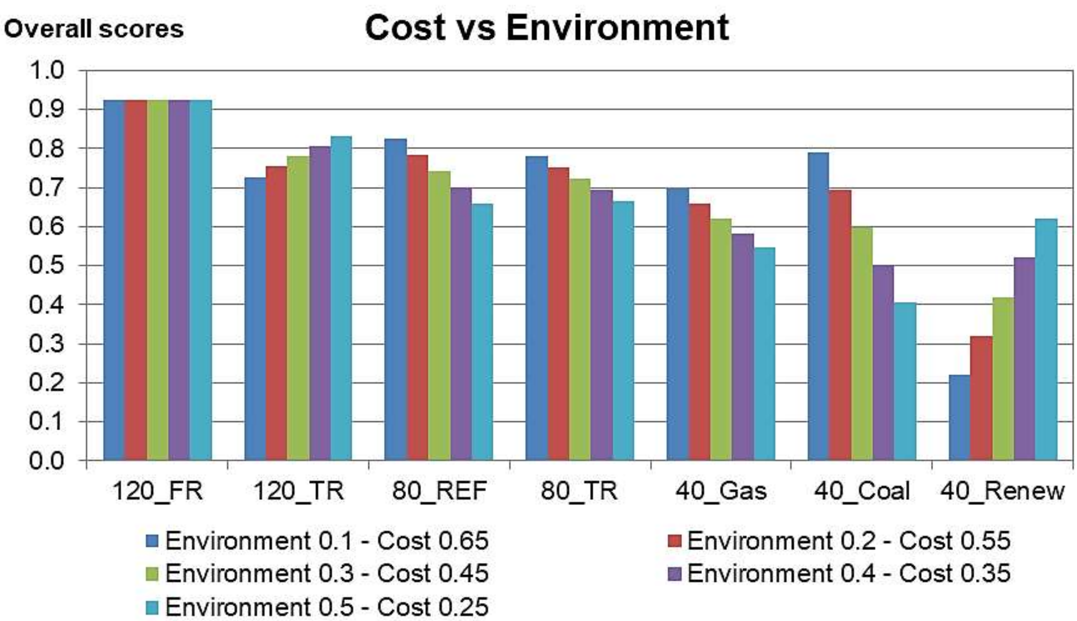


FIG. 3.143. Weight sensitivity analysis – Cost vs Environment.

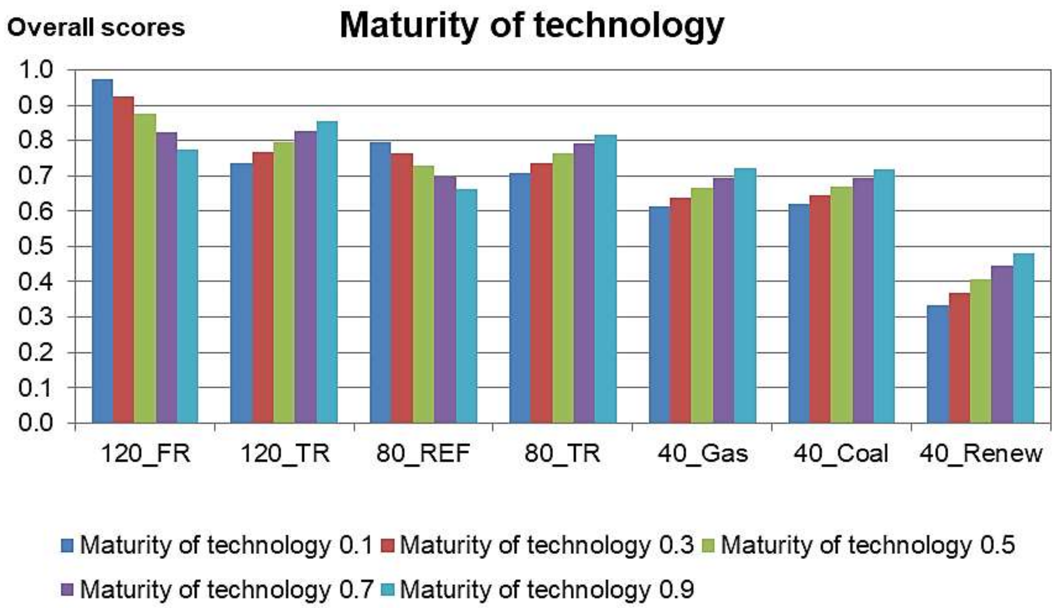


FIG. 3.144. Weight sensitivity analysis – Maturity of technology.

Preliminary results (Figs 3.143 and 3.144) show that the 40_Coal and 40_Renew scenarios are highly sensitive to changes in the environmental high-level objective weight. The preferability of the 120_TR scenario increases as more emphasis is put on the environmental high-level objective weight. The overall score of the 120_FR scenario is unaffected by changing the cost or environment high-level objective weights. Both the 120_FR and 80_REF scenarios are highly sensitive to changes in the maturity of technology KI weight, since they both employ FR and closed nuclear fuel cycle technologies whose performance has yet to be demonstrated at a commercial level. If the weight of the maturity of technology KI is set at a value more than 0.7 (in respect to the performance high-level objective), the 120_FR scenario loses its advantage over some of the alternative options.

To complete the second objective for this study the following KIND-ET extension tools were used:

- Domination Identifier – an analytical tool for identification of non-dominated and dominated options among the set of considered feasible options;
- Overall Score Spread Builder – an express tool for evaluation of option overall score spreads caused by uncertainties in weighting factors and the objective tree structure;
- Ranks Mapping Tool – a visualization tool to highlight the options taking the first rank for different combinations of high-level objective weights.

To identify dominated and non-dominated scenarios the Domination Identifier tool was used. The domination analysis for the whole KI set concluded that there were no dominated scenarios due to the fact that scenarios 120_FR and 80_TR, although having very good scores compared to alternative scenarios, rely on innovative technologies and therefore have a low maturity of technology KI rating. If nevertheless FRs and closed NFC technologies would mature as reliable and safe technologies for innovative nuclear power development, these scenarios would dominate the competition, as shown in Fig. 3.145.

Domination table		Dominating options						
		120_FR	120_TR	80_REF	80_TR	40_Gas	40_Coal	40_Renew
Dominated options	120_FR		-	-	-	-	-	-
	120_TR	<		-	-	-	-	-
	80_REF	-	-		-	-	-	-
	80_TR	-	-	<		-	-	-
	40_Gas	-	-	-	-		-	-
	40_Coal	<	-	<	-	-		-
	40_Renew	<	-	-	-	-	-	

FIG. 3.145. Dominated and dominating options in case when FR and closed NFC technologies will be commercialized as the matured power generation technologies (screenshot from Domination Identifier).

An evaluation of overall score spreads caused by uncertainties in weighting factors and the objective tree structure using the Score Evaluator toolkit was completed. Scenarios with high number of low KI scores showed adverse results compared with alternate options. As expected, scenario 120_FR shows impressive robustness against variations of weighing factors (Fig. 3.146).

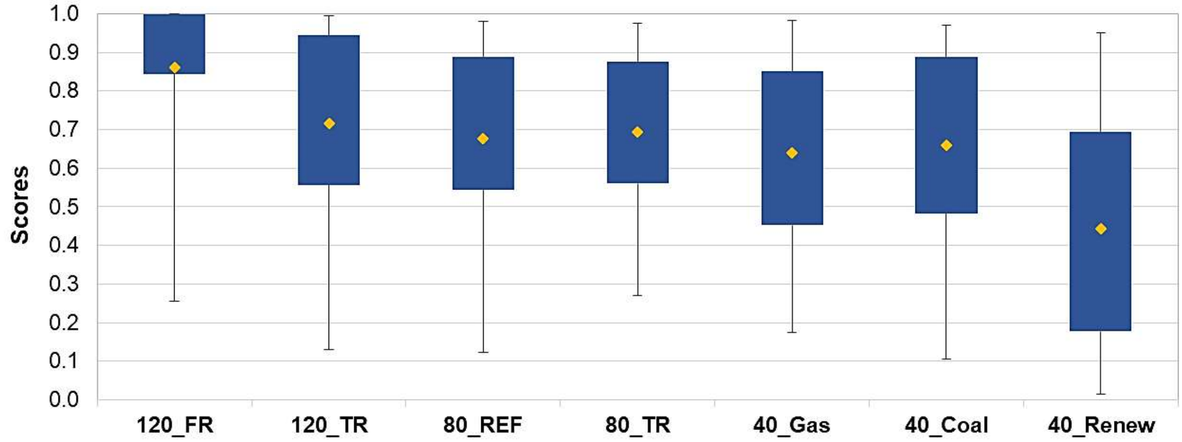


FIG. 3.146. Score spreads caused by uncertainties in weighting factors (mean value, 5^{th}, 25^{th}, 75^{th}, 95^{th} percentiles are shown).

The Ranks Mapping tool is intended for problems assuming group decision making when it is necessary to find trade-off options, which may be suitable for different decision makers having different criteria sets. The current study employs three high-level objectives: cost, performance and environment. Since the 120_FR scenario is clearly dominating every other scenario with the underlying KI weight assumptions considered (Fig. 3.147), it would be reasonable to evaluate an alternate ‘scenario’ where the maturity of technology plays a larger part in the decision making process. Many innovative nuclear power technologies are under development and often it is unclear how and when they will be commercialized in the future. Figure 3.148 shows the distribution of overall scores using the Ranks Mapping tools with Maturity of technology KI weight set at 0.5 and resource sustainability and waste management weight each set at 0.25.

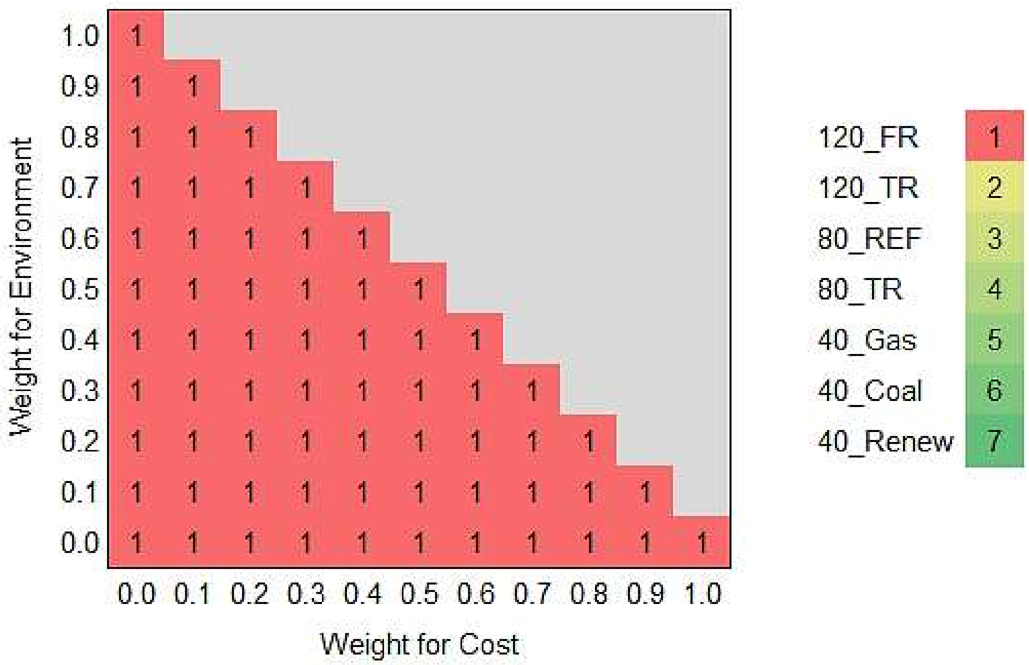
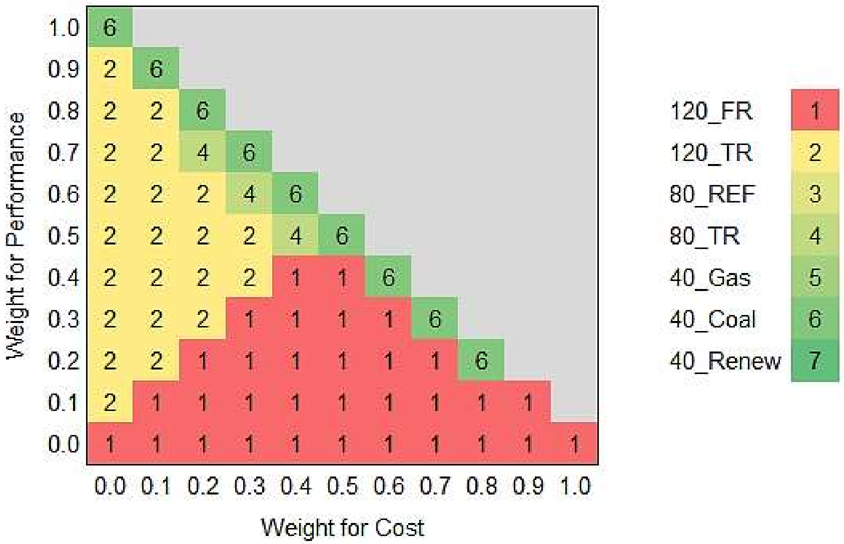
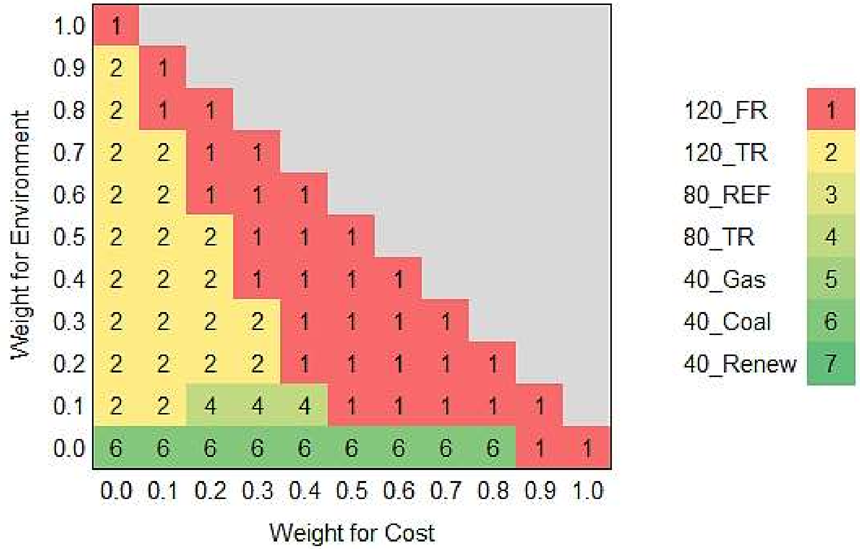


FIG. 3.147. Ranks mapping tool results with maturity of technology weight set to 0.3.



(a)



(b)

FIG. 3.148. Ranks mapping tool results with maturity of technology weight set to 0.5: (a) Performance versus Cost, (b) Environment versus Cost.

As a result, the distribution of overall scores for different scenarios with different weights attributed to high-level objectives in the KIND-ET comparative evaluation tool could be examined more thoroughly and clearly by using the Ranks Mapping tool. For example, if one was to nullify the environmental impact factor of CO_2 emissions from fossil fuel generation during the decision making process, then the 40_Coal scenario could be considered the more preferable option. On the other hand, if potential economic and environmental benefits are valued over technology maturity risks, then the 120_FR scenario is a clear frontrunner in terms of overall score. It needs to be noted that the 40_Renew scenario with large scale renewable power development showed overall poor results in this particular study due to the selected KI set. The cumulative effect of underperforming economics (the low-capacity factors and operating lifetimes for renewable energy in system studies that model time periods exceeding 60 years have an adverse effect on LCOE) and significant material and land requirements have highlighted the problems with large-scale wind or solar power development strategies.

3.11.7. Conclusions

Application of the MAVT method for judgment aggregation and the KIND approach provided an excellent platform for comparing alternative scenarios within the RGP3 model. Advantages and disadvantages from implementing different energy development strategies were explored and investigated by combining simulation modelling and the KIND-ET tool including its extensions. The KIND approach could be used for further studies related to national nuclear and general energy development strategies. Using the tools developed by the IAEA, this study was able to highlight some of the more nuanced issues concerning potential trade-offs between cost and CO_2 mitigation. A comprehensive study using the KIND approach on developing various regional or global energy systems could support the effort to mitigate climate change and pollution.

3.12. COMPARATIVE EVALUATION AND RANKING OF DIFFERENT POWER TECHNOLOGIES BASED ON THE INTEGRATED NEEDS & KIND FRAMEWORK (RUSSIAN FEDERATION)

This chapter presents structured report of the fourth of the four case studies done by experts from the Russian Federation.

3.12.1. Introduction

This section presents the results of a case study on a comparative evaluation and ranking of different power technologies which are considered for future deployment in the Russian power sector. The performed analysis was based on a combination of approaches proposed under the Project on New Energy Externalities Development for Sustainability (NEEDS), funded within Framework Programme 6 of the European Commission for Research, Technological Development and Demonstration, and the INPRO collaborative project KIND ('NEEDS & KIND framework'). The set of key indicators along with approaches for their assessment, including relevant databases were borrowed from the NEEDS project and adapted for the present study. The approach to aggregating judgments is based on the IAEA/INPRO KIND approach to carrying out comparative evaluations. In addition, the study includes the results of the advanced uncertainty treatment in regard to weighing factors using relevant tools developed within the CENESO collaborative project. The comparative analysis considered six possible Russian power generation technologies (the technology-level consideration), including two nuclear (nuclear power plants based on light water reactor and sodium cooled fast reactor technologies), two fossil fuel (pulverized coal and gas turbine combined cycle power plants) and two renewable (wind and photovoltaic power plants) power generation options. Thirty-six key indicators arranged in a four-level objective tree were involved which were assessed using the NEEDS databases and Russian-specific data sources. The presented results demonstrate the outstanding performances of nuclear power technologies (especially fast reactor technologies) to achieve the goals of sustainable energy development in the case of Russia, the overall performance of which is even better than that of renewable technologies. Some steps are also outlined for further considerations and extensions of the analysis performed with the aim of obtaining more rigorous conclusions regarding the most preferred technological options for the Russian power sector.

3.12.2. Scope and objective of the study, problem formulation

A multi-criteria framework for a comparative evaluation of the performance of energy and fuel cycle technologies is becoming more popular with each passing year due to the possibility of a comprehensive consideration of the situation throughout the life cycle, where not only purely economic factors play an important role, but also factors that cannot be represented in economic categories characterized by multiple environmental and social criteria [3.1] play important roles. When carrying out this kind of analysis and ranking of competing energy and fuel cycle technologies at the technological level as part of the multi-criteria decision analysis, it is necessary to solve the following main problems [3.3, 3.7]:

— To specify a set of key indicators characterising economic, environmental and social aspects and to arrange them into an appropriate multi-level hierarchical structure;
— To collect relevant information for the formation of databases specifying the technical characteristics along with the economic, environmental and social impacts of the considered options for evaluating the selected set of key indicators reflecting different sustainability dimensions;
— To develop a decision support model using the multi-criteria decision analysis framework based on objective evaluations and subjective judgments expressed by the decision-makers, subject matter experts and stakeholders;
— To apply this decision support model including an uncertainty/sensitivity analysis to identify merits and demerits associated with each option in order to highlight the most preferred options for different perspectives and to provide final advice regarding the most attractive alternative for real-world deployment.

When performing multi-criteria comparisons of nuclear versus non-nuclear power generation options, it is necessary to overcome the same challenging points so as to meet the basic requirements, such as selected key indicators that need to be applied in a balanced way both for nuclear and non-nuclear options. Relevant databases are to be formed that will provide representative evaluations of all the performance criteria for all the options with appropriate accuracy (it especially refers to social indicators) and support correct interpretation of ranking results assuming that the final objective of the study is not to select the most preferable options for deployment but to highlight merits and demerits associated with each option.

Given these points, the present case study attempted to conduct a comparative evaluation and ranking of different power technologies, which are considered for future deployment in the Russian power sector. Before formulating a specific problem that would be considered, the following are short descriptions of priorities in the Russian energy sector long term development and a validated conceptual base for the formation of the criteria set for performing the comparative evaluation of the options considered in this study.

3.12.2.1. Priorities in the Russian energy sector long term development

The energy strategy of the Russian Federation up to 2030 is aimed at maximising the use of domestic energy sources, implementing the energy sector potential to sustain economic growth and stimulating strategic development throughout the country. The energy strategy outlines the following key priorities: improving energy efficiency, reducing environmental impact, enhancing sustainable development, developing technology as well as increasing effectiveness and competitiveness [3.58, 3.59].

The structural policy for the energy sector over the next 10–15 years includes:

— Improving the efficiency of natural gas utilisation and increasing the share of its domestic consumption, especially in ecologically sensitive regions;
— In-depth processing and comprehensive utilisation of hydrocarbon raw materials;
— Improving the coal quality and stabilising coal production volumes;
— Intensifying local and renewable energy resource development;
— Prioritising electricity generation development based on competitive and ecologically clean power plants;
— Improving the safety and reliability of the first generation NPPs, developing advanced NPPs.

The new policy in energy technologies is aimed at:

— Radically improved effectiveness and efficiency of energy production at all stages of a fuel cycle;
— Efficient decentralization of energy supplies;
— Environmental and accident safety, reliability of energy supply;
— Development of new technologies for the sustainable evolution of the power industry: ecologically clean coal fired power plants; safe nuclear power plants; efficient processes for the utilisation of new sources of power, etc.

The energy strategy of the Russian Federation, initially earmarked to last until 2030, was extended to 2035 to implement the governmental decisions. The revised energy strategy is less ambitious with regard to the policy tasks, forecasts of the domestic energy demand, and the development of Russia's electric power [3.60, 3.61].

It assumes that fossil fuel will remain the basic contributor to Russia's energy supply; however, there will be a regular annual reduction in its share caused by the development of noncarbon power plants and the renovation of existing thermal plants. The prevailing demand for gas will remain while the consumption of liquid and solid fuels continues decreasing. This decrease will be coupled with an increase in the share of noncarbon energy resources. The expected increase in gas prices will become an important factor in improving energy efficiency through replacing current equipment with combined cycle gas turbine plants as well as developing central heating based on the combined heat and power plants. An increase in gas power plant generation efficiency along with a considerable increase in domestic gas prices and coal consumption will reduce the fraction of gas in primary energy consumption by power plants.

As for various power sectors, the electric power industry will become more intense due to the technologies for noncarbon energy production and storage. Thermal power plants will hold the lead in electricity production, although their share will slightly decrease. The share of nuclear power plants will be preserved, and the total share of hydropower plants and nonconventional and renewable energy sources will increase accordingly. Additionally, it is expected that the market competitiveness of nuclear power will be supported by the increasing fuel prices for thermal power plants. Advancements in the projects for the nuclear power industry will also contribute to their market competitiveness. However, with regard to the nonconventional and renewable energy sources in Russia and the costs of their integration into a power system, the renewable sources in the centralized power supply zone will have remained noticeably more expensive by the end of the period as compared to thermal power plants. Thus, the entire spectrum of promising power generation technologies is considered for electricity generation in the Russian Federation. Therefore, it is important to highlight the merits and demerits of each technological option through the lens of sustainable development concepts and identify the most preferred alternative for different stakeholder priorities.

3.12.2.2. The NEEDS project: scope, approaches and deliverables

The New Energy Externalities Development for Sustainability (NEEDS) project was a research project funded within Framework Programme 6 (FP6) of the European Commission for Research, Technological Development and Demonstration (the project duration is 2004–2009) [3.62]. The project was "intended to provide direct, usable inputs to the formulation and evaluation of energy policies in the overall framework of sustainability, considering their "economic, environmental and social" aspects[28]. The NEEDS emphasis was on the policy relevance of results.

NEEDS was a multidisciplinary endeavour combining the sectorial competencies in the areas of energy technologies, environmental, social and economics assessments together with the relevant methodological decision support approaches and frameworks (life cycle assessment (LCA), database development and mathematical modelling, qualitative and quantitative methods and tools including MCDA). The long series of Deliverables and Technical Papers were produced by individual Work packages within the seven Research Streams featured by NEEDS.

The NEEDS research team included more than 200 scientists and researchers and contributions from external stakeholders and policymakers. More than 60 partner organisations with different geographical, disciplinary and cultural backgrounds have participated in the project that required a structured approach to consensus-building to manage multiple conflicting views on the issues.

NEEDS helped to answer the following policy queries:

— Multifaceted evaluation of energy technologies (by relying upon foresight techniques, Life Cycle Assessments (LCA), evaluation of externalities, stakeholder perception and acceptance);
— "Formulation, optimisation and impact assessment of energy policies" through "scenario-building, modelling", multi-criteria "analysis, and their monitoring and evaluation based on sustainability indicators, green accounting" [3.62];
— "Investment decisions primarily based on Social Cost Benefit Analyses" [3.62].

As part of the NEEDS project, 26 generation technologies were considered, including two nuclear (one PWR and one SFR), 16 fossil (10 coal and lignite, and six natural gas) and eight renewable (three biomass, four solar and one wind) technologies. Two approaches were applied in the framework of the project: external cost estimation and MCDA-based frameworks.

As a result of the systematic process, a set of criteria and indicators was determined for evaluating the sustainability of electricity supply technologies. Table 3.67 based on data from Ref. [3.63] lists the evaluation criteria used in the NEEDS project (this set of criteria was also applied in the present study).

The proposed set of criteria and indicators representing consensus within the research streams, was surveyed by the external stakeholders. The survey results showed strong support among the stakeholders for the proposed set of criteria and indicators. The proposed set underwent limited streamlining in order to remove a small number of primarily overlapping indicators. Then this set was used in comparative evaluations of the sustainability of the technological options based on MCDA in view of sustainable development.

Although nuclear energy demonstrates the lowest total costs in the external cost estimation framework used in NEEDS, its rank in the MCDA structure is generally not the highest, losing to the renewables. Such result is owing to the various social factors having been considered without their inclusion into external costs. As shown in [3.62], "renewables show the most robust" behaviour, "i.e., in comparison to fossil and nuclear options" they demonstrate "a lower dependence of ranking on the differences in preference profiles; this applies especially to solar technologies". "Coal technologies perform worse than centralized natural gas options; the latter are in the midfield and have ranking comparable to the nuclear one. The performance of "Carbon Capture and Storage" (CCS) is mixed, i.e., fossil technologies with CCS may rank better or worse than the corresponding technologies without CCS, depending on …CCS option is used" [3.62].

TABLE 3.67. EVALUATION CRITERIA USED IN THE NEEDS PROJECT

High-level objectives	Areas	Sub-areas	Short title of key indicator	Unit
ENVIRONMENT RELATED	RESOURCE USE	Energy	Fossil fuel	MJ/kWh
			Uranium fuel	MJ/kWh
		Minerals	Ore (metal)	kg (Sb-eq.)/kWh
	IMPACT ON CLIMATE	—	GHG emissions	kg (CO_2-eq.)/kWh
	IMPACT ON ECOSYSTEMS	Normal operation	Land use	PDF*·m^2·a/kWh
			Ecotoxicity	PDF·m^2·a/kWh
			Acidification/ Eutrophication	PDF·m^2·a/kWh
		Severe accidents	Hydrocarbons	t/kWh
			Land contamination	km^2/kWh

* Potentially damaged fraction

TABLE 3.67. EVALUATION CRITERIA USED IN THE NEEDS PROJECT (cont.)

High-level objectives	Areas	Sub-areas	Short title of key indicator	Unit
	IMPACTS FROM WASTE	—	Chemical waste	kg/kWh
			Radioactive waste	m^3/kWh
SOCIAL Social related criteria	SECURITY	Political continuity	Security of supply	Ordinal scale
			Waste repository	Ordinal scale
			Adaptability	Ordinal scale
	POLITICAL LEGITIMACY	—	Conflicts	Ordinal scale
			Public participation	Ordinal scale
	RISK	Normal operation	Mortality	YOLL**/kWh
			Morbidity	DALY***/kWh
		Severe accidents	Accident mortality	Fatalities/kWh
			Max. fatalities	Fatalities/accident
		Perceived	Normal operation	Ordinal scale
			Perceived acc.	Ordinal scale
		Terrorism related	Terror potential	Ordinal scale
			Terror-effects	Expected fatalities
			Nuclear proliferation	Ordinal scale
	RESIDENTIAL ENVIRONMENT RELATED	—	Landscape	Ordinal scale
			Noise	Ordinal scale

** Years of life lost

*** Disability adjusted life years

3.12.3. Inputs, methods and assumptions used

The inputs, methods and assumptions for this case study are presented in a structured form below.

3.12.3.1. Power generation options under consideration

In the present study, based on technology-level considerations, six power generation technologies that are planned to be used for electricity production in the Russian Federation were considered, including two options for using nuclear fuel, two options for using fossil fuels and two options for using renewable energy sources. Below are brief descriptions of these six technologies: nuclear power plants with pressurized water reactors (PWRs), nuclear power plants with sodium-cooled fast reactors (SFRs), pulverized coal power plants (CPPs), gas turbine combined cycle power plants (GTCCs), solar photovoltaic power plants (SPVs), and wind power plants (WPPs).

Nuclear power plants with pressurized water reactors

A pressurized water reactor is a Generation III design for a nuclear reactor that uses low-enriched uranium oxide fuel and operates in a once-through fuel cycle. This reactor type has higher reliability, safety and efficiency compared to the existing Generation II prototypes, which leads to reduction in the amount of spent nuclear fuel and radioactive waste per unit of electricity generated, unlike in the early generation reactor types. Nevertheless, minor risks of a severe accident and the proliferation of fissile materials are still possible. The PWR operational lifetime is expected to be 60 years.

Nuclear power plants with sodium-cooled fast reactors

A sodium-cooled fast reactor is a Generation IV design for a nuclear reactor with a fast neutron spectrum. This reactor type allows breeding of fissile material (namely, fissile plutonium-239 isotope) by absorption of neutrons by the non-fissile uranium-238 isotope. It is assumed that a sodium-cooled fast reactor operates in a closed-fuel cycle where the plutonium from the reprocessed spent fuel from co-existing Generation III reactors can also be used as MOX fuel for SFRs. Due to the use of sodium as a coolant, this reactor type has higher efficiency than PWRs. Higher burn-up of the SFR fuel reduces the volume of fresh and spent fuel flows. This reactor is characterized by its inherent safety features, but it is impossible to completely eliminate the risk of a severe contamination release to the environment as well as the risk of proliferation associated with fissile materials. The SFR operational lifetime is expected to be 60 years.

The scale of nuclear power deployment in the Russian power sector is a debatable topic: the levelized unit electricity cost for new NPPs in the Centre Interconnected Power System is about 1.7 times higher than that of gas turbine combined cycle power plants. However, the predicted increase in gas prices and predicted decrease in costs of building the new generation NPPs as well as an increase in the NPP capacity factors up to 90% and a decrease in the cost of capital make nuclear generation economically comparable to gas-fired power generation [3.61].

Pulverized coal power plants

Pulverized coal combustion is the technology most widely used today for power generation. A pulverized coal power plant is based on pulverized coal being burned in a boiler. Different coals can be burned in pulverized coal power plants, but this technology may not be the best for coals with high ash contents. The pulverized “coal is blown with part of the combustion air into the boiler through the burners. Secondary and tertiary air is also added in the burners or directly in the combustion chamber” [3.62]. Steam is produced to drive a turbine generator. Coal combustion results in large amounts of carbon dioxide and other atmospheric pollutants. Emissions of sulphur dioxide and particles can be effectively removed by the use of filters. Conventional pulverized coal power plant units operate at nearly atmospheric pressure, which simplifies the material flows through the plant. Transportation needs for the delivery of large amounts of coal cause noise pollution in rail-freight transit regions. The operational lifetime is expected to be about 40 years.

In the Russian Federation, coal-fired thermal power plants have occupied an ‘intermediate’ position in terms of relative capital requirements between combined-cycle gas turbine units and NPPs. However, these plants will encounter increasing competition from gas and nuclear power and in the long run this competition may increase even further with the possible introduction of various steps to limit greenhouse gas emissions after 2030 under the Paris Agreement [3.61].

Gas turbine combined cycle power plants

A power plant with gas turbine combined cycle (GTCC) is based on “direct combustion of natural gas in a gas turbine generator” and “the waste heat generated by this process is then used to” generate “steam for” its later “use in a steam generator” [3.62]. “GTCC plants have relatively low CO_2 emissions per unit of generated electricity compared to other fossil power plants” [3.62] but, at the same time, they generate significant NOx emissions due to the high combustion temperature needed for high efficiency. One of the main advantages of a GTCC as a power generation technology is its flexibility in operation, which allows them to be effectively used both for generating baseload power and for covering peak loads with shorter duration. The operational lifetime is expected to be about 30 years. In the Russian Federation, the share of the imported equipment in the GTCC is large, and due to changes in the macroeconomic environment, this factor substantially increases the uncertainty of the cost of construction of combined-cycle units. However, this factor will gradually become weaker as the production of the domestic gas turbines is mastered [3.61].

Solar photovoltaic power plants

A solar photovoltaic power plant is a wafer-based crystalline silicon semiconductor technology. “Photovoltaic (PV) systems are energy devices” designed “to directly convert sun energy into electricity. The basic building block of a PV system is PV cell, which is a semiconductor device converting solar energy into direct current electricity” [3.62]. More cells in series form a PV module. “More modules connected in series form” the “so-called ‘string’. More strings connected in parallel form the actual PV” generator [3.62]. “PV systems are highly modular. The main distinction is between PV modules made of crystalline semiconductor (single and multi-crystalline silicon) and thin films (amorphous silicon, cadmium telluride, copper indium diselenide)” [3.62]. The operational lifetime is expected to be about 25 years.

Wind power plants

Wind farms consist of multiple wind turbines connected to a single transformer station. This approach is more cost effective due to the economy-of-scale effect than individual turbines. Existing wind turbines have more advanced variable-speed pitch-regulated turbines equipped with sophisticated generators and control systems. Their operational lifetime is assumed to be 30 years.

The central problem of using the wind and solar power plants in Russia is their lack of economic competitiveness in the zones of the centralized power and gas supply. At the current level of capital costs, the electric power generated by new wind and solar power plants is 3.3–5.0 times more expensive than that of the power generated by new GTCC plants. The competitiveness of the wind and solar power plants is reduced due to the associated costs of their integration into the power supply system: the need for either partial duplication of capacities, e.g., increasing the gas turbine power plants, or installation of energy storage systems that control the electricity output of renewables [3.61].

3.12.3.2. Approaches to comparative evaluations of power generation options

Power generation technologies can be compared at both the technological and scenario levels. In this study, they were considered at the technological level, i.e., without considering any system-level evaluation, including resource and infrastructure constrains and restrictions. Two approaches are widely used for comparative evaluations and rankings of power generation technologies. The first approach involves the calculation of total costs (the sum of direct costs and external costs — externalities). The second approach is based on the multi-criteria decision analysis framework that combines assessments of specific economic, environmental and social attributes and criteria associated with various technologies with the decision-maker/stakeholder preferences.

The advantage of the first approach is that it is conceptually simple and provides an unambiguous ranking of technologies. However, when implementing this approach, experts may encounter difficulties and huge uncertainties associated with the monetisation of external effects, which may lead to a contradiction in the final rating. The main problem is that not all sustainability criteria can easily be monetized, in particular, social criteria (such as risk perception, public acceptance etc.) can hardly be considered within this approach.

The advantages of the second approach include the fact that its implementation makes it possible to familiarize decision-makers and stakeholders with the strengths and weaknesses of competing power generation technologies by involving them directly in the discussion and decision making process within the constructive and fact-based framework. The MCDA can consider social, environmental and other factors that are difficult to monetize, or their monetisation is associated with great uncertainties. On the other hand, the implementation of the MCDA-based comparison procedure is a more complex and time-consuming process that benefits from the involvement of many interested stakeholders who are expected to agree on a set of criteria and their hierarchical organisation, the procedure for evaluating the criteria, the relative importance of the criteria along with other decision support model parameters. Despite the fact that social indicators are explicitly included, their quantitative assessment is not always reliable and clearly determined. These points can be considered as the main drawbacks of this approach.

3.12.3.3. Key indicators and the objective tree

All the 36 evaluation criteria proposed in the NEEDS project [3.62] were used for the comparative evaluation of the six considered power generation technologies in the present study, namely:

— 11 environmental indicators, including three indicators characterising the consumption of energy and non-energy resources, one indicator for impacts on climate change and five indicators for impacts on ecosystems, two indicators for wastes;

— nine indicators for economics, including one indicator to address impacts on customers, two indicators characterizing the overall economy and six indicators characterizing the utility;
— sixteen social indicators (12 of which are related to ecology), including three indicators to examine security and reliability of energy supply, two indicators characterizing legitimacy and political stability, nine indicators to address social and individual risks and two indicators to characterize quality of life.

All the key indicators were arranged in the objective tree in the same manner as it was done in the NEEDS project (see Fig. 3.149). In terms of the INPRO comparative evaluation approach, this objective tree is a four-level one with the three high-level objectives, 11 areas and 17 sub-areas. The goals (scale directions for indicators) for all the key indicators are similar to the goals in the NEEDS project, excluding the 'Direct job' indicator which was changed to the 'min' (in the NEEDS project it was specified as a stakeholder-dependent indicator).

Economic evaluations of power generation technologies were taken from the publications of the Energy Research Institute of the Russian Academy of Sciences (ERI RAS) [3.61, 3.64, 3.65]. In the absence of Russia-specific data on some indicators, either the NEEDS project data were used (if there were no significant differences in the evaluations of such indicators among the countries participating in the project) or it was decided to assign to such indicators the same zero-values for all the options (if the NEEDS project data spreads for the relevant indicators were significant). The final normalized key indicator values for the considered options are presented in Fig. 3.150.

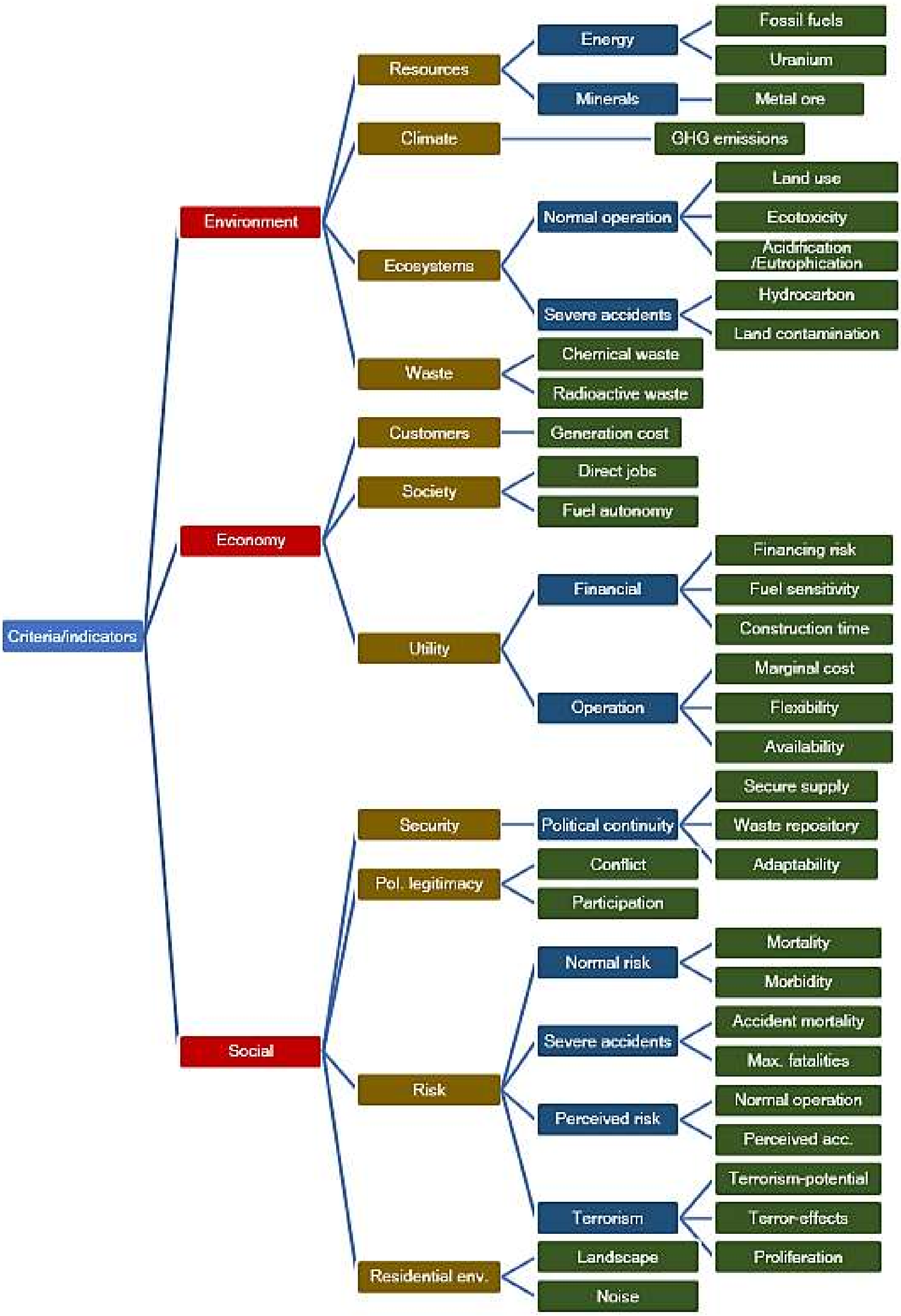


FIG. 3.149. Objective tree.

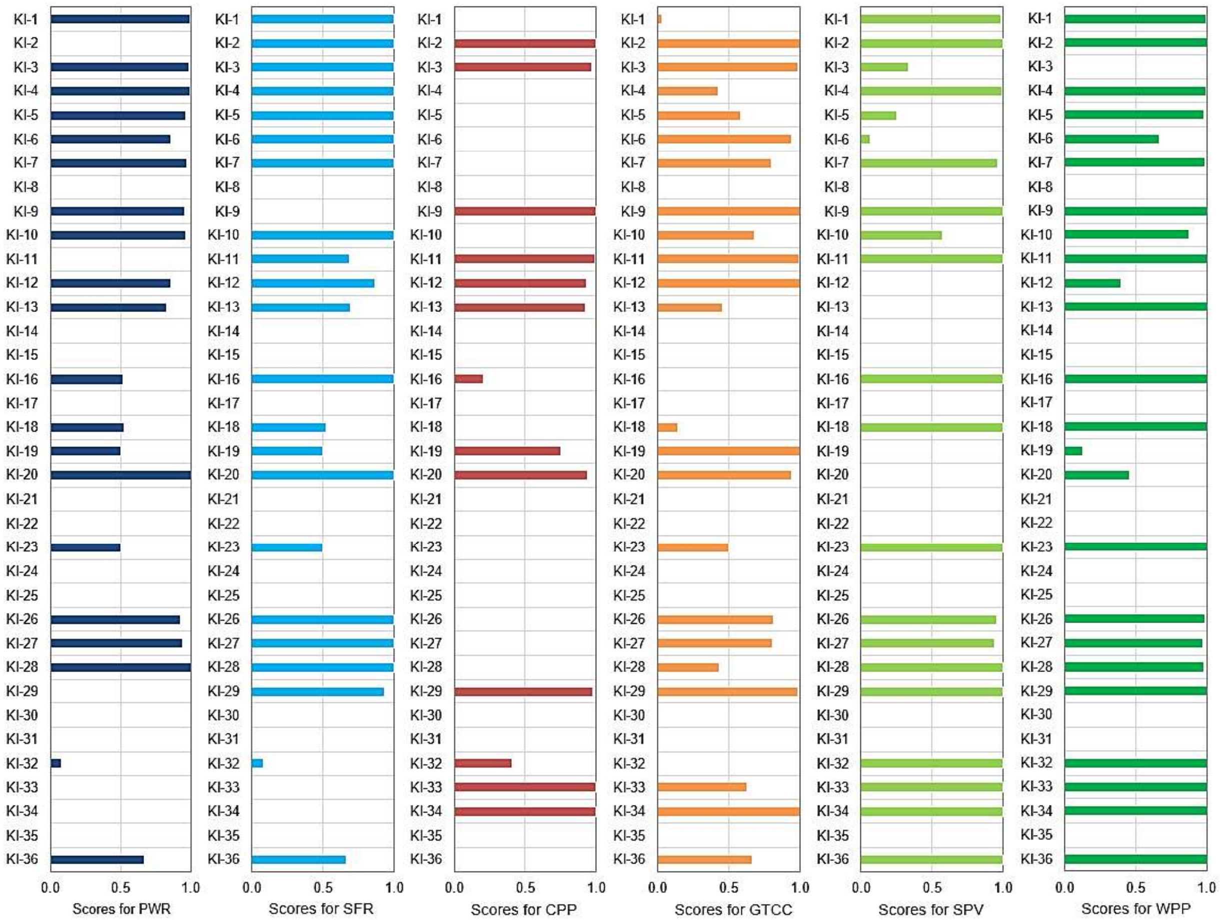


FIG. 3.150. Normalized key indicator values.

3.12.3.4. Weighting options

The 'equal weights' option was used as a starting point for the analysis, based on the assumption that all the factors at each level of the objective tree had the same relative importance. This approach can be applied when there is no information from experts and decision makers or when available information about the relative importance of the criteria is insufficient [3.41, 3.46]. However, even if there is no detailed information on weights, the 'equal weights' evaluation approach, combined with a detailed sensitivity/uncertainty analysis, makes it possible to conclude about the potential of the considered options from different perspectives.

Three other weighting options, different from the 'equal weight' option, were also considered with particular emphasis on the environmental criteria, economic criteria and social criteria, respectively (Fig. 3.151).

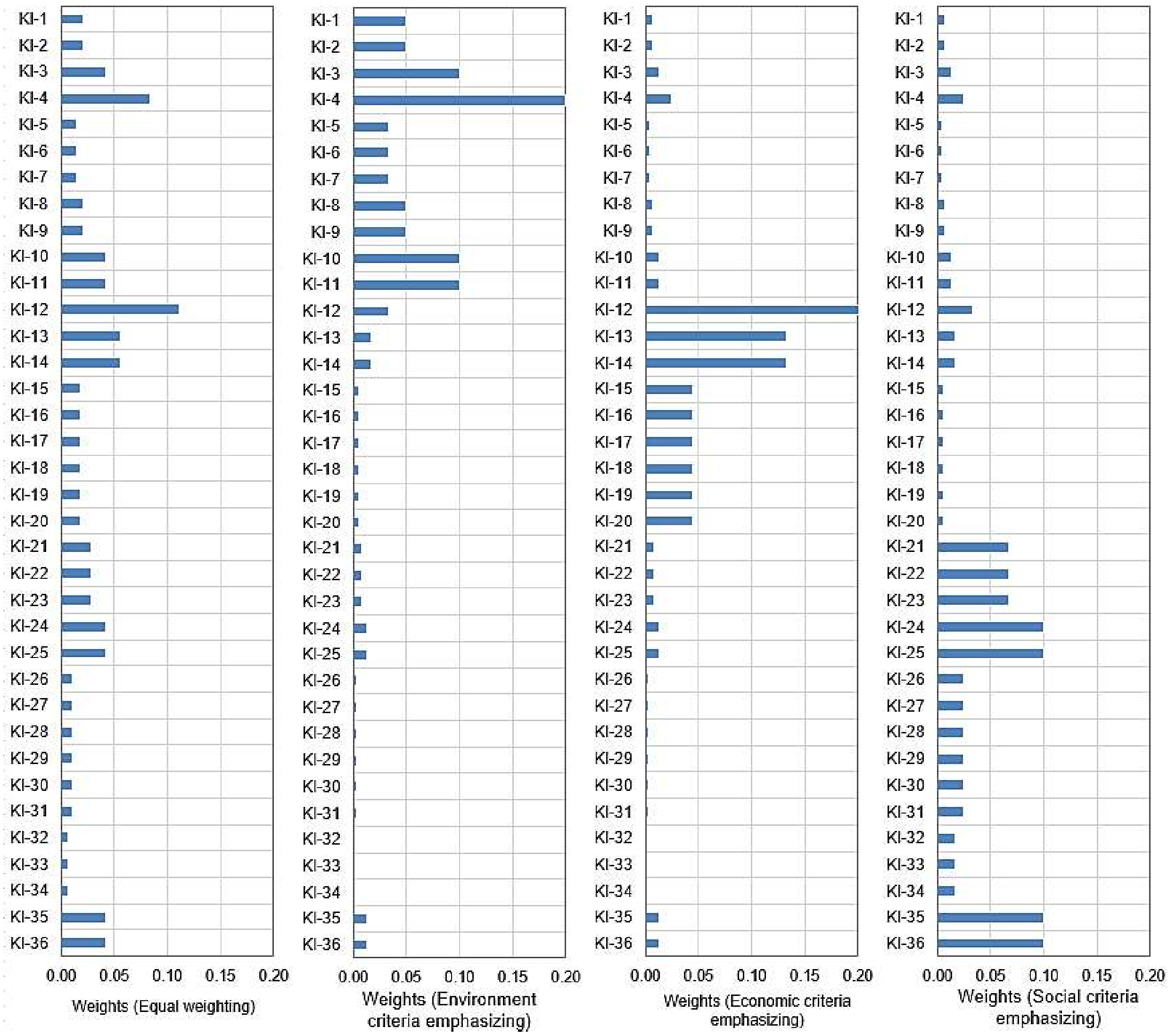


FIG. 3.151. Weighting options.

3.12.3.5. Judgement aggregation procedure

The IAEA/INPRO tools (namely, the KIND-ET tool and its extensions) for comparative evaluations of NES options and sensitivity/uncertainty analyses regarding key factors important for decision making [3.1] were adapted for comparisons and rankings of the considered power generation options. The comparative evaluation and ranking of the considered power generation options were carried out using the Multi attribute Value Theory implemented in KIND-ET: it involved the additive form of the multi attribute value function and linear functions for single attribute value functions for all the evaluation criteria specified for the local domains as the basic assumptions regarding the judgement aggregation procedure [3.1].

The performed analysis also includes the advanced uncertainty treatment in regard to weighing factors, single attribute value function forms and key indicators using relevant tools developed within the CENESO collaborative project, namely Overall Score Spread Builder, Ranks Mapping Tool, Uncertainty Propagator [3.1].

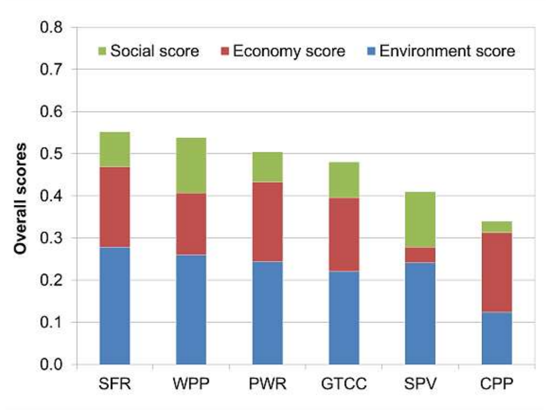
3.12.4. Ranking results and analysis

The ranking results and analysis for this study are presented in a structured form below.

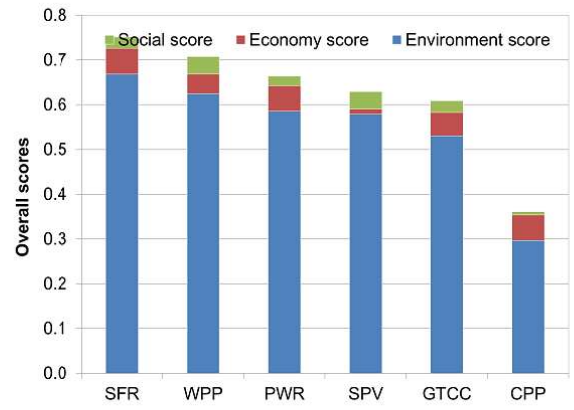
3.12.4.1. Ranking results for different weighting options

Screening for dominance performance demonstrates that all the options are non-dominated, i.e., among the entire set of options, there are no options that would be absolutely worse for at least one of the remaining ones. It means that each alternative can occupy the first place in ranking if the relevant conditions (priorities) permit.

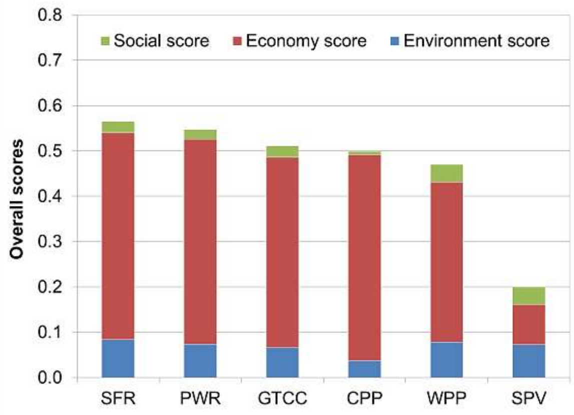
It is to be expected that considering non-monetized social, environmental and economic factors and indicators will result in the ratings of options obtained within the MCDA-based evaluation framework that is significantly different from the ratings based on the assessments of the levelized cost of electricity for the same alternatives. Thus, according to the assessment based on the levelized cost of electricity criterion for the situation considered in this study, the most attractive option is GTCC, being followed by CPP, PWR and SFR, WPP, SPV [3.61]. Figure 3.152 shows the ranking results for the considered weighting options, including the decomposition of the overall scores into high-level objective scores. Table 3.68 provides the overall scores and their components according to the structure of the objective tree for the equal weighting. As one can see, the multi-criteria approach favours nuclear and renewable energy sources. It needs to be noted that, in contrast to the results presented in the NEEDS project, in this study, given the differences between the Russian and European assessments of some social and economic indicators, nuclear technologies as a whole seem to be more attractive power generation options than renewable energy sources. At the same time, Generation IV fast reactors (SFR) are a more effective and attractive alternative than Generation III pressurized water reactors (PWR).



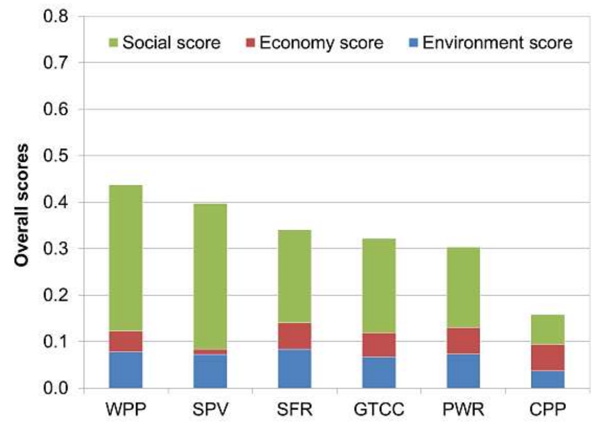
(a)



(b)



(c)



(d)

FIG. 3.152. Ranking results with breakdown of the overall scores into high-level objective scores: (a) equal weighting, (b) emphasis on environment criteria, (c) emphasis on economy criteria, (d) emphasis on social criteria.

The inclusion of a wide range of social criteria leads to a general downgrade of nuclear technology and an increase in the attractiveness of renewable energy sources, of which WPP seems to be more attractive than SPV. CPP is less effective in the framework of the MCDA-based comparison than the other options, while GTCC ranks close to nuclear technology. In general, the following trend is observed: an emphasis on the environmental criteria reduces the attractiveness of fossil energy sources compared to other technologies, an emphasis on the economy criteria reduces the attractiveness of renewable energy sources, and an emphasis on social criteria reduces the attractiveness of nuclear technology. Table 3.68 also presents more refined judgments regarding the merits and demerits of each option under consideration by providing the opportunity to conclude about the contribution of individual evaluation aspects (areas and sub-area scores) into the high-level objective and overall scores, respectively (a list of indicators within each aspect can be found in Table 3.67).

TABLE 3.68. OVERALL SCORES AND THEIR COMPONENTS FOR THE EQUAL WEIGHTING

Levels	PWR	SFR	CPP	GTCC	SPV	WPP
Overall scores						
Overall scores	0.505	0.552	0.340	0.481	0.409	0.539
High-level objective scores						
Environment	0.244	0.279	0.123	0.221	0.241	0.260
Economy	0.189	0.190	0.189	0.175	0.037	0.147
Social	0.072	0.083	0.027	0.085	0.131	0.131
Areas scores						
Resources	0.062	0.083	0.061	0.062	0.055	0.042
Climate	0.083	0.083	0.000	0.036	0.082	0.083
Ecosystems	0.059	0.042	0.021	0.053	0.039	0.057
Waste	0.040	0.070	0.041	0.070	0.065	0.078
Customers	0.096	0.096	0.103	0.111	0.000	0.044
Society	0.046	0.039	0.051	0.025	0.000	0.056
Utility	0.047	0.056	0.035	0.039	0.037	0.048
Security	0.014	0.014	0.000	0.014	0.028	0.028
Political legitimacy	0.000	0.000	0.000	0.000	0.000	0.000
Risk	0.030	0.042	0.027	0.043	0.061	0.062
Residential environment	0.028	0.028	0.000	0.028	0.042	0.042
Sub-areas scores						
Energy resource use	0.021	0.042	0.021	0.021	0.041	0.042
Mineral resource use	0.041	0.042	0.040	0.041	0.014	0.000
Potential impacts on the climate	0.083	0.083	0.000	0.036	0.082	0.083
Ecosystem impacts from normal operation	0.039	0.042	0.000	0.032	0.018	0.037
Ecosystem impacts from severe accidents	0.020	0.000	0.021	0.021	0.021	0.021
Potential impacts due to waste	0.040	0.070	0.041	0.070	0.065	0.078
Economic effects on customers	0.096	0.096	0.103	0.111	0.000	0.044
Economic effects on society	0.046	0.039	0.051	0.025	0.000	0.056
Financial impacts on utility	0.010	0.019	0.004	0.000	0.019	0.019
Factors related to a utility company's operation of a technology	0.037	0.037	0.031	0.039	0.019	0.029
Political continuity	0.014	0.014	0.000	0.014	0.028	0.028
Political legitimacy	0.000	0.000	0.000	0.000	0.000	0.000
Normal operation risk	0.019	0.021	0.000	0.017	0.020	0.020
Risk from severe accidents	0.010	0.020	0.010	0.015	0.021	0.021
Perceived risk	0.000	0.000	0.000	0.000	0.000	0.000
Risk of terrorism	0.001	0.001	0.017	0.011	0.021	0.021
Quality of the residential environment	0.028	0.028	0.000	0.028	0.042	0.042

3.12.4.2. Merits and demerits of the considered power generation options

While interpreting the ranking results, it is not enough to indicate that one option is more attractive than the other one: it is necessary to explain the reasons for this. A possible way to meet this requirement is to decompose the overall scores into specific components in accordance with the structure of the objective tree. This enables all parties interested in the results of the analysis to observe the contribution of each individual aspect to the final scores of alternatives. Such decomposition can be in some detail performed at various levels of the objective tree.

Figure 3.153 highlights the merits and demerits of the power generation options in terms of the area scores for the weighting option #1: the higher the area score, the better performance of the option for relevant aspects. To simplify the perception of quantitative data on the area' scores, the 'conditional formatting' technique displaying simple icons was used: good (green), acceptable (orange), bad (red). Such representation shows in a user-friendly manner the strong and weak points of each technological option. To avoid misinterpretation of the evaluation results, one needs to remember what kind of indicators are included in each area (see Table 3.67) and what weighting option at the lower levels of the objective tree was applied (in this case — equal weighting at the lower levels of the objective tree). In particular, it can be seen that both SPV and WPP have the highest scores for the social evaluation areas, being followed by SFR, GTCC, PWR, and CPP. For the environment evaluation areas, the area scores for SFR and WPP are the most attractive, while CPP is less attractive in this regard. For the economy evaluation areas, PWR, SFR, CPP, GTCC demonstrate similar highly attractive performances, while SPV performance is rather low.

Areas scores	PWR	SFR	CPP	GTCC	SPV	WPP
Resources	0.062	0.083	0.061	0.062	0.055	0.042
Climate	0.083	0.083	0.000	0.036	0.082	0.083
Ecosystems	0.059	0.042	0.021	0.053	0.039	0.057
Waste	0.040	0.070	0.041	0.070	0.065	0.078
Customers	0.096	0.096	0.103	0.111	0.000	0.044
Society	0.046	0.039	0.051	0.025	0.000	0.056
Utility	0.047	0.056	0.035	0.039	0.037	0.048
Security	0.014	0.014	0.000	0.014	0.028	0.028
Political legitimacy	0.000	0.000	0.000	0.000	0.000	0.000
Risk	0.030	0.042	0.027	0.043	0.061	0.062
Residential environment	0.028	0.028	0.000	0.028	0.042	0.042

FIG. 3.153. Merits and demerits of the power generation options (screenshot from KIND-ET).

The performed analysis on highlighting the merits and demerits of the power generation options in terms of the area scores confirms the observation of the NEEDS project[29] [3.62]; thus, the technological performance profile plays a decisive impact on the rating of the technologies under consideration. This effect is especially pronounced for technologies that have a highly differentiated performance profile: it means that such technological options have high values for some indicators while other indicators have low values. Nuclear technologies are the most representative example of such technologies: with equal importance of environmental, economic and social areas and with focus on protection of the climate and ecosystems, on

[29] https://cordis.europa.eu/project/id/502687

minimization of risks and improvement of accessibility for consumers, nuclear energy technologies take the highest places in the ranking. On the other hand, emphasising to the criteria associated with radioactive waste and contamination of the territory as a result of potential accidents as well as aversion to the risks of terrorist threats and the potential for conflict reduce the attractiveness of nuclear technologies.

3.12.5. Uncertainty and sensitivity analysis

The outputs of the uncertainty and sensitivity analysis performed within this case study are presented in a structured form below.

3.12.5.1. Global uncertainty analysis with respect to weights

The ranking results described above were obtained for the four predefined different weighting options to demonstrate general MCDA-based evaluation trends. At the same time, it is obvious that there is considerable uncertainty in the priorities of the energy sector deployment in the long term, and, as a result, the weighting factors are characterized by significant uncertainty if the long term perspective is considered. Therefore, examining how the uncertainties in the weights will affect the overall scores of the options under consideration is of great interest. Thus, it is required to rank options in the absence of information on the development priorities (the relative importance/weights of key indicators) and determine the probability of a certain option preference.

The applied approach simulates a situation when independent expert groups with different views on the relative importance of key indicators and development priorities ranking options, and relevant information (overall scores and ranks) is presented in the form of statistical distributions using the box and whiskers plot. Based on this information, it is possible to identify the most promising option, assess its stability and the probability for its preference.

The following two cases of uncertainties in the weights were considered within this approach:

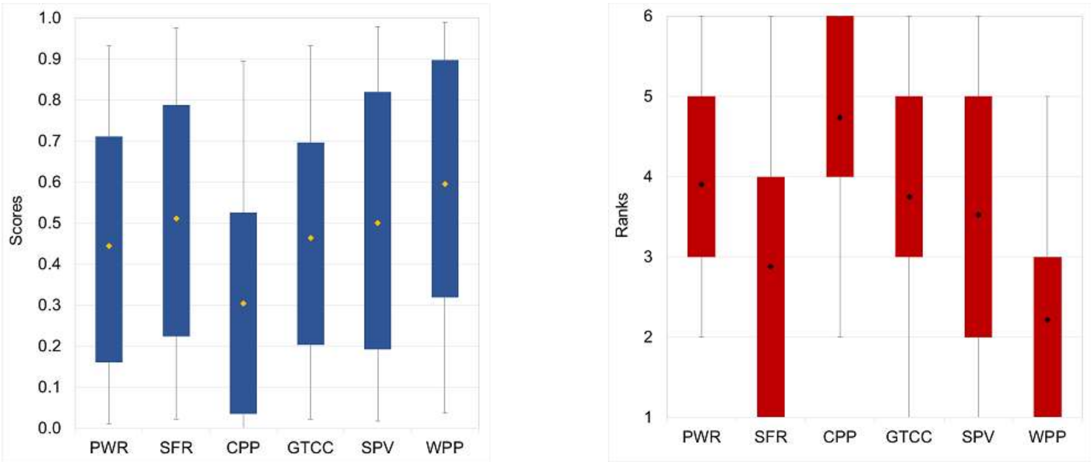
- Case I assumes that all the weights were uncertain, including high-level objectives, area, sub-areas and key indicators weights;
- Case II assumes that only the high-level weights were uncertain, while the other weights at the lower levels of the objective tree were specified based on the equal weighting concept.

The spreads in the overall scores and ranks for the options considered for both cases of modelling uncertainties in the weights are shown in Fig. 3.154 (the mean values: 5th, 25th, 75th, and 95th percentiles). The probabilities for options to take a certain place in the ranking are presented in Table 3.69. The number of investigated weight combinations was 10 000, assuming that all the weights were uniformly distributed within (0,1), provided that the sum of the weights for each combination was unity.

Case I shows that, given the highest level of uncertainties in priorities, all the options can potentially take the first place in the ranking, but some of them are the most likely to be found in the first place, while others are less likely to (see Table 3.69). WPP is a technological option that is the most likely to take the first place in the ranking followed by SFR for this case (the case of the highest level of uncertainties in priorities). At the same time, SPV, CPP and PWR are less likely to take the first place for the considered case of modelling uncertainties in weights.

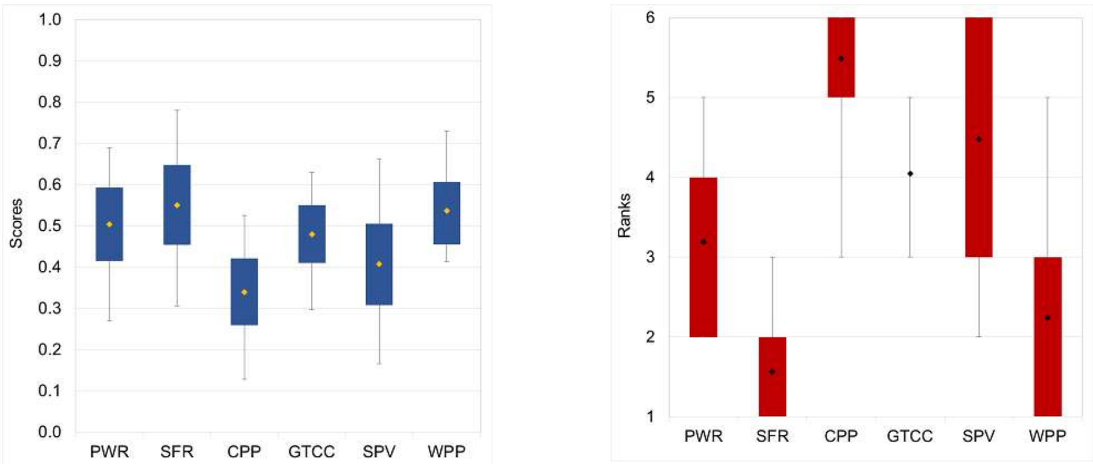
Case II, characterized by reduced uncertainties because only the high-level weights were uncertain, shows that the most attractive technologies which can be found in the first place in the ranking are only SFR (most likely) and WPP (less likely). The other technological options cannot be in first place at all. It is interesting to note that SFR in this case can take only upper places in the ranking (not lower than 4). The highest spread in ranks is demonstrated by SPV (from rank #2 to rank #6) while GTCC shows the lowest spread (from rank #3 to rank #5).

The overall conclusion that can be made based on the results of comparing the spreads in the overall scores and ranks for the considered two cases of modelling uncertainties in the weights is that, by involving national subject-matter experts and eliciting stakeholder preferences in order to specify the relative importance of aspects under consideration, it is possible to significantly reduce uncertainties in overall performance score and make more sharpened conclusions regarding the potential of each option.



(a) *(b)*

Case I – All weights are uncertain



(c) *(d)*

Case II – Only the high-level objective weights are uncertain

FIG. 3.154. Spreads in the overall scores (a), (c) and ranks (b), (d).

TABLE 3.69. PROBABILITIES FOR OPTIONS TO OCCUPY A CERTAIN RANK

Case I – All the weights are uncertain

Rank	PWR	SFR	CPP	GTCC	SPV	WPP
1	2	28	2	13	5	49
2	17	13	10	8	34	19
3	21	26	11	19	13	11
4	27	13	15	21	15	9
5	12	14	14	34	18	9
6	20	6	49	6	15	4

Case II – Only the high-level objective weights are uncertain

Rank	PWR	SFR	CPP	GTCC	SPV	WPP
1	0	62	0	0	0	38
2	30	20	0	0	17	32
3	38	16	6	18	11	11
4	15	2	5	58	12	8
5	17	0	22	23	26	11
6	0	0	66	0	34	0

3.12.5.2. Global sensitivity analysis with respect to the high-level objective weights

The global sensitivity analysis with respect to the high-level objective weights was performed in order to identify alternatives that could potentially occupy the first place in the ranking (this was assumed to be the equal weighting option at the lower levels of the objective tree). The performed analysis indicates the weight ranges of the high-level objectives for which a certain option can take the first place in the ranking (the so-called 'map of preferences', see Fig. 3.155: the abscissa axis shows the possible weight values for the 'Environment' high-level objective; the ordinate axis shows the possible values for the 'Economy' high-level objective weight; the applicate axis corresponds to the possible values for the 'Social' high-level objective weight; the sum of these weights is equal to unity). This diagram demonstrates that only SFR and WPP can take the first place in ranking, if only the high-level objectives are varied, and the equal weights approach is applied for the lower levels of the objective tree: WPP is the most attractive option if the social high-level objective is dominant over the others, whereas SFR becomes the most promising alternative in the cases when the economy and environment high-level objectives are highly important.

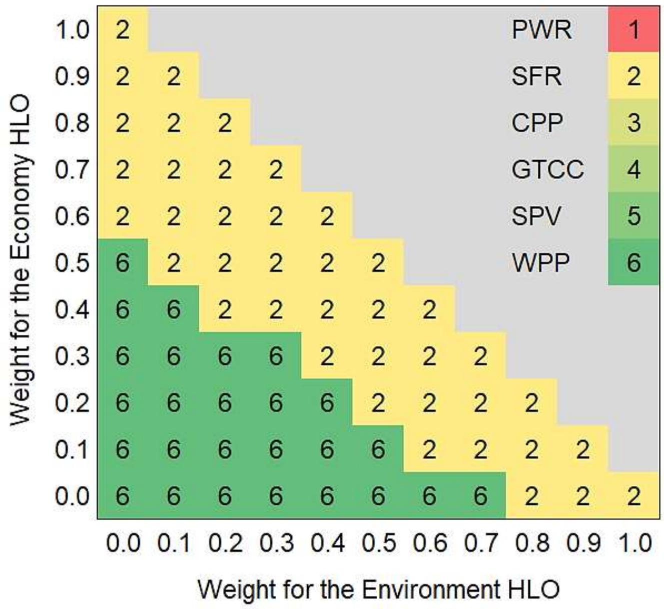


FIG. 3.155. Mapping of the first-rank options.

3.12.5.3. Local uncertainty analysis with respect to single attribute value functions, weights and key indicators

As a rule, the exact forms of single attribute value functions are unknown; instead, the parameters of single attribute value functions are characterized by a certain range of values. Uncertainty analyses of single attribute value functions examine changes in the final results (overall scores and ranks of alternatives) due to variations in single attribute value functions. The uncertainty analysis performed below is based on the classical error analysis framework [3.1] for evaluating the uncertainties in options' overall scores due to the uncertainties in the forms of single attribute value function as well as minor uncertainties in the weights and key indicators.

Uncertainties in the overall scores due to above-mentioned uncertain factors are depicted in Fig. 3.156 for the equal weighting option. The approach implemented here assumes that the absolute uncertainties in the exponent powers specifying the forms of single attribute value functions for the indicators used are equal to ±1.0 (best estimate values of the exponent powers are zero), and 10% relative uncertainties in weights and key indicators. Based on this assumption, the uncertainties in the overall scores were evaluated due to the uncertainties in the single attribute value functions, the uncertainties in the weights and key indicators (to compare and demonstrate contributions of different uncertain factors to the overall uncertainties in the scores, see Table 3.70).

As can be seen from Table 3.70, the relative uncertainties in the overall scores of the options lie within the range of 4.0–6.0% due to the considered uncertain factors. Figure 3.156 shows that the rank order considering associated uncertainties is the same as that one which has been already identified while using the 'base case' assumptions. In general, these data indicate that the ranking order is not very sensitive to the minor uncertainties associated with the single attribute value functions, weights, and key indicators. The same observations are also valid for the other weighting options.

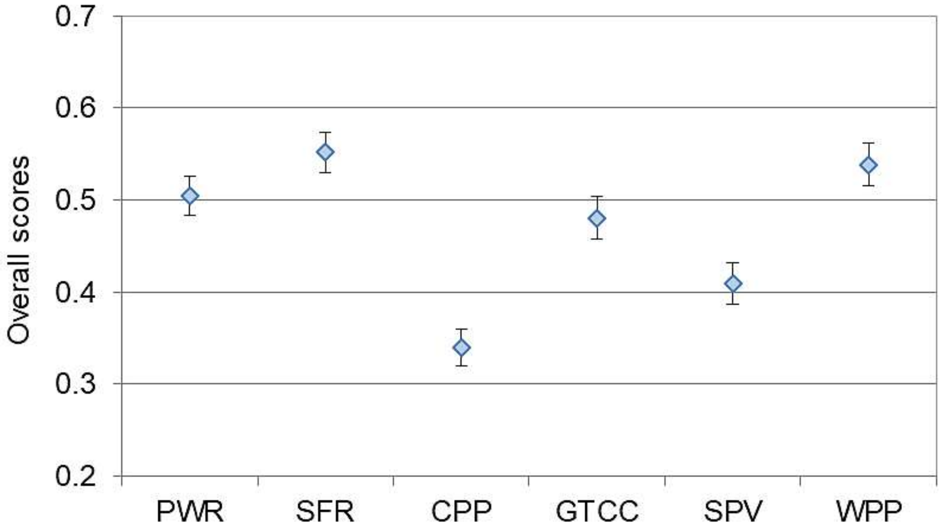


FIG. 3.156. Overall scores and uncertainties.

TABLE 3.70. OVERALL SCORES AND UNCERTAINTIES INCLUDING COMPONENTS

	PWR	SFR	CPP	GTCC	SPV	WPP
Best estimate	0.505	0.552	0.340	0.481	0.409	0.538
Absolute uncertainties	0.021	0.022	0.020	0.023	0.022	0.023
contribution due to the uncertainties in the key indicators	0.010	0.009	0.013	0.011	0.018	0.012
contribution due to the uncertainties in the single attribute value functions	0.011	0.012	0.005	0.015	0.007	0.014
contribution due to the uncertainties the in weights	0.016	0.016	0.013	0.015	0.012	0.014

3.12.6. Discussion

Discussion of the results of this case study is presented in a structured form below.

3.12.6.1. Applicability of the MCDA-based framework for the comparative evaluation and ranking of power generation options

In general, this study shows that the comparative evaluation of the sustainability and attractiveness of various power generation technologies based on the MCDA-based framework is feasible and can serve as the basis for structuring discussions on future energy supply and supporting informed decision making. Relevant decision support models can help decision makers to form conclusions about the most promising options for different priorities, including those specified based on the sustainable energy development concept, which provides a harmonious combination of social, economic and environmental factors.

The evaluation results indicate that, if the power generation technologies are compared on the basis of only economic indicators without considering other sustainability dimensions and objectives, a one-sided picture may evolve where preference is given to the fossil fuel power generation options. The multi-criteria decision analysis framework for comparing and ranking alternatives offers solutions which are different from those obtained by using the approaches based on purely economic criteria, such as the levelized cost of electricity; preferences are given to the energy production options which have the highest system efficiency considering the requirements of the sustainable development concept. In the present case study, these are nuclear technologies and renewables.

Moreover, it is worth mentioning that this approach allows to more fully consider national priorities in the energy sector deployment and specific performance data on power generation technologies that can significantly change the ranking results for similar problems but different conditions. Thus, in contrast to the results of the European analysis performed in the NEEDS project, where the highest rankings were taken by renewables followed by nuclear technologies, in the present study considering Russia-specific conditions, the inverse situation is observed: the highest rankings are taken by nuclear technologies followed by renewables. The performed evaluation clearly indicates the significant advantages of nuclear technologies, especially fast reactors, for the Russian Federation as the power generation technologies with enhanced sustainability that allows for the large-scale energy system development in accordance with the sustainable development goals. Based on these technologies, it is possible to implement low-carbon development scenarios that are of high importance for the Russian energy sector in the face of growing environmental challenges and make the energy sector more social-oriented.

On the whole, the study performed demonstrates that MCDA methods allow determination of the most promising power generation alternative from a set of available ones based on multiple evaluation criteria at the system level. MCDM considers the criteria, considering their conflicting nature, which characterize technical efficiency, resource requirements and economic indicators along with other performance metrics. The use of these methods ensures that the decision making process will be consistent, comprehensive, transparent, reproducible, and verifiable.

The main benefit of aggregating expert judgements based on formalized mathematical methods is that they allow one to structure discourse and organise effective examination to identify the most promising options among those available, with a quantitative demonstration of the advantages and disadvantages of the compared options. This helps to provide well-reasoned conclusions about the attractiveness of the options under consideration, which can be used to justify the final decision to be made.

To reinforce the use of the multi-criteria analysis results as the basis of highly responsible strategic management decisions affecting the interests of various groups, it is advisable to involve supporters of different points of view on the problem as well as consider their visions of its solution. This will help to develop a single set of performance indicators to evaluate the options and assumptions used. Particular attention is to be paid to the impact of uncertainties (both objective and subjective) on the ranking results. Conducting such an examination, can, at least, help to achieve a clear understanding of the strengths and weaknesses of each of the possible options based on a quantitative analysis. At most, if the participants of the examination will have a constructive attitude, they will be able to select the most acceptable compromise option.

3.12.6.2. Steps forward identifying national policy options and energy scenarios

The obtained results are quite illustrative: it would make sense to consider much more possible prospective power generation technologies, and to refine relevant performance databases adapting them for Russia-specific conditions. It could also be considered that some technologies can be used in a multi-purpose way (e.g., sodium-cooled fast reactors, which can be used not only for commercial production of electricity but for burning of minor actinides and producing isotopes for their subsequent use in medicine and industry). Extensions enabling considerations of applications involving heating systems along with power generation technologies, and performance of comparative evaluations of energy scenarios, are to be welcomed. Export potentials of power generation technologies are also important factors to be involved in the decision making process at the national level.

Future work could consider feedback from MCDA applications at the national level, facilitate communication with national subject-matter experts and initiate the elicitation of stakeholder preferences. Building capacities in the Russian Federation to promote the comprehensive and consistent application of state of the art judgment aggregation methods and tools in the energy sector is considered by Russian experts participating in IAEA's CENESO project to be of high importance. Customising existing and developing new tools (including formation and utilisation of the LCA- and LCI-based databases, adapting the advanced assessment approaches based on the concept of sustainability indicators, approaches to stakeholder preferences assessment as well as advanced frameworks for simulating the deployment of energy systems) for operationalising new evaluation methodologies to support decision making could be quite useful at the national level in the Russian energy sector.

3.12.7. Conclusions

The presented results delineate some preliminary conclusions about the most effective ways of enhancing the national power generation system sustainability based on the multi-criteria evaluation paradigm that assumes a harmonious combination of social, economic and environmental factors. The need for such considerations is due to the results of comparisons of the power generation technologies on the basis of only economic indicators, without considering other sustainability dimensions and objectives, show a one-sided picture giving preference to the fossil fuel power generation options. The multi-criteria decision analysis framework for comparing and ranking alternatives offers solutions different from those obtained by using the approaches based on the economic criteria: preferences are given to the energy production options which have the highest system efficiency considering the requirements of the sustainable development concept.

The results also show the outstanding performances of nuclear power technologies (especially fast reactors) for meeting sustainable energy development goals in the case of Russia — their overall performance is even better than that of renewable technologies. In particular, it was presented that the focus on the environment reduces the attractiveness of the fossil power technologies in comparison to the other technologies. The focus on the economy decreases the attractiveness of renewables. The focus on social aspects reduces the attractiveness of nuclear technology.

To obtain more rigorous conclusions about the most preferred technological options for the Russian power sector, it would be necessary to extend the analysis framework and revise technology performance data. In addition, the involvement of stakeholders, public representatives, and decision makers could elicit their preferences to be considered in the analysis.

3.13. COMPARATIVE EVALUATION OF DIFFERENT POWER GENERATION SYSTEMS WITH TIME DEPENDENCE CONSIDERATION (THAILAND)

This chapter presents structured report of a case study done by experts from the Kingdom of Thailand.

3.13.1. Introduction

The Thailand Power Development Plan (PDP) has been revised in 2015 by the Ministry of Energy (Thailand) together with Electricity Generating Authority of Thailand (EGAT) in order to improve the energy security by considering fuel diversification, appropriate cost of power generation for long term economic competitiveness, and lessening CO_2 emission intensity. The development of the new PDP 2015 is focused on decreasing dependence on power plants using natural gas (NGPPs), increasing the use of coal-fired power plants (CPPs) by applying clean coal technology, increasing the power import from neighbouring countries, and promoting the use of renewable energy sources [3.66].

From the background of Thailand’s power generation, about 65% of the whole power generation depends on natural gas power plants; therefore, it is needed to diversify energy sources to increase the energy security by including the use of coal-fired power plants. However, it is difficult to construct CPPs due to the public awareness and acceptance of them. Integrated coal Gasification Combined Cycle (IGCC) power plants have been considered as the most appropriate clean coal technology. A nuclear power plant has been also proposed in PDP 2015. However, Thailand is one of the newcomer countries to deploy this technology. Therefore, the potential to start the construction of a first nuclear power plant (NPP) needs to be comparatively evaluated with the existing energy system in Thailand such as coal-fired power plants (CPPs) and natural gas power plants (NGPPs), and also including a new clean coal technology like integrated coal gasification combined cycle (IGCC). This study is focused not only on the difference of energy sources evaluation, but the time dependent effects on some key indicators are also taken into consideration. The supporting data of the study were taken from relevant national or international organizations in the form of articles, reports, presentations, as well as expert judgments.

3.13.2. Objective and problem formulation

The objective of the study was to apply the set of KIs developed for newcomer countries in KIND-ET and its extensions where three new functions, including Domination Identifier, Overall Score Spread Builder and Ranks Mapping Tool are provided in Microsoft Excel form to expand the KIND-ET capability. The study performed by the Thailand team is focused on the comparative evaluation of diverse energy sources for power generation: between a first nuclear power plant (NPP) and non-nuclear power plants. For non-nuclear power plants, this study considers conventional coal-fired power plants (CPPs), integrated coal gasification combined cycle plants (IGCCs) and natural gas power plants (NGPPs) based on key indicators developed under the framework of the KIND collaborative project (KIND CP) for newcomer countries. This study also considers that the score of some key indicators, such as in the area of infrastructure, may change with time and therefore can influence the evaluation results. Therefore, two scenarios of four energy system options are proposed. For the first scenario, called the 0^{th} year case, the construction of a new power generation plant is assumed to start in a few years which can have an effect on the readiness of some key indicators, especially in the area of infrastructure and the area of national security of NPPs and IGCCs. Next the second scenario, called the 20^{th} case, is proposed to consider that construction of a new power generation is started in the next 20 years in order to have enough time development in some key indicators. In addition, the 20th year case is consistent with the Power Development Plan in Thailand (PDP 2015) on the possibility of the first nuclear power plant in Thailand.

The KIs set belongs to two high level objectives (HLOs): Cost and Acceptability. Four specific areas are considered: Economics (corresponding to Cost HLO), and National security, Public acceptance and Infrastructure (corresponding to Acceptability HLO). The comparative evaluation is performed based on a set of 11 key indicators (KIs).

Levelized unit electricity cost (LUEC) (KI.1) and cash flow (KI.2) are two KIs taken into consideration in the Economics area. Degree of dependence on suppliers (KI.3) is the only KI in the area of National security. Survey of public acceptance (KI.4), external cost (KI.5) and risks of accidents (KI.6) are selected for the evaluation of Public acceptance area. The Infrastructure area consists of five KIs, including status of legal framework (KI.7), status of state organizations (KI.8), availability of infrastructure to support owner/operator (KI.9), government policy (KI.10), and availability of human resources (KI.11).

3.13.3. Formulation of alternatives

The construction of the first nuclear power plant in Thailand is considered to be a Generation III+ light water cooled reactor. Therefore, the data obtained for a nuclear power plant (NPP) was compiled from average values of six reference plants of ABWR, AP1000, ATMEA1, VVER1200, ACPR1200 and APR1400. For non-nuclear energy system, the existing power generation technologies like conventional coal-fired power plants (CPPs) and natural gas power plants (NGPPs) are the options in the evaluation, even though the government plans to reduce the power generation from CPPs to 20% of the whole electricity generation in 2036 and attempts to increase energy reliability by lessening the dependency on one particular fuel. Integrated coal gasification combined cycle (IGCC) technology is also introduced as an energy system option to enhance the utilization of domestic resources (lignite) in Mae Moh coal mining. The main characteristic of the selected NPP, CPP, IGCC and NGPP are presented in Table 3.71.

TABLE 3.71. PARAMETERS FOR THE COMPARATIVE EVALUATION OF THE LUEC AND THE CASH FLOW FOR NPP, CPP, IGCC AND NGPP (0^{TH} YEAR)

No.	Parameters	Units	NPP	CPP	IGCC	NGPP
1	Net electric power	MW(e)	1000–1400	600	600	600
2	Construction period	Years	4–6	3.5–4.5	3.5–4.5	2.5-3
3	Lifetime of plant	Years	60	40	40	40
4	Average load factor	-	0.9	0.75	0.75	0.75
5	Decommissioning cost	mill/kW(e)·h	0–0.14	0.03–0.12	0.03–0.12	0.04–0.13
6	Overnight cost	US $/kW(e)	2710.5–5824.5	813–2496	4016–4669	627–1246
7	Contingency cost	%	10-20	5	5	5
8	Capital investments schedule	—	Uniform	Uniform	Uniform	Uniform
9	Real discount rate	%	7–11	7–11	7–11	7–11
10	PUES[30]	mill/kW(e)·h	81.6–147.7	81.6–147.7	81.6–147.7	81.6–147.7
11	Market income	million US $	14973	14973	14973	14973
12	Market share	—	1	1	1	1
13	Profit margin	%	11	11	11	11
14	Time of growth	Years	3.09–4.33	1.85	1.85	1.85
15	Adjusting coefficient	—	1	1	1	1
16	Variable operation and maintenance cost	mill/kW(e)·h	9.88–18.70	1.67–11.11	1.67–11.11	3.10–6.13
17	Fuel price	US $/GJ	—	3.44	3.44	6.23
18	Real fuel price escalation rate (RFE)	%/year	—	1.8	1	1
19	Nuclear fuel backend cost	US $/kg	379-2449	—	—	—
20	Unloaded fuel average burnup	MW d/kg	54.2	—	—	—
21	Net thermal efficiency	%	32.6	32.6	35.4 - 44	43.7
22	Reactor first core average power density	kW/kg	32.6	—	—	—
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	—	—	—

Note: 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 (EGAT), or expert judgments.

[30] PUES is reference price for unit of electricity sold.

3.13.4. Identification of key indicators

To apply a comparative evaluation of energy system scenarios among NPP, CPP, IGCC and NGPP, a set of KIs comprising four areas: Economics, National security, Public acceptance, and Infrastructure is developed. The Levelized Unit Electricity Cost (LUEC) and cash flow are KIs in the area of Economics while the degree of dependence on supplier is the KI in the area of National security. As for the area of Public acceptance, the risks of accidents and the survey of public acceptance are the KIs. Status of legal framework, status of state organizations, availability of infrastructure to support owner/operator, government policy, and availability of human resources are selected to be the KIs in the area of Infrastructure. In summary, there are 11 KIs in four different areas used in this study. The list of KIs and their abbreviations are presented below (Figure 3.157):

- KI.1: Levelized unit electricity cost;
- KI.2: Cash flow;
- KI.3: Degree of dependence on supplier(s);
- KI.4: Survey of public acceptance;
- KI.5: External cost;
- KI.6: Risks of accidents;
- KI.7: Status of legal framework;
- KI.8: Status of state organizations;
- KI.9: Availability of infrastructure to support owner/operator;
- KI.10: Government policy;
- KI.11: Availability of human resources.

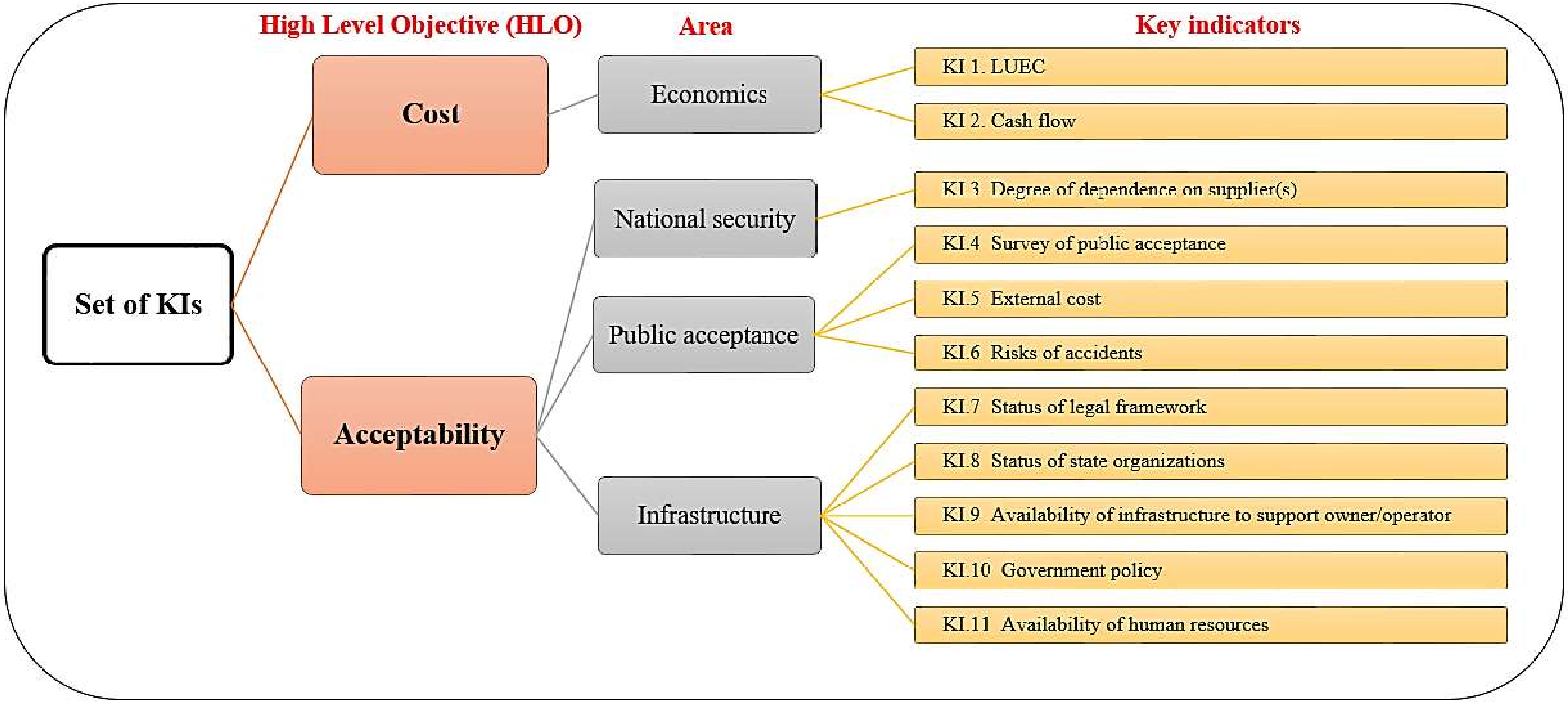


FIG. 3.157. The objective tree structure.

3.13.5. Determination of key indicator values

The values for each KI corresponding to the considered power plants were established using the calculation results applying a 10 point scoring scale and an actual value. Details regarding the considered set of KIs are given below.

3.13.5.1. Area of Economics

There are two important key indicators to be evaluated in the area of Economics, namely the levelized unit electricity cost (LUEC) and the cash flow. For the present case study, the Nuclear Economics Support Tool (NEST) [3.67] was used to perform the comparative evaluation of the two indicators for all the power plants of interest.

(a) Levelized Unit Electricity Cost (LUEC)

The parameters presented in Table 3.71, which are based on Thailand's situation as of November 2018, and expert judgments, are adopted in the evaluation. For the 20th year case, the overnight cost and the variable operation and maintenance cost of the NPP and the IGCC, which are the new technologies at the moment, are assumed to decrease by 20% due to construction and operating experience. Those costs of CPP and NGPP remain unchanged since both technologies are currently mature and the economy of experience cannot be further expected. The escalation rates in Table 3.71 are used to calculate the fuel prices at the 20th year. Uranium price is assumed to increase by 1% per year based on the 30-year world statistical data. The LUECs of the NPP, CPP, IGCC and NGPP are shown in Table 3.72. For the 0th year case, it can be seen that IGCC has the largest LUEC, followed by NPP, CPP and NGPP. This is because the integrated gasification combined cycle (IGCC) has relatively high overnight construction costs comparing to other CPP technologies. The overnight construction costs of NPP are even larger than that of IGCC which is partially due to the lack of experience in the region. Even though the prices of coal and natural gas are quite high, LUECs of CPP and NGPP are much lower than the other two, thanks to the moderate overnight construction costs.

As for the case of 20th year, the LUEC of IGCC remains high although the overnight construction costs are significantly reduced. This happens because of the increase in fuel price with the escalation rate of 1.8% per year. LUECs of CPP and NGPP also increased due to the escalation of the fuel prices. On the other hand, NPP becomes more attractive with the lowest LUEC due to the reduction in the overnight construction costs. The increase in uranium price hardly affects the NPP's LUEC.

TABLE 3.72. THE COMPARATIVE EVALUATION OF THE LUEC FOR NPP, CPP, IGCC AND NGPP IN THE 0TH YEAR AND THE 20TH YEAR CASES

	The 0th year				The 20th year			
	NPP	CPP	IGCC	NGPP	NPP	CPP	IGCC	NGPP
LUEC (mils/kWh)	96	81	118	77	81	100	118	101

(b) Cash flow

The investments on all energy systems are over the investment limits.[31] However, the calculation assumes that the investment will be based solely on the equity (no loan from banks considered), which is unrealistic. For example, if the ratio of equity to debt is set to 50 to 50, the investment on the other energy systems would be definitely covered by the investment limit, and the investment on NPP would have a high chance to be smaller than the investment limit. Therefore, it is too soon to reject the NPP with this key indicator.

The next step is to evaluate the differences between the weighted average cost of capital (WACC) and the internal rate of return (IRR) and between WACC and the return of investments (ROI). The WACC can be calculated as:

$$WACC = s_e \times r_e + (1 - s_e) \times r_d \times (1 - t) \tag{3.2}$$

Most values are taken from the 2009 MIT Update [3.68] as there is no NPP in Thailand at the time of this publication. The inflation rate is not considered in order to simplify the evaluation. The equity share, debt share, required rate of return on equity are, as follows: 50%, 50% and 15% for NPP and 40%, 60% and 12% for CPP and IGCC, respectively. The required rate of return on debt is set to 9% based on the value of real discount rate given in Table 3.71. The tax rate is not considered. The calculated WACCs for the NPP is 12% and the CPP, IGCC and NGPP have the same WACC of 10.2%. As the influence of time was not considered in the calculation of WACC (the inflation rate was not considered), the WACC is compared with the ROI. The 50th percentile values of the IRR and ROIs for all power plants as well as the difference between the WACC and the ROI in this study are summarized in Table 3.73. A negative value of the difference between WACC and ROI will imply that the investment on that energy system is not attractive.

TABLE 3.73. THE COMPARATIVE EVALUATION OF THE CASH FLOW FOR NPP, CPP, IGCC AND NGPP IN THE 0TH YEAR AND THE 20TH YEAR CASES

	The 0th Year				The 20th Year			
	NPP	CPP	IGCC	NGPP	NPP	CPP	IGCC	NGPP
Investment (M$)	7049	1192	3128	642	5639	1192	2502	642
Limit (M$)	6110	3047	3047	3047	6110	3047	3047	3047
IRR	10.9%	18.9%	8.5%	29.1%	13.0%	14.1%	8.4%	18.3%
ROI	14.4%	20.2%	9.1%	31.6%	18.3%	11.3%	8.1%	13.6%
WACC	12.0%	10.2%	10.2%	10.2%	12.0%	10.2%	10.2%	10.2%
ROI-WACC	2.4%	10.0%	-1.1%	21.4%	6.3%	1.1%	-2.1%	3.4%

A 10 point scoring scale is used for the comparative evaluation of this key indicator. The score for the cash flow can be evaluated from the result of two indicators, investment and the difference between ROI and WACC. The weight factor of both indicators is determined equally. The energy system receives full score for investment when the investment is smaller than the

[31] The investment limit is estimated by the NEST tool based on the total income and profit (See Chapter 3.3 of "INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Economics" [3.67]).

investment limit and receives nothing when it exceeds this limit. The energy system with the largest difference between ROI and WACC receives full score, while others are calculated accordingly. Table 3.74 shows the score for cash flow of the four energy systems in two scenarios.

TABLE 3.74. THE SCORE OF CASH FLOW FOR NPP, CPP, IGCC AND NGPP IN THE 0^{TH} YEAR AND THE 20^{TH} YEAR CASES

	The 0^{th} Year				The 20^{th} Year			
	NPP	CPP	IGCC	NGPP	NPP	CPP	IGCC	NGPP
Investment	0.0	10.0	0.0	10.0	10.0	10.0	10.0	10.0
ROI-WACC	1.5	4.9	0.0	10.0	10.0	3.0	0.0	6.1
Cash flow	0.8	7.5	0.0	10.0	10.0	6.5	5.0	8.1

3.13.5.2. Area of National Security

The degree of dependence on supplier(s) (foreign vs domestic) will be used as the key indicator for the comparative evaluation between the NPP, CPP, IGCC and NGPP in Thailand. The results will show the degree of dependence on oversea suppliers, implying a somewhat lower level of the national security if that energy system is selected.

(a) Degree of Dependence on Supplier(s)

To evaluate the Degree of Dependence on Supplier(s) (DDS), the following areas were taken into consideration:

— Technology;
— Construction;
— Fuel supply;
— Operation;
— Maintenance;
— Waste management;
— Decommissioning.

An appropriate weighting factor (wf) was assigned to each area of interest based on the priority. The scoring scale and criterion are shown in the Table 3.75 below.

TABLE 3.75. SCORING SCALE CRITERIA

Scoring scale	Criterion
10	Imported entirely
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

The evaluation results are reported in Table 3.76. The DDS of each energy system will be given by the summation of the products of weighting factor (*wf*) and the score (s) in each area, as demonstrated in the following equation.

$$DDS = \sum (wf \times s) \tag{3.3}$$

TABLE 3.76. THE COMPARATIVE EVALUATION OF DEGREE OF DEPENDENCE ON SUPPLIER(S)

Area	WF	The 0th Year				The 20th Year			
		NPP	CPP	IGCC	NGPP	NPP	CPP	IGCC	NGPP
Technology	0.25	10	10	10	10	10	10	10	10
Construction	0.15	8	4	8	4	8	2	4	2
Fuel supply	0.15	10	4	4	2	10	4	4	10
Operation	0.125	8	2	8	2	8	2	2	2
Maintenance	0.125	8	4	8	4	8	4	4	2
Waste management	0.1	10	0	0	0	10	0	0	0
Decommissioning	0.1	8	0	4	0	8	0	2	0
Total (score × wf)	—	9	4.45	6.7	4.15	9	4.15	4.65	4.8

It is expected that the situations for NPP at the 0th year and at the 20th year will remain unchanged. In the area of Technology, the maximum score (10) for DDS is assigned as Thailand has had no plan for the development of power plant technologies. This is also the reason for giving 10 to the other kinds of power plant technologies. For Construction area, the score 8 is assigned to the NPP cases (at the 0th year and at the 20th year). The reason is that the main parts of NES will be constructed under the supervision of the technology holder(s), while labour and certain services are expected to be available in the country. In the area of Fuel supply, the scores for both NPP cases are 10 based on the fact that Thailand has no plans for uranium mining, milling and fuel fabrication. In the areas of Operation, Maintenance and Decommissioning, the score 8 is assigned to both NPP cases. This is because for the first instalment of NPP, the majority of experts and services (up to 60%) for operation maintenance and decommissioning is to be obtained from the technology holder(s). For Waste management area, Thailand has expressed interest to send the spent nuclear fuel back to the country of origin. Therefore, NPP cases receive the score 10 in this area of evaluation.

For the CPP, this kind of power plant has been operated in Thailand for at least 40 years. At the 0th year with this long experience, local labour and services need to be able to contribute more than 60% to the construction and maintenance. At the 20th year, with even longer experience, more than 80% of domestic support is expected for construction. Therefore, the scores 4 and 2 are assigned in the area of construction at the 0th year and the 20th year, respectively. For Maintenance area, however, the support within the country is expected to still remain the same, so both CPP cases receive the score 4. In the area of Fuel supply, according to the Energy Policy and Planning Office, Ministry of Energy (Thailand), 75% of fuel supply for the CPP was recently (2018) taken from Mae Moh Mine and 25% was imported from Indonesia and Australia. In addition, the Ministry of Energy also claimed that Mae Moh Mine will be able to provide 75% of the fuel supply for the next 30 years[32]; as a result, the score 4 is given to both CPP cases. For Waste management and Decommissioning, 0 is assigned to both CPP cases based on the fact that all products, labour, expertise or services involved in these areas are available in the country.

The IGCC is considered as a new technology in Thailand. At the 0th year, the scores 10 and 8 are assigned in the areas of Technology and Construction, respectively, based the reasons similar to those used in the NPP cases. For the 20th year scenario, the score for Technology given to IGCC still remains at 10. However, the score for Construction decreases to 4, considering the longer experience of Thailand with coal technologies. In the area of Fuel supply, the score 4 is given to both scenarios due to the situation described above, in the CPP fuel supply cases. For Operation of the IGCC at the 0th year, only up to 40% of the support is expected to be available in the country. At the 20th year, the domestic support is expected to increase up to 99%. In these conditions, the scores 8 and 2 are assigned to the area of Operation at the 0th and 20th years, respectively. The situation would be similar in terms of Maintenance; thus, the IGCC cases receive the scores 8 and 4, respectively. For Waste management of IGCC, no international support is necessary in both cases. Decommissioning of IGCC, however, would still require some international assistance. The score in this area is assigned to be 4 at the 0th year and, subsequently, it would decrease to 2 at the 20th year.

The first NGPP project in Thailand was started in 1977. Currently, the NGPP accounts for up to 70% of the total electricity generation in the country. The long experience with the NGPP makes it require the least international support among the power generating options. In the areas of Construction and Maintenance the scores 4 and 2 are assigned to the 0th year and the 20th year scenarios, respectively. For the Fuel supply area, a major change in DDS is expected since the natural gas in the gulf of Thailand is running low and it is expected to run out in 2020[33]. The scores 2 (less than 20% imported at the 0th year) and 10 (100% imported at the 20th year) are given in this area. In the area of Operation, the score 2 is given in the 0th year case as the technology was completely transferred, and the situation will remain unaffected after 20 years. Waste management and decommissioning of NGPP could rely entirely on the domestic support, so the score 0 is given for both NGPP cases in these areas.

3.13.5.3. Area of Public Acceptance

(a) Survey of public acceptance

Survey of public acceptance could be evaluated by compilation of the results for surveys on opinions of the public toward the introduction of the 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 the local opinions on the energy system project.

The survey of public acceptance presented in this report is a data compilation reflecting public attitudes toward installations of an NPP and the selected Non-NPP (CPP, IGCC and NGPP) in Thailand. The data were taken from a number of research and questionnaires. However, only the latest survey data, collected after the public turning points of the energy systems (i.e., the Fukushima Daiichi NPP accident and Mae Moh sulphur dioxide emissions for the CPP), are used in the evaluation. This is because the survey data before these public turning points do not

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[32] http://www.eppo.go.th/index.php/en/en-energystatistics/coal-and-lignite

[33] https://www.egat.co.th/en/news-announcement/web-articles/fsru-a-new-option-for-fuel-imported-to-strengthen-thailand-s-power-security

reflect the current situation in the country, and the results of the evaluation may be unrepresentative if these data are included. On the other hand, the NGPP technology is proven and is already operated, so the score of the NGPP is to be 10 in the 20th year scenario because people have more confidence in the technology and management on the NGPP system project. However, the survey of public acceptance related to the IGCC is unavailable. Nonetheless, the Thailand team supposes that the IGCC technology could have less impact to the public health due to lower CO_2 emission and ash volume. Therefore, the score of IGCC in the 20th year scenario is to be 8, which is less than the NGPP and higher than the CPP scores, due to its status as new technology for Thailand in the power generation.

The percentages of agreement and disagreement on the power plant installations from each data set will be normalized. Subsequently, the results obtained will be multiplied by the number of samples. Finally, the summation of the products from the previous step will be divided by the sample size. The results will then be converted back into percentage which will be scored in the scale of 1–10. The data and evaluation results are shown in Table 3.77.

TABLE 3.77. THE DATA AND EVALUATION RESULTS FOR SURVEY OF PUBLIC ACCEPTANCE IN THAILAND

Case	The 0th Year				The 20th Year			
Type	NPP	CPP	IGCC	NGPP	NPP	CPP	IGCC	NGPP
Public acceptance	2	6	6	8	2	6	8	10

(b) External cost

The idea is to find an appropriate parameter that can be used in a comparative evaluation of different technologies and fuel cycle for electricity generation. Therefore, the external cost is an indicator for a comparative evaluation of the waste products, and adverse effects, from the different power sources. It takes into consideration the whole process chain from fuel extraction, power generation, the impacts released from construction materials and transportation, waste disposal, and health effects from toxic emission, water pollution, radioactive waste and climate change due to the greenhouse gases by means of a life cycle assessment (LCA). This indicator is different from the LUEC which evaluates the internal cost of an energy system. External cost could better reflect the real cost of the society and environment effects of the energy systems via monetary units [3.69].

In this study, reliable reports or papers which estimated the external cost based on the non-OECD data were referred to considering the insufficient resources to evaluate the external cost for Thailand.

The external cost of two coal-fired power plants in two different locations of Thailand has been estimated by Shrestha et al. [3.70]. The first one was 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 Mae Moh plant, a 300-MW(e) lignite fired plant employing an Electro-Static Precipitator (ESP) and making use of Flue Gas Desulphurization (FGD), which was installed in Mae Moh area, in the northern part of the country. The previously mentioned study estimated external cost using a simplified method, with only two pollutants: the particulate matter PM10 particles (particles with the diameter of 0.01 mm found in dust and smoke) and SO_2 (not included CO_2 emission) taken into consideration; the results were reported as monetary unit cost by converting the unit cost. In this calculation, an average annual energy output of each plant is estimated from a load factor of 80%.

The results of external cost obtained from various references [3.69–3.71] are distinctive and wide-ranging; therefore, the mean values are used to calculate the average external cost of each power plant, see Table 3.78. The external costs were assumed not to change over the 20th year scenario. The results show the average external cost of each power plant. The lower average costs correspond to better score of a power plant (the target here is to have minimum average external cost).

TABLE 3.78. EXTERNAL COST OF ELECTRIC GENERATION PER MW(E) H (UNIT: US $ IN 2010)

Data source	Coal		NPP	NGPP
	CPP	IGCC		
RFF/ORNL 1995	$2.3	—	$0.5	$0.4
Rowe et al 1995	$1.3–1.4	—	$0.2	$0.3
ExternE 2005	$27–202	—	$3.4–9.4	$13.4–53.8
NRC 2010	$2–126	—	—	$0–5.8
Epstein et al 2011	$180.7	—	—	—
Rafaj and Kypreos 2007	$58.0	$57	$10.5	$29.5
Shrestha et al 2003*	$0.37**–1.79***	—	—	—
Average (US $/MWh)	$74.5	$57	$4.4	$14.7

* The calculation is based on the inflation rate of 2.5% to convert into 2010 US $.
** Thapsake plant.
*** Mae Moh plant.

(c) Risks of accidents

Embarking countries may not have adequate resources to perform the evaluation, and in this case, reference is made to reports or papers considered to be reliable. Since P. Burgherr *et al.* [3.71] gathered a lot of information before investigating the risks of all power plants to the public in both OECD and non-OECD countries; the results obtained for the non-OECD countries seem appropriate for the present evaluation. There are five sub-indicators which affect the risks of accidents, see Table 3.79. The first four sub-indicators including accident rate, fatality rate, maximum fatalities of a single accident and accident cost rate, are evaluated for the period 1970–2008 [3.72]. It is found that the first three sub-indicators have had the same values for more than 20 years. Another sub-indicator, maximum cost of a single accident, is evaluated based on the costs of failure from a preliminary assessment of major energy accidents in the period 1907–2007 [3.73]. It is found that there are lower rates of change for maximum accident cost of NPP, CPP, IGCC and NGPP within 20 years. Therefore, the time dependence could not affect the risk of accidents. The scores for the 20th year scenario were assumed not to change with time when the power plant construction is planned.

TABLE 3.79. SUB INDICATORS FOR RISKS OF ACCIDENTS AND THEIR SCORES

No.	Sub indicators	Weighting factor	NPP	CPP	IGCC	NGPP
1	Accident rate (per GW(e) y)	0.2	2	10	10	5
2	Fatality rate (per GW(e) y)	0.2	0	10	10	7
3	Maximum fatalities of a single accident	0.2	10	6	6	6
4	Accident cost rate (EUR-cent per kW(e)h)	0.2	8	10	10	8
5	Maximum cost of a single accident (MEUR)	0.2	10	4	4	6
	Risks of accidents	—	6	8	8	6.4

3.13.5.4. *Area of Infrastructure*

(a) Status of legal framework

Due to the long experience of CPP and NGPP deployment (>20 yrs.) in Thailand, the legal framework for the CPP and NGPP installation and operation has been well developed, see Table 3.80.

TABLE 3.80. WEIGHTING FACTORS AND THE SCORES FOR LEGAL FRAMEWORK

Items	Weighting factors	The 0th year				The 20th year			
		NPP	CPP	IGCC	NGPP	NPP	CPP	IGCC	NGPP
Operation safety	0.33	4	10	10	10	10	10	10	10
Environmental protection	0.33	4	10	10	10	10	10	10	10
Waste management	0.33	4	10	10	10	10	10	10	10
Weighted score		4	10	10	10	10	10	10	10

The legal framework for the IGCC may not significantly different from that of the CPP. As for the NPP, the legal framework is currently in the process of development to cover all of aspects related to NPP installation, operation, and decommissioning. It is considered that the NPP legal framework is partially available and not sufficient in term of performances and percentage of implementation at this moment. This corresponds to what IAEA experts have suggested to improve during the Integrated Nuclear Infrastructure Review (INIR) mission in Thailand on December 13-18, 2010 [3.74]. At the next twenty years, the legal framework for NPP is expected to be ready for the 1st NPP project of the country.

(b) Status of State Organizations

The weighting factors and the scores for state organizations are given in Table 3.81.

TABLE 3.81. WEIGHTING FACTORS AND THE SCORES FOR STATE ORGANIZATIONS

Items	Weighting factors	The 0th year				The 20th year			
		NPP	CPP	IGCC	NGPP	NPP	CPP	IGCC	NGPP
Operation safety	0.33	4	10	10	10	10	10	10	10
Environmental protection	0.33	4	10	10	10	10	10	10	10
Waste management	0.33	4	10	10	10	10	10	10	10
Weighted score		4	10	10	10	10	10	10	10

Here, applied were similar reasons to the rationale stated in the status of the legal framework [3.74].

(c) Availability of infrastructure to support owner/operator

Table 3.82 presents weighting factors for availability of infrastructure to support the owner/operator.

TABLE 3.82. WEIGHTING FACTORS FOR AVAILABILITY OF INFRASTRUCTURE TO SUPPORT THE OWNER/OPERATOR

Items	Weighting factors	The 0th year				The 20th year			
		NPP	CPP	IGCC	NGPP	NPP	CPP	IGCC	NGPP
Domestic industries	0.5	4	8	8	8	10	10	10	10
Government	0.5	4	6	6	6	10	10	10	10
Weighted score		4	7	7	7	10	10	10	10

According to the Report [3.75] prepared by Chulalongkorn University in Thailand, the infrastructure of domestic industries and government to support the owner/operator of an NPP is partially available and not sufficient in term of performances and quantification at this moment. Several areas of infrastructure for the NPP construction, installation, and operation are partially available and are required to be developed domestically or imported from other international organizations, if needed. In the meantime, the infrastructure of domestic industries and government to support the owner/operator of a CPP and NGPP proves to be nearly sufficient due to long experiences of CPP and NGPP deployment in Thailand. The infrastructure of domestic industries of IGCC is considered not significantly different compared with those of CPP and NGPP at this moment.

At the next twenty years, the infrastructure to support the owner/operator of all technologies is expected to be sufficient.

(d) Government policy

Table 3.83 shows the selected weighting factors for government policy.

TABLE 3.83. WEIGHTING FACTORS FOR GOVERNMENT POLICY

Items	Weighting factors	The 0th year				The 20th year			
		NPP	CPP	IGCC	NGPP	NPP	CPP	IGCC	NGPP
Existing	0.7	2	10	10	10	10	10	10	10
Reachable and understandable	0.3	2	4	4	4	10	10	10	10
Weighted score		2	7	7	7	10	10	10	10

According to the government document of PDP 2015 [3.66] and related information, Thailand has positively promoted the CPP, NGPP, and IGCC technologies to be deployed in the country for the next 20 years, while the NPP situation is not clearly defined. So, the government policies regarding the CPP, NGPP, and IGCC are considered to exist, but are not sufficiently reachable and understandable for public, at this moment. As for the NPP, the government policy is considered to be non-existent at the present time.

In the next twenty years, government policy of all technologies is assumed to become fully available, reachable and understandable.

(e) Availability of human resources

Table 3.84 gives the weighting factors used for the availability of human resources.

TABLE 3.84. WEIGHTING FACTORS FOR AVAILABILITY OF HUMAN RESOURCES

Items	Weighting factors	The 0th year				The 20th year			
		NPP	CPP	IGCC	NGPP	NPP	CPP	IGCC	NGPP
Establishment and operation	0.33	4	10	10	10	10	10	10	10
Regulatory agency	0.33	4	10	10	10	10	10	10	10
Research and Academics	0.33	2	4	4	4	10	10	10	10
Weighted Score		3.3	8	8	8	10	10	10	10

IAEA experts have suggested to Thailand to take significant actions for the development of human resources for an NPP project during the Integrated Nuclear Infrastructure Review (INIR) mission in Thailand on December 13-18, 2010 [3.74]. For all technologies, the human resource needed for research and academic environment is considered to be available in a limited number. In the next 20 years, the human resource for all required sections is expected to be sufficient.

The scores and weighting factors are determined based on the available information, relevant previous studies and opinions of evaluators who are Thai experts in the various fields of nuclear power. Scoring criteria for each section are classified into six levels as described in Table 3.85.

TABLE 3.85. SCORING CRITERIA FOR EACH SECTION

Level	Score	Description
1	0	Not available at this moment
2	2	Very limited
3	4	Partially available and not sufficient in term of performances and quantification at this moment
4	6	Available but not fully sufficient in term of performances and numbers at this moment
5	8	Nearly sufficient in term of performances and numbers at this moment
6	10	Absolutely sufficient at this moment

3.13.6. Selection of a MCDA method

The comparative evaluation for the Thailand case study is performed by using KIND-ET Excel based accompanied by the set of key indicators which were developed for newcomer countries under the framework of the KIND CP. KIND-ET uses the MAVT method (multi attribute value theory). Linear single attribute value functions are considered together with a local domain in which minimum and maximum domain values are set equal to the minimum and maximum of KI values given in the performance table.

3.13.7. Determination of weights including uncertainties

In this study, two scenarios for four energy systems, with the difference in time, are taken into consideration. The score of comparative evaluation for those scenarios are presented in Table 3.86. Two high-level objectives, namely ‘Cost’ and ‘Acceptability’, are classified for the comparative evaluation. Acceptability is further divided into three areas of assessment as follows: ‘National security’, ‘Public acceptance’ and ‘Infrastructure’. Table 3.81 also contains the considered KIs (11 KIs, described in detail in the section 3.13.5) and the goal established for each KI.

Regarding a newcomer country with the first NPP, the weight factors of the HLOs are defined as 0.3:0.7 for Cost/Acceptability, because in this situation, the ’Acceptability’ is considered to be more important than the ‘Cost’. The weighting factors of both scenarios are assumed the same with no change with time; their values evaluated following expert opinions are shown in Table 3.87.

TABLE 3.86. PERFORMANCE TABLE

HLO	Areas	Indicators	Abbr.	Goal	The 0th year				The 20th year			
					NPP	CPP	IGCC	NGPP	NPP	CPP	IGCC	NGPP
Cost	Economics	Levelized unit electricity cost	KI.1	min	96	81	118	77	81	100	118	101
		Cash flow	KI.2	max	0.8	7.5	0.0	10.0	10.0	6.5	5.0	8.1
Acceptability	National security	Degree of dependence on supplier(s)	KI.3	min	9	4.45	6.7	4.15	9	4.15	4.65	4.8
	Public acceptance	Survey of public acceptance	KI.4	max	2	6	6	8	2	6	8	10
		External cost	KI.5	min	4.4	74.5	57	14.7	4.4	74.5	57	14.7
		Risks of accidents	KI.6	min	6	8	8	6.4	6	8	8	6.4
	Infra-structure	Status of legal framework	KI.7	max	4	10	10	10	10	10	10	10
		Status of state organizations	KI.8	max	4	10	10	10	10	10	10	10
		Availability of infrastructure to support owner/operator	KI.9	max	4	7	7	7	10	10	10	10
		Government policy	KI.10	max	2	7	7	7	10	10	10	10
		Availability of human resources	KI.11	max	3.33	8	8	8	10	10	10	10

TABLE 3.87. WEIGHTING FACTORS

High-level objectives	High-level weights	Areas	Areas weights	Abbr.	KI weights	Final weights
Cost	0.3	Economics	1	KI. 1	0.5	0.150
				KI. 2	0.5	0.150
Acceptability	0.7	National security	0.2	KI. 3	1	0.140
		Public acceptance	0.5	KI. 4	0.33	0.116
				KI. 5	0.33	0.116
				KI. 6	0.33	0.116
		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

The comparative evaluation of all key indicators is determined as a linear function and uses the local domains of single attribute value function. The single attribute values function of each scenario is separately comparative evaluated in each time scenario, as shown in Table 3.88.

TABLE 3.88. SINGLE ATTRIBUTION VALUE OF THE COMPARATIVE EVALUATION BETWEEN NPP, CPP, IGCC AND NGPP

HLO	Areas	Abbr.	The 0th year				The 20th year			
			NPP	CPP	IGCC	NGPP	NPP	CPP	IGCC	NGPP
Cost	Economics	KI.1	0.54	0.90	0.00	1.00	1.00	0.49	0.00	0.46
		KI.2	0.08	0.75	0.00	1.00	1.00	0.30	0.00	0.62
Acceptability	National security	KI.3	0.00	0.94	0.47	1.00	0.00	1.00	0.90	0.87
	Public acceptance	KI.4	0.00	0.67	0.67	1.00	0.00	0.50	0.75	1.00
		KI.5	1.00	0.00	0.25	0.85	1.00	0.00	0.25	0.85
		KI.6	1.00	0.00	0.00	0.80	1.00	0.00	0.00	0.80
	Infrastructure	KI.7	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00
		KI.8	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00
		KI.9	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00
		KI.10	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00
		KI.11	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00

3.13.8. Ranking alternatives with the selected MCDA method

The ranking alternatives for this case study are discussed below in accordance with the considered scenarios.

3.13.8.1. Scenario I: The 0th year case

Ranking results of the comparative evaluation of the 0th year case show that if the construction of a new power plant is required in this present year (0th year), a natural gas power plant (NGPP), rather than a coal-fired power plant (CPP), an integrated coal gasification combine cycle (IGCC) and nuclear power plant (NPP), respectively, is the most attractive for Thailand, with the highest score of 0.956, as illustrated in Table 3.89. The reasons for the NGPP attractiveness are based on the advantage on the cost, the acceptability and the readiness of infrastructure, comparatively with the other energy systems. Considering the CPP, even though its technology has been proven and Thailand has a long experience with the CPP, the score area of public acceptance is quite low as compared with the NGPP. Therefore, the attractiveness of the CPP is less than the one for the NGPP. Figure 3.158 presents the structure of area scores which can identify the areas that provide a chance to significantly improve the power plant attractiveness.

TABLE 3.89. RANKING RESULT OF THE COMPARATIVE EVALUATION BETWEEN NPP, CPP, IGCC AND NGPP FOR THE 0TH YEAR CASE

Levels	The 0th year			
	NPP	CPP	IGCC	NGPP
Multi attribute value function	0.323	0.666	0.382	0.956
High-level objective scores				
Cost	0.092	0.248	0.000	0.300
Acceptability	0.231	0.418	0.382	0.656
Areas scores				
Economics	0.092	0.248	0.000	0.300
National security	0.000	0.131	0.066	0.140
Public acceptance	0.231	0.077	0.106	0.306
Infrastructure	0.000	0.210	0.210	0.210

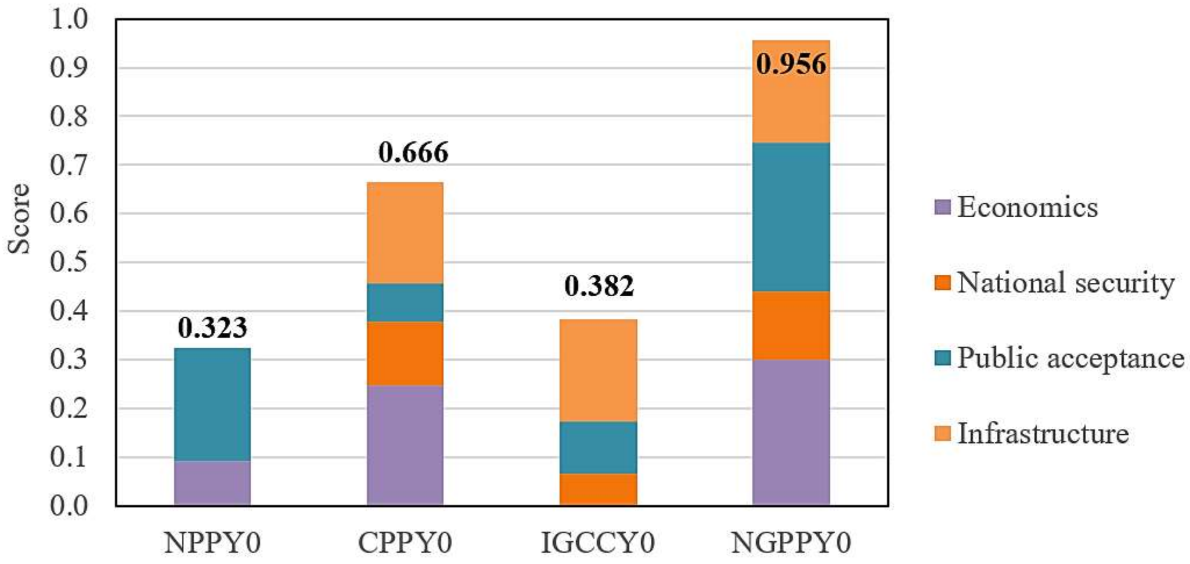

FIG. 3.158. The structure of area scores for NPP, CPP, IGCC and NGPP for the 0th year case.

3.13.8.2. Scenario II: The 20th year

Ranking results of the comparative evaluation of the 20th year case, as illustrated in Table 3.90, show that if the increasing demand of power generation is not urgently needed in the present time and the construction plan of a new power generation can be postponed, happening in the next 20 years, it seems likely that the NPP becomes more attractive with the score of 0.531. However, the NGPP is still the most attractive energy system with the score of 0.590. The shift of construction plan into the next 20 years can potentially increase the score of economic area in the NPP and eliminate the advantage score in the infrastructure area obtained by the other energy systems. This would result in more attractiveness of the NPP. Figure 3.159 presents the structure of area scores which can identify the areas that provide a chance to significantly improve the power plant attractiveness.

TABLE 3.90. RANKING RESULT OF THE COMPARATIVE EVALUATION BETWEEN NPP, CPP, IGCC AND NGPP FOR THE 20TH YEAR CASE

Levels	The 20th year			
	NPP	CPP	IGCC	NGPP
Multi attribute value function	0.531	0.316	0.241	0.590
High-level objective scores				
Cost	0.300	0.118	0.000	0.162
Acceptability	0.231	0.198	0.241	0.428
Areas scores				
Economics	0.300	0.118	0.000	0.162
National security	0.000	0.140	0.126	0.121
Public acceptance	0.231	0.058	0.115	0.306
Infrastructure	0.000	0.000	0.000	0.000

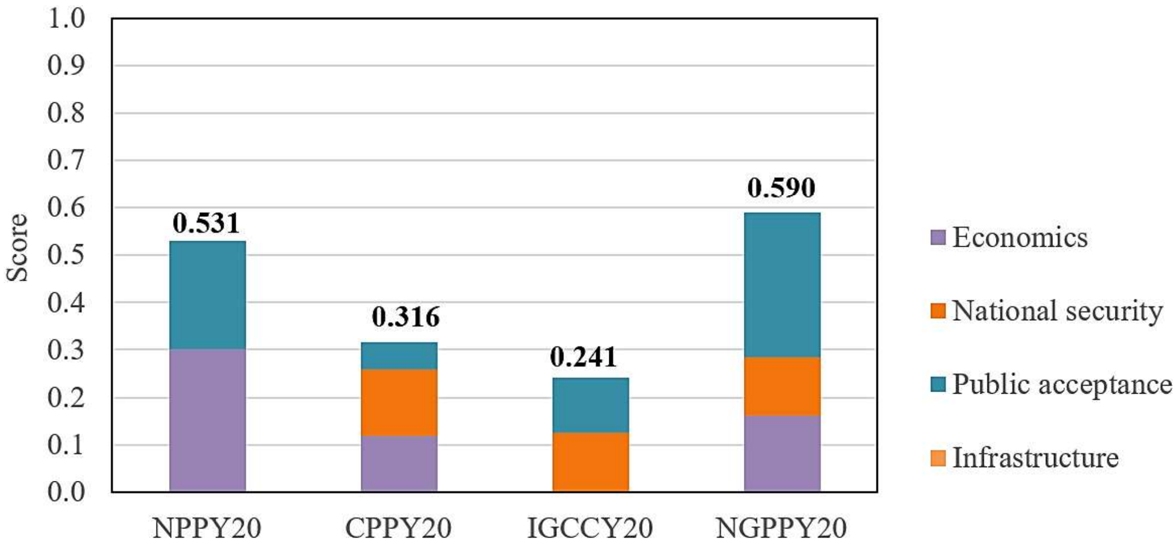

FIG. 3.159. The structure of area scores for NPP, CPP, IGCC and NGPP for the 20th year case.

3.13.9. Sensitivity and uncertainty analysis

New functional extensions for KIND-ET, including with domination identifier, overall score spread builder and ranks mapping tool, are implement in the comparative evaluation.

3.13.9.1. Scenario I: The 0th year

The result of domination test for the 0th year case, as illustrated in Figs 3.160 and 3.161, shows that the CPP and the IGCC are dominated by the natural gas power plant (NGPP).

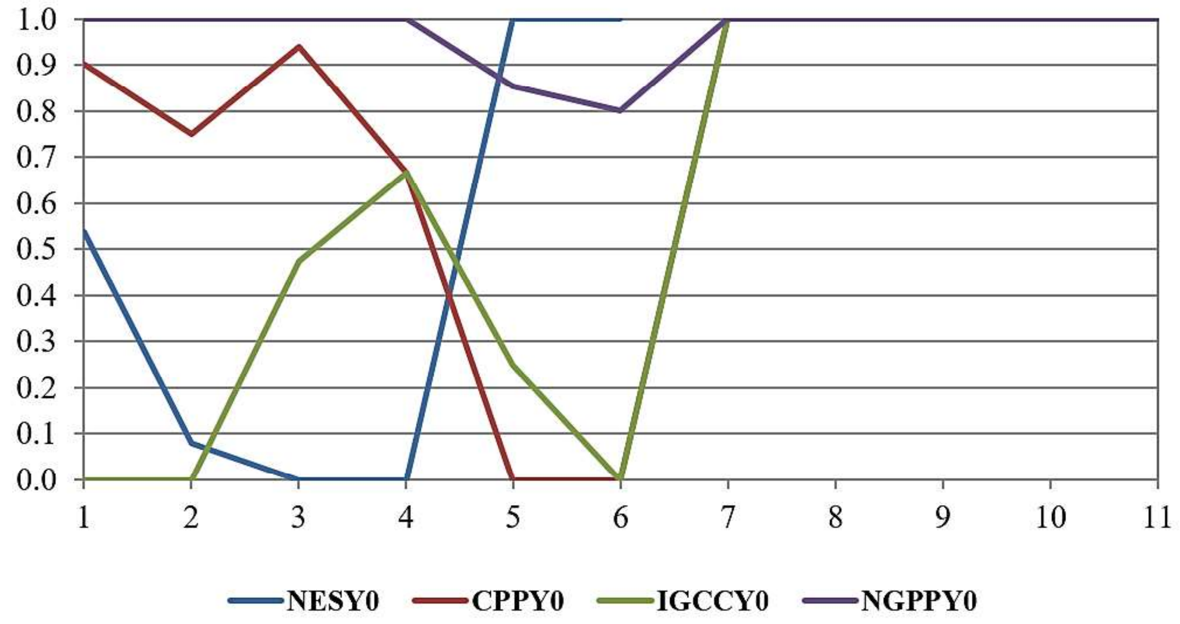

FIG. 3.160. The scores of each key indicator for NPP, CPP, IGCC and NGPP for the 0th year.

Domination table		Dominating options			
		NESY0	CPPY0	IGCCY0	NGPPY0
Dominated options	NESY0		-	-	-
	CPPY0	-		-	<
	IGCCY0	-	-		<
	NGPPY0	-	-	-	

FIG. 3.161. Domination table between NPP, CPP, IGCC and NGPP for the 0th year case (screenshot from Domination Identifier).

Next, evaluations of option overall score spreads are performed to examine the impact on ranking results of uncertainties in weighting factors. Ten thousand weight combinations are performed for all options and demonstrate the spread of overall scores for each weight via a box and whisker plot, see Figs 3.162 and 3.163.

	NPPY0	CPPY0	IGCCY0	NGPPY0
Mean	0.2077	0.7810	0.6411	0.9717
Standart deviation (SD)	0.2439	0.2337	0.2728	0.0425
Maximum value (Max)	0.9999	1.0000	1.0000	1.0000
Quartile (Q3, 75%)	0.3200	0.9512	0.8817	0.9993
Median	0.1008	0.8659	0.6866	0.9929
Quartile (Q1, 25%)	0.0238	0.6971	0.4487	0.9617
Minimum value (Min)	0.0000	0.0001	0.0001	0.8001

Calculations for chart

Bottom	0.0238	0.6971	0.4487	0.9617
2 Q Box	0.0770	0.1688	0.2379	0.0312
3 Q Box	0.2192	0.0853	0.1951	0.0064
Whisker -	0.0238	0.6971	0.4486	0.1616
Whisker +	0.6799	0.0488	0.1183	0.0007

FIG. 3.162. Screenshot from Overall Score Spread Builder for NPP, CPP, IGCC and NGPP for the 0th year case.

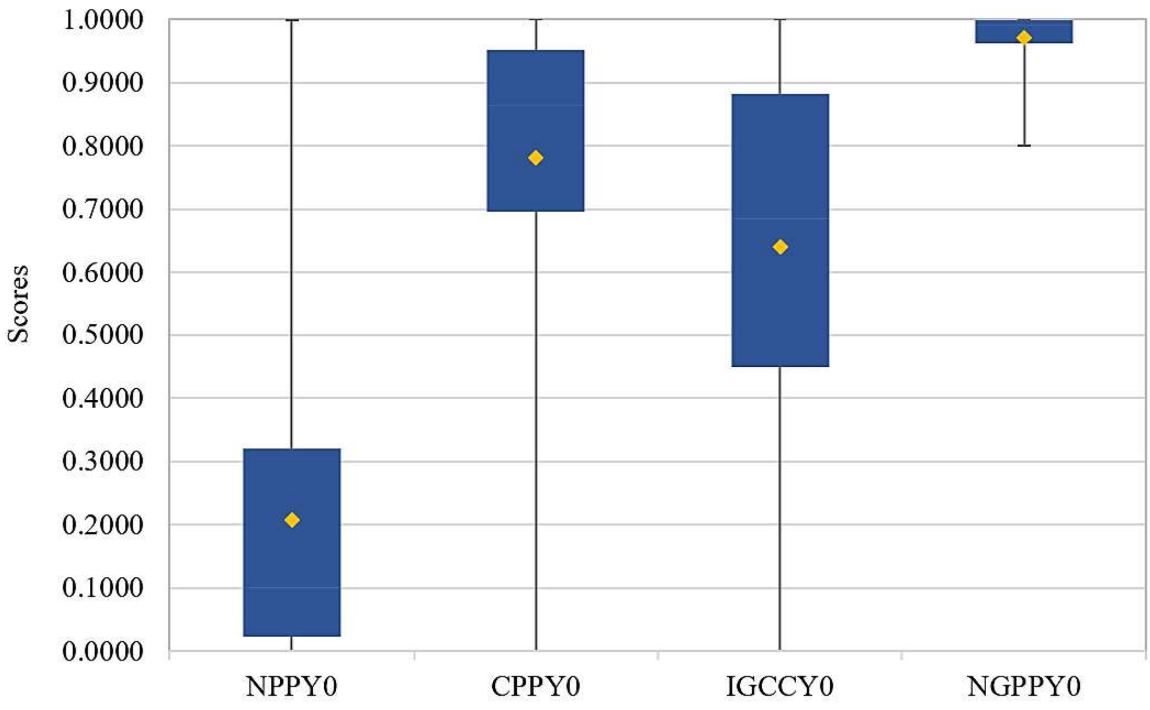

FIG. 3.163. Box and whisker for NPP, CPP, IGCC and NGPP for the 0th year case.

Ranks mapping of this comparative evaluation for four energy options is shown in Fig. 3.164. The weight factor of HLO for Cost-to-Acceptability is defined as 0.3:0.7 by expert judgement. Right now, the weight factor of Acceptability is considered more important than Cost because it consists of the area of public acceptance which has significant impact in a democratic country like Thailand. Figure 3.163 shows that the construction of natural gas power plant for the 0^{th} year case is the most preferable option than other power generations.

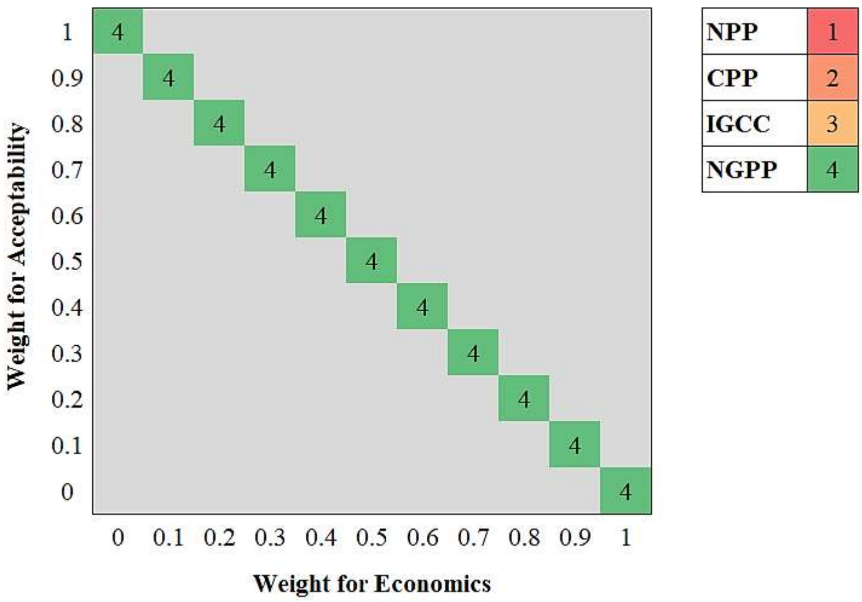

FIG. 3.164. Ranks mapping for NPP, CPP, IGCC and NGPP for the 0^{th} year case.

3.13.9.2. Scenario II: The 20^{th} year

The results of the domination test for the 20^{th} year case show that no power plant option dominates the others. Figures 3.165 and 3.166 present the result.

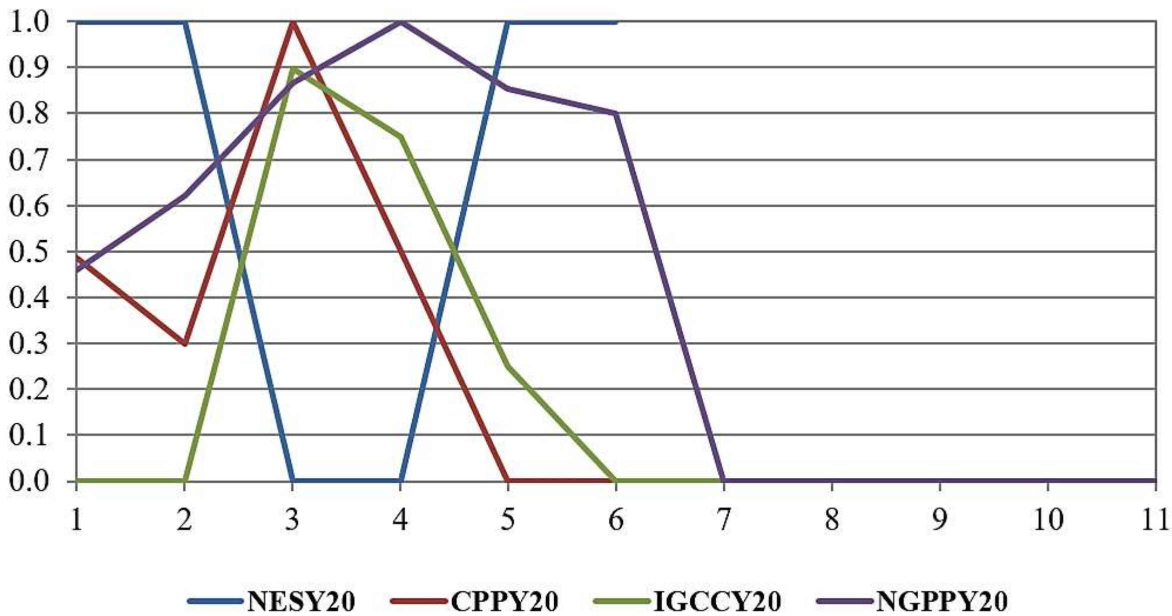

FIG. 3.165. The scores of each key indicator for NPP, CPP, IGCC and NGPP for the 20^{th} year.

Domination table		Dominating options			
		NESY20	CPPY20	IGCCY20	NGPPY20
Dominated options	NESY20		-	-	-
	CPPY20	-		-	-
	IGCCY20	-	-		-
	NGPPY20	-	-	-	

FIG. 3.166. Domination table between NPP, CPP, IGCC and NGPP for the 20th year case (screenshot from Domination Identifier)

Next, evaluations of option overall score spreads are performed to examine the uncertainties in weighting factors impact on ranking results. Ten thousand weight combinations are performed for all options and demonstrate the spread of overall scores for each weight via a box and whisker plot. The results are presented in Figs 3.167 and 3.168.

	NPPY20	CPPY20	IGCCY20	NGPPY20
Mean	0.3113	0.1760	0.1485	0.3604
Standard deviation (SD)	0.2982	0.1955	0.1948	0.2623
Maximum value (Max)	0.9999	0.9978	0.8946	0.9983
Quartile (Q3, 75%)	0.5267	0.2641	0.2119	0.5669
Median	0.2075	0.1058	0.0623	0.3298
Quartile (Q1, 25%)	0.0508	0.0259	0.0107	0.1233
Minimum value (Min)	0.0000	0.0000	0.0000	0.0000

Calculations for chart

Bottom	0.0508	0.0259	0.0107	0.1233
2 Q Box	0.1567	0.0798	0.0515	0.2065
3 Q Box	0.3192	0.1583	0.1496	0.2371
Whisker -	0.0508	0.0259	0.0107	0.1233
Whisker +	0.4732	0.7337	0.6827	0.4314

FIG. 3.167. Screenshot from Overall Score Spread Builder for NPP, CPP, IGCC and NGPP for the 20th year case.

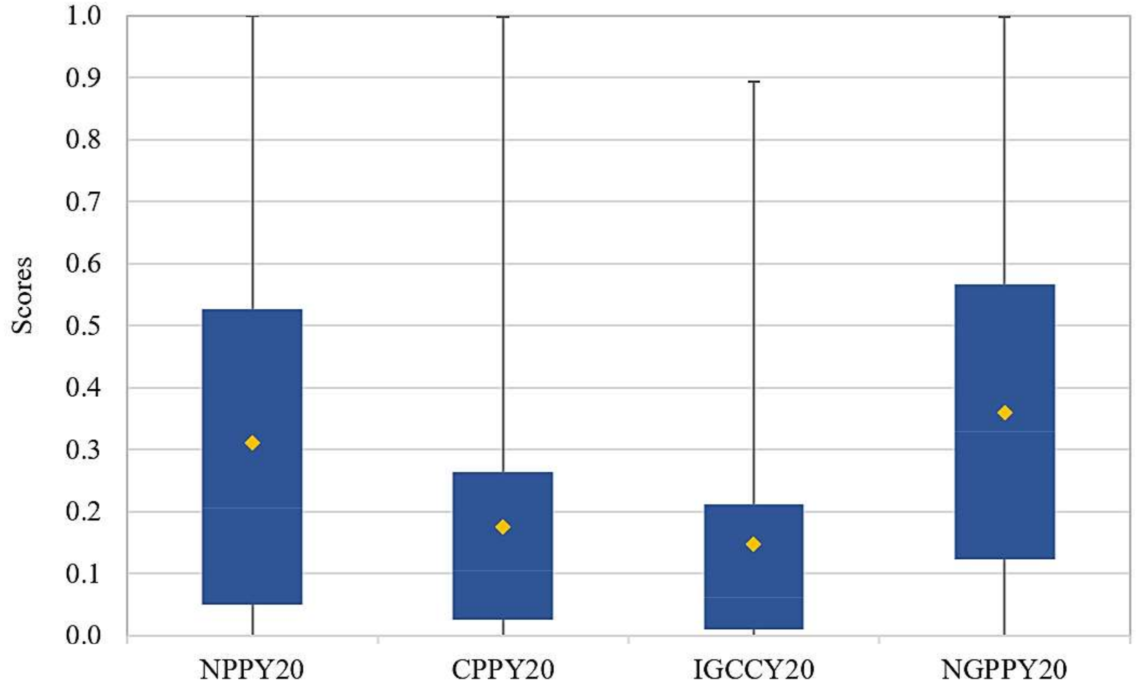

FIG. 3.168. Box and whisker for NPP, CPP, IGCC and NGPP for the 20th year case.

Ranks mapping of this comparative evaluation for four energy options of the 20th year case shows in Fig. 3.169 that if the weight factor of Acceptability becomes less significant or less than 0.4, the NPP can become more preferable option than the NGPP. The possibility of NPP implementation in Thailand can increase when the construction plan is postponed in the next 20 years due to the limitation on high LUEC, less cash flow, no national security in fuel and construction, and unreadiness of infrastructure, especially in government policy at the present time. However, the attractiveness of a nuclear power plant will increase if the development on all key indicators in the area of infrastructure is prepared.

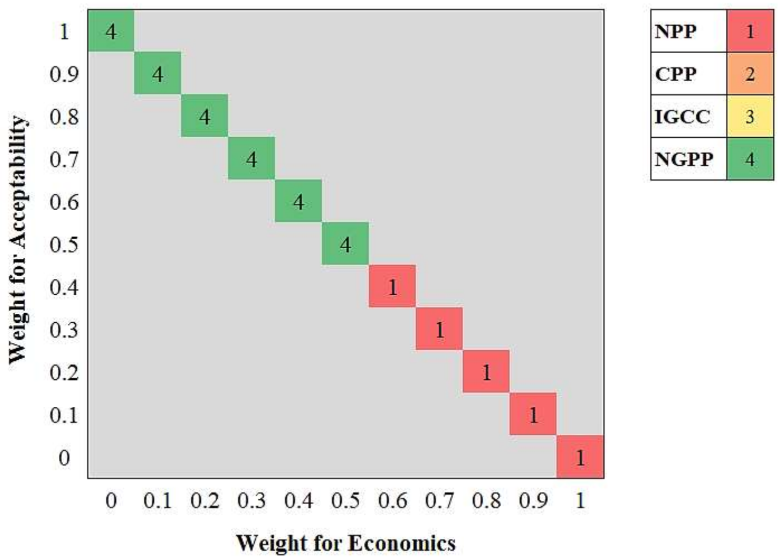

FIG. 3.169. Rank mapping for NPP, CPP, IGCC and NGPP for the 20th year case.

3.13.10. Conclusions

The results of the comparative evaluation show that the natural gas power plant (NGPP) is the most preferable option for the 0th year case, mainly based on the availability of fuel resource, less emissions, more attractive cost, the readiness in infrastructure and the acceptance of the public. The coal-fired power plant can take advantage of the high score in Economics area for the 0th year case, but the CPP can be considered only as a second option, due to the lower acceptance by the public. While the integrated coal gasification combined cycle, which is a clean coal technology, is introduced instead of a coal-fired power plant, the fuel economics are still higher than CPP and the technology is quite new, resulting into lower score in area of public acceptance than the NGPP.

For the 20th year case, the attractiveness of a nuclear power plant is significantly increased due to the development of infrastructure by that time, and the lower significance in the Acceptability high level objective. However, the most attractive option is the NGPP because of the existing long experience on this technology as well as the public acceptability of such power plants.

3.14. COMPARATIVE EVALUATION OF LONG TERM SPENT NUCLEAR FUEL MANAGEMENT SCENARIOS (UKRAINE)

This chapter presents structured report of the first of the two case studies done by experts from Ukraine.

3.14.1. Introduction

The total electricity generation in Ukraine was 159 TW·h in 2018. The 15 nuclear energy reactors of the VVER design produced 85.4 TW·h. The total installed capacity of the nuclear reactor fleet is 13.8 GW and produced 53% of the electricity generation in Ukraine's energy system in 2019. Nuclear energy is the key factor of energy independence of Ukraine.

The New Energy Strategy to 2035 [3.75] was approved by the Ministry Cabinet of Ukraine in August 2017. The electricity generation prognosis till 2035 is presented in Table 3.91.

TABLE 3.91. ELECTRICITY GENERATION IN UKRAINE, TW×H

Electricity generation option	2015	2020	2025	2030	2035
Nuclear	88	85	91	93	94
Thermo	61	60	64	63	63
Hydro	7	10	12	13	13
Renewable	2	9	12	18	13
Total	157	164	178	185	195

The New Energy Strategy to 2035 predicts the next main steps for the Ukrainian nuclear energy development in the medium term:

- To 2020:
  - Increasing of nuclear reactors' capacity factors;
  - Deployment of electricity grids;
  - Lifetime extension of exiting nuclear reactors;
  - Identification of type, design and main technical parameters of nuclear technology for construction of new nuclear units after 2030;
  - Development of a roadmap of new nuclear unit construction after 2030;

- Finance accumulation for NPP decommissioning.

— To 2025:

- NPP lifetime extension according to results of the periodic safety assessment;
- Construction of 1 GW of nuclear generation.

— To 2030:

- Construction of 1 GW of nuclear generation;
- Replacement of the hydrocarbon energy generation by other types where it is economically and technically feasible.

The New Energy Strategy to 2035 has no information about directions for the final SNF management. A 'wait and see' strategy is envisaged and includes the long term storage of spent nuclear fuel in dry storage containers with the ability to identify further directions of SNF management in accordance with international experience. The 'wait and see' strategy is a consequence of the lack of national infrastructure for the reprocessing or geological disposing of SNF. Additionally, the overall direction for the SNF final strategy for NPPs still remains non-defined in many countries around the world.

On 5 June 2019, the Conception of the State Economy Program of Ukrainian NPP's SNF management to 2024 [3.77] has been approved. The concept identifies the next directions of safe and cost effective treatment of spent nuclear fuel produced by the operating NPPs in Ukraine:

— SNF technological storage in reactor cooling pools until the level of residual heat emission become acceptable for further transportation;
— Storage of spent nuclear fuel produced at the Zaporizhzhya NPP within the stipulated term of the project (50 years);
— Shipping of the SNF from Rivne NPP, Khmelnytsky NPP and South-Ukrainian NPP to a foreign reprocessing plant for technological storage and reprocessing (this is active before the commissioning of a Centralized Dry Storage of SNF of VVER-type reactors of domestic NPP);
— Construction and operation of a Centralized Storage facility in the Chernobyl NPP exclusion zone.

The Council Directive 2011/70/EURATOM of 19 July 2011[3.78] indicates the requirement for determination of SNF status (a valuable raw material or radioactive waste (RW)). Also, the appropriate management of SNF in order to isolate and reduce environmental impacts is needed. Thus, a long term strategy for SNF management is envisaged at the national level. Considering the need to ensure the safety of the nuclear energy development in Ukraine, the definition of the final scenario of SNF management is to be based on a comparative analysis of all possible options for nuclear fuel cycles in the long run.

A comparative analysis of SNF management options for the long term period after 2035 was carried out by NNEGC Energoatom (Ukraine). The IAEA program MESSAGE [3.20] was used for the calculation of KIs.

General assumptions about the nuclear energy operation in Ukraine include a 50% share of NPP electricity production in the national electricity generation mix, as the electricity production is increased from 160 TW·h in 2015 to 310 TW·h in 2050. The electricity production remains unchanged until 2100 due to the intensive introduction of energy saving technologies. Accepted projected values of power generation up to 2050 and 2100 years can generate a significant error, but it allows determining trends in the management of spent nuclear fuel. The lifetime of operating reactors VVER-440 and VVER-1000 is taken as 50 years. The construction of Units 3 and 4 of Khmelnitsky NPP (specific capital expenditures is 2,400 $ / kW) is planed to 2030. Specific capital expenditures for the new nuclear unit are taken at $ 5000 / kW. The lifetime of new reactors is 60 years.

Eight NFC scenarios are considered in this case study, as follows:

(1) Open NFC:

- (1.1) Accumulation of SNF without reprocessing or geological disposal;
- (1.2) Accumulation of SNF in the Centralized Dry Storage facility and in the Dry Storage facility at Zaporizhzhya NPP. The limited SNF reprocessing is foreseen before construction and commissioning of the Centralized Dry Storage facility;
- (1.3) Accumulation of SNF in Centralized Dry Storage facility and SNF reprocessing after end of the time for storage in Dry Storage facility at Zaporizhzhya NPP (the reprocessing only of SNF which is accumulated in Dry Storage facility at Zaporizhzhya NPP to 2051);
- (1.4) Accumulation of SNF in the Centralized Dry Storage facility and SNF shipped to Geological Disposal after storage in the Dry Storage facility at Zaporizhzhya NPP after 2051;
- (1.5) SNF repositories in Geological Disposal after the end of the storage in the Centralized Dry Storage facility and in the Dry Storage facility at Zaporizhzhya NPP.

(2) Partially closed NFC:

- (2.1) Reprocessing of limited SNF which was shipped to the reprocessing plant before 2020 (this is active before the commissioning of a Centralized Dry Storage of SNF of VVER-type reactors of domestic NPP). SNF reprocessing after storage in the Centralized Storage facility and in the Dry Storage facility at Zaporizhzhya NPP. The time of SNF storage in the Centralized Dry Storage facility will be not less than 100 years. The time of SNF storage in the Dry Storage facility at Zaporizhzhya NPP will be not less than 50 years. Use of the reprocessed uranium in CANDU reactors is foreseen. Commissioning of CANDU reactors after 2030 as replacement units is foreseen,
- (2.2) Similar to 2.1, but no use of reprocessed uranium in CANDU reactors. The recycling of reprocessed plutonium in LWR in the form of MOX fuel is considered.

(3) Closed NFC:

- (3.1) Reprocessing of SNF shipped to a reprocessing plant before 2020. SNF reprocessing after storage in the Centralized Dry Storage facility and in the Dry Storage facility at Zaporizhzhya NPP. The time of SNF storage in the Centralize Dry Storage facility is 100 years. The time of SNF storage in the Dry Storage facility at Zaporizhzhya NPP is 50 years. Use of reprocessed uranium in fast reactors (FR) is foreseen. Commissioning of FRs with MOX after 2050.

The results of comprehensive assessment of NFC can be provided by using different technical and economic parameters which characterize of SNF management. For this, a list of national Key Indicators (KIs) was identified based on results of the INPRO collaboration projects GAINS [3.79] and SYNERGIES [3.18] by reflecting national preferences. The main considerations/requirements for KIs generation include:

— Quantities and not qualities to exclude bias in expert opinions;
— The comparative NFC assessment can be based on limited number of initial data;
— To include the indicators of NFC sustainability using IAEA INPRO TECDOC-1575 [3.3].

The list of KIs which were used for comparative evaluation of long term SNF management options is presented in Table 3.92.

TABLE 3.92. KEY INDICATORS OF NATIONAL NFC COMPARISION ASSESSMENT

#	KI	Unit of measurement	Status
1	Average energy per unit mass of natural uranium	MW·y/t HM	A higher value corresponds to a better fulfilment of the criterion
2	The consumption of natural uranium	t HM/MW·y	A lower value corresponds to a better fulfilment of the criterion
3	The amount of spent fuel accumulated per year per unit of energy	t HM/MW·y	Similar to 2
4	The volume of SNF accumulation	t HM	Similar to 2
5	Accumulation of reprocessed U	t HM	Similar to 2
6	Accumulation of reprocessed Pu	t HM	Similar to 2
7	Accumulation of HLW (in the form of fission products) after SNF reprocessing	t HM	Similar to 2
8	Accumulation of MA	kg	Similar to 2
9	Total enrichment capacity on year	SWU/y/MW	Similar to 2
10	Total reprocessing capacity on year	T HM/y/MW	Similar to 2
11	LCOE	US $/kW·h	Similar to 2

The resulting scores of long term strategies for NFC based on different options of the SNF management are presented in Table 3.93.

TABLE 3.93. RESULTING SCORES OF LONG TERM NFC

NFC options	1.1	1.2	1.3	1.4	1.5	2.1	2.2	3.1
Total score	6.092	5.470	4.889	5.522	5.776	3.038	2.985	3.020

According to Table 3.93, the scenario of SNF accumulation up to 2100 is currently optimal based on the considered KIs (Table 3.92), but the 1.1 scenario is not in accordance with Council Directive 2011/70/EURATOM [3.78]. The 1.5 scenario with SNF repositories in Geological Disposal after the end of the storage in the Centralize Dry Storage facility and in the Dry Storage facility at Zaporizhzhya NPP is preferable for further research on a national level.

3.14.2. Objective and problem formulation

The objectives of the Ukrainian case study performed in the CENESO CP framework are:

- Application of KIND-ET for ranking results of NFC based on different SNF management options;
- Interpretation of results of long term NFC comparison;
- Application of KIND-ET extensions for NFC results uncertainties assessment.

Two of the new functional extensions for KIND-ET have been applied in the study:

- Overall Score Spread Builder – an express tool for evaluation of option overall score spreads caused by uncertainties in weighting factors and the objective tree structure;
- Ranks Mapping Tool – a visualization tool to highlight the options taking the first rank for different combinations of high-level objective weights.

3.14.3. Application of KIND-ET for ranking results of NFC based on different SNF management options

Ukraine is a user nuclear technology country with a well-developed nuclear energy infrastructure. The implementation of new nuclear technologies and an NFC is expensive. More preferable is to use the international experience in different areas of nuclear energy and NFC. But for sustainable development of a NFC, nuclear technology innovations are needed. The SNF reprocessing or deep geological disposal is not widely used in the world at the time of this project realisation. Thereby, at the national level, the optimal SNF management option can be found by comparison of evolutionary and innovative nuclear technologies. The application of KIND-ET to the present analysis was realized by comparative evaluation of ‘Evolutionary versus innovative nuclear energy systems’.

The High-Level Objectives (HLOs) used in this study were Cost, Performance and Acceptability.

The Evaluation areas include six areas which characterize the three HLOs:

- Economics for Cost;
- Maturity of technology, Waste management and Environment for Performance;
- Proliferation Resistance and Country Specifics with respect to Acceptability.

The proposed KIND-ET model used the KIs presented in Table 3.92. The country specifics are represented by the Security of Supply (SS) indicator which was added to the national list of KIs. This makes possible to consider the energy independence of the national nuclear energy system (NES) based on diversification of NFC services. The SS indicator is a quantitative KI (not qualitative) for the KIND-ET application. The SS value was based on expert opinion and ranging from 1 (low independence) to 10 (high independence) according to the rule: the SS is maximum for NFC with small needs additional to the national nuclear services.

Figure 3.170 summarizes the indicators arrangement in a hierarchical structure known as an objective tree.

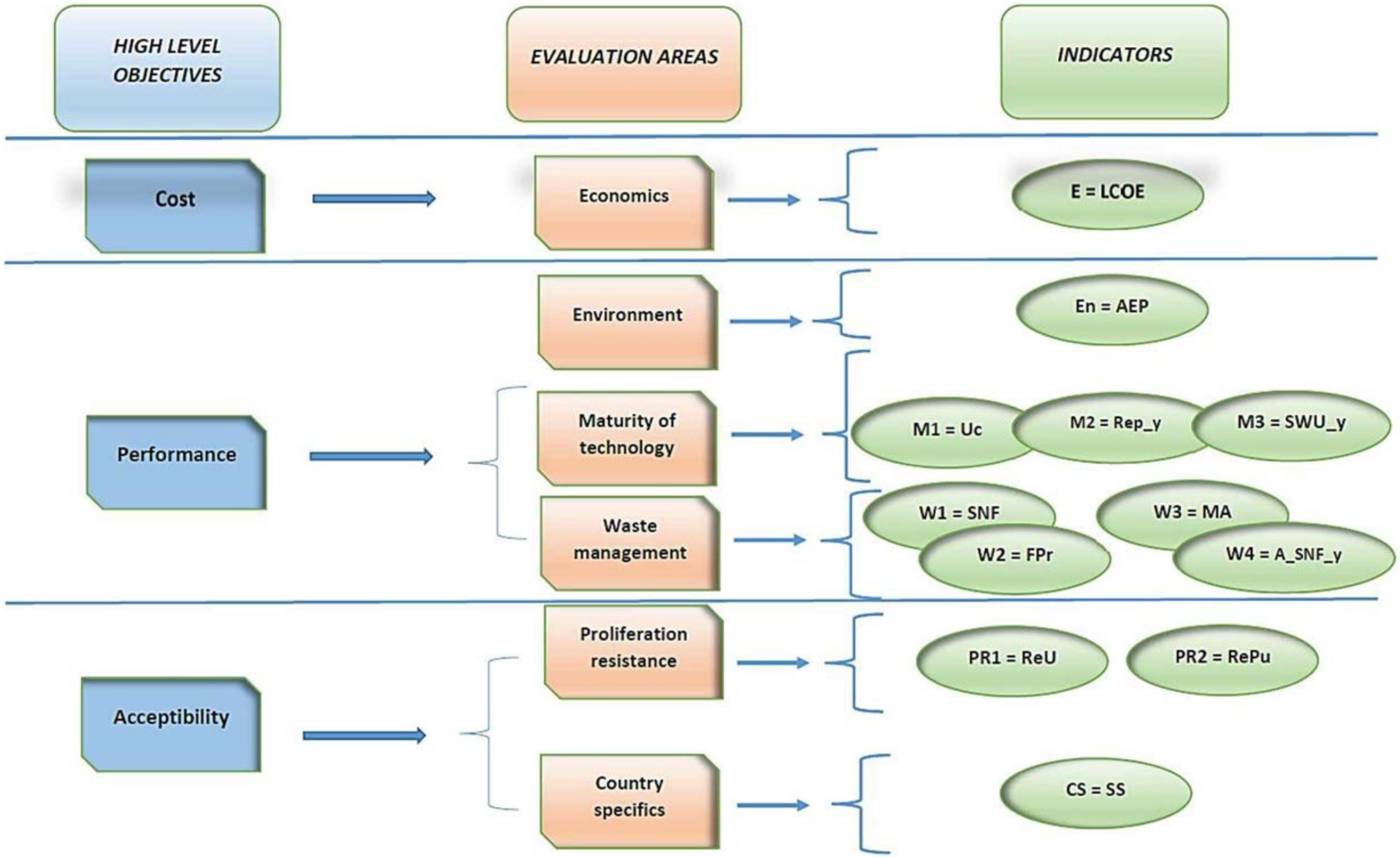

FIG. 3.170. The objective tree.

The list of HLOs, evaluation areas, KIs and their abbreviations, as well as minimum and maximum scores and calculation results for key indicators of different NFCs calculated by the MESSAGE code [3.20] are presented in Fig. 3.171. As opposed to Ukrainian national optimal SNF management directions of research, the KIND-ET was applied to 5 different NFC options (rather than 8 NFC options which were considered before). This allows considering different SNF management options with significant differences between each other.

High-level objectives titles	Areas titles	Indicators titles	Indicators abbr.	MIN score	MAX score	ONFC	ONFC +repr	ONFC +GD	PCNFC	CNFC
cost	Economics	LCOE	E	0	100	22.9	24.9	25.4	29.3	25.1
performance	Environment	Avarage energy production by mass of U	AEP	0	10	7.1	7.1	7.1	8.2	7.2
performance	Maturity of technology	Average U consumption	Uc	0	1	0.14	0.14	0.14	0.12	0.14
performance	Waste management	Avarage SNF accumulation by year	A_SNF_y	0	1	0.022	0.016	0.011	0.017	0.005
performance	Maturity of technology	Enrichment capacity by MW by year	SWU_y	0	1	0.117	0.117	0.117	0.1	0.118
performance	Maturity of technology	Reprocessing capacity by MW by year	Repr_y	0	1	0	0.006	0.003	0.024	0.034
performance	Waste management	SNF stocks	SNF	0	50000	27506	20034	14181	20888	6118
acceptibility	Proliferation resistance	Accumulating of reprocessed U	ReU	0	50000	0	6964	3296	0	20359
acceptibility	Proliferation resistance	Accumulating of reprocessed Pu	RePu	0	1000	0	90	43	210	154
performance	Waste management	Accumulating of FPr	FPr	0	10000	0	427	182	993	1165
performance	Waste management	Accumulating of MA	MA	0	50	0	10	4	22	26
acceptibility	Country specifies	Security of supply	SS	0	10	10	5	8	3	3

FIG. 3.171. Performance table (screenshot from KIND-ET).

The weighting factors for the HLOs and the Assessment areas were selected based on the experts' opinion considering the national priorities and trends for nuclear energy deployment after 2035. The economic challenges and risks of attracting investment for new nuclear reactors construction is of high importance for sustainable development of an NFC in a user country. Based on the existing Ukrainian nuclear energy infrastructure, the KIND-ET application provided the following HLO weightings factors: 0.5 for Cost; 0.3 for Performance; 0.2 for Acceptability. The weighting factors for Assessment areas were selected as follows: 1 for Economics; 0.333 for each of Waste Management, Environment and Maturity of technology; 0.5 for each of Proliferation resistance and Country specifics. The sum of Assessment areas weighting factors for each of the HLOs is to be 1. Figure 3.171 presents information about HLO and Assessment areas weighting factors and results for the final weighting factors calculation.

High-level objectives titles	High-level objectives weights	Areas titles	Areas weights	Indicators abbr.	Indicators weights	Final weights
cost	0.500	Economics	1	E	1	0.500
performance	0.300	Waste management	0.333	A_SNF_y	0.25	0.025
				SNF	0.25	0.025
				FPr	0.25	0.025
				MA	0.25	0.025
		Environment	0.333	AEP	1	0.100
		Maturity of technology	0.333	SWU_y	0.333	0.033
				Repr_y	0.333	0.033
				Uc	0.333	0.033
acceptibility	0.200	Proliferation resistance	0.5	ReU	0.5	0.050
				RePu	0.5	0.050
		Country specifies	0.5	SS	1	0.100

FIG. 3.172. Weighting factors (screenshot from KIND-ET).

Results of the single attribute value functions calculations based on Fig. 3.172 weighting factors by using KIND-ET are presented in Fig. 3.173.

High-level objectives titles	Areas titles	Indicators abbr.	Goal	Form	Exponent power	VF domain	MIN VF domain	MAX VF domain	ONFC	ONFC+repr	ONFC+GD	PCNFC	CNFC
cost	Economics	E	min	lin	1	local	22.9	29.3	1.000	0.688	0.609	0.000	0.656
performance	Environment	AEP	max	lin	1	local	7.1	8.2	0.000	0.000	0.000	1.000	0.091
performance	Maturity of technology	Uc	min	lin	1	local	0.12	0.14	0.000	0.000	0.000	1.000	0.000
performance	Waste management	A_SNF_y	min	lin	1	local	0.005	0.022	0.000	0.353	0.647	0.294	1.000
performance	Maturity of technology	SWU_y	min	lin	1	local	0.1	0.118	0.056	0.056	0.056	1.000	0.000
performance	Maturity of technology	Repr_y	min	lin	1	local	0	0.034	1.000	0.824	0.912	0.294	0.000
performance	Waste management	SNF	min	lin	1	local	6118	27506	0.000	0.349	0.623	0.309	1.000
acceptibility	Proliferation resistance	ReU	min	lin	1	local	0	20359	1.000	0.658	0.838	1.000	0.000
acceptibility	Proliferation resistance	RePu	min	lin	1	local	0	210	1.000	0.571	0.795	0.000	0.267
performance	Waste management	FPr	min	lin	1	local	0	1165	1.000	0.633	0.844	0.148	0.000
performance	Waste management	MA	min	lin	1	local	0	26	1.000	0.615	0.846	0.154	0.000
acceptibility	Country specifies	SS	max	lin	1	local	3	10	1.000	0.286	0.714	0.000	0.000

FIG. 3.173. Single attribute value functions table (screenshot from KIND-ET).

The results of the KIND-ET application for NFC options ranking based on Fig. 3.172 weighting factors are shown in Fig. 3.174. The rank for NFC options HLO and Assessment areas is presented separately. This is useful for understanding of differences in NFC options for decision makers.

Levels	ONFC	ONFC+repr	ONFC+GD	PCNFC	CNFC
Multi-attribute value function	0.785	0.512	0.564	0.249	0.400
High-level objectives scores					
Cost	0.500	0.344	0.305	0.100	0.337
Performance	0.035	0.038	0.048	0.084	0.025
Acceptibility	0.250	0.130	0.211	0.065	0.038
Areas scores					
Economics	0.500	0.344	0.564	0.249	0.400
Maturity of technology	0.035	0.038	0.048	0.084	0.025
Waste management	0.000	0.009	0.016	0.008	0.025
Proliferation resistance	0.100	0.061	0.082	0.050	0.013
Environment	0.050	0.031	0.042	0.008	0.000
Country specifics	0.100	0.029	0.071	0.000	0.000

FIG. 3.174. Ranking results (screenshot from KIND-ET).

In Fig. 3.175, the NFC options ranking results decomposed for (a) HLOs, and (b) Assessment areas are presented.

(a)

(b)

FIG. 3.175. Ranking results by: (a) HLOs and (b) assessment areas.

The results of a comparative evaluation of the NFC based on expert judgment may have a significant amount of uncertainty. The differences can be evaluated by flexibility analysis of ranking results with variations of weighting factors. The changing of weighting factors for the Cost and Performance HLOs provided for flexibility analysis. The new values of the HLO weights are 0.2 instead of 0.5 for Cost, and 0.6 instead of 0.3 for Performance. In Fig. 3.176 the comparative evaluation of NFC options ranking results for the base case and modified scenario is presented.

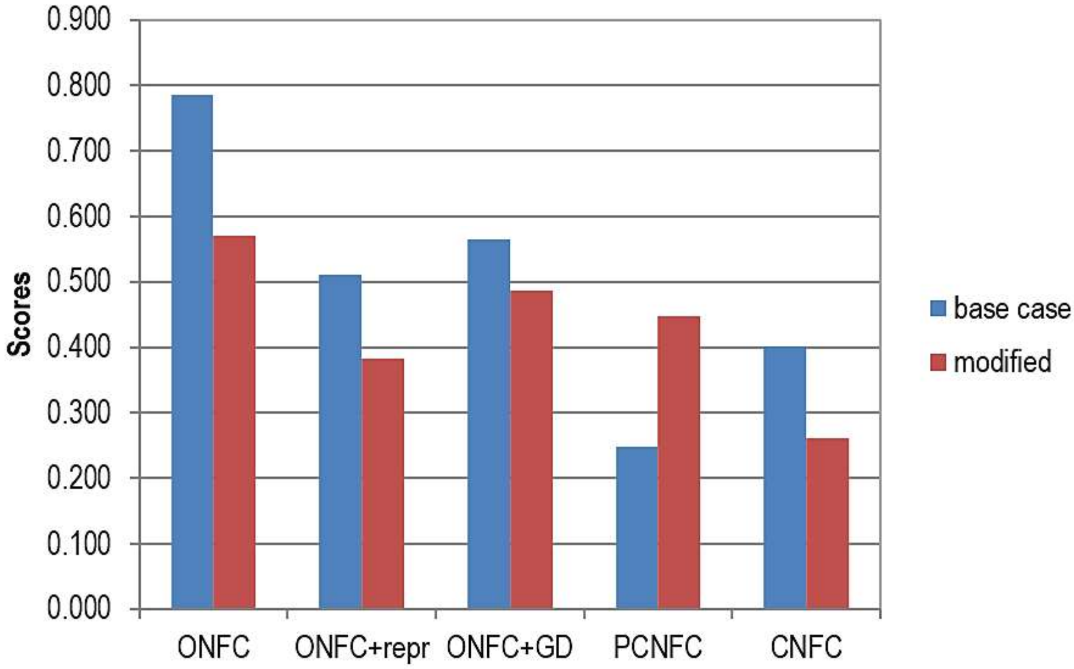

FIG. 3.176. Ranking of NFCs.

According to the KIND-ET application for the base case, the open NFC with SNF accumulation in Dry Storage Facilities has a maximum score (0.785). The minimum score (0.249) was obtained by a partially closed NFC with limited SNF reprocessing and uranium use in CANDU reactors. At the same time, based on the purpose of this study to determine the final direction of the SNF management, the option of accumulating SNF with future placement in a geological repository is more attractive. This NFC score is biggest for the NFC with accumulation and reprocessing of SNF (0.564 and 0.512). The sensitivity analyses show unchangeable ranking results for open NFC with SNF storage in the geological repository. Thus, based on the technical and economic data available at the time of the study for Ukrainian NPPs, the geological disposal of SNF is the most preferable.

The results of the KIND-ET application correspond to results of NFC national comparative evaluation which is shown in Table 3.93.

3.14.4. Uncertainty analysis

Domination Identifier

Application of this KIND-ET extension allows identifying the dominating SNF management options. The functional extensions for KIND-ET were applied to the five NFC options. Visualisation of dominations results is useful for the decision makers. A domination indicator is identified if one NFC fully dominates another NFC over the range of KIs. Results of the Dominations Identifier for the Ukrainian NFC options are shown in Figs 3.177 and 3.178. No NFC is dominant over the range of KIs. This indicates that an NFC can be best and worst at the same time (good by economical and worst by security of supply, for example).

Domination table		ONFC	ONFC+repr	ONFC+GD	PCNFC	CNFC
Dominated options	ONFC		-	-	-	-
	ONFC+repr	-		-	-	-
	ONFC+GD	-	-		-	-
	PCNFC	-	-	-		-
	CNFC	-	-	-	-	
	NES-6	-	-	-	-	-
	NES-7	-	-	-	-	-
	NES-8	-	-	-	-	-
	NES-9	-	-	-	-	-
	NES-10	-	-	-	-	-
	NES-11	-	-	-	-	-
	NES-12	-	-	-	-	-
	NES-13	-	-	-	-	-
	NES-14	-	-	-	-	-
	NES-15	-	-	-	-	-

FIG. 3.177. Domination Identifier worksheet (screenshot from Domination Identifier).

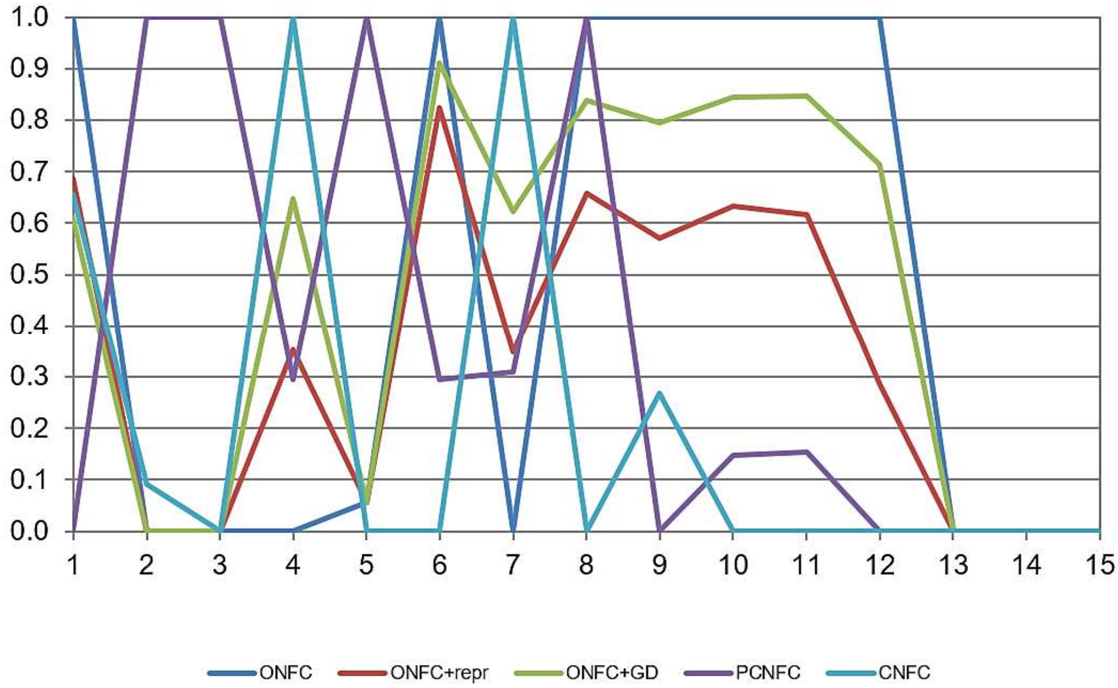

FIG. 3.178. Ranking of NFC.

Overall Score Spread Builder

The Overall Score Spread Builder is useful for the evaluation of option overall score spreads caused by uncertainties in weighting factors and the objective tree structure. Additional to NFCs ranking results (Fig. 3.176), the Overall Score Spread Builder is useful for visualisation of NFC's uncertainties by box and whisker diagrams. The higher whiskers correspond to higher uncertainties.

For the Ukrainian case study, the 15 KIs case sheet was modified for using of 12 KIs according to Table 3.92. The first step for assessment is using of calculation results of single attribute value functions for filling the table ‘Overall score spread builder’ as shown in Figure 3.179.

Single-attr. value functions		KI-1	KI-2	KI-3	KI-4	KI-5	KI-6	KI-7	KI-8	KI-9	KI-10	KI-11	KI-12
Please input here data rearding single-attr. value functions from the KIND-ET model	**ONFC**	1	0	0	0	0.56	1	0	1	1	1	1	1
	ONFC+repr	0.688	0	0	0.353	0.056	0.824	0.349	0.658	0.571	0.633	0.615	0.286
	ONFC+GD	0.609	0	0	0.647	0.056	0.912	0.623	0.838	0.795	0.844	0.846	0.714
	PCNFC	0	1	1	0.294	1	0.294	0.309	1	0	0.148	0.154	0
	CNFC	0.656	0.091	0	1	0	0	1	0	0.267	0	0	0

FIG. 3.179. "Overall score spread builder" table (screenshot from the Overall Score Spread Builder).

The standard deviation, maximum value, minimum value and median are calculated by using the data of Figure 3.173 in the second step. The top and bottom whisker levels which are presented are calculated automatically. Results of calculation for the five NFCs are shown in Figure 3.180.

	ONFC	ONFC+repr	ONFC+GD	PCNFC	CNFC
Mean	0.45947113	0.298024953	0.413365971	0.28718057	0.166542428
Standart deviation (SD)	0.32739817	0.199312671	0.259677316	0.25590562	0.218728548
Maximum value (Max)	0.9999972	0.822527725	0.910471581	0.99994101	0.998462244
Quartile (Q3, 75%)	0.76204536	0.455970101	0.64272097	0.41040152	0.235910382
Median	0.43251234	0.286399514	0.424857185	0.21001962	0.071272404
Quartile (Q1, 25%)	0.14886259	0.120316406	0.170314087	0.08968736	0.013261632
Minimum value (Min)	5.2674E-08	4.79928E-06	6.72845E-06	2.0172E-06	1.33834E-09

Calculations for chart

Bottom	0.14886259	0.120316406	0.170314087	0.08968736	0.013261632
2 Q Box	0.28364975	0.166083108	0.254543098	0.12033226	0.058010772
3 Q Box	0.32953302	0.169570586	0.217863785	0.20038191	0.200381906
Whisker -	0.14886254	0.120311607	0.170307359	0.08968534	0.013261631
Whisker +	0.23795184	0.366557624	0.267750611	0.58953949	0.762551862

FIG. 3.180. Box and whisker tables (screenshot from the Overall Score Spread Builder).

The results of the Overall score spread builder application for the five NFCs are presented on Fig. 3.181.

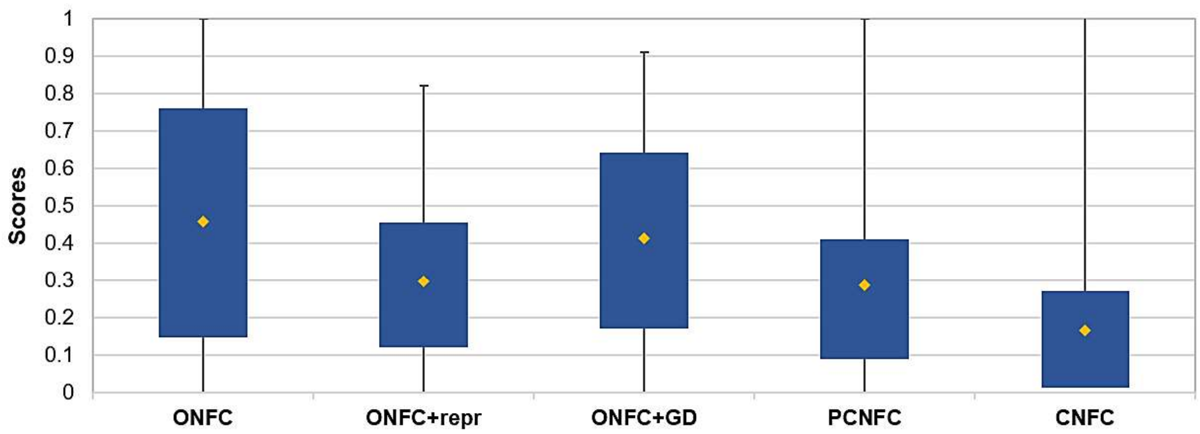

FIG. 3.181. Overall score spreads.

Ranks Mapping Tool

The Ranks Mapping Tool is a visualization tool to highlight the options taking the first rank for different combinations of high-level objective weights. In this way the ranges of weights that are preferable or not preferable for each NFC option can be evaluated. For application of the Ranks Mapping Tool the data for HLO scores of Fig. 3.173 are used. The results of the Ranks Mapping Tool application for assessment of Ukrainian NFCs are presented in Fig. 3.182.

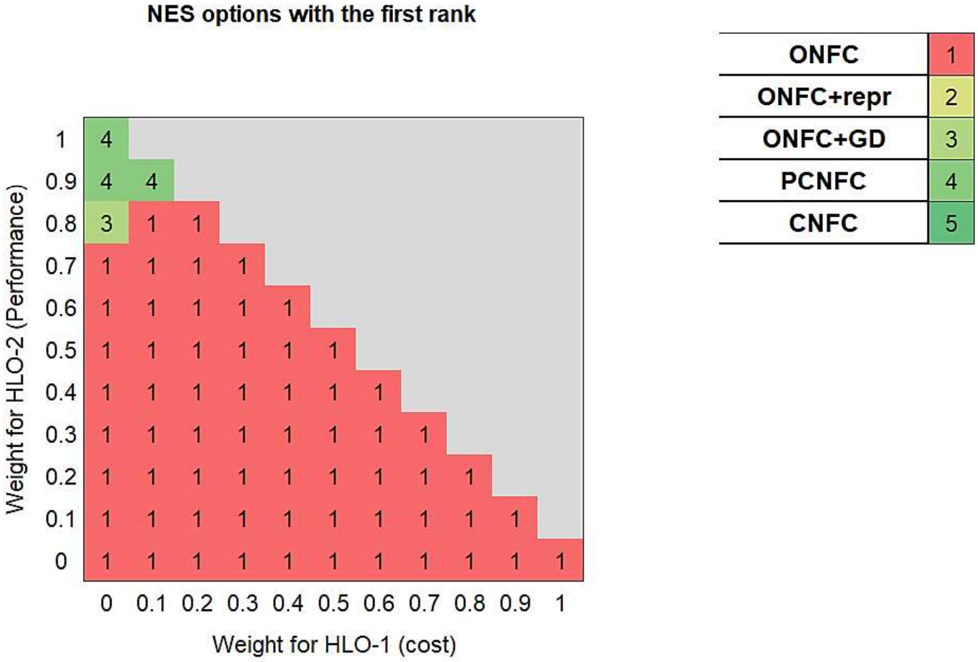

FIG. 3.182. Maximal overall scores for NFCs.

The first rank options diagram shows the domination of the open NFC in a wide range of cost and performance. This is consistent with the NFC deployment experience in the world. If the Cost weight factor is low, the partially closed NFC may be considered for realization on the national level.

3.14.5. Conclusions

In the framework of the case study, the application of KIND-ET for ranking results of NFCs based on the different SNF management options was provided. The national results of long term NFC comparison assessment are confirmed by using of KIND-ET tool based on 12 KIs. Assessment of KIs was realized by NFC modelling using the IAEA's MESSAGE programme. The technical and economic parameters of NFC components were taken from open sources and were considered sufficient for use in the KIND-ET evaluation. Based on the analysis performed, an open NFC with SNF accumulation was shown to be preferable for realization at a national level in the Ukraine. The second score corresponded to an open NFC with SNF geological disposal. The results of HLO weight factors sensitivity analysis gave a similar picture.

The application of the KIND-ET extensions for the NFC uncertainties assessment was realized. The extension of KIND-ET in framework of the CENESO CP included the assessment of uncertainties in the scores of different NESs. The extension of KIND-ET can be considered as additional support for the NES sensitivity analyses.

The extension of KIND-ET is useful for decision makers because it provides visualization of assessment results. It supports decision making by examining the degree of uncertainty based on previously calculated parameters. It is useful to determine the degree of uncertainty of decision making based on previously calculated parameters. This is done by defining whiskers and HLO ranking. The possibility to use both quantitative and qualitative parameters makes KIND-ET and its extension a universal tool for the application on a wide scale.

3.15. KIND-ET APPLICATION TO PERSPECTIVE REACTOR TECHNOLOGIES SELECTION (UKRAINE)

This chapter presents structured report of the second of the two case studies done by experts from Ukraine.

3.15.1. Introduction

Ukraine's energy strategy for the period up to 2035 'Security, energy efficiency, competitiveness' (hereinafter – the Energy Strategy) [3.76], which defined the strategic guidelines for the development of Ukraine's fuel and energy complex, identifies nuclear energy as one of the most cost effective low-carbon energy sources, and the further development of the nuclear energy sector for the period up to 2035 is projected based on the fact that the share of nuclear generation in the total electricity production will increase. The share of the NPPs' electricity generation in the period 2017–2019 was 50–55% of the Ukraine's total electricity production.

At the time of the study, the installed capacity of Ukrainian NPPs was 13,835 GW and includes 15 VVER power units. Considering that almost all NPP power units were put into operation in the period 1980–1990, work is carried out to extend their lifetime.

The lifetime of power units up to 5 GW of installed capacity is expected to expire after 2030. In order to ensure the safe and economic development of nuclear generation in the future, the task of choosing a standard type of reactor technology (RT) for the construction of power units to replace existing ones in Ukraine is necessary. It is assumed that the choice of RT will ensure licensing and safe operation by introducing standard unified regulatory requirements and will reduce financial costs for the manufacture of equipment and construction of power units.

Since the lifetime of Gen III + reactors can exceed 60 years, the choice of the type of RT will also affect the long term development of nuclear energy and the NFC of the Ukraine.

The results of this study were obtained in the framework of a long term programme for the development of nuclear energy in Ukraine [3.76].

3.15.2. Goals and objectives

The main purpose of the study is to use KIND-ET and related tools to select a typical RT that will be used for the replacement of old NPPs and construction of new NPP units to ensure sustainable development of Ukraine's nuclear energy after 2035. At the same time, it is necessary to the national regulatory requirements for safe operation of NPPs, the existing infrastructure for the NPP operation and spent nuclear fuel management, the national vision of nuclear energy development in the United Energy System (UES) of Ukraine and global trends in nuclear technology and NFC.

The objectives of the work are described as follows:

(1) Substantiation of the algorithm for comparative evaluation of reactor technologies on the basis of indicative representatives of the RT;
(2) Development of comparative evaluation criteria (Key Indicators, KIs) for comprehensive analysis;
(3) Carrying out a comparative evaluation using KIND-ET and related tools;
(4) Carrying out the sensitivity analysis for the obtained results of the comparative evaluation

by changing the weighting factors;

(5) Determination of a rational variant of reactor technology.

3.15.3. Initial data, methodology and assumptions used

The following aspects need be taken to account whilst choosing an RT and design of NPP power units:

- Compliance of reactor technology with international safety standards and relevant criteria of WENRA[34], EUR[35], IAEA[36], as well as compliance with regulatory requirements of Ukraine[37];
- Efficiency, reliability, possibility of operation of power units in various modes;
- Application of NPP power units to ensure conditions of reliable operation of Ukrainian NPPs, including potential integration with the European power system;
- The possibility of reliable supply of nuclear fuel, considering domestic uranium reserves, diversification of suppliers and fuel fabricators, the national localization of stages of RT production;
- Ensuring non-proliferation of nuclear materials in accordance with the legislation and international obligations of Ukraine;
- Possibilities of serial construction and further operational support of the fleet of NPPs;
- Conditions of the nuclear fuel cycle in which the existing fleet of NPPs operates.

Based on the world experience in the development of nuclear energy, it is advisable to consider three reactor technologies (PWR, BWR, HWR), which are currently widely developed for electricity generation.

The RT offered on the world market and that can be considered in the analysis are listed in Table 3.94.

[34] https://www.wenra.eu/publications
[35] https://europeanutilityrequirements.eu/Opendocumentation.aspx
[36] https://www.iaea.org/resources/safety-standards
[37] https://snriu.gov.ua/en/nuclear-legislation/legal-acts

TABLE 3.94. LIST OF REACTOR DESIGNS AS REPRESENTATIVES OF RELEVANT REACTOR TECHNOLOGIES

Type	Range of electric power		
	< 300 MW	300 – 700 MW	> 700 MW
PWR	SMR-160 (Holtec Int., USA) NuScale (NuScale Power, LLC, USA)	—	AP1000 (Westinghouse, USA) APR-1400 (KEPCO, Republic of Korea) Hualong-1(HPR1000, China) EPR (Areva, France) ATMEA-1 (Areva+MHI, France & Japan) VVER-1200 (FSUE "Hydropress", RF)
BWR	—	—	ABWR (GE-HITACHI, USA) ESBWR (GE Hitachi Nuclear Energy, USA & Japan)
HWR	—	EC-6 (AECL, Canada)	—

3.15.4. Identification of main directions and criteria

Considering the capabilities of the KIND-ET tool, a three-level criterion evaluation is performed, which includes consideration of three high-level objectives (HLOs): Cost; Performance; and Acceptability.

The presented HLOs include eight evaluation areas:

- Economics;
- Safety;
- Technical indicators;
- Reference;
- General criteria;
- Impact on staff;
- Infrastructure;
- Relationship with the NFC.

A list of 26 key indicators was developed for the present analysis. Although the KIND CP suggests use of no more than 20 indicators, a larger number of indicators allows performing a comprehensive comparative analysis of reactor technologies, considering the significant number of technical and economic parameters that characterize the reactor, as well as the need to consider additional factors related to population and environment. This, in turn, allows performing a comparative analysis of different reactor technologies, based on open sources of technical and economic information about the reactors. The general list of indicators for the comparative evaluation of reactors is given in Table 3.96. The list of indicators is formed on the basis of INPRO-TECDOC-1575 [3.3], GAINS [3.79] and the normative documentation of Ukraine.

TABLE 3.95. A STRUCTURED THREE-LEVEL LIST OF CRITERIA FOR THE ASSESSMENT OF POWER UNITS

Name of top-level goals	Names of assessment areas	Name of criteria (indicators)	Indicators abbr.
Cost	Economics	The cost of construction, including the main objects on the industrial site, USD/kWe	E1
		Possibility of placing replacement capacities on the sites of existing NPPs	E2
		The duration of construction on the site, months/MWe	E3
		Using the principle of standardization of construction	E4
		Using the principle of modular construction	E5
		The level of participation of national industry and national organizations, %	E6
		Specific consumption of natural uranium, kg/kW·day	E7
Technical characteristics	Safety	Core damage frequency (CDF), 1/reactor·year	S1
		Large release frequency (LRF), 1/ reactor·year	S2
		Safety philosophy, including a combination of active and passive systems, with the priority of passive safety systems	S3
		Availability of special measures to prevent severe accidents and limit their consequences	S4
		The period of time before the required response of the operator, hours	S5
		The value of the maximum acceleration on the soil surface, fraction of g[38]	S6
	Technical indicators	Gross power unit efficiency, %	P1
		Coefficient of readiness, %	P2
		Manoeuvring characteristics (unloading depth), %	P3
		Design life cycle of the power unit, years	P4

[38] g is for free fall acceleration.

TABLE 3.95. A STRUCTURED THREE-LEVEL LIST OF CRITERIA FOR THE ASSESSMENT OF POWER UNITS (cont.)

Name of top-level goals	Names of assessment areas	Name of criteria (indicators)	Indicators abbr.
	Reference	Number of power units built and operated	R1
		Number of power units under construction and those planned for construction	R2
		Comparability of reactor technology with that currently used in Ukraine in terms of the NPP	R3
Acceptability	General criteria	Comparability with the requirements of the Nuclear and Radiation Safety (NRS) authority of Ukraine	G1
	Impact on staff	The level of the operating personnel exposure, person • Sv / reactor • year	EN1
	Infrastructure	Logistics with regard to the transportation of heavy weights (possibility of delivery by different modes of transport)	I1
		The need to create a special infrastructure based on the requirements of the RT	I2
	Link with NFC	The possibility of using the existing infrastructure of the "front end", considering the actions currently planned	N1
		Possibility to use the existing (created) infrastructure for SNF management	N2

Figure 3.183 shows the relationship between High Level Objectives, Evaluation Areas and Indicators.

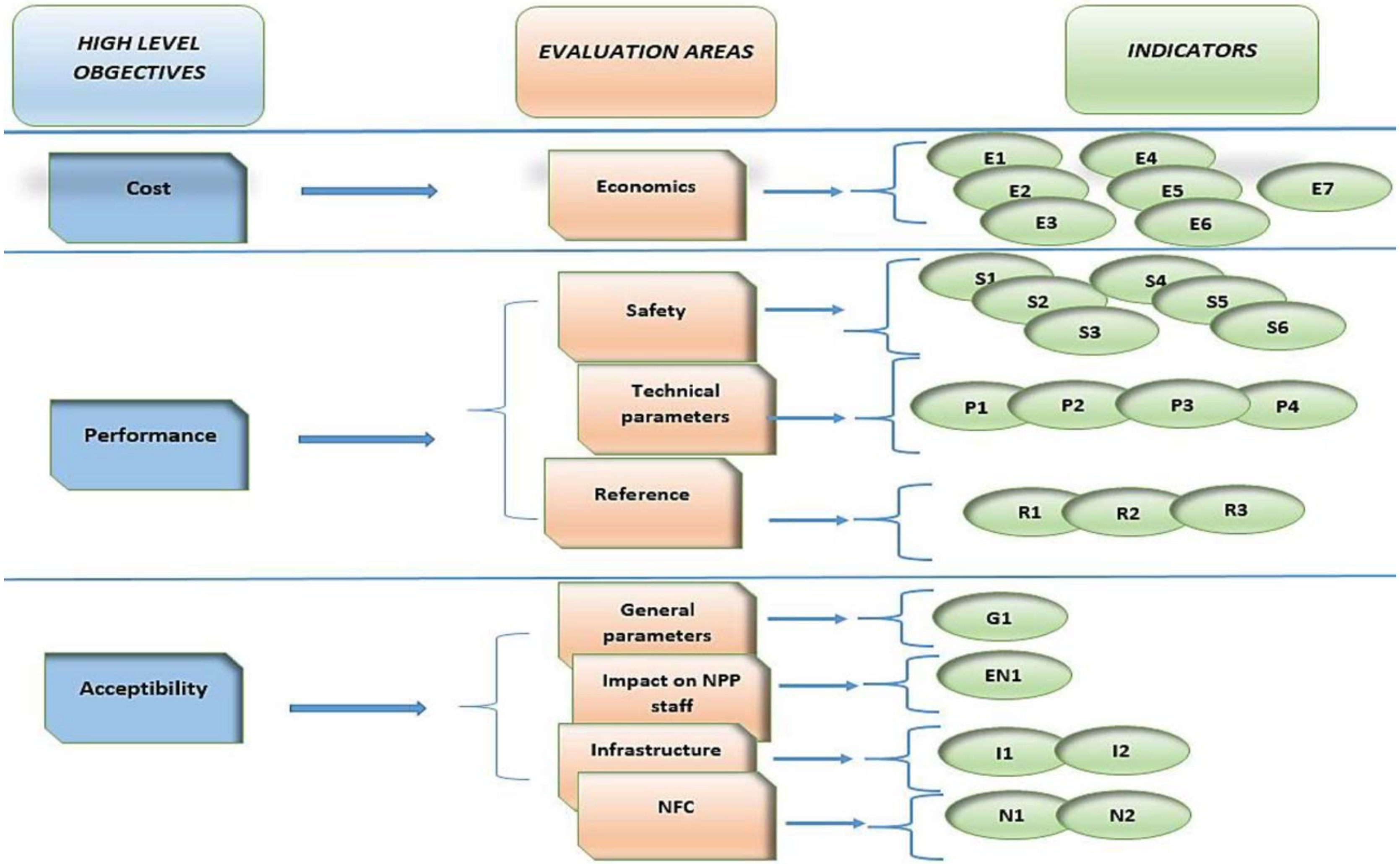

FIG. 3.183. The objective tree.

Criterion E1 - The cost of construction, including the main objects on the industrial site, USD/kW.

The main problem during the implementation of the NPP construction project is the amount of capital investment per kW of installed capacity. The best is the design of the power unit, which corresponds to the smallest amount of investment per 1 kW of installed electric power. The criterion is quantitative.

Criterion E2 - Possibility of placing replacement capacities on the sites of existing NPPs**.**

The availability of ready-made industrial infrastructure, which is present on the sites of existing NPPs, is critical for reducing the time and cost of construction. The criterion is qualitative. The assessment of compliance with the criterion was performed on the basis of expert judgment on a scale of 1–2, where a score of 2 means the presence of such an opportunity, while 1 means the absence of such an opportunity.

Criterion E3 - The duration of construction on the site, months/MW.

An important criterion for reducing the cost and risks of the NPP construction project is to reduce the duration and optimize the construction schedule, particularly due to improved methods of construction and installation. According to this criterion, a quantitative assessment was performed by comparing the duration of construction, related to the installed capacity of the power unit. The criterion is quantitative. The best option meets the smaller value of this criterion.

Criterion E4 - Using the principle of construction standardization.

The criterion affects the total capital costs for NPP construction. According to some estimates, the savings in capital costs from the application of the principle of standardization and serial construction, depending on the country and the number of similar units in the series, can reach 15–40%, while the savings from modular construction methods are estimated only at 1.4–4.0%. Obviously, savings are also achieved through the construction of several power units on the same site. Criterion E4 is qualitatively evaluated on a three-point scale 1–3, and the best of the options corresponds to a score of 3, the worst being 1. A similar approach is applied to criterion E5.

Criterion E 5 - Using the principle of construction by modules.

The impact of criterion E5 on comparative evaluation of reactors is similar to that of Criterion E4. Construction by modules results in a decrease of the general construction time. Modules are transported from the factory to the NPP site as ready reactor elements. Additionally, this criterion makes it possible to consider a large overall capacity NPP based on innovative small reactors.

Criterion E6 - The level of participation of national industry and national organizations, %.

This quantitative criterion significantly affects the final cost of the NPP construction. The level of participation of national organizations is estimated on the basis of expert judgments. The best option meets the larger value of the criterion.

Criterion E7 - Specific consumption of natural uranium, kg/kW·day.

The criterion characterizes the efficiency of natural uranium resources per kW·day of electricity produced. A smaller value of the criterion corresponds to a greater efficiency of reactor technology. The value of this quantitative criterion is determined on the basis of calculations using the initial data on the enrichment and the rate of fuel burnout, the installed capacity utilization factor (ICUF) and plant efficiency.

Criterion S1 - Core damage frequency (CDF), 1/reactor·year.

This is one of the main safety criteria. The value of the criterion was taken according to the data of reactor technology suppliers available for the public access. The best option meets the smaller value of the criterion.

Criterion S2 - Large release frequency (LRF), 1/ reactor·year.

A similar approach is applied to criterion S2.

Criterion S3 - Safety philosophy, including a combination of active and passive systems, with the priority of passive safety systems.

For a qualitative assessment of options, a scale of 1–3 was used, the highest score corresponding to the best option.

Criterion S4 - Availability of special measures to prevent severe accidents and limit their consequences.

For a qualitative assessment of options, a three-point scale of 1–3 was used, the highest score corresponding to the best option. This is a qualitative criterion based on expert judgments formed based on information from the reactor technology supplier.

Criterion S5 - Prohibition against operator involvement, hours.

Natural quantities of the duration of the prohibition (in hours) were used to quantify the options. The best option corresponds to a longer delay on the necessity of action of the power unit operator. This is a quantitative criterion and is based on information from the reactor technology supplier.

Criterion S6 - The value of the maximum acceleration on the soil surface, fraction of g.

To quantify the variants, the values of acceleration on the soil surface in fraction of g were used. The best option meets the larger value of the criterion. This is a quantitative criterion based on the calculated data of the reactor technology supplier.

Criterion P1 - Gross power unit efficiency, %.

The efficiency of the power unit is one of the main quantitative indicators of perfection and economic efficiency of the thermodynamic cycle of the power unit and directly affects the consumption of nuclear fuel. A higher value of efficiency corresponds to the best option. This is a quantitative criterion based on data from the reactor technology supplier.

Criterion P2 - Coefficient of readiness, %.

Is one of the main factors of readiness of the power unit to bear the load during its operation during the calendar year. The higher the factor is, the better the performance of the power unit is. This is a quantitative criterion based on the design data of the reactor technology supplier.

Criterion P3 - Manoeuvring characteristics (unloading depth), %.

Manoeuvring characteristics of a modern power unit operating in a branched power system consisting of different types of generation sources, including renewable energy sources (RES), are characterized by the depth and speed of unloading and loading.

The power unit, the technical characteristics of which allow unloading at the required speed during night power failures in the system, has advantages over power units that operate stably in the basic mode. The higher the percentage of unloading allowed by the unit, the better it meets this criterion. The power units of the SMR reactor technology are best suited for operation in manoeuvring mode. This is a quantitative criterion based on data from the reactor technology supplier.

Criterion P4 - Design life cycle of the power unit, years.

Power units that are designed for long term operation are more cost effective. Therefore, the longer the service life of the unit, the better it meets the requirements of this criterion. This is a quantitative criterion based on data from the reactor technology supplier.

Criterion R1 - Number of power units built and operated.

As part of the 'Reference' assessment, criterion R1 is an indicator of how well a power unit of this type was tested in terms of operational characteristics, reliability and maturity of the project. The more such power units are built in the world, the better it meets this criterion. This is a quantitative criterion based on statistics.

Criterion R2 - Number of power units under construction and those planned for construction.

Another criterion as a part of this direction in conjunction with R1, is the criterion R2, which reflects the opinion of users of reactor technology regarding the positive prospects for the use of the unit. The more users in the world associate the development of nuclear energy in their countries with power units of this type, namely they build or plan to build such power units, the greater their confidence in its reliability, high performance and less doubts about the likelihood of various problems. This is a quantitative criterion based on statistics.

Criterion R3 - Comparability of reactor technology with that currently used in Ukraine.

The ease of adoption of new reactor technology depends on the degree of its comparability with that for which positive experience has already been accumulated. As part of this study, alternative technologies were expertly evaluated for their comparability with VVER technology on a three-point scale 1–3. The highest score, 3, was received by the reactor technology VVER-1200, while the representatives of the PWR technology including SMR received a score of 2, and the reactors of the BWR technology and the CANDU-6 reactor received a score of 1.

Criterion G1 - Comparability with the requirements of the NRS of Ukraine.

The successful licensing of a new reactor technology in Ukraine, embodied by a specific model of a power unit belonging to this technology, depends on the degree of compatibility of its design with regulatory requirements. As part of this study, alternative technologies were expertly assessed for their compatibility with the requirements of the NRS of Ukraine on a three-point scale 1–3. The highest score was received by the VVER-1200 - 3 reactor technology, while the representatives of the PWR technology, including SMR, received 2 points, and the reactors of the BWR technology and the CANDU-6 reactor received 1 point.

Criterion EN1 - The level of the operating personnel exposure, person • Sv / reactor • year.

This is a quantitative criterion, the evaluation of which was performed on the basis of initial data provided by the reactor technology supplier. The better estimate corresponds to a lower value of this value, specifically a lower level of exposure of NPP personnel.

Criterion I1 - Logistics with regard to the transportation of heavy weights (possibility of delivery by different modes of transport).

This is a qualitative criterion, the assessment of which on a scale of 1–3 is based on expert judgment on the comparability of the transport dimensions of the main elements and parts of the reactor and turbine with the size of railway and automobile (flatbed) platforms.

Criterion I2 - The need to create a special infrastructure based on the requirements of the RT.

This is a qualitative criterion, which is expertly assessed on a three-point scale 1–3. The technology for which there is no need to create a special additional infrastructure has a higher rating, and it is possible to use the existing one with different degree of adaptability. Obviously, the highest score on this criterion was received by reactors technology VVER-1200 and SMR - 3 points. PWR technology reactors - 2 points, BWR and CANDU-6 reactors -1 point.

Criterion N1 - The possibility of using the existing infrastructure of the 'front end', considering the actions currently planned.

This is a qualitative criterion, which was expertly assessed on a three-point scale 1–3. The technology for which it is possible to use the existing infrastructure of the 'front end' considering the planned actions, including the construction of a plant for the production of nuclear fuel, has the highest rating. Obviously, the highest score on this criterion was received by reactors technology VVER-1200 and SMR - 3 points. PWR technology reactors - 2 points, BWR and CANDU-6 reactors -1 point.

Criterion N2 - Possibility to use the existing (created) infrastructure for SNF management.

This is a qualitative criterion, which was expertly assessed on a three-point scale 1–3. The technology that provides the opportunity to use the existing infrastructure of the 'front end', considering the construction of centralized spent nuclear fuel storage (CSNFS), etc. It is obvious that the highest score on this criterion was received by reactors technology VVER-1200 and SMR - 3 points. PWR technology reactors - 2 points, BWR and CANDU-6 reactors - 1 point.

Because the KIND objective tree has a multi-level structure, it is correct to use a hierarchical procedure to estimate weights. The main advantage of this approach is that experts in specific fields judge the relative benefits of indicators within a specific area of their evaluation. At the same time, the weighting factors related to the top-level objectives and the areas / directions of evaluation are established on the basis of the preferences of those responsible for decision making.

To perform a multi-criteria comparison using the MAVT method, the experts need to:

- Select a set of operating parameters;
- Prepare a table of operating characteristics;
- Determine the weighting factors;
- Perform sensitivity analysis;
- Interpret the ranking results and formulate recommendations.

3.15.5. Input operating parameters

The information on the operating parameters of the reactors (Table 3.96), on the basis of which a comparative evaluation of reactor technologies using KIND-ET will be performed, was taken using the following open sources of information: IAEA ARIS[39], NRC[40] and General Nuclear Systems[41]. Table 3.97 presents the performance data used in this analysis.

For qualitative parameters, the determination of numerical values was performed according to the following algorithm:

- For each type of reactor, all qualitative parameters are determined by applying expert judgment on the degree of compliance with national regulatory requirements, WENRA and EUR recommendations and IAEA safety standards;
- A higher score determines a higher degree of compliance if a higher compliance is the best result;
- A lower score determines a greater degree of compliance if the better scores correspond to lower values.

[39] https://www.iaea.org/resources/databases/advanced-reactors-information-system-aris
[40] https://www.nrc.gov/reactors/operating/ops-experience/tritium/safety-requirements.html#require
[41] http://news.onr.org.uk/category/nuclear-new-build/general-nuclear-systems-gns/

TABLE 3.96. INPUT OPERATING PARAMETERS

Abbr.	AP-1000	APR-1400	HUALONG-1 (HPR-1000)	EPR-1650	ATMEA-1™	ABWR	ESBWR	EC-6	SMR-160	NuScale	WWER-1200
General Criteria											
G1	2	2	2	2	2	1	1	1	2	2	3
Economics											
E1	6475	4370	3500	5800	8760	4500	8200	4500	4538	4385	4700
E2	2	2	2	1	2	2	2	2	2	2	2
E3	0.031	0.051	0.041	0.065	0.044	0.035	0.031	0.162	0.100	0.075	0.046
E4	3	2	3	2	3	1	3	2	3	3	3
E5	3	2	2	2	2	2	3	1	3	3	2
E6	50	50	50	40	40	40	40	40	70	60	60
E7	0.168	0.189	0.228	0.169	0.181	0.134	0.149	0.120	0.241	0.210	0.173
Reference											
R1	4	7	0	2	0	4	0	11	0	0	2
R2	8	9	8	2	2	11	1	2	0	1	3
R3	2	2	2	2	2	1	1	1	2	2	3
Impact on staff											
EN1	0.7	1.0	1.0	0.5	0.5	1.0	1.0	0.05	0.5	0.33	0.39
Safety											
S1	5.09E-7	1.0E-6	1.0E-6	1.0E-7	1.0E-6	1.0E-6	1.65E-8	1.0E-06	1.0E-7	4.1E-11	1.0E-06
S2	5.94E-8	1.0E-7	1.E-7	5.9E-8	1.0E-7	1.0E-7	1.4E-9	1.0E-07	1.0E-8	1.7E-13	1.0E-7
S3	3	3	3	3	3	1	3	2	3	3	3
S4	3	3	3	3	3	2	3	2	3	3	3
S5	0.5	0.5	0.5	0.7	0.5	0.5	0.25	0.25	0.7	0.7	0.5
S6	0.3	0.3	0.3	0.25	0.3	0.3	0.3	0.3	0.3	0.5	0.2
Infrastructure											
I1	1	1	1	1	1	2	1	3	3	3	3
I2	2	2	2	2	2	1	1	1	3	3	3
Technical parameters											
P1	35.29	36.53	35.73	35.95	34.92	36.17	35.56	35.51	30.48	31.25	36.56
P2	93	90	90	92	92	87	90	90	90	90	90
P3	70	65	60	60	60	65	65	40	90	95	50
P4	60	60	60	60	60	60	60	60	80	60	60
NFC											
N1	2	2	2	2	2	1	1	1	3	3	3
N2	2	2	2	2	2	1	1	1	3	3	3

TABLE 3.97. PERFORMANCE TABLE

Title of assessment area	Title of indicators	Abbr. of indic.	MIN assessment	MAX assessment	AP-1000	APR-1400	Hualong-1	EPR-1650	ATMEA-1	ABWR	ESBWR	CANDU-6	SMR-160	NuScale	WWER-1200
Economics	The cost of construction, including the main objects on the industrial site, USD/kW	E1	3500	8760	6475	4370	3500	5800	8760	4500	8200	4500	4000	4385	4700
	Possibility of placing replacement capacities on the sites of existing NPPs	E2	1	2	2	2	2	1	2	2	2	2	2	2	2
	The duration of construction on the site, months/MW	E3	0.031	0.077	0.060	0.051	0.041	0.065	0.044	0.035	0.031	0.077	0.108	0.067	0.046
	Using the principle of standardization of construction	E4	1	3	3	2	3	1	1	1	1	1	3	3	3
	Using the principle of modular construction	E5	1	3	3	2	2	2	2	2	3	1	3	3	2
	The level of participation of national industry and national organizations, %	E6	20	70	50	50	50	40	40	40	40	40	70	60	60
	Specific consumption of natural uranium, kg/kW·day	E7	0.120	0.241	0.168	0.189	0.228	0.169	0.181	0.134	0.149	0.120	0.241	0.219	0.173
Safety	Core damage frequency (CDF), 1/reactor·year	S1	3E-10	1E-6	5.09E-7	1E-6	1E-6	1E-6	1E-6	1E-6	1.7E-8	1E-6	1E-7	3E-10	1E-6
	Large release frequency (LRF), 1/ reactor·year	S2	2.3E-11	1E-7	5.94E-8	1E-7	1E-7	5.94E-8	1E-7	1E-7	1.4E-9	1E-7	1E-8	2.3E-11	1E-7
	Safety philosophy, including a combination of active and passive systems, with the priority of passive safety systems	S3	1	3	3	3	3	3	3	1	3	2	3	3	3

TABLE 3.97. PERFORMANCE TABLE (cont.)

Title of assessment area	Title of indicators	Abbr. of indic.	MIN assessment	MAX assessment	AP-1000	APR-1400	Hualong-1	EPR-1650	ATMEA-1	ABWR	ESBWR	CANDU-6	SMR-160	NuScale	WWER-1200
	Availability of special measures to prevent severe accidents and limit their consequences	S4	1	3	3	3	3	3	3	1	3	1	3	3	3
	The period of time before the required response of the operator, hour	S5	0.25	0.7	0.5	0.5	0.5	0.7	0.5	0.5	0.25	0.25	0.7	0.7	0.5
	The value of the maximum acceleration on the soil surface, fraction of g	S6	0.2	0.5	0.3	0.3	0.3	0.25	0.3	0.3	0.3	0.3	0.3	0.5	0.2
Technical indicators	Gross power unit efficiency, %	P1	30.48	36.56	35.29	36.53	35.74	35.95	34.92	36.17	35.56	35.51	30.48	30.00	36.56
	Coefficient of readiness, %	P2	87	93	93	90	90	92	92	87	90	90	95	95	90
	Manoeuvring characteristics (unloading depth), %	P3	40	95	70	65	60	60	60	65	65	40	90	95	50
	Design life cycle of the power unit, years	P4	60	80	60	60	60	60	60	60	60	60	80	60	60
Reference	Number of power units built and operated	R1	0	11	4	7	0	2	0	4	0	11	0	0	2
	Number of power units under construction and those planned for construction	R2	0	11	8	9	8	2	2	11	1	2	0	1	3
	Comparability of reactor technology with that currently used in Ukraine in terms of the NPP	R3	1	3	3	3	3	3	3	1	1	1	2	2	3
General criteria	Comparability with the requirements of the NRS of Ukraine	G1	1	3	2	2	2	2	2	1	1	1	2	2	3
Impact on staff	The level of the operating personnel exposure, person • Sv / reactor • year	EN1	0.05	1	0.7	1	1	0.5	0.5	1	1	0.05	0.5	0.33	0.39
Infrastructure	Logistics with regard to the transportation of heavy weights (possibility of delivery by different modes of transport)	I1	1	3	1	1	1	1	1	2	1	3	3	3	3

TABLE 3.97. PERFORMANCE TABLE (cont.)

Title of assessment area	Title of indicators	Abbr. of indic.	MIN assessment	MAX assessment	AP-1000	APR-1400	Hualong-1	EPR-1650	ATMEA-1	ABWR	ESBWR	CANDU-6	SMR-160	NuScale	WWER-1200
	The need to create a special infrastructure based on the requirements of the RT	I2	1	3	3	3	3	3	3	3	3	1	3	3	3
Link with NFC	The possibility of using the existing infrastructure of the "front end", considering the actions currently planned	N1	1	3	2	2	2	2	2	1	1	1	3	3	3
	Possibility to use the existing (created) infrastructure for SNF management	N2	1	3	2	2	2	2	2	1	1	1	3	3	3

Based on Ukraine's national priorities for nuclear energy development, considering the need for unconditional safe operation of NPP units, and minimizing the impact on the environment and humans, the values of weighting factors for HLOs, Areas of evaluation and Key Indicators are established, and are shown in Table 3.98.

TABLE 3.98. WEIGHTING FACTORS

High-level objective	Weighting factors of high-level objectives	Title of areas/directions of assessment	Weighting factors of assessment areas	Abbr. indicator	Weight coefficients of indicators	Final weighting factors
Cost	0.3	Economics	1	E1	0.2	0.060
				E2	0.2	0.060
				E3	0.2	0.060
				E4	0.1	0.030
				E5	0.1	0.030
				E6	0.1	0.030
				E7	0.1	0.030
Performance	0.5	Safety	0.5	S1	0.2	0.050
				S2	0.2	0.050
				S3	0.1	0.025
				S4	0.2	0.050
				S5	0.2	0.050
				S6	0.1	0.025
		Technical indicators	0.3	P1	0.3	0.045
				P2	0.2	0.030
				P3	0.3	0.045
				P4	0.2	0.030
		Reference	0.2	R1	0.2	0.020
				R2	0.3	0.030
				R3	0.5	0.050
Acceptability	0.2	General criteria	0.35	G1	1	0.070
		Impact on staff	0.15	EN1	1	0.030
		Infrastructure	0.3	I1	0.3	0.018
				I2	0.7	0.042
		Link with NFC	0.2	N1	0.5	0.020
				N2	0.5	0.020

Results of single attribute value functions calculations by KIND-ET are presented in Table 3.99.

TABLE 3.99. SINGLE ATTRIBUTE VALUE FUNCTIONS

Evaluation area	Abbr. of indicators	Goal	Form	Exponent	VF domain	MIN VF domain	MAX VF domain	AP-1000	APR-1400	Hualong-1	EPR-1650	ATMEA-1	ABWR	ESBWR	CANDU-6	SMR-160	NuScale	WWER-1200
Economics	E1	Min	lin.	1	Local	3500	8760	0.434	0.835	1.000	0.563	0.000	0.810	0.106	0.810	0.905	0.832	0.772
	E2	Max	lin.	1	Local	1	2	1.000	1.000	1.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	E3	Min	lin.	1	Local	0.031	0.108	0.623	0.734	0.872	0.553	0.834	0.945	1.000	0.404	0.000	0.537	0.802
	E4	Max	lin.	1	Local	1	3	1.000	0.500	1.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	1.000
	E5	Max	lin.	1	Local	1	3	1.000	0.500	0.500	0.500	0.500	0.500	1.000	0.000	1.000	1.000	0.500
	E6	Max	lin.	1	Local	40	70	0.333	0.333	0.333	0.000	0.000	0.000	0.000	0.000	1.000	0.667	0.667
	E7	Min	lin.	1	Local	0.12	0.241	0.603	0.430	0.107	0.595	0.496	0.884	0.760	1.000	0.000	0.182	0.562
Safety	S1	Min	lin.	1	Local	3E-10	1E-06	0.491	0.000	0.000	0.900	0.000	0.000	0.984	0.000	0.900	1.000	0.000
	S2	Min	lin.	1	Local	2.3E-11	1E-07	0.406	0.000	0.000	0.406	0.000	0.000	0.986	0.000	0.900	1.000	0.000
	S3	Max	lin.	1	Local	1	3	1.000	1.000	1.000	1.000	1.000	0.000	1.000	0.500	1.000	1.000	1.000
	S4	Max	lin.	1	Local	1	3	1.000	1.000	1.000	1.000	1.000	0.000	1.000	0.000	1.000	1.000	1.000
	S5	Max	lin.	1	Local	0.25	0.7	0.556	0.556	0.556	1.000	0.556	0.556	0.000	0.000	1.000	1.000	0.556
	S6	Max	lin.	1	Local	0.2	0.5	0.333	0.333	0.167	0.333	0.333	0.333	0.333	0.333	0.333	1.000	0.000
Technical indicators	P1	Max	lin.	1	Local	30.00	56.56	0.807	0.995	0.874	0.906	0.750	0.940	0.847	0.839	0.073	0.000	1.000
	P2	Max	lin.	1	Local	87	95	0.750	0.375	0.375	0.625	0.525	0.000	0.375	0.375	1.000	1.000	0.375
	P3	Max	lin.	1	Local	40	95	0.455	0.364	0.364	0.364	0.364	0.455	0.455	0.000	0.909	1.000	0.182
	P4	Max	lin.	1	Local	60	80	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000

TABLE 3.99. SINGLE ATTRIBUTE VALUE FUNCTIONS (cont.)

Evaluation area	Abbr. of indicators	Goal	Form	Exponent	VF domain	MIN VF domain	MAX VF domain	AP-1000	APR-1400	Hualong-1	EPR-1650	ATMEA-1	ABWR	ESBWR	CANDU-6	SMR-160	NuScale	WWER-1200
Reference	R1	Max	lin.	1	Local	0	11	0.364	0.636	0.000	0.182	0.000	0.364	0.000	1.000	0.000	0.000	0.182
	R2	Max	lin.	1	Local	0	11	0.727	0.818	0.727	0.182	0.182	1.000	0.091	0.182	0.000	0.091	0.273
	R3	Max	lin.	1	Local	1	3	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.500	0.500	1.000
General criteria	G1	Max	lin.	1	Local	1	3	0.500	0.500	0.500	0.500	0.500	0.000	0.000	0.000	0.500	0.500	1.000
Impact on staff	EN1	Min	lin.	1	Local	0.05	1	0.316	0.000	0.000	0.526	0.526	0.000	0000	1.000	0.526	0.705	0.642
Infrastructure	I1	Max	lin.	1	Local	1	3	0.000	0.000	0.000	0.000	0.000	0.500	0.000	1.000	1.000	1.000	1.000
	I2	Max	lin.	1	Local	1	3	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	1.000	1.000	1.000
Correlation with NFC	N1	Max	lin.	1	Local	1	3	0.500	0.500	0.500	0.500	0.500	0.000	0.000	0.000	1.000	1.000	1.000
	N2	Max	lin.	1	Local	1	3	0.500	0.500	0.500	0.500	0.500	0.000	0.000	0.000	1.000	1.000	1.000

The results of KIND-ET application for reactor technologies ranking based on weighting factors given in Table 3.98 are presented in Table 3.100 and Fig. 3.184.

TABLE 3.100. RANKING RESULTS

Evaluation area	AP-1000	APR-1400	Hualong-1	EPR-1650	ATMEA-1	ABWR	ESBWR	CANDU-6	SMR-160	NuScale	WWER-1200
Multi-criteria assessment function for high-level objective	0.624	0.558	0.562	0.525	0.478	0.388	0.461	0.305	0.728	0.760	0.633
Cost	0.212	0.207	0.231	0.100	0.140	0.207	0.179	0.163	0.204	0.228	0.236
Performance	0.306	0.262	0.237	0.317	0.223	0.136	0.242	0.095	0.340	0.340	0.217
Acceptability	0.106	0.097	0.097	0.113	0.113	0.051	0.042	0.048	0.151	0.156	0.189
Assessments by direction of evaluation	—	—	—	—	—	—	—	—	—	—	—
Economics	0.212	0.207	0.231	0.100	0.140	0.207	0.179	0.163	0.204	0.228	0.236
Safety	0.143	0.099	0.099	0.182	0.099	0.036	0.169	0.021	0.211	0.238	0.090
Technical indicators	0.083	0.076	0.067	0.076	0.069	0.063	0.070	0.049	0.104	0.075	0.064
Reference	0.079	0.087	0.072	0.059	0.055	0.037	0.003	0.025	0.025	0.028	0.062
General criteria	0.035	0.035	0.035	0.035	0.035	0.000	0.000	0.000	0.035	0.035	0.070
Impact on staff	0.009	0.000	0.000	0.016	0.016	0.000	0.000	0.030	0.016	0.021	0.019
Infrastructure	0.042	0.042	0.042	0.042	0.042	0.051	0.042	0.018	0.060	0.060	0.060
Correlation with NFC	0.02	0.02	0.02	0.02	0.02	0	0	0	0.04	0.04	0.04

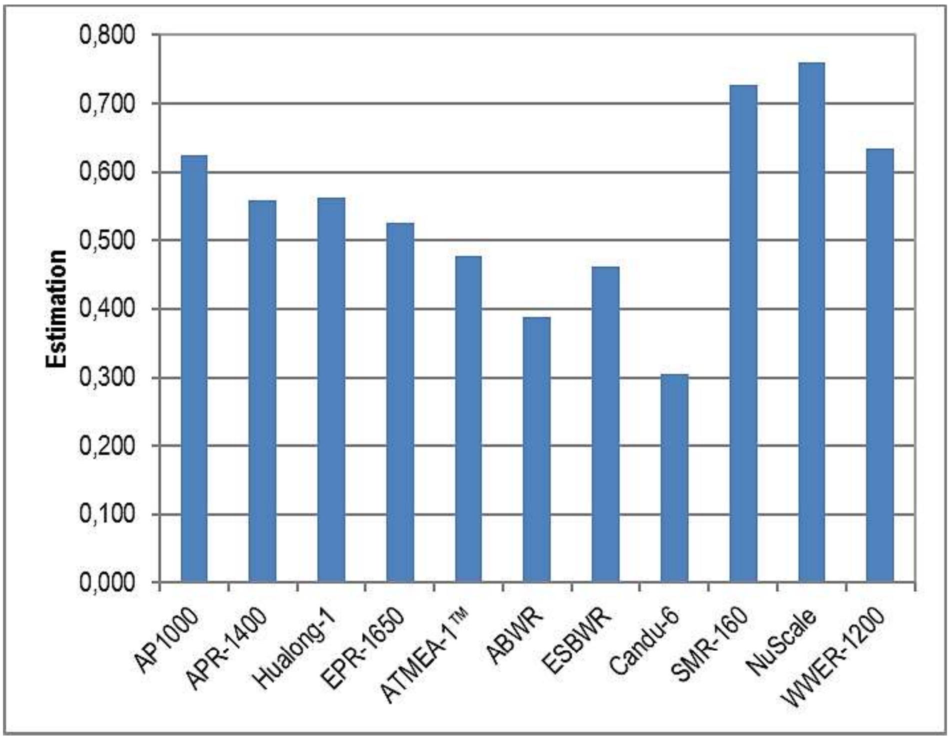

FIG. 3.184. Ranking of reactors.

The scores obtained for considered nuclear technologies comparative evaluation were decomposed at the level of HLOs (see Fig. 3.185) and of Evaluation Areas (see Fig. 3.186).

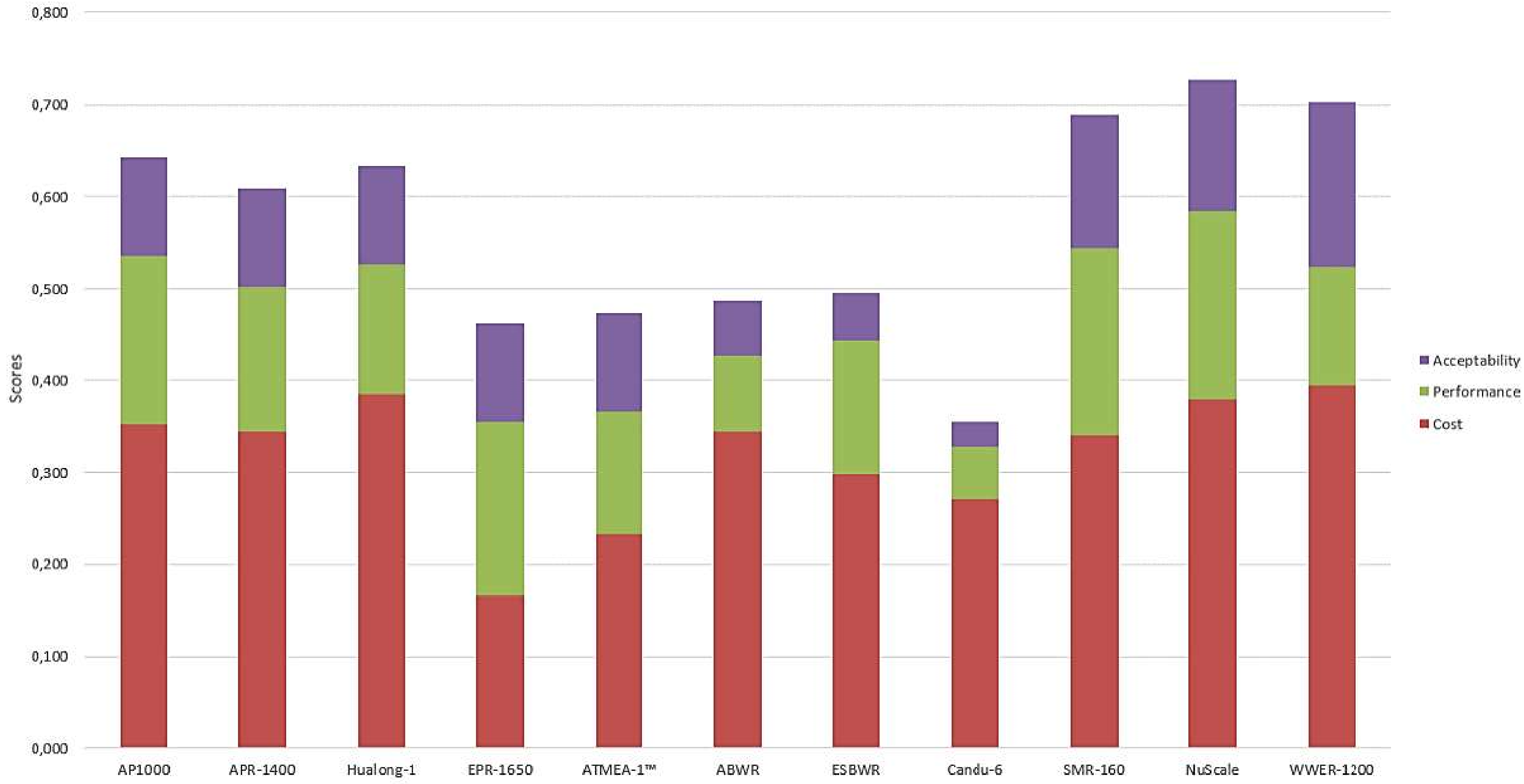

FIG. 3.185. Ranking results of reactors by HLOs.

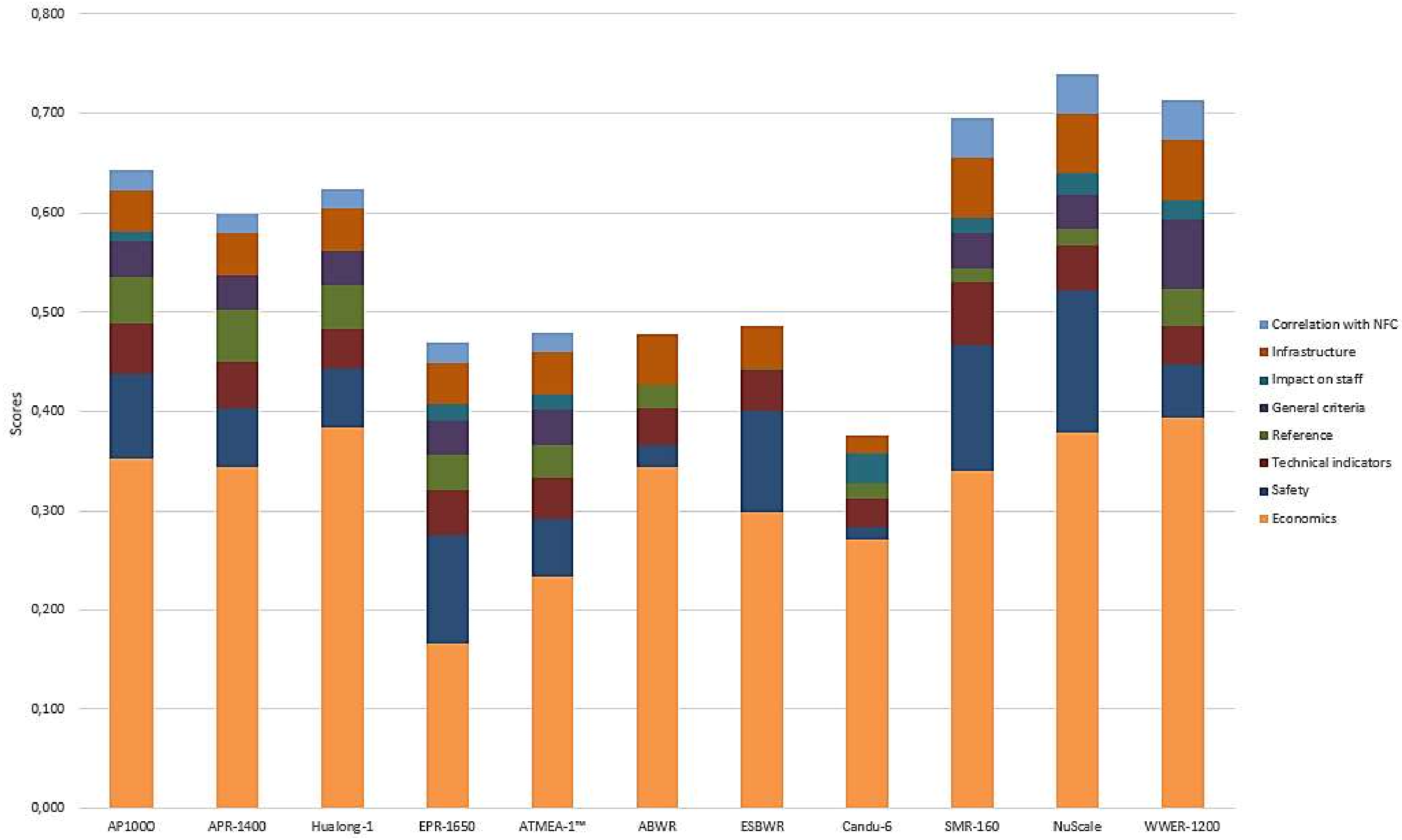

FIG. 3.186. Ranking results of reactors by Evaluation Areas.

It could be noted that the reactors of the SMR technology demonstrated such high integrated scores, primarily due to their high scores for the top-level goals ‘Performance’ and ‘Acceptability’. In terms of ‘Cost’ (‘Economics’), they are very close to the best representative of this parameter of PWR technology - Hualong-1 (0.234) with estimates of 0.228 (NuScale) and 0.204 (SMR-160), while in the areas of ‘Safety’, the ‘Technical Indicators’ included in the ‘Performance’ goal are significantly ahead of most RTs with the same score of 0.340. The best representatives of PWR technology (EPR-1650 and AP1000) for this goal got, respectively, 0.317 and 0.306. According to the ‘Acceptability’ goal, the VVER-1200 reactor has the best score - 0.189, followed by the AP1000 - 0.106. SMR technology reactors with estimates of 0.151 (SMR-160) and 0.156 (NuScale) are ahead of the rest of the RT, with the exception of VVER-1200.

The range of rating integrated assessments variation of the BWR technology reactors is from 0.388 (ABWR) to 0.461 (ESBWR).

It could be noted that the BWR reactors ‘lost’ to the PWR reactors mainly due to the lower estimates obtained under the high-level objective ‘Acceptability’ (well below the rest of the RT), ‘Performance’ (below most RT) and ‘Cost’ (also below most RT).

In turn, the low scores of the BWR technology for the ‘Acceptability and ‘Performance’ objectives are caused by the impact of low scores in the areas of ‘Correlation with the NFC’ and ‘General Criteria’, which are included in the high-level objective ‘Acceptability’ and direction ‘Reference’ (included in the high-level objective ’Performance’).

The CANDU-EC6 reactor, according to a set of criteria established considering the conditions of Ukraine, obtained the lowest integrated score - 0.305 (Fig. 3.185). At the same time, it turned out to be worse in terms of the high-level objective ‘Acceptability’ - 0.048 and ’Performance’ - 0.095 (Fig. 3.185), due to critically low estimates obtained by the reactor in the areas of ‘Corelation with the NFC ‘ (0), ‘Safety’ (0.021), and ‘Infrastructure’ (0.018) (see ranking in Fig. 3.168).

The order of placing of reactor technologies according to the results of integrated assessment (from higher to lower) within the Base mode is as follows: SMR → PWR → BWR → CANDU-EC6.

3.15.6. Sensitivity analysis

Sensitivity analysis was realized in two directions:

— Sensitivity analysis 1 – the impact of two criteria, E1 – ‘Construction Cost’ (USD/kW) and E3 – ‘Construction Duration’ (months /MW), on the evaluation and ranking of alternatives was examined. According to world practice, these criteria in their totality and interrelation have the greatest impact on the viability and success of the NPP construction project. In this case, the impact on the results of the assessment of the simultaneous reduction in Construction Cost and Construction Duration was investigated. It is reasonable to assume that the cost of construction of power units in Ukraine will be lower than abroad. This depends on the amount of national participation/localization that is to be determined separately for each of the power units, which is beyond the scope of this study. The corresponding figures are shown in Table 3.100 for a clear comparison of the basic and modified values E1 and E3. The change of criteria E1 and E2 for the Base Case and the Modified Case is shown in Table 3.101.

- Sensitivity analysis 2 – a change in the values of weighting factors for HLO was performed in accordance with Table 3.102.

TABLE 3.101. PARAMETERS OF MODIFIED CASE 1 FOR SENSITIVITY ANALYSIS 1

Indicators	Abbr. of indicator	MIN	MAX	AP-1000	APR-1400	ABWR	Candu-6	SMR-160	NuScale	Hualong-1	EPR-1650	ESBWR	ATMEA-1	WWER-1200
Overnight capital cost, including the main facilities at the NPP industrial site, USD / kW (for base scenario)	E1	3500	8760	6475	4370	4500	4500	4000	4385	3500	5800	8200	8760	4700
Modified scenario		3000	7800	3500	3800	4100	3900	3700	3800	3000	5000	7800	6800	4600
Duration (Reduced duration) of construction on site, months (months / MW) (for base scenario)	E3	48 (0.031)	36 (0.225)	72 (0.060)	72 (0.051)	48 (0.035)	57 (0.077)	17.33 (0.108)	48 (0.067)	48 (0.041)	108 (0.065)	48 (0.031)	48 (0.044)	54 (0.046)
Modified scenario		42 (0.031)	32 (0.100)	66 (0.055)	66 (0.047)	42 (0.031)	52 (0.070)	16 (0.100)	32 (0.044)	42 (0.036)	72 (0.044)	42 (0.027)	42 (0.038)	48 (0.041)

TABLE 3.102. VALUES OF WEIGHTS FOR SENSITIVITY ANALYSIS 2

Weighting factors for high level objectives	Cost, %	Performance, %	Acceptability, %
Base scenario	30	50	20
Modified scenario	50	30	20

The results of sensitivity analysis 1 for the difference between the Base scenario and the Modified scenario are shown in Fig. 3.187.

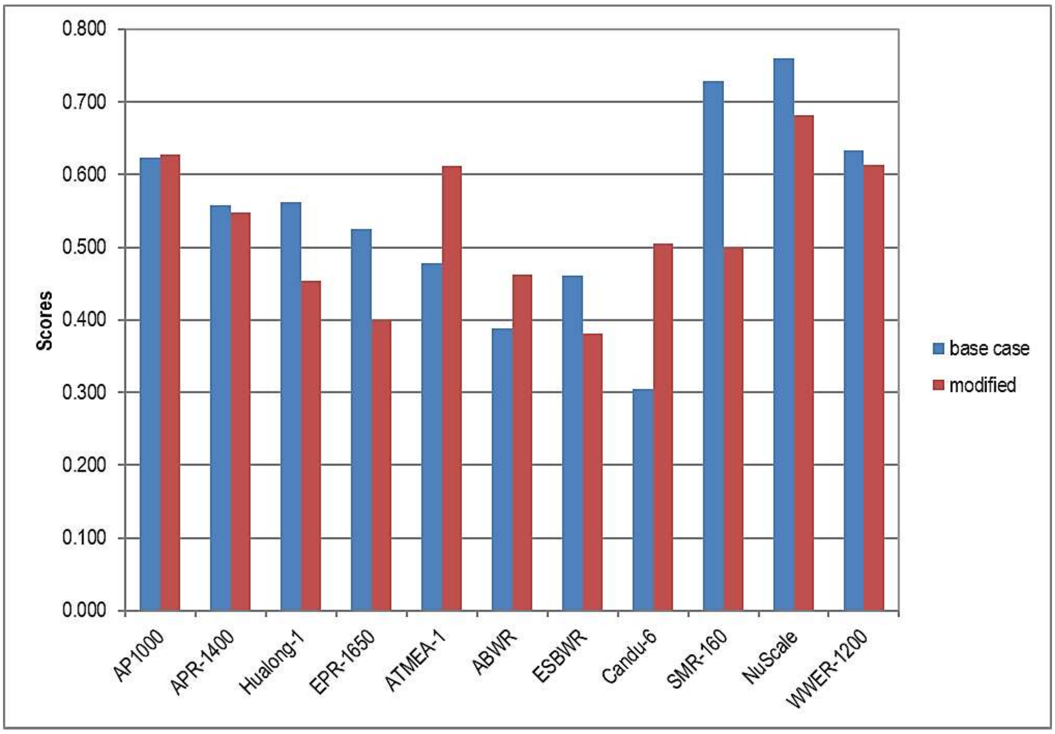

FIG. 3.187. Sensitivity analysis (Base scenario vs Modified scenario).

The results of sensitivity analysis 2 are shown in Fig. 3.188.

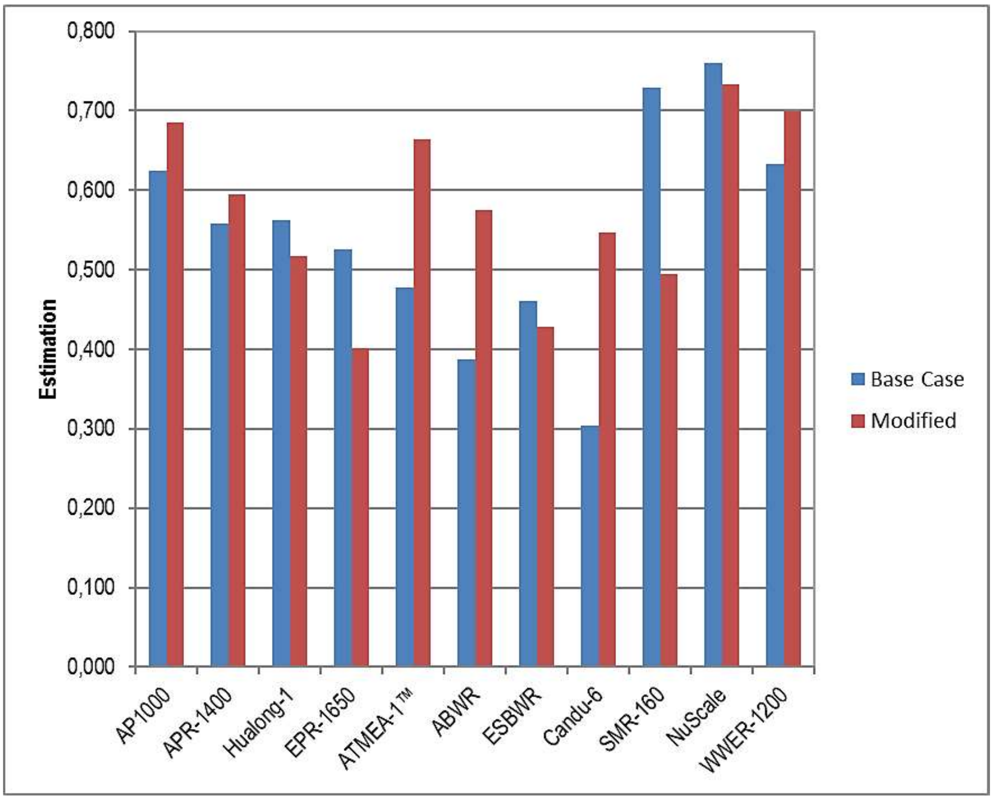

FIG. 3.188. Sensitivity analysis 2 with changing of weighting factors for HLOs.

As part of the **sensitivity analysis**, among power units belonging to the PWR technology the reactor AP1000 - 0.628 has the highest rating, followed by VVER-1200 with a score of 0.614, followed by ATMEA-1™ - 0.611. The total range of scores for the PWR reactors is from 0.400 (EPR-1650) to 0.628 (AP1000), see Table 3.101 and Figure 3.187. Reactor APR-1400 received a score of 0.547, and Hualong-1received a score of 0.454. The CANDU-EC6 reactor has a score of 0.505 (Fig. 3.187). The BWR technology reactors are scored as follows: ABWR - 0.462, and ESBWR - 0.382.

The range of scores of the two reactors of SMR technology were from 0.499 for SMR-160 (better than Hualong-1 and EPR-1650) to 0.682 for NuScale, which is even higher than the best of the reactors of the PWR technology (AP1000 - 0.628). Thus, the reduction in the values of capital costs and reduced construction times (criteria E1 and E3) under the Modified Scenario did not lead to significant changes in the previously defined Base Scenario order of reactor technologies (from best to worst): SMR → PWR → BWR → CANDU-EC6, which demonstrated that SMRs have a sufficient advantage, allowing one of them (NuScale) to maintain the lead over the PWR reactors.

As part of the sensitivity analysis 2, Table 3.102, NuScale - 0.731 received the highest score among all reactors, followed by SMR-160 - 0.695. VVER-1200 got the highest rating position among PWR reactors - 0.685 due to much better initial cost indicators, which increased even more after giving them a higher priority (0.5> 0.3). The range of estimates fluctuation was from 0.440 (EPR-1650) to 0.685 (VVER-1200). Hualong-1 has a rating of 0.618, AP1000 - 0.612, and APR-1400 - 0.578, and the CANDU-E6 reactor - 0.327, see Fig. 3.188.

The highest score among the two representatives of the BWR technology was attained by the reactor ESBWR - 0.448, while ABWR score 0.433.

Thus, the ‘castling in the values of the weighting factors for the two top level goals (‘Cost’ ↔ ‘Performance’) did not lead to changes in the previously defined arrangement of reactor technologies (from best to worst): SMR → PWR → BWR → CANDU -EC6.

3.15.7. Conclusions

In the framework of this case-study, the KIND-ET toolkit was applied to the comparative evaluation of reactor technologies on the example of the analysis of representatives of each of the reactor technologies.

The approach to the choice of reactor technologies for construction in Ukraine is presented.

An algorithm for the assessment of NPP power units (generation III +) available in commercial operation, or soon to be available, has been developed using the KIND-ET and related tools.

The list of input technical and economic data of perspective reactor technologies PWR, BWR, CANDU, that are the most widespread technologies in the world, for application for a comparative evaluation of reactor technologies is formed.

Based on the performed analysis, suggestions are formulated on the priority reactor technology for construction in Ukraine for the long term until 2050 to ensure the sustainable development of nuclear energy. It is considered expedient for the conditions of Ukraine to consider the water cooled reactors, specifically PWRs and SMRs.

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4. COUNTRY-NEUTRAL CASE STUDIES ON THE COMPARATIVE EVALUATION, RANKING AND SCREENING OF NUCLEAR ENERGY DEPLOYMENT SCENARIOS AND FUEL CYCLE OPTIONS

This chapter presents the reports of country-neutral case studies done by international experts and the IAEA secretariat.

4.1. INTEGRATING OF THE GAINS FRAMEWORK AND COMPARATIVE EVALUATION APPROACH FOR RANKING OF GLOBAL AND REGIONAL NUCLEAR ENERGY DEPLOYMENT SCENARIOS

This chapter presents studies on application of the comparative evaluation approach to nuclear energy evolutions scenarios.

4.1.1. Collaborative project GAINS: the framework for scenario analysis and main findings

Within the INPRO collaborative project "Key indicators for innovative nuclear energy systems" (KIND), a case study was carried out on applying several multi-criteria decision analysis (MCDA) methods to comparative evaluations of the nuclear energy system (NES) deployment scenarios investigated in the INPRO collaborative project "Global architecture of innovative nuclear energy systems based on thermal and fast reactors including a closed fuel cycle (GAINS)" which demonstrated the applicability of the KIND approach to comparisons of NES deployment scenarios [4.1, 4.2].

This case study provided a comparative evaluation of eleven global GAINS NES deployment scenarios (within the so-called homogeneous world model) based on nine key indicators arranged in a single level objective tree which were assessed to 2100 and then were aggregated using four possible weighting options. Considering the results of the sensitivity analysis, the additional analysis of alternatives by the supplementary decision support methods and the entire set of graphical and attribute information, the preferable NES options were identified for different experts' preferences regarding NES objectives. Based on this analysis, it was also possible to identify potential merits and demerits concerning relevant nuclear technologies from the viewpoint of the complete NES so as to provide recommendations for improvements of technology performance.

This case study is to be considered as a methodological and preliminary one, because it was focused on an examination of the applicability of different multi-criteria decision support methods to support judgment aggregation within comparative evaluations of NES deployment scenarios and it outlined a possible approach to perform evaluations of this kind. Nevertheless, some conceptual and substantive issues related to performing comparative evaluations of NES deployment scenarios have not yet been covered.

Among the main topics, one could mention the following: consideration and evaluation of the time factor impact within comparative evaluations of NES deployment scenarios, which requires the application of dynamic multi attribute analysis frameworks and identification of the most promising trade-off NES options from the multi-agent viewpoints (positions of the different individual country groups) requiring group decision support methods.

The given case study provides such an in-depth comparative analysis and may be considered as an extension of the previously performed case study on comparative evaluations of the GAINS

NES deployment scenarios and assumes an extensive utilization of advanced uncertainty treatment and group decision making support methods.

4.1.1.1. Collaborative project GAINS

This section provides a short description of the outcomes of the INPRO collaborative project GAINS [4.1, 4.2] and the follow-up endeavours assuming utilization of the project's results for detailed comparative evaluations of the relevant NES options [4.3, 4.4].

Within the GAINS project an analytical framework was proposed, which represents a tool for evaluating and representing the dynamics of key performance indicators associated with NES deployment scenarios for the entire system at the global, regional and national levels that allows it to be considered as a common methodological approach to unifying and specifying material flow representations and related performance indicators [4.2]. The most significant elements of the GAINS analytical framework and outcomes of the project are:

- Metrics and tools for assessing NES deployment scenarios regarding sustainability;
- An internationally verified database with characteristics of existing and advanced nuclear reactors and associated nuclear fuel cycle needed for a material flow analysis, extending the databases previously developed by the IAEA and considering preferences of different countries;
- Homogeneous and heterogeneous (both separate and synergistic) world models comprising groups of non-geographical non-personified countries pursuing different policies with respect to back end of the nuclear fuel cycle [4.1, 4.2];
- Possible global and regional NES architectures involving advanced technological solutions;
- Trial results of analysis of NES deployment scenarios involving a transition from the present fleets of nuclear reactors and nuclear fuel cycle to future sustainable NES architectures involving advanced technological solutions.

The GAINS analytical framework provides a sound basis for structuring relevant data characterizing NES deployment scenarios performance both at the global and regional levels. At the same time, it does not provide practical advice on the utilization of relevant data to formulate integrated expert judgments regarding preferable NES deployment scenarios and relevant technological options in view of their sustainability potential. An associated complementation of the GAINS analytical framework that allows performing comparative evaluations has been provided within the INPRO collaborative project KIND, which has been systematically applied for comparisons of eleven global GAINS NES deployment scenarios based on the elaborated approach to comparative evaluations.

4.1.1.2. Comparison of eleven global GAINS NES deployment scenarios based on the KIND approach

To cover the aforementioned gap within the KIND INPRO/IAEA collaborative project, it was proposed to involve MCDA methods, which represent effective tools for sorting, ranking, selecting the considered NES deployment scenarios in view of their performance, thereby providing an opportunity to make definitive judgments about the more and less preferred NESs (see Table 4.1.). Within this case study, eleven global GAINS NES deployment scenarios were examined which were evaluated by nine key indicators (to 2100 for the so-called homogeneous world model) arranged in a single level objective tree (see Table 4.2.). Four weighting options were considered reflecting possible experts' preferences regarding objectives that NES needs to achieve: equal significance of all indicators (#1); expert preferences based on the questionnaires of the INPRO/IAEA meetings (#2a, #2b); preference to investments minimization (#3); preference to wastes minimization (#4).

TABLE 4.1. CONSIDERED NES DEPLOYMENT SCENARIOS

NES deployment scenario	Denotation[42]
BAU	L1H1
BAU+	L1L2H1
BAU+, FR 'break-even'	L1L2H1F1
BAU+, FR 'medium-BR', medium burn-up	L1L2H1F2
BAU+, FR 'medium-BR', high burn-up	L1L2H1F3
BAU+, FR 'break-even' and ADS	L1L2H1F1A1
BAU+, FR 'medium-BR', medium burn-up, ADS	L1L2H1F2A1
BAU+, FR 'medium-BR', high burn-up, ADS	L1L2H1F3A1
BAU+, FR 'break-even' and MSR	L1L2H1F1M1
BAU+, FR 'medium-BR', medium burn-up, MSR	L1L2H1F2M1
BAU+, FR 'medium-BR', high burn-up, MSR	L1L2H1F3M1

TABLE 4.2. KEY INDICATORS

Key indicators	Units
Natural uranium consumption	kt HM
Annual spent fuel generation	kt HM +FP
Total spent fuel in long term storages	kt HM+FP
Minor actinides stocks in nuclear fuel cycle	t HM
Plutonium stocks in nuclear fuel cycle	t HM
Total enrichment capacities	kt SW
Total reprocessing capacities	kt HM+FP
Total uranium cost	Billion $
Total investments in NPPs	Billion $

Considering the results of the sensitivity analysis, the additional analysis of alternatives by the supplementary decision support methods and the entire set of graphical and attribute information, the most preferable NES options were identified for different experts' preferences regarding NES objectives (see Table 4.3). Based on the comparative evaluation of NES deployment scenarios, it was also possible to identify potential merits and demerits concerning relevant nuclear technologies from the viewpoint of the complete NES so as to provide suggestions for improving their performance.

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

TABLE 4.3. RANKING OF THE NES DEPLOYMENT SCENARIOS

Variants	The most preferable NES			≻	The less preferable NES		
#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 following major suggestions were formulated. If the requirement to minimize investment costs is not determinative and restrictive, the priority could be given to one of the scenarios with F3 type fast reactors (L1L2H1F3, L1L2H1F3A1, and L1L2H1F3M1). The most efficient material flow management (reduction of waste generation, proliferation risks, etc.) is provided by L1L2H1F3M1 which is by 0.7% more costly compared to L1L2H1F3.

If the requirement to minimize investment costs is dominant, the L1L2H1 scenario seems to be a better alternative compared to L1H1. The L1L2H1 scenario will provide a greater system performance without significantly increasing the investment costs (0.8%) in comparison with the cheapest L1H1 option.

The L1L2H1F1 scenario is a trade-off or compromise. This alternative provides an increase in the investment cost by 1.4% in comparison with the cheapest L1H1 scenario and, at the same time, offers an acceptable performance in terms of nuclear materials management in the nuclear fuel cycle.

Of note, from the viewpoint of the complete NES, the F2 type fast reactor is less attractive than its competitors: the F3 type fast reactor, which is more expensive but more efficient for the system in terms of fuel cycle material flow management, and the F1 type fast reactor, which is cheaper but provides a system efficiency comparable to an F2 type fast reactor.

Notwithstanding that the molten salt reactor (MSR) seems more attractive in comparison with the accelerator driven system (ADS), it could be noted that there is no meaningful difference between the MSR and ADS in the considered NES deployment scenarios because of their small share in the systems. As a result, to make a choice between these alternatives, it would be necessary to carry out further analyses assuming their increasing shares in the structures of the corresponding NESs.

4.1.1.3. The need for advanced uncertainty treatment and group decision support within comparative evaluations of NES deployment scenarios

This aforementioned case study is to be considered as a methodological and preliminary one because it was focused on an examination of applicability of different multi-criteria decision support methods to support judgment aggregation within comparative evaluations of NES deployment scenarios and it outlined the possible approach to performing evaluations of this kind. Nevertheless, some conceptual and substantive topics related to performing comparative evaluations of NES deployment scenarios have not yet been covered [4.5].

Among such topics, are the following: consideration and evaluation of an impact of the time factor within comparative evaluations of NES deployment scenarios, which requires the application of dynamic multi attribute analysis frameworks, and an identification of the most promising trade-off NES options from the multi-agent viewpoints (positions of the different individual country groups) requiring application of group decision support methods.

The time dependence of indicator values for NES deployment scenarios in the general case does finally lead to an ambiguity in ranking results obtained for different time frames. The need to consider and examine an impact of the time factor within comparative evaluations of NES deployment scenarios being a part of the decision support process is related to the following fact: contradictions take place not only between various areas and performance measures characterizing safety, proliferation resistance, radioactive waste management, economics, environment, resource consumption and infrastructure aspects but also due to the fact that some measures may demonstrate, for instance, a reduction of long term risks while increasing short term ones. In such cases, it is required to find solutions which can balance the system performance within different time frames.

On the other hand, at present, there are no universal, reliable and generally accepted approaches for incorporating the time factor in comparative evaluation procedures and relevant principles for selecting the most promising compromised solutions. Therefore, systematic identification of scenarios balanced/traded-off for different time frames is not yet possible. This problem may be studied from different standpoints: from formal mathematical procedures assuming aggregating/rolling-up time-dependent indicators of specific static values to non-formal approaches based on advanced uncertainty treatment procedures concerning weights and indicators.

Besides examining the time factor impact within the comparative evaluation procedure, it is necessary to admit that any global NES deployment scenario needs to be considered as a combination of regional (or even national) deployment scenarios. Each group of countries (or even a specific country in general case) is seeking to maximize its benefits and minimize its risks associated with the realization of its NES deployment strategy, which certainly will affect in some degree the strategies being realized in other countries or country groups. Finding a compromised option, which may be considered an adequate or appropriate for all involved parties, is the main task in this regard to be solved by relevant group decision support methods (of note, such compromised option will be probably not the best option for any individual group as well as for the case when the problem is being considered from the global viewpoint).

And again, in this situation, experts are faced with a lack of commonly applied proven methodologies for group decision support for selecting the synergistic strategies of NES deployment with account of different country group priorities.

This problem may also be considered utilizing both formal mathematical procedures assuming aggregating scores assigned to individual parties into overall scores and non-formal approaches based on advanced uncertainty treatment procedures concerning weights and indicators within the synergistic consideration of the set of relevant problems requiring appropriate decision support.

As is shown, the well-known MCDA techniques extended by sophisticated tools for treating uncertainties make it possible to search for compromises among the conflicting factors, including the time factor and the multi-agent perspective that certainly would determine the performance of global NES deployment scenarios. It does additionally confirm that an uncertainty analysis is ultimately necessary to establish a valid basis for decision making.

Given below are the results of an in-depth comparative analysis that may be considered as an extension of the previously performed case study on the comparative evaluation of the GAINS NES deployment scenarios assuming an extensive utilization of methods for advanced uncertainty treatment and group decision support.

All calculations in this case study were carried out using the KIND-ET Excel tool and its three extensions: Domination Identifier, Overall Score Spread Builder and Ranks Mapping Tool [4.1].

This toolkit provides a preliminary screening of options under consideration (in terms of highlighting dominated/non-dominated options), uncertainty examination regarding weighting factors (at the highest and lowest levels of the objective tree) and representation of results in a suitable and understandable form that allows one to rank and sort the options and finally select the most promising trade-off alternative.

4.1.2. Dynamic multi attribute decision making model for comparative evaluations of eleven global NES deployment scenarios

This section demonstrates an application of the dynamic multi attribute decision making framework for a comparative evaluation of eleven global GAINS NES deployment scenarios elaborated in accordance with the GAINS homogeneous world model. This study considers three different time frames: near term perspective (up to 2030), medium term perspective (up to 2050), and long term perspective (up to 2100).

4.1.2.1. Problem statement and major assumptions: scenarios, criteria and weights for different time frames

NES deployment scenarios

In all considered NES deployment scenarios (see Table 4.4.), the annual global nuclear energy generation will reach approximately 1500 GW·year by the mid-century and 5000 GW·year by 2100. The GAINS assumptions impose a constraint on the power production by fast reactors between 2030 and 2050 by specifying a maximum deployment rate depending on the overall nuclear energy growth scenario. The objective is to have a total generation rate of 10 GW·year from fast reactors in 2030 and a total of 400 GW·year in 2050 for the high scenario case. After 2050, the deployment rate of fast reactors is maximized and limited only by the amount of plutonium available and the overall nuclear growth rate. The plutonium inventory in storage was kept close to zero. The following eleven global GAINS NES deployment scenarios were considered in the study (Table 4.4 shows total installed capacities of reactor types up to 2030, 2050 and 2100):

- L1H1: ‘business-as-usual’ (BAU) scenario based on pressurized light water reactors (LWR) (L1) (94% of power generation) and heavy water reactors (HWR) (H1) (6%) operated in a once-through fuel cycle.
- L1L2H1: the BAU+ scenario based on HWR and LWR replacement by high burn-up advanced LWR (ALWR) L2 reactors from 2025.
- L1L2H1F1: scenario with introduction of ’break-even’ (BR ~ 1.0) fast reactors (FR) (F1) into BAU+. The FRs are initially introduced starting with 2021. The objective is to have a total generation rate of 10 GW·year from FRs in 2030 for both growth cases and a total of 400 GW·year in 2050 for the high case.
- L1L2H1F2: scenario with introduction of fast breeder reactors (BR ~ 1.2) (F2) into BAU+.

- L1L2H1F3: scenario with introduction of high burn-up fast breeder reactors (BR ~ 1.2) (F2) into BAU+. The fuel for the high burn-up breeder contains minor actinides (MAs) and, hence, this reactor contributes to MA burning.
- L1L2H1F1A1: scenario L1L2H1F1 with introduction of ADS (A1), which comprises a subcritical fissionable assembly driven by a spallation neutron source. The objective of ADS is transmutation of MAs. In order to reduce the amount of MAs in the abovementioned scenarios, it is necessary to introduce an installed capacity of about 148 GW of ADSs (approximately 3% of the total installed capacity). The ADSs are only introduced between 2075 and 2100 to reduce the amount of MAs.
- L1L2H1F2A1: L1L2H1F2 scenario with introduction of ADS (A1).
- L1L2H1F3A1: L1L2H1F3 scenario with introduction of ADS (A1).
- L1L2H1F1M1: L1L2H1F1 scenario with introduction of molten salt reactor (MSR) (M1) for MA burning. In order to reduce the amount of MAs in the abovementioned scenarios, it is necessary to introduce an installed capacity of about 160 GW of MSRs. This accounts for around 3% of total installed capacity.
- L1L2H1F2M1: L1L2H1F2 scenario with introduction of MSR (M1) for MA burning.
- L1L2H1F3M1: L1L2H1F3 scenario with introduction of MSR (M1) for MA burning.

TABLE 4.4. TOTAL INSTALLED CAPACITY, GW

Reactor type	L1H1	L1L2H1	L1L2H1F1	L1L2H1F2	L1L2H1F3	L1L2H1F1A1	L1L2H1F2A1	L1L2H1F3A1	L1L2H1F1M1	L1L2H1F2M1	L1L2H1F3M1
Near term perspective (as of 2030)											
LWR	822.5	224.7	224.7	224.7	224.7	224.6	224.6	224.6	224.6	224.6	224.6
ALWR	0	597.8	586.1	586.1	586.1	586.1	586.1	586.1	586.1	586.1	586.1
HWR	52.5	52.5	51.7	51.7	51.7	51.8	51.7	51.8	51.8	51.8	51.8
FR1	0	0	11.8	0	0	11.8	0	0	11.8	0	0
FR2	0	0	0	11.8	0	0	11.8	0	0	11.8	0
FR3	0	0	0	0	11.8	0	0	11.8	0	0	11.8
ADS	0	0	0	0	0	0	0	0	0	0	0
MSR	0	0	0	0	0	0	0	0	0	0	0
Medium term perspective (as of 2050)											
LWR	1762.5	129.1	129.1	129.1	129.1	129.0	129.0	129.0	129.0	129.0	129.0
ALWR	0	1633.4	1163.4	1163.4	1163.4	1163.5	1163.5	1163.5	1163.5	1163.5	1163.5
HWR	112.5	112.5	82.5	82.5	82.5	82.5	82.5	82.5	82.5	82.5	82.5
FR1	0	0	470.6	0	0	470.6	0	0	470.6	0	0
FR2	0	0	0	470.6	0	0	470.6	0	0	470.6	0
FR3	0	0	0	0	470.6	0	0	470.6	0	0	470.6
ADS	0	0	0	0	0	0	0	0	0	0	0
MSR	0	0	0	0	0	0	0	0	0	0	0
Long term perspective (as of 2100)											
LWR	5875.0	0	0	0	0	0	0	0	0	0	0
ALWR	0	5875.0	3307.2	2384.2	2676.8	3401.4	2691.0	2659.5	3400.9	2684.0	2659.5
HWR	375.0	375.0	211.1	152.2	170.9	217.1	171.8	169.8	217.1	171.3	169.8
FR1	0	0	2571.1	0	0	2311.7	0	0	2298.1	0	0
FR2	0	0	0	3495.2	0	0	3071.7	0	0	3038.4	0
FR3	0	0	0	0	3202.2	0	0	3175.7	0	0	3175.7
ADS	0	0	0	0	0	147.6	104.0	39.2	0	0	0
MSR	0	0	0	0	0	0	0	0	160.3	140.1	39.2

Evaluation criteria and their arrangement

Within the present case study, eight key indicators were selected to characterize resource consumptions, infrastructure requirements, waste management issues, proliferation resistance, and economics, which were arranged in a three-level objective tree (see Fig.4.1). It is assumed that all indicators are to be minimized. This set of indicators provides the most general information regarding the performance of relevant NES options.

All the indicators were quantitatively evaluated up to the final years of the near term, medium term, and long term perspectives (to 2030, 2050 and 2100, respectively) (see Table 4.5) based on data presented in supplementary materials to the GAINS collaborative project report [4.3] (relevant fuel cycle material flows calculations for all scenarios were carried out using NFCSS (former VISTA) software tool [4.6]).

The set of indicators specifying the performance of relevant NES deployment scenarios consists of:

- 'Cumulative natural uranium consumption' (KI-1) is a uranium resource utilization measure representing the total consumed uranium since 1970 by all types of nuclear reactors up to 2030, 2050 and 2100 correspondingly.
- 'Cumulative enrichment capacities' (KI-2) characterizes the needs for uranium enrichment to produce nuclear fuel for the relevant reactor types and represents total uranium enrichment capacities utilized from 2008 up to 2030, 2050 and 2100, respectively.
- 'Cumulative reprocessing capacities' (KI-3) represents the needs for SNF reprocessing and specifies total SNF reprocessing capacities utilized from 2008 up to 2030, 2050 and 2100, respectively.
- 'Cumulative inventories of SNF in storage facilities' (KI-4) presents a possible measure for the waste management performance and corresponds to the integral SNF amount from all types of nuclear reactors accumulated in at-reactor and away-from-reactor storage facilities by 2030, 2050 and 2100, respectively.
- 'Cumulative depleted uranium stocks' (KI-5) is another possible measure for the nuclear waste management performance, representing the total depleted uranium stocks accumulated from 1970 up to 2030, 2050 and 2100, respectively.
- 'Cumulative inventories of Pu in NFC' (KI-6) characterizes the total plutonium inventories which are circulated and accumulated at all fuel cycle steps up to 2030, 2050 and 2100, respectively.
- 'Cumulative inventories of MA in NFC' (KI-7) represents the total MA inventories which are circulated and accumulated at all fuel cycle steps up to 2030, 2050 and 2100, respectively.
- 'NPP investment costs' (KI-8) is a possible measure of NES economic performance and specifies the total discounted investments for NPP construction up to 2030, 2050 and 2100, respectively. The following assumptions were made to evaluate this indicator: the overnight capital construction costs of existing nuclear reactor types, LWR and HWR, were assumed to be equal to 4000 $/kWe; for the construction of new types of nuclear reactors, ALWR, FR1, FR2, FR3, ADS, 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 chosen to be 5%.

In comparison with the preliminary study [4.1, 4.2], the set of indicators has been changed: two previously used indicators 'Annual SNF generation' and 'Total uranium cost' have been excluded to avoid double counting, and a new one, 'Total depleted uranium'[43], was added. Moreover, these indicators were arranged within the three-level objective tree (see Fig.4.1).

[43] In the BAU scenario, the tails assay is 0.3% and is constant during the whole period. For other scenarios, the tails assay is first set as 0.3% and is changed to 0.2% from 2015 accompanied by ALWR (L2) introduction.

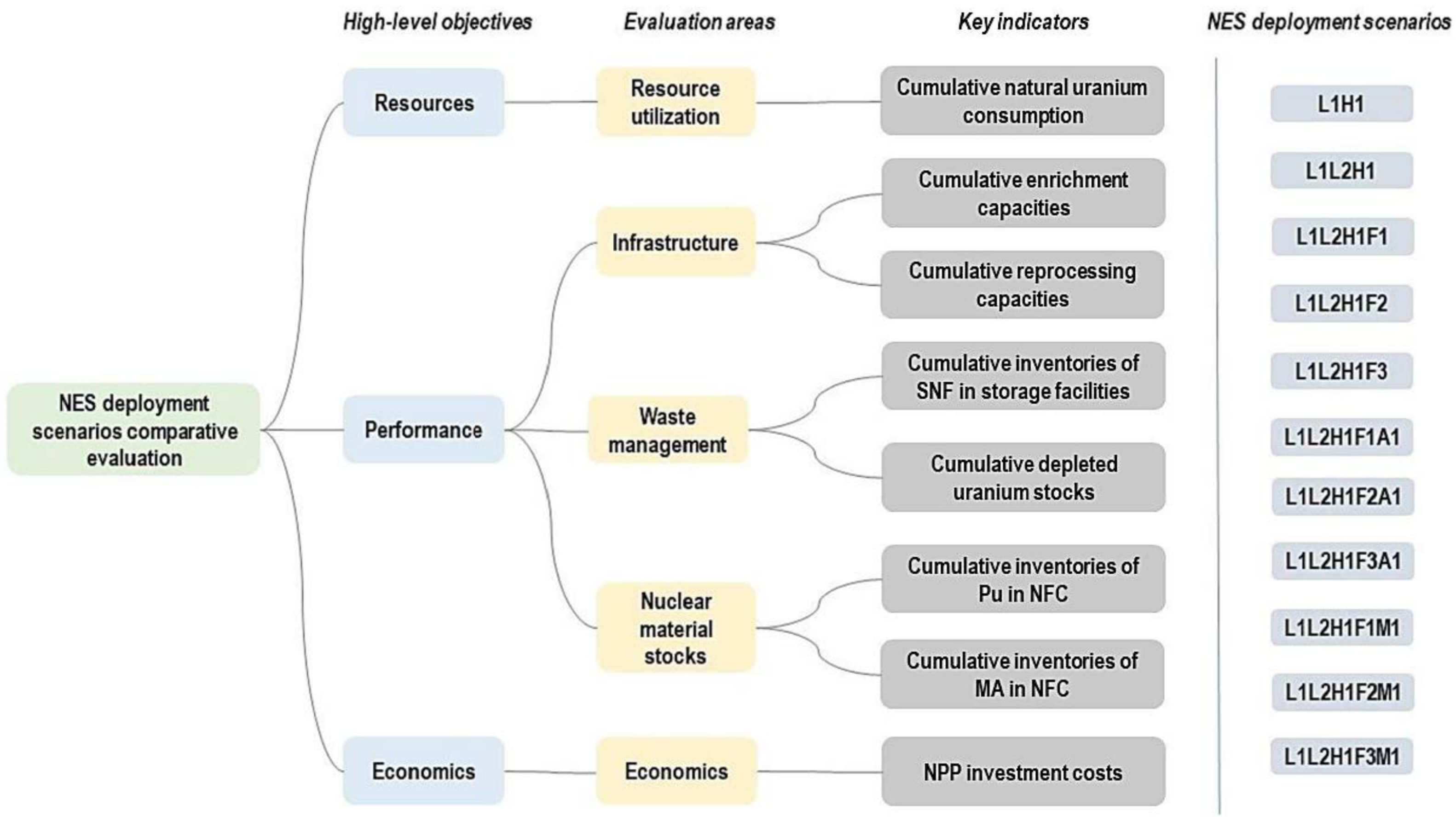


FIG. 4.1. Objective tree.

TABLE 4.5. PERFORMANCE TABLE

KIs[44]	L1H1	L1L2H1	L1L2H1F1	L1L2H1F2	L1L2H1F3	L1L2H1F1A1	L1L2H1F2A1	L1L2H1F3A1	L1L2H1F1M1	L1L2H1F2M1	L1L2H1F3M1
					Near term perspective (as of 2030)						
KI-1	4703.4	4074.5	4060.6	4060.6	4060.6	4078.6	4078.6	4078.6	4078.6	4078.6	4078.7
KI-2	1641.9	1851.9	1840.1	1840.1	1840.1	1825.5	1825.5	1825.5	1825.5	1825.5	1825.5
KI-3	0.0	0.0	9.1	9.5	9.7	8.9	9.4	9.6	8.9	9.4	9.6
KI-4	608.6	585.1	575.8	575.6	574.9	576.0	575.8	575.0	576.0	575.8	575.0
KI-5	4022.8	3412.9	3400.1	3399.5	3399.6	3418.1	3417.5	3417.6	3418.1	3417.5	3417.7
KI-6	4694.0	4733.0	4727.0	4735.0	4697.0	4728.2	4736.6	4698.7	4728.2	4736.6	4698.8
KI-7	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
KI-8	1910.2	2030.0	2030.7	2031.7	2032.8	2030.9	2031.9	2032.9	2030.9	2031.9	2032.9
					Medium term perspective (as of 2050)						
KI-1	10146.1	8282.3	7365.7	7365.7	7365.7	7384.2	7384.3	7384.4	7384.3	7384.2	7384.8
KI-2	4695.0	5490.1	4699.6	4699.6	4699.6	4685.5	4685.5	4685.6	4685.5	4685.5	4685.9
KI-3	0.0	0.0	488.5	476.8	446.8	476.5	465.1	439.2	476.5	465.1	439.2
KI-4	1338.6	1200.6	696.8	732.2	710.2	708.8	743.8	717.9	708.8	743.8	717.9
KI-5	8653.2	6915.0	6057.7	6021.5	6050.0	6076.2	6040.1	6068.6	6076.2	6040.0	6069.0
KI-6	10211.0	10338.0	9504.0	10217.0	8488.0	9625.1	10338.6	8570.1	9625.1	10338.5	8570.5
KI-7	2.3	1.8	1.9	1.8	1.6	1.9	1.8	1.6	1.9	1.8	1.6

[44] The following units for indicators measurement are used in the table: [KI-1]=kt HM; [KI-2]=kt SWU; [KI-3]= kt HM+FP; [KI-4]=kt HM+FP; [KI-5]=kt HM; [KI-6]=t HM; [KI-7]=t HM; [KI-8]=Billion US $.

TABLE 4.5. PERFORMANCE TABLE (cont.)

KIs[45]	L1H1	L1L2H1	L1L2H1F1	L1L2H1F2	L1L2H1F3	L1L2H1F1A1	L1L2H1F2A1	L1L2H1F3A1	L1L2H1F1M1	L1L2H1F2M1	L1L2H1F3M1
KI-8	2840.2	3046.8	3062.2	3082.8	3103.3	3062.4	3082.9	3103.5	3062.4	3082.9	3103.5
Long term perspective (as of 2100)											
KI-1	49753.6	37839.4	25803.1	22913.1	23765.4	26124.3	23973.1	23640.6	25867.1	23805.5	23642.8
KI-2	26905.7	31332.5	20831.2	18318.7	19058.9	21080.1	19210.8	18919.0	20853.6	19063.3	18921.0
KI-3	0.0	0.0	3546.3	4074.8	3173.3	3486.9	3682.6	3160.0	3441.0	3650.0	3136.6
KI-4	6900.9	5667.6	1862.2	1748.0	1689.5	1886.2	2094.8	1681.9	1905.3	2100.0	1704.7
KI-5	42338.5	31612.9	20190.9	16894.6	18459.1	20539.0	17977.1	18360.0	20308.0	17837.3	18361.9
KI-6	52031.0	52167.0	36744.0	48156.0	33455.0	37215.2	49185.9	34094.5	36351.9	48271.0	33808.5
KI-7	11.7	7.1	8.2	6.8	4.4	8.0	6.6	4.3	4.7	4.0	3.5
KI-8	4105.6	4138.2	4163.5	4213.2	4253.2	4164.1	4209.5	4251.5	4164.5	4210.1	4253.7

Screening for dominance

Screening for dominance or preliminary screening implies identifying non-dominated and dominated options among the set of considered feasible ones, i.e., such options for which all the performance indicator values are worse than those of options dominating them. Overall scores of dominated options will always be lower than those of dominating options. Screening for dominance was performed using the Domination Identifier KIND-ET extension.

Near term perspective. Among all the considered scenarios, only L1L2H1F3M1 is dominated, namely by L1L2H1F3A1. This is because KI-6 for L1L2H1F3A1 has a slightly better performance than for L1L2H1F3M1, but all other indicators are the same, however, these differences cannot be considered as significant.

Medium term perspective. Among all the considered scenarios, only L1L2H1F3M1 is dominated, namely by L1L2H1F3A1. This is because KI-2 and KI-7 for L1L2H1F3A1 have a slightly better performance than for L1L2H1F3M1, but all other indicators are the same, however, these differences cannot be considered as more or less significant.

Long term perspective. All the scenarios are non-dominated ones for the long term perspective.

In summary, it could be noted that within the near term and medium term perspectives there are no significant differences between the scenarios based on the same fast reactors (F1, F2 or F3). The minor differences may be explained by errors in data preparation when the fuel cycle material flow model was being elaborated. All the scenarios are to be considered as non-dominated ones and included for consideration within near-, medium- and long term perspectives.

[45] The following units for indicators measurement are used in the table: [KI-1]=kt HM; [KI-2]=kt SWU; [KI-3]= kt HM+FP; [KI-4]=kt HM+FP; [KI-5]=kt HM; [KI-6]=t HM; [KI-7]=t HM; [KI-8]=Billion US $.

Weighting factors

The advantage of screening for dominance or preliminary screening is that it precedes the definition of weights. However, screening procedure on itself does not substitute for ranking for which a defined MCDA procedure still needs to be performed, but this time only for the non-dominated options, the number of which may be the same or less than that of the originally defined options. Reducing the number of options to be ranked generally improves the resolution and simplifies interpretation of the ranking results [4.7].

The following assumptions were made to prepare the base case weighting options for the aggregations of indicators within Multi attribute Value Theory (MAVT) independently for the near-, medium- and long term perspectives: the weight values tend to become uniform for the more distant periods.

Near term perspective. The highest priority is given to the 'Economics' high-level objective, followed by the 'Resources' high-level objective: in terms of weights, they obtain 50 and 40%, respectively (see Table 2.3). The less important is the 'Performance' high-level objective: it takes 10%. Within the 'Performance' high-level objective, the highest priority is given to the 'Infrastructure' evaluation area (70%) whereas the 'Waste management' and 'Nuclear materials stocks' evaluation areas are of lower importance (20 and 10%, respectively). KI-2 and KI-3 have similar importance within the 'Infrastructure' evaluation area (50% each). The same is true for KI-6 and KI-7 within the 'Nuclear materials stocks' evaluation area. KI-4 has the higher importance in comparison with KI-5 within the 'Waste management' evaluation area (90 and 10% respectively).

Medium term perspective. The only assumption made to assess weight values for the medium term perspective is that at each level of the objective tree the significance/importance of all the high level objectives, evaluation areas and indicators are identical. At the evaluation area level, equal weighting factors were assigned to each evaluation area, depending on their belonging to the high-level objectives. These factors were also determined based on the requirements that the sum of all weighting factors for each area is to be equal to unity. At the final level (level of key indicators), the weighting factors for each indicator included in the corresponding evaluation area were assumed to be equal as well. The final weighting factors calculated in accordance with the described assumption for each indicator are shown in Table 4.6. and Fig.4.2.

Long term perspective. For the long term perspective, the so-called 'equal weights' (or 'mean weights') option was applied. This weighting option assumes that the weights are determined by equation $w_i = 1/n$, where n is the number of key indicators [4.8–4.10]. This implies that all indicators are of equal importance. This approach can be applied when the there is no information from decision-makers and experts or information on the relative importance of criteria is not sufficient to reach a decision. In case there is no information on expert defined weights, using the equal weight approach combined with sensitivity analysis for weights could still help derive a meaningful conclusion regarding preferences in the considered options.

Table 4.6. and Fig.4.2 contain the base case weighting factors for the near-, medium- and long term perspectives, clearly illustrating the main trend of the given assumptions, i.e., to uniform weight values for the more distant periods.

TABLE 4.6. BASE CASE WEIGHTING FACTORS

High-level objectives	High-level objective weights	Areas	Area weights	Indicators	Indicator weights	Final weights
Near term perspective (as of 2030)						
Resources	0.4	Resources	1	U consumption	1	0.4
Performance	0.1	Infrastructure	0.7	Enrichment	0.5	0.035
Performance	0.1	Infrastructure	0.7	Reprocessing	0.5	0.035
Performance	0.1	Waste management	0.2	SNF storage	0.9	0.018
Performance	0.1	Waste management	0.2	Depleted uranium	0.1	0.002
Performance	0.1	Nuclear materials stocks	0.1	Pu stocks	0.5	0.005
Performance	0.1	Nuclear materials stocks	0.1	MA stocks	0.5	0.005
Economics	0.5	Economics	1	Total investments	1	0.5
Medium term perspective (as of 2050)						
Resources	0.333	Resources	1	U consumption	1	0.333
Performance	0.333	Infrastructure	0.333	Enrichment	0.5	0.056
Performance	0.333	Infrastructure	0.333	Reprocessing	0.5	0.056
Performance	0.333	Waste management	0.333	SNF storage	0.5	0.056
Performance	0.333	Waste management	0.333	Depleted uranium	0.5	0.056
Performance	0.333	Nuclear materials stocks	0.333	Pu stocks	0.5	0.056
Performance	0.333	Nuclear materials stocks	0.333	MA stocks	0.5	0.056
Economics	0.333	Economics	1	Total investments	1	0.333
Long term perspective (as of 2100)						
Resources	0.125	Resources	1	U consumption	1	0.125
Performance	0.75	Infrastructure	0.333	Enrichment	0.5	0.125
Performance	0.75	Infrastructure	0.333	Reprocessing	0.5	0.125
Performance	0.75	Waste management	0.333	SNF storage	0.5	0.125
Performance	0.75	Waste management	0.333	Depleted uranium	0.5	0.125
Performance	0.75	Nuclear materials stocks	0.333	Pu stocks	0.5	0.125
Performance	0.75	Nuclear materials stocks	0.333	MA stocks	0.5	0.125
Economics	0.125	Economics	1	Total investments	1	0.125

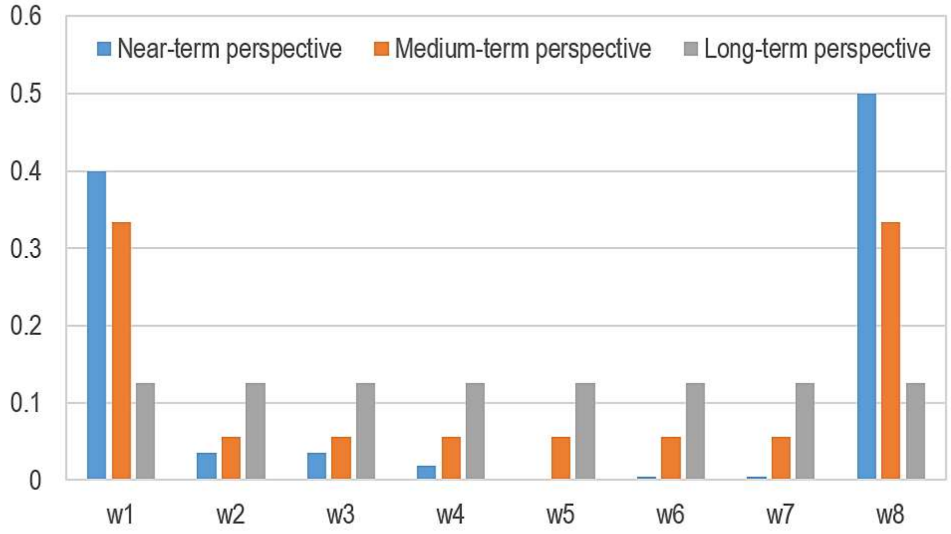


FIG. 4.2. Base case weighting options.

It needs to be noted that diverse sets of weights could be applied iteratively to simulate and analyse different perspectives reflecting the interests and preferences of different involved stakeholders. Within this study, such examinations were not intentionally performed, because this would call for considering the specifics of global preferences and standpoints on nuclear energy development and sustainability issues. Nevertheless, an extended uncertainty/sensitivity analysis of ranking results with respect to weights was carried out to demonstrate the rank order sensitivity to different possible weight variants. This analysis made it possible to identify such an option, which can be considered a consensual one for near-, medium- and long term perspectives.

4.1.2.2. Ranking of NES deployment scenarios for different time frames

While MCDA models are focused on selecting the preferable option from a finite number of feasible alternatives for which all criteria/attributes evaluated as of a specific period (static evaluations), within dynamic multi attribute decision making models, the selection process considers the performance-time dependence of options under consideration during different time frames: the final decision is to be made based on all information collected at multiple periods.

Some studies based on applications of dynamic multi attribute decision support frameworks are focused on decision support problems, in which the original decision information is usually collected at different periods and the final decision is to be made considering all available data. There are some other studies, in which different, separated and interlinked decisions are to be made either regularly or just at the end of the process.

To deal with decision making in dynamic environments, different approaches have been proposed [4.10–4.13] to commonly model the problem as a three-dimensional decision matrix, which is firstly transformed into a conventional two-dimensional decision matrix by aggregating the time dimension, and next the problem is solved through traditional MCDA models. The crucial phase of similar approaches is the selection of an appropriate aggregation operator for computing dynamic ratings due to its properties that can highly modify the computation cost and obtain very different results attending to the type of reinforcement supported by the aggregation operator. Different uncertainty analysis frameworks are used for populating such models based on fuzzy, interval or grey numbers, etc.

The following are specific features associated with comparison of NES deployment scenarios considering the time factor and aspects to be considered when performing such comparative evaluations. Usually, detailed data on nuclear material flows and related performance indicators are given for each year from a current year up to 2100 (or even farther): these data are obtained from calculations using fuel cycle modelling software tools. Therefore, it is not obvious by default as of which year the performance indicators are to be evaluated so as to be used for further aggregation and, in this regard, relevant ambiguities arise, which in general may produce differences in ranking options. Commonly, it is expected that there may be some discrepancies between decision makers' and experts' preferences regarding indicators (weighting options) and associated uncertainties for the near-, medium- and long term perspectives.

Considering the aforementioned aspects, it seems appropriate that a dynamic multi attribute decision support framework for selecting the most preferable trade-off NES deployment scenario is to provide an identification of such an option, which may be considered consensual for near-, medium- and long term perspectives balancing associated performance and risk within different periods. This framework needs to be based on an extended application of advanced uncertainty treatment techniques coupled with concepts of group decision support. To realize this approach, NES deployment scenarios were ranked for the base case weighting option for the near-, medium- and long term perspectives independently, spreads in overall scores for the whole set of options were evaluated by uncertainties in weighting factors, and the first-rank options were identified for different combinations of high-level objective weights.

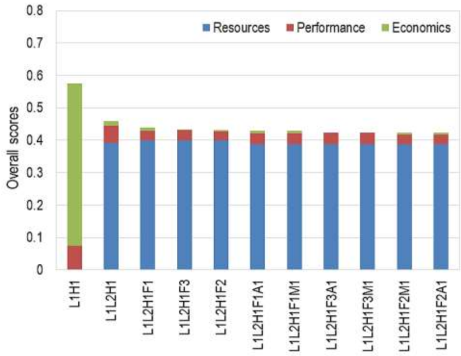
Given below are the ranking results for the base case option (Fig.4.3) to demonstrate a decomposition of overall scores of options into individual high-level objectives according to the structure of the objective tree and results of the uncertainty analysis in regard to weights: Fig. 4.4 shows spreads in overall scores (mean value, 5th, 25th, 75th and 95th percentiles) and Fig. 4.5 illustrates areas of high-level objective weights for which some options from the given feasible set may be given the first rank.

All calculations were carried out using the MAVT-based comparison model with the additive multi attribute value function. This study considers linear decreasing single attribute value functions for all indicators.

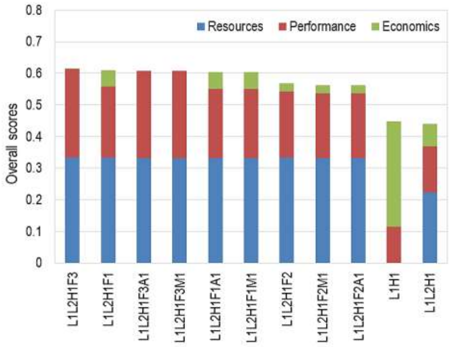
As Fig.4.3 shows, for the near term perspective, L1H1 seems to be more attractive option followed by L1L2H1, L1L2H1F1, L1L2H1F3, L1L2H1F2 and all other advanced options with ADS and MSR with very small differences in the overall scores (the difference in the scores between L1L2H1 and L1L2H1F2A1 is 0.035). Therefore, it may be concluded that, due to their similarity (or unresolvedness) for this perspective, it will be necessary to perform a sensitivity/uncertainty analysis to make a more subtle differentiation of these options. Of note, the advanced options with the F2 fast reactor (L1L2H1F2M1 and L1L2H1F2A1) occupy the last two places.

For the medium term perspective, formally, the most preferable option is L1L2H1F3 for the base case weights followed by L1L2H1F1, for which the overall score is only 0.004 less than that of L1L2H1F3. The third and fourth ranks are taken by the advanced NES options with the F3 fast reactor (L1L2H1F3A1 and L1L2H1F3M1). The advanced NES options with the F1 fast reactor (L1L2H1F1A1 and L1L2H1F1M1) have the fifth and sixth ranks. Of note, there are very small differences between the overall scores for options ranking from the first to sixth (~0.01): in this case, a sensitivity/uncertainty analysis is also required for a more subtle differentiation. The ranks from the seventh to nineth go to the NES options with F2 fast reactors (L1L2H1F2, L1L2H1F2M1 and L1L2H1F1A1). L1H1 and L1L2H1 take the next-to-last and last ranks, respectively.

For the long term perspective, the most preferable option is L1L2H1F3M1 for the base case weights followed by L1L2H1F1M1. Options L1L2H1F3A1 and L1L2H1F3 have the third and fourth ranks, respectively. The fifth and sixth ranks are taken by L1L2H1F1 and L1L2H1F1A1. They are followed by the NES options with the F2 fast reactors (L1L2H1F2M1, L1L2H1F2 and L1L2H1F1A1). L1H1 and L1L2H1 have the last and next-to-last ranks.



(a)



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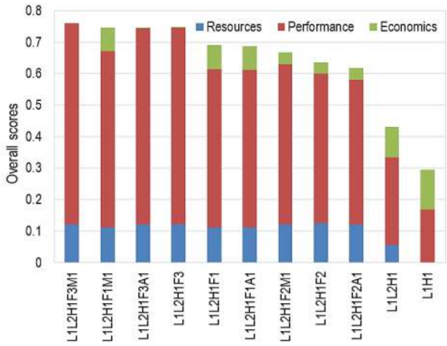


(c)

FIG. 4.3. Ranking results for the base case weighting option[46]: (a) near term perspective, (b) medium term perspective, (c) long term perspective.

[46] Evaluation of overall scores was performed by using the KIND-ET tool.

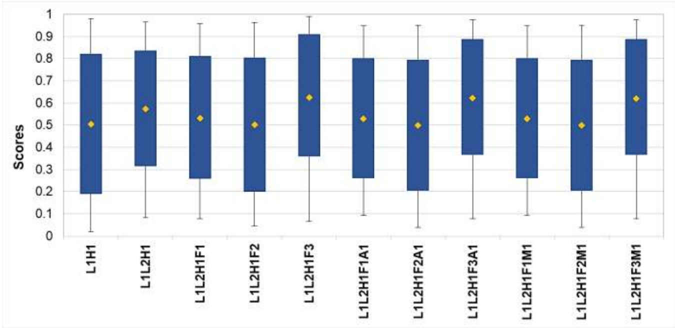
Table 4.7 additionally provides data regarding high-level objective scores for different periods to highlight potential merits and demerits associated with the options. Of note, the resolution of options with the period becomes more pronounced.

TABLE 4.7. HIGH-LEVEL OBJECTIVES SCORES OF NES DEPLOYMENT SCENARIOS FOR DIFFERENT PERIODS

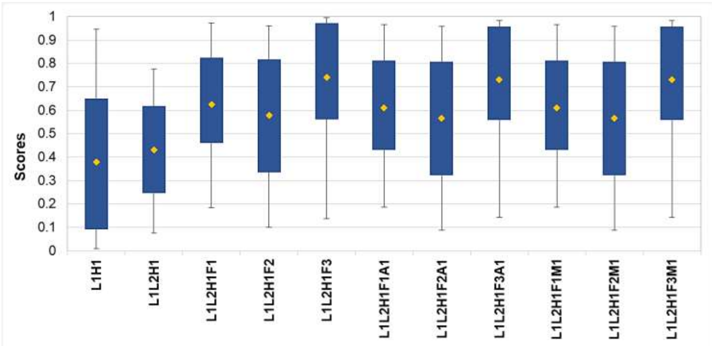
High-level objectives	L1H1	L1L2H1	L1L2H1F1	L1L2H1F2	L1L2H1F3	L1L2H1F1A1	L1L2H1F2A1	L1L2H1F3A1	L1L2H1F1M1	L1L2H1F2M1	L1L2H1F3M1
Near term perspective											
Resources	0.000	0.391	0.400	0.400	0.400	0.389	0.389	0.389	0.389	0.389	0.389
Performance	0.075	0.055	0.030	0.027	0.032	0.032	0.030	0.034	0.032	0.030	0.034
Economics	0.500	0.012	0.009	0.005	0.001	0.008	0.004	0.000	0.008	0.004	0.000
Medium term perspective											
Resources	0.000	0.223	0.333	0.333	0.333	0.331	0.331	0.331	0.331	0.331	0.331
Performance	0.114	0.145	0.224	0.209	0.280	0.220	0.205	0.277	0.220	0.205	0.277
Economics	0.333	0.072	0.052	0.026	0.000	0.052	0.026	0.000	0.052	0.026	0.000
Long term perspective											
Resources	0.000	0.055	0.112	0.125	0.121	0.110	0.120	0.122	0.111	0.121	0.122
Performance	0.168	0.278	0.503	0.475	0.624	0.501	0.460	0.623	0.560	0.509	0.638
Economics	0.125	0.097	0.076	0.034	0.000	0.076	0.037	0.002	0.075	0.037	0.000

The utilization of the base case weights for ranking options identified a low resolution of the given options; therefore, it is required to perform an analysis on how the overall scores may vary due to weights changes. The weight uncertainty impact on ranking results was examined using stochastic (probabilistic) variations of weights by determining the probability distributions of the scores. This allowed making judgments regarding spreads in the overall scores in spite of the lack of detailed information usually gained by means of experts' and stakeholders' elicitations in an iterative process.

Within this approach, it is assumed that all of the weights are randomly and uniformly distributed in the range from 0 to 1, constrained only by normalization conditions. In fact, the distribution function for generating imprecise information has minor influence on the statistic results. All the other assumptions were unchanged. For each weight combination, the MAVT-based evaluation was performed to identify the overall scores of options. Associated probability distributions in overall scores were obtained by means of Monte Carlo simulations. For a reliable estimation of probability distributions of the scores, 10,000 weight combinations were considered.



(a)



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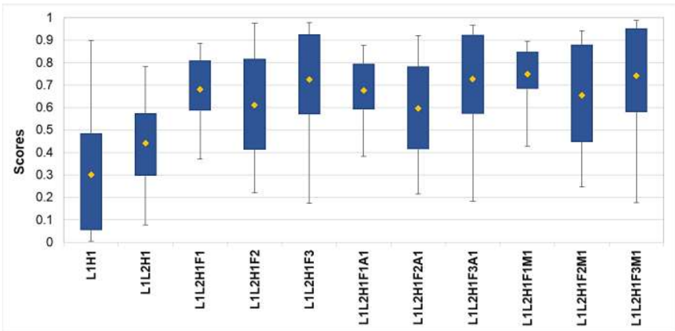


(c)

FIG. 4.4. Spreads in overall scores (mean value, 5th, 25th, 75th and 95th percentiles are shown)[47]: (a) near term perspective, (b) medium term perspective, (c) long term perspective.

The overall score spreads resulting from weight uncertainties are box and whisker plots for near-, medium- and long term perspectives (Fig.4.4) that allows concluding about the ranges of scores changes for each option. Fig.4.4 clearly shows a trend to the reduction of associated uncertainties in the overall scores in course of time, making the resolution of options to be more pronounced. This trend may be explained by indicator values that become more diverse over time, thereby increasing statistical differences between options. The more preferable options in the statistical sense become scenarios with the F3 and F1 fast reactors: the options with F3 have higher mean values, but the ones with F1 have lower dispersions. Differences between the 25th and 75th percentiles of the overall scores (Δ) are shown in Table 4.8 (to confirm the

[47] Spreads in overall scores were evaluated by using the Overall Score Spread Builder.

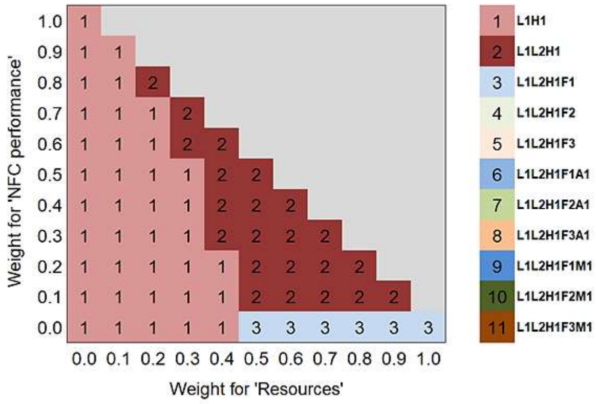
aforementioned trend). The overall scores distributions allowed evaluating the probability for a given option to be more attractive than the other ones for near-, medium- and long term perspectives (see Table 4.9), making it possible to use this information as a decision rule if nothing is known about preferences. According to this rule, the options with F3 seem to be the most attractive.

TABLE 4.8. DIFFERENCES BETWEEN 25TH AND 75TH PERCENTILES OF OVERALL SCORES (Δ)

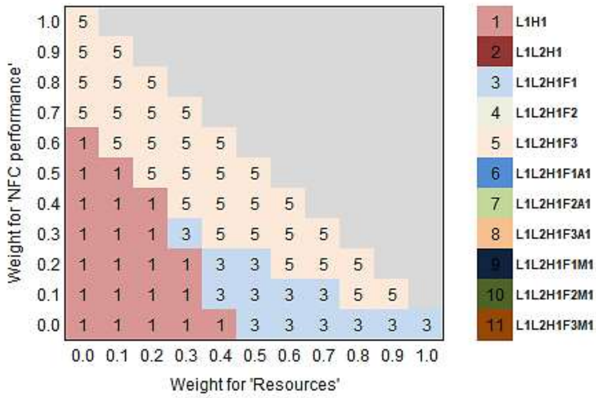
	L1H1	L1L2H1	L1L2H1F1	L1L2H1F2	L1L2H1F3	L1L2H1F1A1	L1L2H1F2A1	L1L2H1F3A1	L1L2H1F1M1	L1L2H1F2M1	L1L2H1F3M1
Near term perspective											
Δ	0.63	0.52	0.55	0.61	0.55	0.54	0.59	0.52	0.54	0.59	0.52
Medium term perspective											
Δ	0.56	0.37	0.36	0.48	0.41	0.38	0.48	0.40	0.38	0.48	0.40
Long term perspective											
Δ	0.43	0.28	0.22	0.40	0.36	0.20	0.37	0.35	0.17	0.43	0.37

TABLE 4.9. PROBABILITY THAT THE OVERALL SCORE OF THE GIVEN OPTION IS HIGHER THAN SCORES OF OTHER OPTIONS

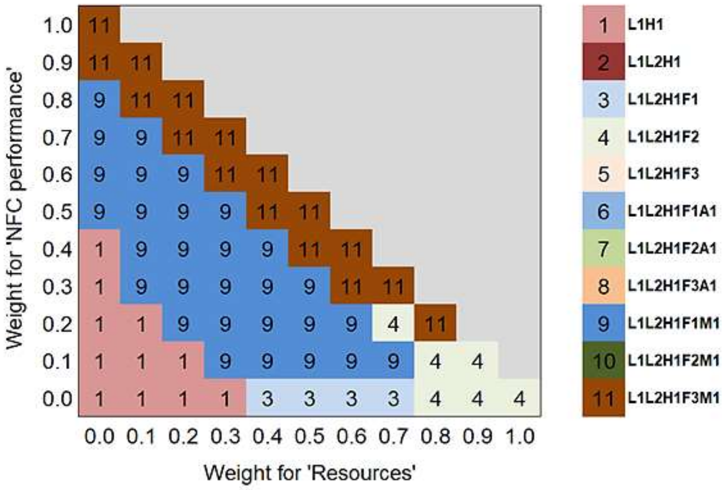
	L1H1	L1L2H1	L1L2H1F1	L1L2H1F2	L1L2H1F3	L1L2H1F1A1	L1L2H1F2A1	L1L2H1F3A1	L1L2H1F1M1	L1L2H1F2M1	L1L2H1F3M1
Near term perspective											
P, %	36.9	15.8	1.2	0.3	38.9	0.1	0.0	6.9	0.0	0.0	0.0
Medium term perspective											
P, %	21.6	6.7	8.5	1.8	54.6	0.2	0.0	5.6	0.7	0.3	0.0
Long term perspective											
P, %	12.0	7.1	4.9	12.4	12.2	0.0	0.0	3.3	10.3	0.9	36.9



(a)



(b)



(c)

FIG. 4.5. Mapping of the first-rank options[48]*: (a) near term perspective, (b) medium term perspective, (c) long term perspective.*

The evaluation of spreads in the overall scores allows making judgments regarding the robustness of the given options but does not provide information/guidance for experts as to where to move to find a consensus, i.e., a single trade-off NES option which seems to be acceptable for different time perspectives. For this purpose, it is reasonable to highlight areas in the weight space (primarily regarding high-level objective weights) and relevant options, which could take the first rank.

The results of uncertainty examinations in view of high-level weight variations were presented in the form of heat map diagrams for the three high-level weights assigned to the high-level objectives, separately for the near-, medium- and long term perspectives (Fig. 4.5). Such uncertainty analyses make it possible to demonstrate a set of options, which can take the first rank and relevant weighting factor ranges.

[48] Mapping of the first-rank options was performed with the Ranks Mapping Tool.

To build a corresponding diagram, weights for the three high-level objectives were simultaneously varied over the 0 to 1 range. As the weights are to fulfil the normalization condition constraining their summation equal to unity, only two of them can be independently selected, whereas the third one is calculated. The most favoured options may be obtained using MAVT with the corresponding weights for high-level objectives varied as independent variables within the area [0.1] × [0.1] considering the normalization condition.

The results of such an analysis in view of weights variation are illustrated in Fig. 4.5. The coloured areas indicate the weights combinations for which a specific option takes the first rank. Thus, this picture demonstrates a map of preferences and provides a better understanding of how promising and robust each option ranking is in a view of high-level objective weights. The associated domains allow concluding about the rank stability of options and identifying conditions for which relevant options may take the first rank.

For the near term perspective, L1H1, L1L2H1 and L1L2H1F1 can take the first rank with the probability for preference of a relevant option (hereinafter the relative share of relevant areas in the high-level objective space) equal to 57.6, 33.3 and 9.1%, respectively.

For the medium term perspective, L1H1, L1L2H1F1 and L1L2H1F3 can take the first place with the probability for preference of a relevant option equal to 33.3, 19.7 and 47.0 %, respectively.

For the long term perspective, L1H1, L1L2H1F1, L1L2H1F2, L1L2H1F1M1 and L1L2H1F3M1 can take the first place with the probability for preference of a relevant option equal to 16.7, 6.1, 9.1, 43.9 and 24.2%, respectively.

The following tendency can be observed. The probability for preference of L1H1 is reduced over time (57.6, 33.3 and 16.7% for the near-, medium- and long term perspectives, respectively) and this option becomes the most attractive one for the low weight values of the 'Performance' and 'Resources' high-level objectives. The probability for preference of L1H1F1 and L1L2H1F1M1 are increased over time (9.1, 19.7 and 50% for the near-, medium- and long term perspectives, respectively) and these options become the most attractive ones for the mid-values of high-level objective weights.

Scenarios based on the F3 fast reactor (L1L2H1F3 for the medium term perspective, L1L2H1F3 and L1L2H1F3M1 for the long term perspective) may become the most attractive choices for weighting options with the low weight value of the ‘Economics’ high-level objectives.

Scenarios with the F2 fast reactor cannot obtain the first rank for the near- and medium term perspectives. The L1L2H1F2 scenario arises in the long term perspective for the weighting options assuming the higher weight value of the ‘Resources’ high-level objective.

4.1.2.3. Results and discussions

As is seen from the performed analyses, the ranking results as well as the results of the sensitivity/uncertainty analysis and relevant suggestions concerning the most attractive options are dissimilar for the different periods/perspectives. The further the time perspective is considered, the more resolved and stable the ranking results become.

In this regard, which time moment to select to perform comparative evaluations is still an open question complicated by that fact that the priorities regarding NES objectives are usually different within different time frames. To meet this challenge in some way, it is necessary to apply dynamic multi attribute analysis frameworks requiring a simultaneous consideration of different time-perspectives and finding a consensus utilizing advanced uncertainty treatment approaches.

A possible way to find such a consensus is to involve the results of the sensitivity/uncertainty analysis and the entire set of graphical and attribute information and to perform, if needed, an additional analysis of alternatives by supplementary decision support and visualization methods. Based on such considerations, it is also possible to clarify potential merits and demerits concerning relevant nuclear technologies from the viewpoint of the complete NES within different time frames that provides judgments regarding performance of relevant technologies.

The performed analysis clearly demonstrates that the F3 fast reactor is the most effective in the system in terms of optimization of nuclear material flows and relevant deployment scenarios, especially in combination with the M1 molten salt reactor (due to the fact that the MSR shows higher effectiveness in these scenarios in comparison with ADS in the system). The F3 fast reactor may provide an outstanding performance of the relevant NES option in the case when the NES economic performance is unimportant.

Scenarios with the F2 fast reactor cannot be promising if scenarios based on F1 and F3 are available: from the viewpoint of the complete NES, the F2 fast reactor is less attractive than its competitors: the F3 fast reactor, which is more expensive but more efficient for the system in terms of fuel cycle material flow management; and the F1 fast reactor, which is cheaper but provides the system efficiency comparable to the F2 fast reactor.

Special attention is to be paid to scenarios with the F1 fast reactor. Relevant options are ranked directly after the most promising options based on the F3 fast reactor and can take the first rank if it is required to improve the economic performance while retaining an adequate nuclear material flow performance and resource utilization. Such cases have a place within near- and medium term perspectives. In this regard, scenarios based on the F1 fast reactor may be considered as trade-off options for the near-, medium- and long term perspectives.

The analysis confirms the old proverb “the perfect is the enemy of the good” when considering dynamical problems related to comparative evaluations of relevant options. Namely, the F3-based options have the highest potential for the long term perspective, but they are too costly to be attractive for the near term perspective. The F1-based options are cheaper and more attractive for the near- and medium term perspective. The F1-based options do not offer the best performance but offer acceptable performance in terms of nuclear materials management in the nuclear fuel cycle for the long term perspective.

The analysis has also demonstrated that in terms of balancing the system performance within different time frames, it seems reasonable not to deploy the single best technological solution as soon as possible, which may deteriorate a short term expected NES performance (especially economic performance), but to develop a less effective option satisfying the near- and medium term perspective objectives assuming that this option will be replaced or supplemented by a more advanced option later. In this regard, there are no reasons to contra-distinguish one technological option to another – a balanced solution for different perspectives may be found in mixing different technological options.

4.1.3. Multi-group decision support model for comparison of synergetic and non-synergetic NES deployment scenarios

To make decisions in some cases implies involving groups of decision makers instead of a single decision-maker. Therefore, the question arises how many individual preferences can be consolidated to produce a collective choice. The transition from a single decision-maker to multiple decision-makers complicates the decision support procedure. The problem is no longer in selecting the most favoured option among the non-dominated ones according to one decision-maker's preferences. In such cases, the decision support process could be extended to consider possible conflicts among involved interest groups – actors, who may have different objectives or common interests.

The decision making involving groups of decision makers most commonly employs the methodologies providing for group comparison of options carried out through compromise, voting, consensus or aggregating methods (the aggregation of individual priorities and judgments) [4.14–4.16].

4.1.3.1. Problem statement and major assumptions: scenarios, criteria and weights for different country groups

Most studies on the future of nuclear energy are based on a homogeneous global model, which suggests the world is rapidly converging toward global solutions for economic, social, and environmental challenges. However, according to [4.4], "it does not take into account the barriers to cooperation between different parts of the world or national preferences and capabilities. To complement this model, the GAINS project developed a heterogeneous model based on grouping countries with similar fuel cycle strategies, Fig. 4.6. This model can facilitate a more realistic analysis of transition scenarios toward a global architecture of innovative nuclear energy systems". Heterogeneous world model could also illustrate the global benefits that would result from some countries introducing innovative nuclear technologies. "The heterogeneous world model developed by GAINS organizes countries into groups according to their strategies" regarding "SNF management":

- NG1: The "general strategy is to recycle" SNF — "the group plans to build, operate and manage SNF recycling facilities and permanent" geological "disposal facilities for highly radioactive waste" [4.4].
- NG2: The "general strategy is to either directly dispose" SNF "or reprocess" SNF "abroad — the group plans to build, operate and manage permanent" geological "disposal facilities for highly radioactive waste (in the form of" SNF "and/or reprocessing waste) and/or" to work "synergistically with another group to have" its "fuel recycled" [4.4].
- NG3: The "general strategy is to use fresh fuel and send" SNF "abroad for either" recycling "or disposal, or the back-end strategy is undecided — the group has no plans to build, operate and manage" SNF "recycling facilities or permanent" geological "disposal facilities for highly radioactive waste. They may obtain fabricated fuel from abroad and may arrange for export of their" SNF [4.4].

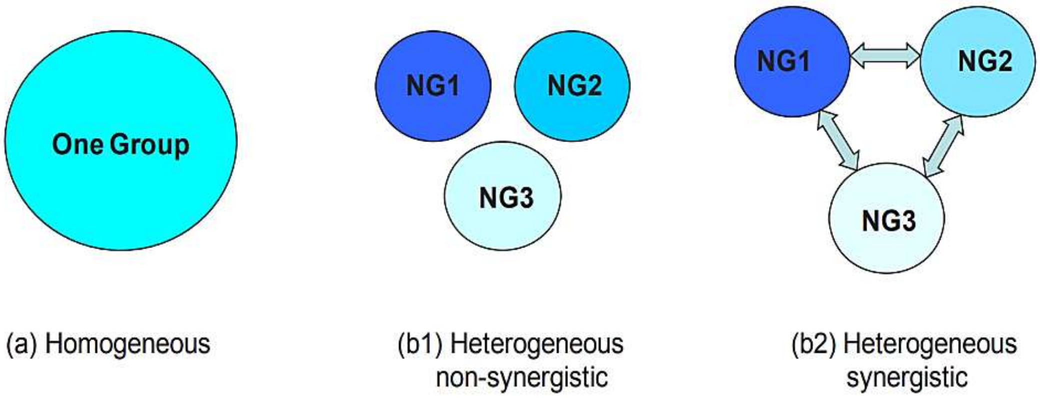


FIG. 4.6. Homogeneous versus heterogeneous world models.

It is obvious that each group of countries is seeking to maximize its benefits and minimize its risks related to the realization of its NES deployment strategy, which certainly will affect in some degree on the strategies being realized in other countries or country groups. Finding a compromise option, which may be considered to be appropriate for all involved parties, is the main task in this regard to be solved by relevant group decision support methods.

NES deployment scenarios

The present study considered six separate and synergistic heterogeneous world models (three of them are separate and the other three are synergistic) which consist of the following reactor technologies: LWR, ALWR, HWR, FR-1, -2 and -3. These scenarios will be further indicated as (in accordance with the relevant abbreviations used in the supplementary materials to the GAINS report [4.3]):

(a) Separate NES deployment scenarios:

(i) NG0Sep-High-L1L2H1F1;
(ii) NG0Sep-High-L1L2H1F2;
(iii) NG0Sep-High-L1L2H1F3.

(b) Synergistic NES deployment scenarios:

(i) NG0Syn-High-L1L2H1F1;
(ii) NG0Syn-High-L1L2H1F2;
(iii) NG0Syn-High-L1L2H1F3.

In addition, the results of a comparative evaluation of these scenarios from the global standpoint that allows contrasting a global ranking with the ranking from NG1, NG2 and NG3 standpoints are presented.

In all the considered NES deployment scenarios, the annual global nuclear energy generation reaches approximately 1500 GW·year by the mid-century and 5000 GW·year by 2100. The shares of nuclear energy generation in groups related to the total nuclear energy generation by the year 2100 are:

— 40% in NG1 (recycle based architecture);

— 40% in NG2 (mature once-through fuel cycle architecture);
— 20% in NG3 (elements of once-through fuel cycle architecture).

Of note, the demand projection (high case) is the same as was considered in Chapter 4.2 of this document representing the homogenous world model. All the six scenarios considered here consist of the same set of reactor types, which were investigated in Chapter 4.2. Therefore, in addition to comparisons of the NES deployment scenarios within the separate and synergistic heterogeneous models, it would be interesting to compare these results with the results obtained within the homogenous world model. Relevant comments will be provided in the Results and Discussion section.

Evaluation criteria and their arrangement

The heterogeneous world model makes it possible to calculate indicators individually for each country group (NG1, NG2, NG3), whereas the "homogeneous model could only provide indicators for the world as a whole" [4.4]. The same set of indicators and their arrangement were used for all the country groups and the global case [4.3]. In the general case, the set of indicators may vary for different country groups, because expectations and performance representations for different country groups may differ in what concerns NES objectives. Nevertheless, for the sake of simplicity and without loss of generality within the current study, a typical set of indicators was used which may be evaluated based on data contained in the supplementary materials to the GAINS report.

Table 4.10 provides data on key indicators for each group of countries and for the whole world evaluated as of 2100. The following points are to be highlighted for a better understanding of the ranking results presented below.

NG1 standpoint. All the indicator values for this group of countries are different for the whole set of scenarios considered. This group of countries plays a key role in the global NES architecture, because it offers the reprocessing services for NG2 and NG3 and its structure strongly depends on deployed technological options considering relevant demands on the fuel cycle back-end services in other country groups.

NG2 standpoint. All the three separate NES deployment scenarios for this group provide the identical overall performance. Performances of the synergetic scenarios related to the fuel cycle back-end are different, but their performances concerning the fuel cycle front-end are the same as for the separate NES deployment scenarios.

NG3 standpoint. All the NES deployment scenarios for this group excluding NG0Syn-High-L1L2H1F1 provide the similar overall performance. For realization of NG0Syn-High-L1L2H1F1, it is required to reprocess SNF that arises in NG3. For this reason, this scenario is characterized by an increased KI-3 value and reduced KI-4, KI-6 and KI-7 values, all other indicators have the same value as in other scenarios for this country group.

Global standpoint. The indicators values for the whole world are the results of summation for the individual groups of countries (NG1, NG2, NG3). As mentioned, global standpoint considerations allow one to compare the ranking results obtained using group decision support methods and classical MCDA methods considering a single decision-maker. In addition, it allows confronting the ranking results obtained within the homogenous and heterogeneous world models.

TABLE 4.10. PERFORMANCE TABLE

KIs	NG0Sep-High-L1L2H1F1	NG0Sep-High-L1L2H1F2	NG0Sep-High-L1L2H1F3	NG0Syn-High-L1L2H1F1	NG0Syn-High-L1L2H1F2	NG0Syn-High-L1L2H1F3
NG1 (as of 2100)						
KI-1	10719.7	9347.5	9764.6	6178.5	6178.5	6178.5
KI-2	8512.3	7318.7	7681.0	4620.4	4620.4	4620.4
KI-3	1542.6	1785.7	1371.0	1729.7	2008.7	1405.5
KI-4	798.7	704.6	686.4	420.0	453.7	383.5
KI-5	8346.3	6794.4	7535.3	4105.1	4105.1	4247.2
KI-6	15.3	20.4	14.0	25.0	27.2	18.6
KI-7	3.5	2.9	1.9	6.4	4.2	2.6
KI-8	1848.8	1872.4	1891.4	1856.1	1885.0	1913.8
NG2 (as of 2100)						
KI-1	16073.8	16073.8	16073.8	16073.8	16073.8	16073.8
KI-2	13185.5	13185.5	13185.5	13185.5	13185.5	13185.5
KI-3	0.0	0.0	0.0	1115.0	636.4	790.7
KI-4	2420.5	2420.5	2420.5	1305.5	1784.1	1629.8
KI-5	13429.8	13429.8	13429.8	13429.8	13429.8	13429.8
KI-6	22.2	22.2	22.2	8.3	14.3	12.4
KI-7	3.0	3.0	3.0	1.0	1.9	1.6
KI-8	1837.1	1837.1	1837.1	1837.1	1837.1	1837.1
NG3 (as of 2100)						
KI-1	5691.7	5691.7	5691.7	5691.7	5691.7	5691.7
KI-2	4961.6	4961.6	4961.6	4961.6	4961.6	4961.6
KI-3	0.0	0.0	0.0	131.0	0.0	0.0
KI-4	826.5	826.5	826.5	695.5	826.5	826.5
KI-5	4753.4	4753.4	4753.4	4753.4	4753.4	4753.4
KI-6	7.8	7.8	7.8	6.1	7.8	7.8
KI-7	1.0	1.0	1.0	0.7	1.0	1.0
KI-8	464.0	464.0	464.0	464.0	464.0	464.0
Global situation (as of 2100)						
KI-1	32485.2	31113.0	31530.2	27944.0	27944.0	27944.0
KI-2	26659.4	25465.8	25828.1	22767.5	22767.5	22767.5
KI-3	1542.6	1785.7	1371.0	2975.7	2645.1	2196.2
KI-4	4045.8	3951.7	3933.4	2421.1	3064.3	2839.8
KI-5	26529.6	24977.6	25718.5	22288.3	22288.3	22430.4
KI-6	45.2	50.3	44.0	39.5	49.2	38.8
KI-7	7.6	6.9	5.9	8.2	7.1	5.2
KI-8	4150.0	4173.5	4192.5	4157.3	4186.1	4214.9

Screening for dominance

When applying the screening for dominance technique to identify non-dominated and dominated options among the set of considered feasible options for each group of countries and for the whole world, the following observations were made:

NG1 standpoint. All NES deployment scenarios for NG1 are non-dominated.

NG2 standpoint. All NES deployment scenarios for NG2 are to be considered as non-dominated (NG0Sep-High-L1L2H1F1, NG0Sep-High-L1L2H1F2 and NG0Sep-High-L1L2H1F3 provide the identical performance).

NG3 standpoint. All NES deployment scenarios for NG3 are to be considered as non-dominated (NG0Sep-High-L1L2H1F1, NG0Sep-High-L1L2H1F2, NG0Sep-High-L1L2H1F3, NG0Syn-High-L1L2H1F2 and NG0Syn-High-L1L2H1F3 provide the identical performance).

Global standpoint. All NES deployment scenarios for the whole world are non-dominated.

Weighting factors

The base case weighting option for all groups of countries without loss of generality was evaluated by the same method which was used for identifying weights for the long term perspective considered in Chapter 2 of this publication, i.e., the so-called ‘equal weights’ (or ‘mean weights’) option. This weighting option assumes that all indicators are of equal importance [4.7, 4.8].

As was already mentioned, this approach may be applied when there is no information from decision-makers and experts or information on the relative importance of criteria is not sufficient to reach a decision that is rather typical of the long term perspective. In this case the equal weight approximation with subsequent sensitivity analysis to weights is to be applied. According to this assumption, any individual base-case weight is equal to 0.125 within the present study.

As already mentioned, the main goal of applying group decision support methods is searching for a compromised option, which may be considered adequate or appropriate for all involved parties. Of note, such a compromised option will be probably not the best one for any individual group as well as for the case when the problem is considered from the global viewpoint.

A lack of commonly applied proven methodologies for group decision support for selecting the conjoint strategies of NES deployment with account of different country groups’ priorities is a characteristic feature. This complicates achieving a coordinated conclusion regarding a preferable technology related or institutional alternative.

Relevant decision support problems may be considered utilizing both formal mathematical procedures assuming aggregating scores assigned to individual parties into overall scores and non-formal approaches based on advanced uncertainty treatment procedures concerning weights and indicators within the conjoint consideration of a set of relevant problems requiring appropriate decision support. Both of these approaches will be applied and examined below.

Shown below are the ranking results for the base-case option for each group of countries and the whole world (Fig. 4.7): the overall scores of options are broken down into high-level objectives according to the structure of the objective tree. The results of the uncertainty analysis in regard to weights are presented in Fig. 4.8 which demonstrates spreads in overall scores (mean value, 5th, 25th, 75th and 95th percentiles) and Fig. 4.9 illustrating areas of high-level objective weights for which some options from the given feasible set may take the first rank (all results provided for each group of country and the whole world). Fig. 4.10 presents the group's aggregate scores of options and the results of the uncertainty analysis concerning importance of weights of country groups.

Comparative evaluation of synergetic and non-synergetic NES deployment scenarios

The ranking results for the base case weighting option for NG1, NG2, NG3 and global standpoints are presented in Fig. 4.7. This figure also provides a decomposition of overall scores on specific scores in accordance with the objective tree structure. The following general observations could be mentioned: all the three separate NES deployment scenarios (NG0Sep-High-L1L2H1F1, NG0Sep-High-L1L2H1F2, NG0Sep-High-L1L2H1F3) take the last three ranks for NG1, NG2, and global standpoints. From the NG3 standpoint, these separate scenarios and two synergetic scenarios (NG0Syn-High-L1L2H1F2, NG0Syn-High-L1L2H1F3) have the same overall scores. It may be concluded that there is a consensus among different standpoints that separate NES deployment scenarios are the least attractive options in comparison with synergetic ones.

Three synergetic NES deployment scenarios (NG0Syn-High-L1L2H1F1, NG0Syn-High-L1L2H1F2, NG0Syn-High-L1L2H1F3) reach the three first positions but there are some differences in which scenarios can take the first rank and second ranks. For the NG2 and NG3 standpoints, the most attractive scenario is NG0Syn-High-L1L2H1F1. NG0Syn-High-L1L2H1F3 may be considered as an option taking the second rank (it is clearly so for NG2, but NG3 is indifferent regarding NG0Syn-High-L1L2H1F2 and NG0Syn-High-L1L2H1F3 because their overall scores are equal). For the NG1 and global standpoints, the most attractive scenario is NG0Syn-High-L1L2H1F3. NG0Syn-High-L1L2H1F1 takes the second place.

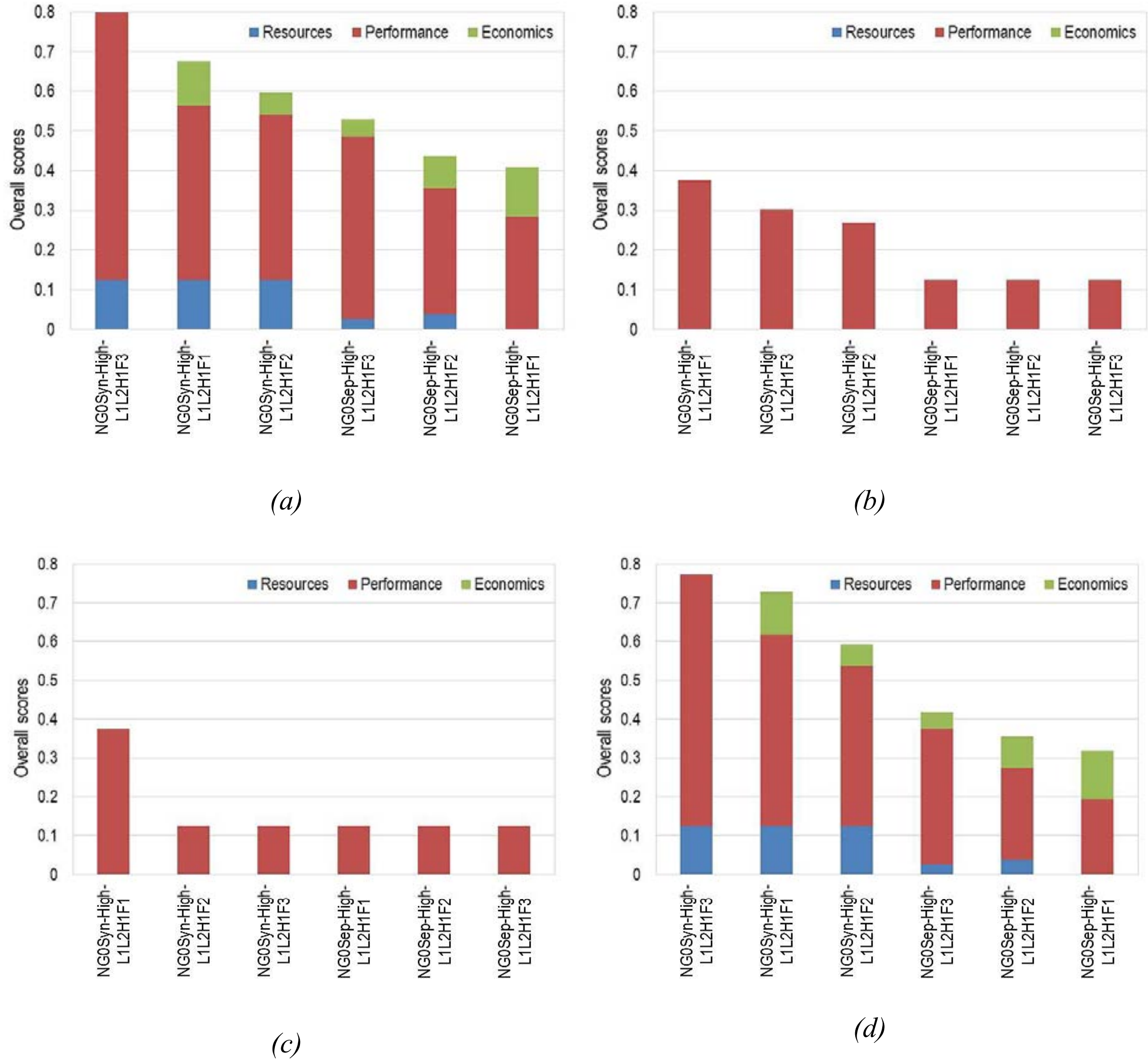


FIG. 4.7. Ranking results for the base case weighting option: (a) NG1 standpoint; (b) NG2 standpoint; (c) NG3 standpoint; (d) global standpoint.

Given below are some general comments regarding the structure of the overall scores for the options from different standpoints. Table 4.11 arranges for data on high-level objective scores highlighting potential merits and demerits associated with the options given.

NG1 standpoint. The NG0Syn-High-L1L2H1F3 option has the highest performance score that provides a chance for this option to take the first place even if this option has the lowest economics score. The second rank is taken by NG0Syn-High-L1L2H1F1 with the better economic score and less attractive performance score as compared to the NG0Syn-High-L1L2H1F3. The resource scores of all the synergetic options are the same and they are higher than those of the separate scenarios. A potential merit of the separate scenarios is higher values of the economics scores as compared to the synergetic scenarios (because of the smaller share of fast reactors in the reactor fleet) but the low performance and resources scores do not allow the separate scenarios to achieve higher ranks.

NG2 standpoint. The 'resource' and 'economics' high-level objective scores of all the options are equal to zero because the relevant indicators belonging to these objectives have identical values for the whole set of options. The differences in overall scores of the given options are due to the indicators belonging to the 'performance' high-level objective. NG0Syn-High-L1L2H1F1 has the highest performance value because this scenario requires more effective reprocessing of NG2 SNF to produce plutonium to feed the F1 fast reactors being deployed in NG1.

NG3 standpoint. The 'resource' and 'economics' high-level objective scores of all the options are equal to zero because the relevant indicators belonging to these objectives have identical values for the whole set of options. The performance scores for all the scenarios of this group excluding NG0Syn-High-L1L2H1F1 are analogous and lower than that of NG0Syn-High-L1L2H1F1. For NG2 and NG3, NG0Syn-High-L1L2H1F1 has the highest performance value because this scenario requires more effective reprocessing of NG3 SNF to produce plutonium to feed the F1 fast reactors being deployed in NG1.

Global standpoint. For the global standpoint, the ranking results are explained the same way as it is done for the NG1 standpoint. The scores of the 'resource' and 'economics' high-level objectives for NG1 and the whole world are identical. The scores of the 'performance' high-level objective for these two standpoints are strongly correlated (the correlation coefficient is equal 0.94).

Of note, the overall scores ranges are different for different standpoints: for NG1, the overall scores are within the range from 0.4 to 0.8; for NG2 and NG3, the overall scores are within the range from 0.1 to 0.4. This fact needs to be considered while explaining the ranking results obtained based on overall scores of individual groups aggregated into global overall scores.

The spreads in overall scores for NG1, NG2, NG3 and global standpoints with indication of mean value, 5th, 25th, 75th and 95th percentiles are shown in Fig. 4.8. The approach used for evaluating the spreads was described in Chapter 2.

NG1 standpoint. Among all the options for this group, NG0Syn-High-L1L2H1F1 and NG0Syn-High-L1L2H1F3 need to be considered in detail: these two options have more attractive spreads in overall scores allowing them to reach the highest values. At the same time, the F3-based option has a smaller spread in scores as compared to the F1-based option, which makes NG0Syn-High-L1L2H1F3 more attractive than NG0Syn-High-L1L2H1F1 for this group.

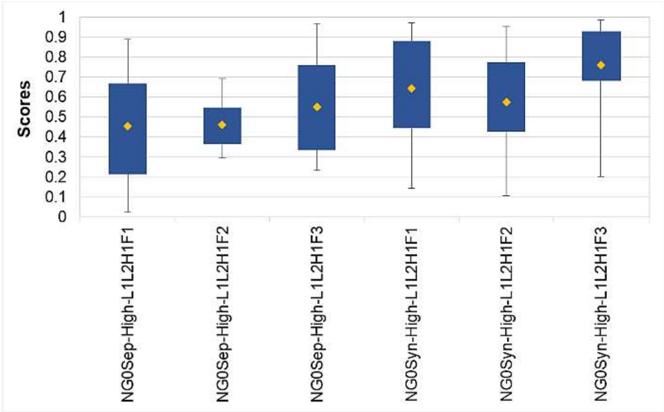
NG2 standpoint. The spreads in overall scores for all the three separate scenarios in this group are the same: the mean value is 0.108 while the 25th and 75th percentiles for them are 0.002 and 0.113, respectively. NG0Syn-High-L1L2H1F1 is characterized by higher overall scores as compared to NG0Syn-High-L1L2H1F2 and NG0Syn-High-L1L2H1F3 in the statistical sense: all the statistical measures (the mean value, 5th, 25th, 75th and 95th percentiles) seem to be more attractive for NG0Syn-High-L1L2H1F1. NG0Syn-High-L1L2H1F3 may be considered as the next attractive option after NG0Syn-High-L1L2H1F1.

NG3 standpoint. The spreads in overall scores for all the scenarios in this group excluding NG0Syn-High-L1L2H1F1 are identical (all the statistical measures are the same as for the three separate scenarios for NG2). It can be unambiguously concluded that the NG0Syn-High-L1L2H1F1 option is the most attractive one for this group being statistically distinguished as compared to others (the mean value is 0.404 while the 25th and 75th percentiles for them are 0.091 and 0.694, respectively).

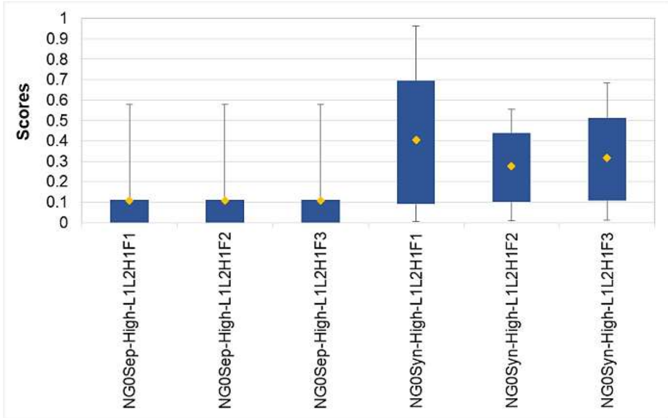
Global standpoint. The tendencies in spreads in overall scores for the global standpoint are similar to those observed for the NG1 standpoint with one difference: NG0Syn-High-L1L2H1F1 and NG0Syn-High-L1L2H1F3 have more similar spreads in overall scores as compared to the NG1 standpoint that makes them less distinctive for the global standpoint.

TABLE 4.11. HIGH-LEVEL OBJECTIVE SCORES OF NES DEPLOYMENT SCENARIOS FOR DIFFERENT STANDPOINTS

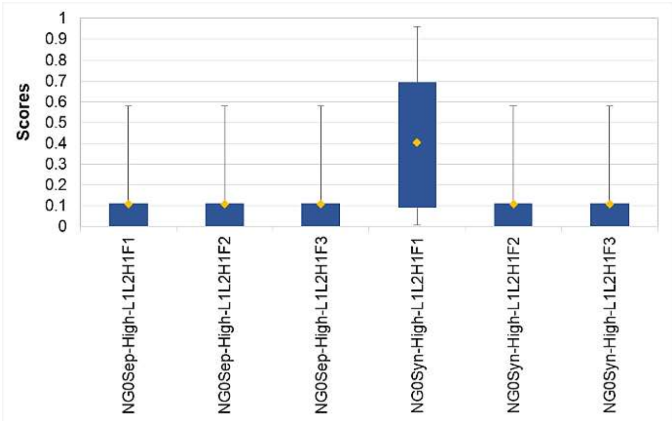
High-level objectives	NG0Sep-High-L1L2H1F1	NG0Sep-High-L1L2H1F2	NG0Sep-High-L1L2H1F3	NG0Syn-High-L1L2H1F1	NG0Syn-High-L1L2H1F2	NG0Syn-High-L1L2H1F3
NG1						
Resources	0.000	0.038	0.026	0.125	0.125	0.125
Performance	0.284	0.318	0.459	0.440	0.416	0.674
Economics	0.125	0.080	0.043	0.111	0.055	0.000
NG2						
Resources	0.000	0.000	0.000	0.000	0.000	0.000
Performance	0.125	0.125	0.125	0.375	0.268	0.302
Economics	0.000	0.000	0.000	0.000	0.000	0.000
NG3						
Resources	0.000	0.000	0.000	0.000	0.000	0.000
Performance	0.125	0.125	0.125	0.375	0.125	0.125
Economics	0.000	0.000	0.000	0.000	0.000	0.000
Global situation						
Resources	0.000	0.038	0.026	0.125	0.125	0.125
Performance	0.193	0.238	0.349	0.492	0.411	0.649
Economics	0.125	0.080	0.043	0.111	0.055	0.000



(a)



(b)



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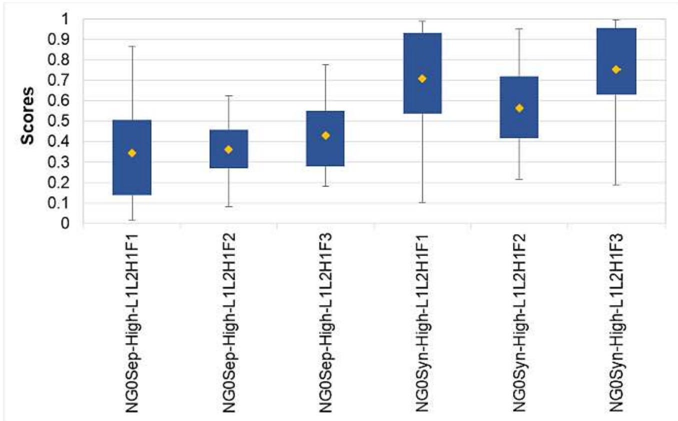


(d)

FIG. 4.8. Spreads in overall scores (the mean value, 5^{th}, 25^{th}, 75^{th} and 95^{th} percentiles are shown): (a) NG1 standpoint, (b) NG2 standpoint, (c) NG3 standpoint, (d) global standpoint.

Figure 4.9 illustrates the mapping of the first-rank options for the NG1, NG2, NG3 and global standpoints according to the procedure described in Chapter 4.2. Such visualization is especially useful for problems assuming group decision making when it is necessary to find trade-off options, which may be suitable for different decision-makers. In such situations, a screening of the most preferable options for different weight combinations and different perspectives allows a better understanding of which directions experts could move to find a compromise.

NG1 standpoint. NG0Sep-High-L1L2H1F1, NG0Syn-High-L1L2H1F1 and NG0Syn-High-L1L2H1F3 are the options that can take the first rank for NG1 (the probabilities of preferences for relevant options are equal to 8, 62 and 30%, correspondingly). NG0Syn-High-L1L2H1F1 occupies the central area of the high-level objective weight space while NG0Syn-High-L1L2H1F3 is becoming the most attractive option for the low values of the ‘economics’ high-level objective weight. NG0Sep-High-L1L2H1F1 can take the first rank if the ‘economics’ high-level objective weight is high.

NG2 standpoint. NG0Syn-High-L1L2H1F1 occupies about 83% of the high-level objective weight space, thereby confirming that this option is the most attractive and robust one for NG2. Formally, any separate scenario can also take the first rank (the performance of all the separate scenarios is identical for NG2) if the weight of the 'performance' high-level objective is equal to zero. The probability of preferences for this option is about 17%.

NG3 standpoint. The situation with the first-rank options for NG3 is the same as for NG2: NG0Syn-High-L1L2H1F1 is the most attractive and robust option for NG3.

Global standpoint. The trends for the global standpoint regarding the first-rank options are similar to those observed for the NG1 standpoint with one difference: the probability of preferences for NG0Syn-High-L1L2H1F1 is increasing while probabilities of preferences for NG0Syn-High-L1L2H1F3 and NG0Sep-High-L1L2H1F1 are decreasing in comparison with the NG1 standpoint.

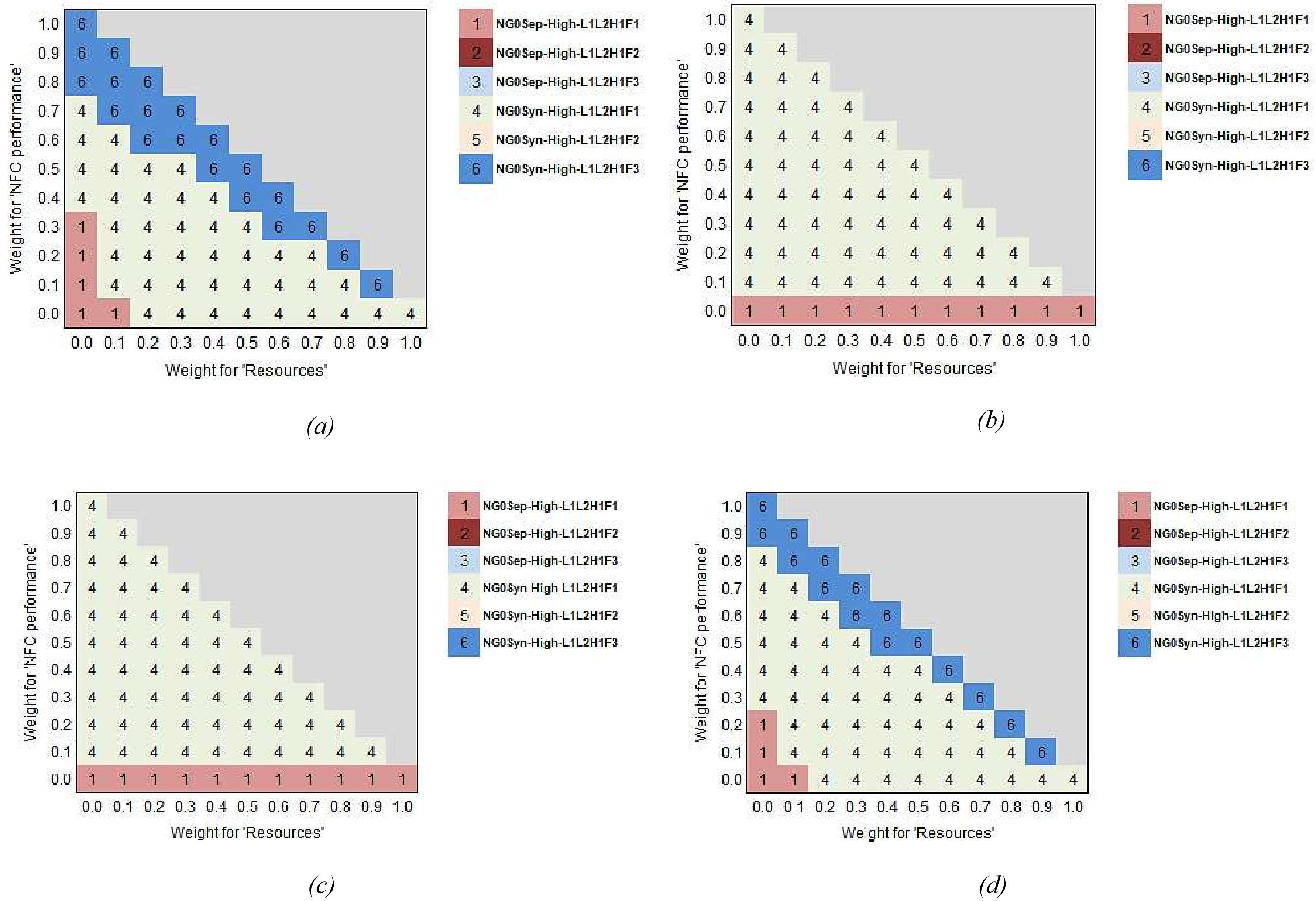


FIG. 4.9. Mapping of the first-rank options: (a) NG1 standpoint, (b) NG2 standpoint, (c) NG3 standpoint, (d) global standpoint.

The simplest way to extend the MAVT framework for group decision making assumes that the groups' aggregate value depends on the values attained by the particular group actors [4.16]. This approach assumes aggregating the values of options assigned to different actors (the value function represents the strength of the preference). The group's aggregate value function can be represented as:

$$V(x_i) = \sum W_k \sum w_{ki} v_{ki}(x_i) \tag{4.1}$$

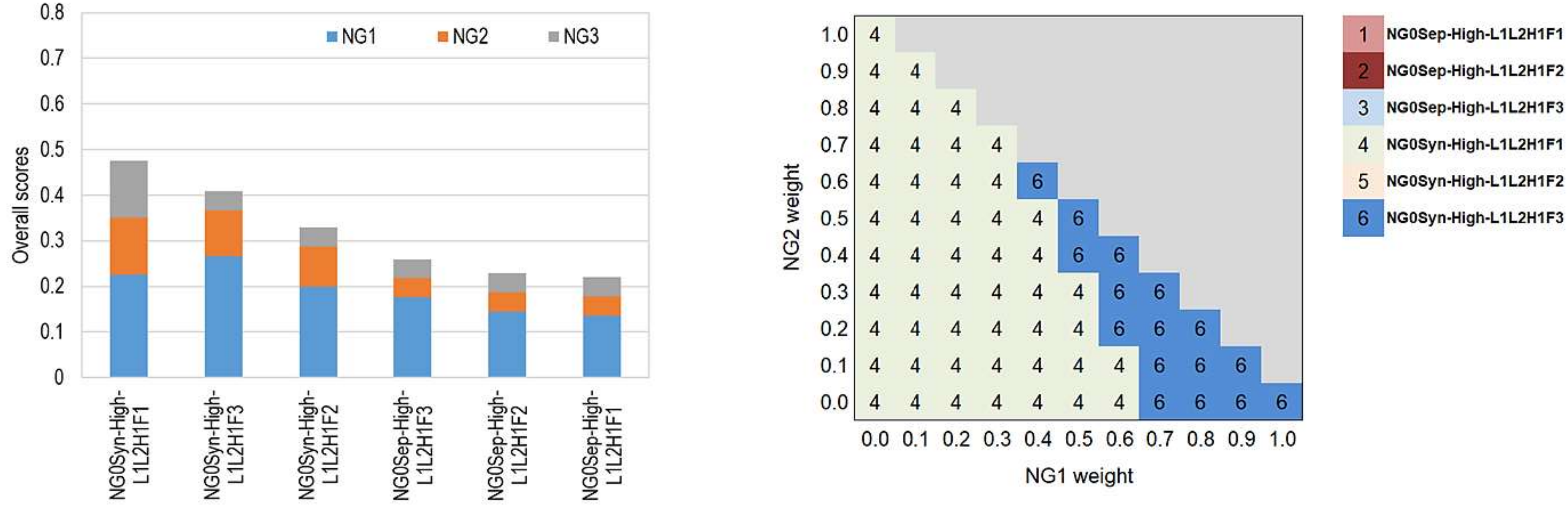
where W_k is the importance weight of the *k-th* group actor/decision maker, and the latter summation corresponds to the overall scores for the option x_i for this actor.

While using the MAVT framework in the group decision support, the individual overall scores are evaluated, aggregated and used for deriving relevant decision support advice for the whole group. Nevertheless, it is still required to carry out a detailed uncertainty analysis in order to mitigate the possibility of biases.

Following this approach, Fig. 4.10. (a) shows aggregated overall scores of options weighted according to the equal weighting approach (equal importance of each country group), demonstrating that, within such an approach to the group decision support, NG0Syn-High-L1L2H1F1 is the most preferred option followed by NG0Syn-High-L1L2H1F3. These two options have the aggregated overall scores equal to 0.48 and 0.41, respectively. The highest contribution to the aggregated overall scores is provided by NG1, the lowest contribution to the aggregated overall scores is provided by NG3.

Considering that the importance weight is a per-se concept, which cannot be explicitly articulated, an uncertainty analysis concerning the importance weights is required. Figure 4.10 (b) represents the mapping of the preferred options for different country group importance weights, showing that NG0Syn-High-L1L2H1F3 may become the most attractive scenarios for the high importance weight for NG1 and the low importance weight for NG2 in the aggregation procedure. The probability of preferences for NG0Syn-High-L1L2H1F3 is equal to 24% and the probability of preferences for NG0Syn-High-L1L2H1F1 is equal to 76%. Thus, it may be concluded that NG0Syn-High-L1L2H1F1 is a more robust preferred option from the regional viewpoint.

It is worth noting that, from the global standpoint, the most preferred option is NG0Syn-High-L1L2H1F3 followed by NG0Syn-High-L1L2H1F1, their relevant overall scores are equal to 0.77 and 0.73, respectively (see Fig. 4.7(d)). This fact indicates that the differences in ranking may occur if the problem is considered from the regional and global positions: the most preferred option from the global position (identified using classical MCDA methods assuming a single decision-maker) may not correspond to the most preferred option obtained considering regional distinctions, specifics and preferences (evaluated using group decision support methods).



(a) (b)

FIG. 4.10. Overall aggregate values: (a) ranking results for the equal country group importance weights; (b) mapping of the preferred options for different country group importance weights.

4.1.3.2. Results and discussions

The performed analysis has demonstrated that there is a consensus among different standpoints that the separate NES deployment scenarios are the least attractive options in comparison with the synergetic ones. Among all the considered synergetic scenarios, two of them may be provided for the final selection, namely, NG0Syn-High-L1L2H1F1 an NG0Syn-High-L1L2H1F3.

NG0Syn-High-L1L2H1F1 seems to be the most attractive option for the NG2 and NG3 standpoints, while NG0Syn-High-L1L2H1F3 is the most attractive for the NG1 standpoint and if the problem is considered from the global position (without considering regional aspects and preferences). NG0Syn-High-L1L2H1F1 directly follows NG0Syn-High-L1L2H1F3 in the ranking results for the NG1 and global standpoints and is characterized by a better economic performance and lower performance characterizing efficiency of nuclear material management in the nuclear fuel cycle.

The following general observation has been clearly illustrated: differences in ranking may occur if the problem is considered from the regional and global positions. The most preferred option from the global position obtained using classical MCDA methods assuming a single decision-maker may not correspond to the most preferred option identified considering regional distinctions, specifics and preferences found using group decision support methods.

Considering the results of uncertainty examinations demonstrating the probability for preferences of relevant options and the results of aggregating individual overall scores into overall scores, it can be concluded that NG0Syn-High-L1L2H1F1 seems to be a trade-off and more robust option. Notwithstanding the fact that this option does not have the highest potential for NG1, it may be rather promising for NG1 because its deployment provides benefits in terms of improving the economic performance and keeping the fuel cycle performance at a level acceptable for NG1.

At the same time, if the global priorities dominate the national ones, the most perspective option will be NG0Syn-High-L1L2H1F3, which is the most promising option for the NG1 and global standpoints and is the second most promising option for NG2 and an indifferent option for NG3. For real-world problems, the mentioned ambiguity may be resolved by applying the additional group decision and negotiation support methods (social choice or voting rules, etc.).

This section provides the results of the NES deployment scenarios compared within the heterogeneous world model, including two groups, i.e., separate and synergetic ones. In this regard, it is interesting to contrast these results with the results obtained within the homogeneous world model, which is most commonly used when studying NES deployment scenarios (see Chapter 2 of this document). The main point here is that all relevant global homogeneous NES deployment scenarios are more preferred than synergetic heterogeneous ones, which, in their turn, are more attractive than separate heterogeneous ones. Hence, the NES deployment scenarios elaborated within the homogeneous world model may be considered as demonstrating the marginal cooperative capabilities, i.e., there are no constraints on cooperation in the relevant fuel cycle areas.

Finally, it is worth noting that the joint comparative evaluations (including the detailed uncertainty examination) of the options from the standpoints of all the involved actors' positions make it possible to identify the availability of consistent and inconsistent options for the individual participants and to highlight directions for reaching a compromise. This consideration may help identify suitable trade-off options and associated costs, benefits and risks for each individual actor or determine whether a second round of comparative evaluations is needed for some actors to reach a consensus.

4.1.4. Conclusions

The present case study has provided an in-depth comparative analysis of the GAINS NES deployment scenarios based on an extensive utilization of advanced uncertainty treatment and group decision support methods. This study was focused on two tasks:

(1) To consider and evaluate the time factor impact within comparative evaluations of NES deployment scenarios, which necessitates applying dynamic multi attribute analysis frameworks;
(2) To identify the most promising trade-off NES options from the multi-agent viewpoints (positions of different country groups), which requires group decision support methods.

Within the first task, a comparative evaluation was carried out for eleven global GAINS NES deployment scenarios (within the homogeneous world model) based on eight key indicators arranged in the three-level objective tree, which were assessed as of 2030, 2050 and 2100.

Within the second task, a comparative evaluation was carried out for six regional GAINS NES deployment scenarios (within the heterogeneous world model for separate and synergistic scenarios) based on eight key indicators arranged in the three-level objective tree, which were assessed as of 2100.

It was observed that the ranking results, results of sensitivity/uncertainty analyses and relevant suggestions concerning the most attractive options are different for the different periods/ perspectives. The more distant the time perspective is, the more resolved and stable the ranking results are. The applied dynamic multi attribute analysis frameworks with simultaneous consideration of different time perspectives make it possible to reach a consensus, utilizing advanced uncertainty treatment approaches within different time frames.

It is found that all the relevant global homogeneous NES deployment scenarios are more preferred than the synergetic heterogeneous ones, which, in their turn, are more attractive than the separate heterogeneous ones. Hence, the NES deployment scenarios elaborated within the homogeneous world model may be considered as demonstrating the marginal cooperative capabilities, i.e., there are no constrains on cooperation in the relevant areas.

The differences in ranking may occur if the problem is considered from the regional and global positions. The most preferred option from the global position found using classical MCDA methods assuming a single decision maker may not correspond to the most preferred option obtained considering regional distinctions, specifics and preferences identified using group decision support methods. In this regard, when performing a comparative evaluation of joint NES deployment scenarios assuming to identify the most preferred option, it is required to clarify which priorities are dominated within the relevant case studies, i.e., national or global ones.

Based on the results of the sensitivity/uncertainty analysis, the additional analysis of alternatives by the supplementary decision support methods and the entire set of graphical and attribute information, the preferable NES options for the homogeneous and heterogeneous world models were identified considering preferences assigned to different time frames and different country groups (NG1, NG2 and NG3) regarding NES objectives. It was also possible to clarify potential merits and demerits concerning relevant nuclear technologies in terms of the complete NES that made it possible to provide advice for improving their performance.

The analysis refined the previous case study within the KIND collaborative project on the application of several MCDA methods to comparative evaluations of 11 global GAINS NES deployment scenarios (within the homogeneous world model) based on nine key indicators arranged in the single level objective tree, which were assessed as of 2100 and then aggregated using four possible weighting options.

Notwithstanding that the sets of key indicators and their structuring in the previous and present studies are different and the scope of this study also includes consideration of different time frames and regional perspectives, both studies provide very similar suggestions for the most promising scenarios and highlight merits and demerits of the relevant technological options. This is, in principle, a very good circumstance, demonstrating confidence (stability/robustness) of conclusions concerning merits and demerits of options under consideration regardless of the applied comparative evaluation methodologies.

At the same time, the added value provided by the more detailed analysis presented in this document is that it was possible to highlight the potential of the NES deployment scenarios with the F1 fast reactor more clearly, namely as trade-off options balancing the NES performance within the different time frames and regional standpoints. A general observation on this point is given below.

From the global standpoint (the homogeneous world model), the most effective in the system is the F3 fast reactor in terms of nuclear material flow optimization in the system and relevant deployment scenarios, especially in combination with the M1 molten salt reactor (because the MSR shows higher effectiveness in these scenarios in comparison with ADS in the system): it may provide an outstanding performance of the relevant NES option in the case when the NES economic performance is of no importance.

The scenarios with the F1 fast reactor closely follow the most promising options based on the F3 fast reactor and can take the first rank if it is required to improve the economic performance while retaining an adequate nuclear material flow performance and resource utilization. Such cases take place within the near- and medium term perspectives. In this regard, the scenarios based on the F1 fast reactor may be considered as trade-off options for the near-, medium- and long term perspectives.

From the regional standpoint (the heterogeneous world model), the synergetic scenario with the F1 fast reactor seems to be the most attractive trade-off option in case the national priorities dominate the global one. If the global priorities dominate the national ones, the most perspective option will be the synergetic scenario with the F3 fast reactor.

Finally, from the viewpoint of the complete NES for both the homogeneous and heterogeneous world models, the scenarios with the F2 fast reactor cannot be promising if the F1- and F3-based scenarios are available; the F2 fast reactor is less attractive than its competitors, i.e., the F3 fast reactor, which is more expensive but more efficient for the system in terms of fuel cycle material flow management, and the F1 fast reactor, which is cheaper but provides system efficiency comparable to the F2 fast reactor.

A detailed consideration of the NES deployment scenarios from different perspectives and viewpoints presented in this document has included examination of NESs involving simultaneously different types of fast reactors to explore possible synergies among them leading to enhanced NES sustainability. In this regard, different fast reactor technologies are not to be considered as competing options but, on the contrary, they could be viewed as necessary elements to achieve a NES structure that is more balanced on costs, benefits and risks.

In the end, it could be concluded that the utilization of well-known MCDA techniques extended by sophisticated tools for treating uncertainties makes it possible to search for compromises among the conflicting factors, including the time factor and the multi-agent perspective that certainly is to determine the performance of global NES deployment scenarios. It does additionally confirm that an uncertainty analysis is a necessary step in order to provide a sound basis for decisions.

4.2. APPLICABILITY OF THE KIND COMPARATIVE EVALUATION APPROACH TO SCREENING OF A LARGE SET OF NUCLEAR ENERGY SYSTEM AND FUEL CYCLE OPTIONS

This country-neutral case study demonstrates the applicability of the INPRO/KIND comparative evaluation approach to evaluation and screening of a large set (several dozens) of nuclear energy system/fuel cycle options. The analyses below are based on the fuel cycle performance data obtained from the fuel cycle evaluation and screening study supported by the U.S. Department of Energy (U.S. DOE) [4.17]. The primary goal of the present study was to cross-check the U.S. DOE fuel cycle evaluation and screening framework vs. the INPRO/KIND comparative evaluation approach as well as the relevant analytical tools. The reason to perform this case study was that the INPRO/KIND comparative evaluation approach and tools are more focused on ranking, although they can probably be used for classification and screening as well. The methodological patterns used in the classification and screening studies differ from the ones applied in pure ranking studies which require no or limited preference information. Preliminary considerations based on the INPRO comparative evaluation and ranking toolkit have demonstrated that the relevant analytical tools can be applied not only for the options' ranking and selecting the most preferable option from a given set, but also for classification and screening studies. In this regard, a specific analysis based on the well-known U.S. DOE fuel cycle evaluation and screening study will make it possible to confirm and demonstrate the relevant capabilities of the INPRO toolkit.

4.2.1. Background

In 2011, the Office of Nuclear Energy of the U.S. DOE launched a study to evaluate and screen different fuel cycle alternatives of potential national interest [4.17]. The study tackled a variety of cradle to grave nuclear fuel cycles including once-through as well as closed nuclear fuel cycles with a recycle of plutonium or all transuranics. The objective was to identify a few nuclear fuel cycle options with the potential to improve significantly over what is being offered by the present-day nuclear fuel cycle. The results were intended to strengthen the basis for prioritisation of the R&D activities. The study was completed in 2014: the obtained information about the potential benefits and challenges of nuclear fuel cycle options was intended "to strengthen the basis and provide guidance for the activities undertaken by the U.S. Department of Energy, Office of Nuclear Energy, Fuel Cycle Research and Development program" [4.18]. The investigation of nuclear fuel cycle options was based on the following pre-defined strategies for the nuclear fuel cycle [4.18]:

— “Once-through — a “once-through” fuel cycle uses nuclear fuel only once in the nuclear fission system, followed by storage and disposal”. A once-through “fuel cycle processes intact spent nuclear fuel for waste management purposes only (e.g., to separate long-lived isotopes from short-lived” ones “and then dispose of them) but does not include re-use of such fuel” [4.18].
— “Limited recycle — a “limited-recycle” fuel cycle recycles fuel one or” more “times, either in the same nuclear fission system or” in “another” one. “Spent fuel, high- and low-level” wastes “are disposed of in limited-recycle fuel cycle options” [4.18].
— “Continuous recycle — a “continuous-recycle” fuel cycle recycles fuel indefinitely, either in the same nuclear fission system” or in “another” one. Only high- and low-level wastes “are disposed of; no spent fuel is disposed of in continuous-recycle fuel cycle options” [4.18].

An approach considering the fundamental characteristics of the fuel cycle rather than specific technologies for its implementation made it possible to create a comprehensive number of alternatives, including once-through or closed nuclear fuel cycles, reactors with thermal, fast and intermediate neutron spectra, and accelerator driven systems (ADS) with uranium based and thorium-based fuel, as shown in Table 3 in Ref. [4.18].

The study addressed 4398 groups representing the full spectrum of nuclear fuel cycle alternatives, including 30 once-through nuclear fuel cycles, 336 single recycles, and 4032 two stage recycles. Starting with this set of fuel cycle option groups, many of them were combined into larger groups using a series of operations based on the similarity of their expected physics-based performance with respect to the evaluation criteria. Towards the end, these fuel cycle options were compiled into 40 fuel cycle groups, called Evaluation Groups (EGs), including 8 once-through evaluation groups, 10 limited recycle evaluation groups and 22 continuous recycle evaluation groups that were considered to be sufficient to comprehensively represent all the fuel cycle options to inform on their potential for significant improvements, see Table 3 in Ref. [4.18].

The criteria for evaluation were structured into nine groups representing the evaluation areas of safety, economics, environment, proliferation resistance, nuclear security and the sustainable development objectives. Benefits were addressed with the first six groups, while the other three were used to evaluate risks (challenges). A multi attribute unitality analysis (MAUT) has then been performed to evaluate the selected nuclear fuel cycle alternatives on a comparative basis [4.18]. Eleven sets of weighting factors were considered, and additional parametric variations were carried out to reflect the range of possible policy guidance and illustrate the effects of specific policy choices. The analysis was based on the Fuel Cycle Evaluation and Screening Software (SET Tool)[49]. Based on the approach applied, the following groups of the most promising, additional potentially promising and other potentially promising fuel cycles were identified:

— Most promising fuel cycles:
  - “EG23 Continuous recycle of U/Pu with new natural-U fuel in fast critical reactors;
  - EG24: Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors;

[49] More details about the SET tool can be found at: https://fuelcycleevaluation.inl.gov/SitePages/Fuel%20Cycle%20Evaluation%20and%20Screening%20Software%20(SET%20Tool).aspx

- EG30: Continuous recycle of U/TRU with new natural-U fuel in both fast and thermal critical reactors;
- EG29: Continuous recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors" [4.18].

— Additional potentially promising fuel cycles:

- "EG06: Once-through using Th fuel to very high burnup in thermal ADS;
- EG07: Once-through using natural-U fuel to very high burnup in thermal or fast ADS;
- EG08: Once-through using Th fuel to very high burnup in fast ADS;
- EG09: Limited recycle of U/TRU with new natural-U fuel to very high burnup in fast critical reactors;
- EG26: Continuous recycle of ^{233}U/Th with new Th fuel in thermal critical reactors;
- EG28: Continuous recycle of ^{233}U/Th with new Th fuel in fast critical reactors;
- EG33: Continuous recycle of U/Pu with new natural-U fuel in both fast ADS and thermal critical reactors;
- EG34: Continuous recycle of U/TRU with new natural-U fuel in both fast ADS and thermal critical reactors;
- 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;
- EG40: Continuous recycle of ^{233}U/Th with new Th fuel in fast ADS and thermal critical reactors" [4.18].

— Other potentially promising fuel cycles:

- "EG04: Once-through using natural-U fuel to very high burnup in fast critical reactors;
- EG10: Limited recycle of 233U/Th with new Th fuel in fast and/or thermal critical reactors;
- EG14: Limited recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors" [4.18].

Within this case study, in order to demonstrate the applicability of the INPRO/KIND comparative evaluation approach and toolkit to evaluation and screening of multiple (several dozens of) nuclear energy system/fuel cycle options, the relevant analysis was carried out based on the fuel cycle performance data from the U.S. DOE fuel cycle evaluation and screening study. The results of this analysis are summarized as follows:

— Most promising fuel cycles: EG23, EG24, EG30, EG29.
— Additional potentially promising fuel cycles: EG06, EG07, EG08, EG09, EG26, EG28, EG33, EG34, EG37, EG38, EG40.
— Other potentially promising fuel cycles: EG04, EG10, EG14.

As it can be seen, these results are in full compliance with those presented in the U.S. DOE report [4.18]. The details of the case study are provided below.

4.2.2. Screening as an MCDA based process

The primary MCDA objective is to help a decision maker to choose, rank or sort alternatives within a finite set according to multiple criteria and information about decision-makers' preferences [4.19]. Regarding the basic MCDA problem of choosing the best alternative, it is useful for a decision maker to start by eliminating options that will apparently not warrant further attention [4.20]. This kind of analysis can be carried out using limited preference information. This procedure is known as screening [4.21]. Formally speaking, screening is an MCDA-based process that reduces a large set of alternatives to a smaller one that most likely includes the best option. The more options are considered, the more valuable screening is.

Since screening can reduce later efforts on selecting the most preferable option by focusing on more attractive ones from the overall set of feasible alternatives, some of the options from the initial set could be screened out from further consideration. The more preference information is involved in screening, the more options can be screened out. Theoretically, preference information can be sufficiently detailed so that only a single option is left after screening. At the same time, information provided by decision-makers for screening is usually incomplete due to the fact that decision analysts may prefer not to spend many efforts on a comprehensive examination of preference information within the screening phase.

Worth noting is that screening can be interpreted through the sorting or classification framework since screening assists in arranging alternatives into several groups. The following specific requirement can sometimes be put forward for the screening procedure: screening need to give the decision-maker a range of options that emphasizes different aspects of the decision problem. It means that screening is not to give favour to a particular set of values, nor is it to yield a set of options that are essentially similar.

Many MCDA-based analytical approaches have been proposed to screen alternatives: Pareto optimality-based screening; screening techniques based on trade-off weights; non-trade-off weights; aspiration levels; data envelopment analysis along with many other heuristic frameworks [4.211]. For screening, it is possible to modify the popular MCDA methods. Different screening techniques can be characterized by different screening efficiencies and require different preference information.

It was also proposed to carry out sequential screening assuming that different screening procedures can be sequentially applied to the initially screened set of alternatives specified in the previous steps [4.5]. The follow-up screening procedures could be based on more detailed preference information, and they can be applied when the decision-makers are not satisfied with the result of the initial screening.

Pareto optimality-based screening is considered as a basic and prime screening technique. This technique does not require any preference information, but its screening efficiency is rather low. Other screening techniques requiring more preference information can be applied to the Pareto optimality screened set of options to produce more refined screening.

The U.S. DOE fuel cycle evaluation and screening study [4.17] applied a heuristic screening and classifying approach that made it possible to highlight the high- and low-efficiency options and group the high-efficiency options into the categories of the most promising, additional potentially promising and other potentially promising fuel cycles.

The INPRO/CENESO extensions of the INPRO/KIND comparative evaluation [4.1] approach can also be used for screening and classifying a large set of options within the sequential screening procedure using the Pareto optimality and trade-off weights-based screening procedures (the last one can be applied both for the cases of limited and detailed preference information).

4.2.3. Criteria, objective tree, weighting factors and major assumptions

The U.S. DOE evaluation and screening study considered nine U.S. DOE specified evaluation areas[50]: nuclear waste management, proliferation risk, nuclear material security risk, safety, environmental impact, resource utilisation, development and deployment risk, institutional issues, financial risk and economics. The nuclear waste management, proliferation risk, nuclear material security risk, safety, environmental impact, resource utilisation evaluation areas were combined into the benefit criteria groups, which, according to the INPRO terminology, are called high-level objectives. The development and deployment risk, institutional issues, financial risk and economics evaluation areas are included into the challenge high-level objective.

A set of relevant key indicators were developed for each evaluation area (the total number of key indicators is 27). It is worth noting that not all of the challenge and benefit key indicators were involved directly in the screening procedure due to the lack of objective data on the considered fuel cycle performances (relevant explanations can be found in [4.17]). Table 4.12 contains key indicators evaluated and used in the aggregation procedure during screening. The three-level objective tree for the decision problem under consideration is shown in Fig. 4.11.

TABLE 4.12. LIST OF KEY INDICATORS

High-level objectives	Evaluation areas	Key indicators	Com.
Challenge	Development and deployment risk	Development time (not used by itself, but in combination with dev cost)	b
		Development cost (not used by itself, but in combination with dev time)	b
		Development time and cost (not a metric, but a combination of 2 metrics)	c
		Deployment cost from prototypic validation to FOAK commercial	a
		Compatibility with the existing infrastructure	a
		Existence of regulations for the fuel cycle and familiarity with licensing	a
		Existence of market incentives and/or barriers to commercial implementation	a
	Institutional issues	Compatibility with the existing infrastructure	d
		Existence of regulations for the fuel cycle and familiarity with licensing	d
		Existence of market incentives and/or barriers to commercial implementation	d
	Financial risk & economics	Levelized cost of electricity	b

[50] Here and elsewhere the terminology of the INPRO KIND and CENESO collaborative projects is used, which differs from the terminology used in the U.S. DOE screening study. The list of correspondence is as follows: evaluation criteria (U.S. DOE) correspond to evaluation areas (INPRO), evaluation metrics (U.S. DOE) corresponds to key indicators (INPRO).

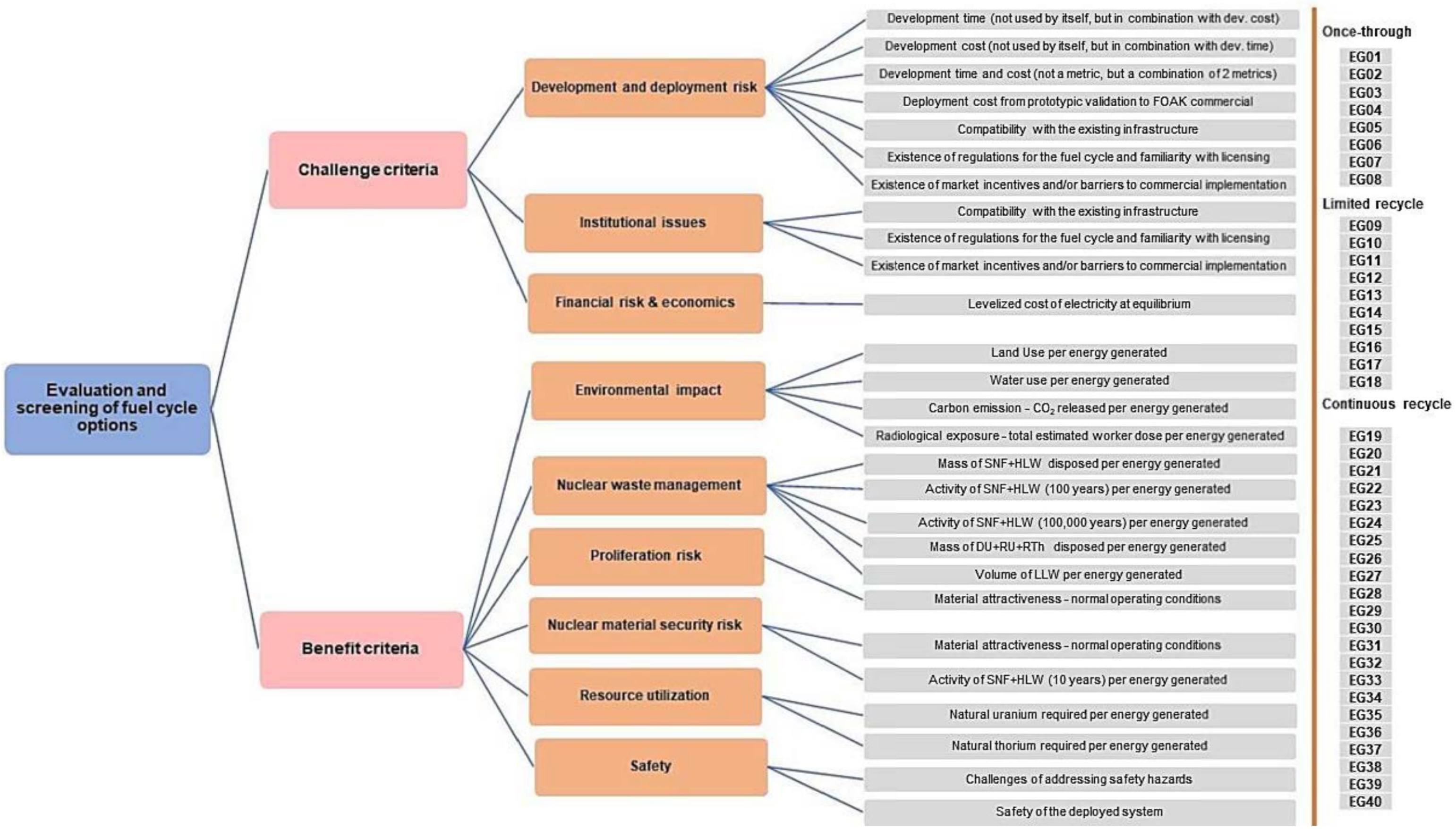


FIG. 4.11. Objective tree.

In [4.17], 11 sets of weighting factors were considered to reflect the range of possible policy guidance and illustrate the effects of specific policy choices. Relevant weighting options for the benefit evaluation areas and weights for the challenge and benefit key indicators used for the screening are presented in Tables 4.13 and 4.14, respectively. As the tables show, the weights for the challenge and benefit key indicators were fixed in the U.S. DOE screening study while the weights for the benefit evaluation areas were varied. The final weighting factors for the key indicators can be evaluated based on the hierarchical weighting procedure.

In [4.17], for the purpose of screening, the challenge and benefit evaluation areas were not aggregated into a single overall performance metric to trade-off merits and demerits associated with each option. The screening procedure applied assumed ranking of options based solely on benefit scores. Challenge scores were used indirectly to distinguish fuel cycle groups with different attractiveness, such as the most promising, additional potentially promising and other potentially promising fuel cycles.

The analysis was based on the calculated benefit and challenge scores. These scores were evaluated for each fuel cycle group and represented as a benefit vs. challenge graph. As far as the emphasis in this evaluation and screening is to identify fuel cycles that offer the potential for substantial improvements over the evaluation group EG01, the analysis was focused on the assessment of such incremental benefits associated with each fuel cycle group. For the evaluation groups identified as promising (the ‘thresholds’ and ‘sweep lines’ approaches were used), the incremental benefit to incremental challenge ratio was also considered.

The following analysis was conducted to consider both the increased benefits and the challenges of achieving them. For each of the potentially promising sets of fuel cycle groups identified by the threshold values, evaluation groups in that sets were ranked based on the incremental benefit to incremental challenge ratio. The incremental term was defined by the difference in performances on the benefit and challenge scores between the promising fuel cycles and evaluation group EG01.

Apart from reproducing this original approach to the screening of fuel cycle options based on the INPRO comparative evaluation and ranking toolkit, which is important for the cross-verification of the SET and INPRO toolkits, the present study also explored several other screening methods in order to obtain new, or unique, or refined insights beyond those obtained by the main analyses applied in the U.S. DOE screening study.

Following this line, below are the results obtained with the INPRO toolkit [4.1] populated by the fuel cycle performance data from the U.S. DOE evaluation and screening study. As demonstrated for the case of similar assumptions, the INPRO tools applied to the problem under consideration yields the results which are identical to those presented in [4.17]. Also, one can find that the INPRO tools may complement the original screening analysis scope through the lens of the INPRO comparative evaluation approach that can give some additional insight into the overall performances of different fuel cycle options.

TABLE 4.13. WEIGHTING OPTIONS FOR BENEFIT EVALUATION AREAS

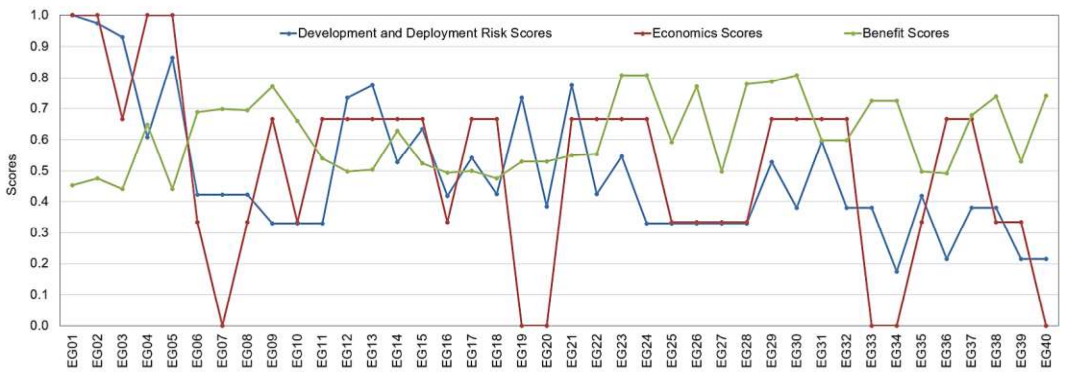
	1.Equal criteria trade-off Factors	2. Emphasise changes in nuclear waste management	3. Emphasise changes in resource utilization	4. Emphasise changes in environmental impact	5. Emphasise changes in safety	6. Reduce physical impacts of producing nuclear power	7. Nuclear waste management, resource utilisation, and safety	8. Unlimited Natural fuel resources	9. Resource utilisation, environmental impact & safety	10. Nuclear waste management & resource Utilisation	11. Nuclear waste management & safety
Environmental impact	25.0%	10.0%	10.0%	70.0%	10.0%	33.3%	0.0%	33.3%	33.3%	0.0%	0.0%
Nuclear waste management	25.0%	70.0%	10.0%	10.0%	10.0%	33.3%	33.3%	33.3%	0.0%	50.0%	0.0%
Resource utilisation	25.0%	10.0%	70.0%	10.0%	10.0%	33.3%	33.3%	0.0%	33.3%	50.0%	0.0%
Safety	25.0%	10.0%	10.0%	10.0%	70.0%	0.0%	33.3%	33.3%	33.3%	0.0%	50.0%

TABLE 4.14. WEGHTS FOR CHALLENGE AND BENEFIT KEY INDICATORS

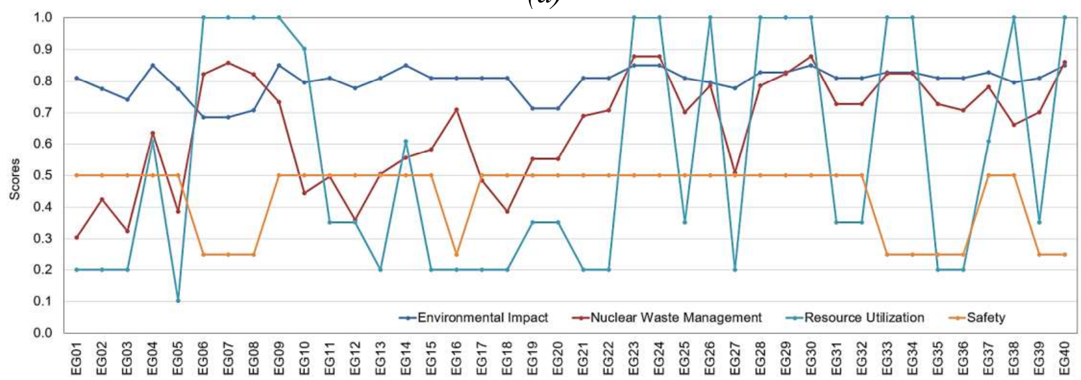
Development and deployment risk	
Development time and cost (not a metric, but a combination of 2 metrics)	50.0%
Deployment cost from prototypic validation to FOAK commercial	25.0%
Compatibility with existing infrastructure	10.0%
Existence of regulations for the fuel cycle and familiarity with licensing	10.0%
Existence of market incentives and/or barriers to commercial implementation	5.0%
Environmental impact	
Land use per energy generated	25.0%
Water use per energy generated	25.0%
Carbon emission – CO_2 released per energy generated	25.0%
Radiological exposure – total estimated dose per energy generated	25.0%
Nuclear waste management	
Mass of SNF+HLW disposed per energy generated	50.0%
Activity of SNF+HLW (100 years) per energy generated	10.0%
Activity of SNF+HLW (100,000 years) per energy generated	10.0%
Mass of DU+RU+RTh disposed per energy generated	15.0%
Volume of LLW per energy generated	15.0%
Resource utilisation	
Natural uranium required per energy generated	80.0%
Natural uranium required per energy generated	20.0%
Safety	
Challenges of addressing safety hazards	100.0%

4.2.4. Preliminary aggregation of the performance data

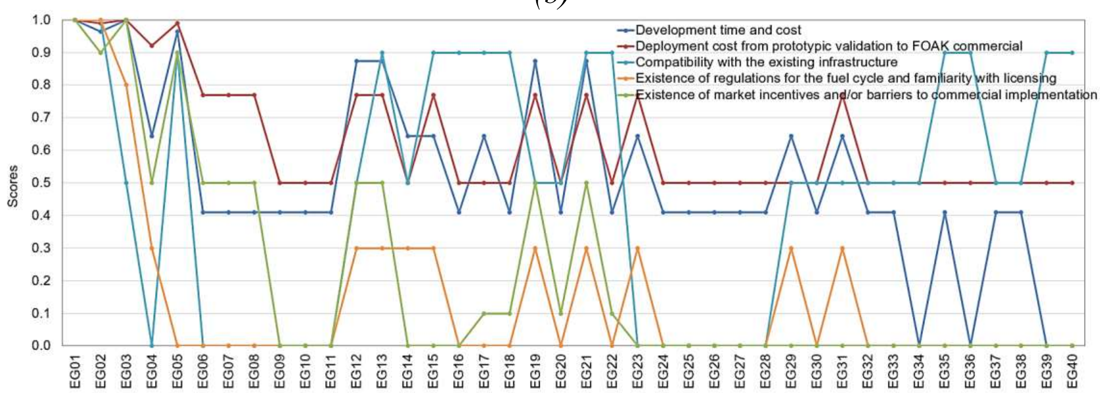
A preliminary judgement aggregation was carried out to highlight performances of the fuel cycle evaluation groups. Figure 4.12 shows the fuel cycles' performance scores obtained for each high-level objective according to the key indicator values (the higher the score, the higher the performance of the option). A set of equal criteria trade-off factors (Table 4.13) in combinations with weighting options for the challenge and benefit criteria (Table 4.14) was applied. This preliminary aggregation clearly demonstrates in aggregated terms the merits and demerits associated with each option under consideration at different levels, due to which it is possible to form the basis for interpreting the results of the follow-up MCDA-based analysis. Also, these results can be used for cross-checking the fuel cycle evaluation and screening software (SET Tool) and KIND-ET tools. The relevant analysis performed has demonstrated that both tools provide identical evaluation results.



(a)



(b)



(c)

FIG. 4.12. Scores for: (a) evaluation areas, (b) benefit criteria, (c) development and deployment risk criteria.

4.2.5. Pareto optimality-based screening: screening for dominance

As was already mentioned, Pareto optimality-based screening is a prime screening technique that does not require any preference information (weighting factors): for its implementation, it is enough to evaluate only performance data for all options under consideration. Due to this, the screening efficiency of this technique is rather low: in case of need, other screening approaches requiring preference information can be applied later on to produce more refined screening.

Pareto optimality-based screening identifies dominated and non-dominated options (one option dominates another if its performance is at least as good as the dominated option on all criteria and better on at least one criterion). Dominated options could be excluded from the comparative procedure as they never take the first rank due to the fact that their overall scores are always lower than the overall scores for the options which dominate them.

The Pareto optimality-based screening procedure involves identifying preference direction (positive or negative) for each criterion, pair-wise comparing alternatives based on their performance data, determining dominated and non-dominated alternatives (as well as alternatives with the identical performance, if any), removing dominated alternatives, and retaining non-dominated ones (as well as alternatives with the identical performance, if any). This procedure is implemented in the Domination Identifier extension of KIND-ET [4.1]. Domination Identifier was applied to three groups of the performance data: (1) only benefit criteria, (2) only challenge criteria and (3) both benefit and challenge criteria. The goal was to identify the dominated and non-dominated options as well as ones with identical performance for each group of criteria. The results of applying Domination Identifier to the problem under consideration are presented in Tables 4.15, 4.16 and 4.17.

Table 4.15 shows options with the highest performances on the benefit and challenge criteria separately (the most attractive options for all relevant key indicators): for the benefit criteria, these options are EG23, EG24, and EG30 (all of them have the identical performance); for the challenge criteria, it is the EG01 option characterized by the highest performance among all considered options. These options are the only non-dominated options among all the studied fuel cycles for the relevant key indicators and only these options will always have the first rank whatever weighting factors are used. This suggests that options EG23, EG24 and EG30 are the most promising fuel cycles for the benefit criteria.

Table 4.16 shows options with identical performance on the benefit and challenge criteria separately. Identical performance of options means that the overall scores for these options for all possible combinations of weighting factors will be the same. This information is important for the correct interpretation of further evaluation and screening results. Table 4.17 contains dominated options in case both benefit and challenge criteria are applied. This table also indicates options that dominate relevant dominated options. As seen, there is no single fuel cycle option which can be considered as the most efficient one if all the benefit and challenge criteria are applied simultaneously unlike when ranking is carried out using solely the benefit criteria (see comments for Table 4.15).

Table 4.18 indicates the promising fuel cycle groups according to the U.S. DOE evaluation and screening study; the dominated options for both benefit and challenge criteria are also highlighted here. Consequently, it can be concluded that among the 18 options specified in the U.S. DOE study as promising fuel cycles only eight can be considered as satisfying the basic formal screening requirement, i.e., that the screened options need to include the best option (while dominated options never can be the best ones). If it is necessary to further reduce the set of promising options, this information can be highly useful. Thus, the most promising fuel cycle options that are to be kept after Pareto optimality-based screening are EG23, EG29 and EG30 (three of the four initially indicated); the additional potentially promising fuel cycles are EG07, EG08 and EG40 (three of the 11 initially indicated); and the other potentially promising options are EG04 and EG14 (two of the three initially indicated). Such reductions in the number of promising fuel cycles can be considered as primary refined screening results obtained using the INPRO toolkit.

TABLE 4.15. OPTIONS WITH THE HIGHEST PERFORMANCES ON THE BENEFIT AND CHALLENGE CRITERIA

Benefit criteria	Challenge criteria
EG23 ≈ EG24 ≈ EG30	EG01

TABLE 4.16. OPTIONS WITH IDENTICAL PERFORMANCES ON THE BENEFIT AND CHALLENGE CRITERIA

Benefit criteria	Challenge criteria
EG19 ≈ EG20	EG06 ≈ EG08
EG23 ≈ EG24 ≈ EG30	EG09 ≈ EG11 ≈ EG24
EG31 ≈ EG32	EG13 ≈ EG21
EG33 ≈ EG34	EG14 ≈ EG29
	EG10 ≈ EG25 ≈ EG26 ≈ EG27 ≈ EG28
	EG16 ≈ EG35
	EG18 ≈ EG22
	EG30 ≈ EG32 ≈ EG37

TABLE 4.17. DOMINATED OPTIONS FOR THE BENEFIT AND CHALLENGE CRITERIA

#	Dominated options	Comments: dominated versus dominating options
1	EG05	EG05<EG02
2	EG06	EG06<EG08
3	EG09	EG09<EG23, EG24, EG30
4	EG10	EG10<EG09, EG23, EG24, EG26, EG28, EG29, EG30, EG38
5	EG11	EG11<EG04, EG09, EG23, EG24, EG30
6	EG16	EG16<EG35
7	EG17	EG17<EG13
8	EG18	EG18<EG13, EG17
9	EG20	EG20<EG19
10	EG24	EG24<EG23, EG30
11	EG25	EG25<EG23, EG24, EG29, EG30, EG37
12	EG26	EG26<EG23, EG24, EG29, EG30
13	EG27	EG27<EG09, EG15, EG21, EG22, EG23, EG24, EG25, EG28, EG29, EG30, EG31, EG32, EG37, EG38
14	EG28	EG28<EG23, EG24, EG29, EG30
15	EG32	EG32<EG30, EG31, EG37
16	EG33	EG33<EG29, EG30
17	EG34	EG34<EG29, EG30, EG33, EG40
18	EG36	EG36<EG22
19	EG37	EG37<EG30
20	EG38	EG38<EG29, EG30

TABLE 4.18. PROMISING FUEL CYCLE GROUPS ACCORDING TO THE CLASSIFICATION IN THE U.S. DOE EVALUATION AND SCREENING STUDY

Fuel cycle groups		
Most promising	Additional potentially promising	Other potentially promising
EG23, *EG24*, EG29, EG30	*EG06*, EG07, EG08, *EG09*, *EG26*, *EG28*, *EG33*, *EG34*, *EG37*, *EG38*, EG40	EG04, *EG10*, EG14

Options underlined and written in italics are dominated ones for both benefit and challenge criteria, they can be excluded from further consideration.

4.2.6. MAVT-based judgement aggregation and ranking results

For illustrative purposes, to demonstrate the ranking results provided for different assumptions regarding the sets of criteria involved in the evaluation, the MAVT-based judgement aggregation was carried out for the equal weights option (weighting option 1 for the benefit evaluation areas from Table 4.13 and criteria weights from Table 4.14). The following sets of criteria were considered:

- Case 1 — only the benefit criteria are used to evaluate the overall scores of options (this is the basic approach implemented in the U.S. DOE evaluation and screening study).
- Case 2 — the benefit as well as financial risk and economics criteria are used to evaluate the overall scores of options (with the equal weights for both criteria groups).
- Case 3 — the benefit, financial risk and economics, development and deployment risk criteria are used to evaluate the overall scores of options (with the equal weights for all three criteria groups).

The relevant ranking results for the assumptions made are shown in Figs 4.13–4.15: for Cases 1, 2 and 3, respectively, which were obtained using the additive MAVT model implemented in KIND-ET [4.1]. These figures show the overall scores with breakdowns into areas' scores according to the assumptions regarding the sets of evaluation areas involved. It is worth noting that the results of evaluating the options' overall scores obtained for Case 1 are in full agreement with the results presented in [4.17]. This suggests that in similar conditions the SET and KIND-ET tools yield the identical evaluation results. The ranking results presented in Fig. 4.13 show that the first 18 places in ranking are occupied by the most promising, additional potentially promising and other potentially promising fuel cycles specified in the U.S. DOE study.

Involving the financial risk and economics as well as development and deployment risk criteria in the judgement aggregation procedure sufficiently changes the ranking order of the options. It follows that not only the other potentially promising fuel cycles but also the fuel cycles initially screened out within the U.S. DOE study may be more attractive than even the most promising and additional potentially promising fuel cycles. Moreover, taking these criteria into account helps to resolve the ambiguity in rating between options having the same rank (to differentiate them), specified in the case of ranking based solely on the benefit criteria. This change in the ranking order, while financial risk and economics as well as development and deployment risk criteria are involved, occurred due to the fact that, for these criteria, the EG01 option is the undoubted leader (as the use of Pareto optimality-based screening showed). All other once-through fuel cycles also demonstrate fairly high performances on the challenge criteria, thereby compensating for their low performance on benefit criteria.

This observation suggests that, if instead of the screening task aimed at providing information for the R&D prioritisation, the problem of selecting the most preferable option for the further real-life deployment is considered based on the same performance data but taking into account financial risk and economics as well as development and deployment risk criteria, in such a case the most preferable option may not belong to the group of the most promising, additional potentially promising and other potentially promising fuel cycles specified in the U.S. DOE evaluation and screening study. The factors of the availability, affordability and acceptability of technologies requiring minimisation of financial, development and deployment risks may nullify the potential benefits associated with the most promising, additional potentially promising and other potentially promising fuel cycles.

The final selection of the most preferable fuel cycle option (in the case of the statement of the corresponding problem which is, however, not considered in the present study) can be carried out after the weighting factors for the benefit, financial risk and economics, development and deployment risk criteria groups are evaluated. These weighting factors could represent the relative importance of these criteria groups for decision-makers and different stakeholders. The scores of the evaluation areas together with the results of the preliminary judgment aggregation allow explaining the results of selecting the most preferable option.

Figure 4.15 confirms that all the dominated options specified in Table 4.16 have been ranked worse than those of the options which dominate them. Therefore, all the dominated options can be excluded from consideration as non-perspective ones if relevant dominating options are available for implementation.

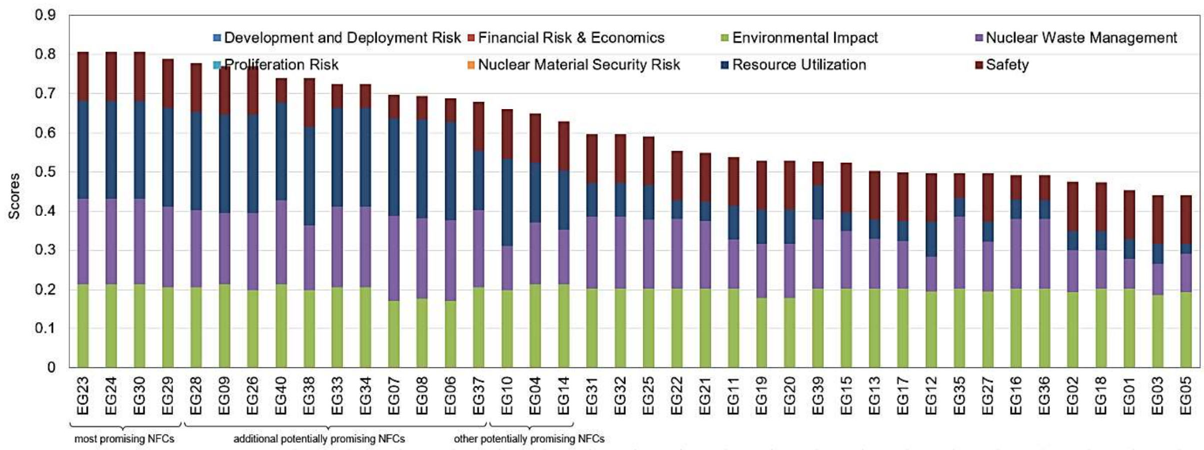


FIG. 4.13. MAVT-based ranking results for ranking the options based on only the benefit criteria with breakdown of the overall scores into the scores of the evaluation areas.

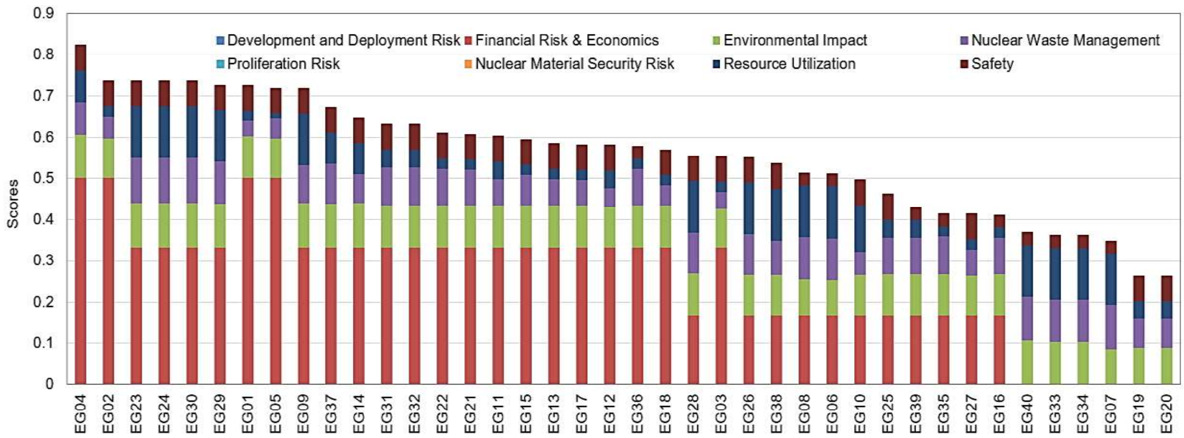


FIG. 4.14. MAVT-based ranking results for ranking the options based on the benefit and financial risk and economics criteria with breakdown of the overall scores into the scores of the evaluation areas.

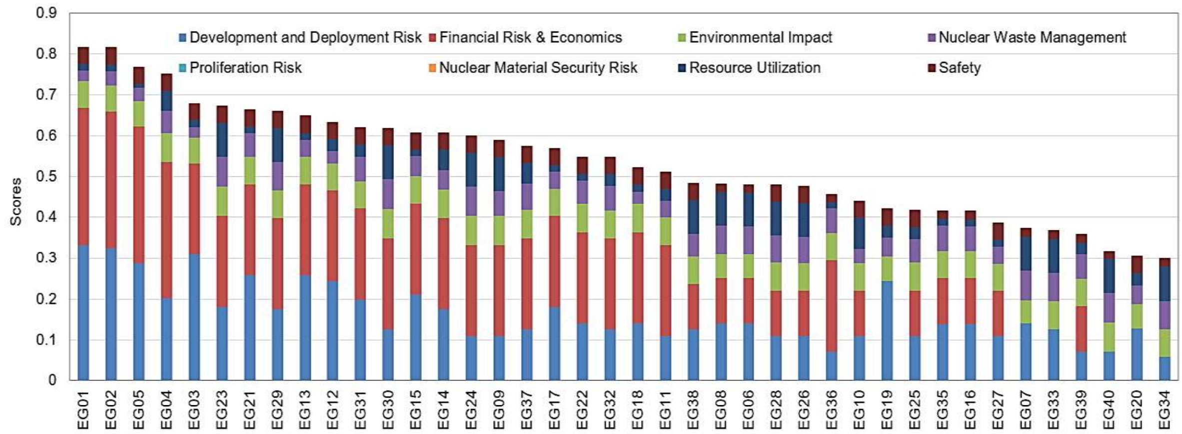


FIG. 4.15. MAVT-based ranking results for ranking the options based on the benefit, financial risk and economics, development and deployment risk criteria with breakdown of the overall scores into the scores of the evaluation areas.

Table 4.19 provides the ranks of the options for different weighting factors (see Tables 4.13 and 4.14) in the case of ranking solely on the benefit criteria. Colour codes are presented in a user-friendly manner. It is worth noting that, while assessing the ranks, it is assumed that the options having the same overall scores obtain the same rank. However, when duplicate numbers are present, this affects the ranks of the following numbers. Also, the first column contains the most promising, additional potentially promising and other potentially promising fuel cycles specified in the U.S. DOE study (marked as *, ** and ***, respectively). The last column shows the differences between the possible maximal and minimal ranks for each alternative in the given groups of weighting factors, which allows us to conclude about the stability of ranks.

The table shows that Options EG23, EG24, EG30 have the same rank, i.e., the first rank (because these options provide identical performance on all the benefit criteria), for all the groups of weighting factors. This fact confirms the results of the Pareto optimality-based screening (see Tables 4.15 and 4.16) demonstrating that these options dominate all the others for the benefit criteria. Option EG29, which is also classified as the most promising one within the U.S. DOE study, may take ranks from the fourth to the sixth, its most probable rank being the fourth. For some perspectives, the options belonging to the additional potentially promising fuel cycles, namely, first of all, EG09, EG40 and, with lesser degree, EG07, EG26, EG28, EG33, EG34, can also provide overall performances on the benefit criteria that are comparable with performances of the most promising fuel cycle group. This circumstance indicates that it is possible to implement follow-up sub-screening of fuel cycle options within the specified groups of fuel cycle attractiveness.

The most stable rank orders are shown by the options from the most promising fuel cycle group: EG23, EG24, EG30, and EG29. Options EG26, EG28, EG38, EG37, and EG09 of the additional potentially promising fuel cycle group as well as Options EG14 and EG04 of the other potentially promising fuel cycle group provide intermediate stability of ranks (the difference between the maximal and minimal ranks is about 6–14). Less stable rank orders are taken by Options EG08, EG06, EG07, EG33, EG34, EG40, and EG10: the difference between the possible maximal and minimal ranks is about 25–29.

Table 4.19 shows that the ranks of EG19 and EG20, the ranks of EG31 and EG32 as well as the ranks of EG33 and EG34 are identical for each pair and for all the weighting factors. It means that the relevant groups of options provide identical performances (as shown in Table 4.16). Within the present study, the full-scale Pareto optimality-based screening was not applied for the benefit criteria in the case when EG23, EG24, EG30 are excluded from consideration. In case of need, such an analysis can be implemented to identify pair-wise relative efficiencies for all the other fuel cycles with the purpose of identifying dominated and non-dominated alternatives among these options. It is worth mentioning that the average ranks evaluated for weighting options from #2 to #11 provide a very good agreement with the ranks specified for weighting option #1 — equal criteria trade-off factors. Therefore, the equal weights approach can be used as the basic one for screening when there is no specific information about decision-makers' preferences. It is important to assess the overall agreement between the ranks obtained for different perspectives. Kendall's W (also known as Kendall's coefficient of concordance) can be used to evaluate concordance of the assessors. Kendall's W values range from 0 (no concordance) to 1 (full concordance). The coefficient of concordance could be used to determine a global measure of the concordance between the ratings given for different priorities and can be evaluated by the following formula:

$$W = \frac{12}{m^2 \cdot (n-1) \cdot n \cdot (n-1)} \cdot \sum_{j=1}^{n} \left(R_j - \frac{m \cdot (n+1)}{2} \right)^2 \tag{4.2}$$

with $R_j = \sum_{l=1}^{m} r_l(a_j)$, where m is the number of perspectives, n is the number of alternatives.

For the ranks presented in Table 4.19, Kendall's W=0.824 (χ^2=353.5124), which suggests that the ranking results are in good agreement for the different weighting options.

TABLE 4.19. RANKS OF OPTIONS FOR DIFFERENT WEIGHTING FACTORS (IN CASE OF RANKING ON THE BENEFIT CRITERIA)[51]

Fuel cycle options	1. Equal criteria trade-off factors	2. Emphasise changes in nuclear waste management	3. Emphasise changes in resource utilization	4. Emphasise changes in environmental impact	5. Emphasise changes in safety	6. Reduce physical impacts of producing nuclear power	7. Nuclear waste management, resource utilisation, and safety	8. Unlimited natural fuel resources	9. Resource utilisation, environmental impact & safety	10. Nuclear waste management & resource utilisation	11. Nuclear waste management & safety	Difference in ranks: $Rank_{max} - Rank_{min}$
EG01	38	40	38	33	28	38	39	39	26	39	40	14
EG02	36	35	36	36	26	36	36	35	34	36	35	10
EG03	39	39	39	40	29	39	38	40	35	38	39	11
EG04***	17	20	17	12	11	17	17	14	13	17	15	9
EG05	40	38	40	37	30	40	40	37	37	40	36	10
EG06**	14	12	14	27	36	13	13	33	17	9	21	27
EG07**	12	6	12	25	34	11	10	24	17	5	17	29
EG08**	13	11	13	21	35	12	13	27	15	9	21	26
EG09**	6	13	6	4	6	9	7	7	1	13	8	12
EG10***	16	30	15	15	10	16	16	34	9	16	34	25
EG11	24	31	22	22	18	28	26	22	19	30	28	13
EG12	31	37	26	34	24	34	29	38	23	32	38	15
EG13	29	33	30	26	22	32	31	21	26	34	27	13
EG14***	18	26	18	14	12	18	18	17	13	18	23	14
EG15	28	27	29	24	21	31	28	20	26	31	18	13
EG16	34	24	34	30	39	24	34	28	38	24	31	15
EG17	30	34	31	28	23	33	32	23	26	35	29	12
EG18	37	36	37	32	27	37	37	36	26	37	36	11

[51] When the ranks of the options are assessed, it is assumed that the options having the same overall scores obtained the same ranks. However, the presence of duplicate options with the same scores affects the ranks of subsequent numbers.

TABLE 4.19. RANKS OF OPTIONS FOR DIFFERENT WEIGHTING FACTORS (IN CASE OF RANKING ON THE BENEFIT CRITERIA) (cont.)

Fuel cycle options	1. Equal criteria trade-off factors	2. Emphasise changes in nuclear waste management	3. Emphasise changes in resource utilization	4. Emphasise changes in environmental impact	5. Emphasise changes in safety	6. Reduce physical impacts of producing nuclear power	7. Nuclear waste management, resource utilisation, and safety	8. Unlimited natural fuel resources	9. Resource Utilisation, Environmental Impact & Safety	10. Nuclear waste management & resource utilisation	11. Nuclear waste management & safety	Difference in ranks: $Rank_{max} - Rank_{min}$
EG19	25	28	23	38	19	29	23	30	24	27	24	19
EG20	25	28	23	38	19	29	23	30	24	27	24	19
EG21	23	22	28	20	17	27	25	13	26	29	13	16
EG22	22	19	27	19	16	25	22	11	26	25	11	16
EG23*	1	1	1	1	1	1	1	1	1	1	1	0
EG24*	1	1	1	1	1	1	1	1	1	1	1	0
EG25	21	18	21	18	15	21	21	12	19	21	12	9
EG26**	7	10	7	10	7	10	5	8	7	11	5	6
EG27	33	32	33	35	25	35	30	26	33	33	26	10
EG28**	5	9	5	6	5	8	6	5	5	12	6	7
EG29*	4	5	4	5	4	5	4	4	5	6	4	2
EG30*	1	1	1	1	1	1	1	1	1	1	1	0
EG31	19	16	19	16	13	19	19	9	19	19	9	10
EG32	19	16	19	16	13	19	19	9	19	19	9	10
EG33**	10	7	10	8	32	5	11	18	11	6	19	27
EG34**	10	7	10	8	32	5	11	18	11	6	19	27
EG35	32	21	32	29	38	23	33	25	38	23	30	17
EG36	35	25	35	31	40	25	35	29	38	25	32	15
EG37**	15	14	16	13	9	15	15	6	16	15	7	10
EG38**	9	15	9	11	8	14	8	16	7	14	14	9
EG39	27	23	25	23	37	21	27	32	36	21	33	16
EG40**	8	4	8	7	31	4	9	15	10	4	16	27

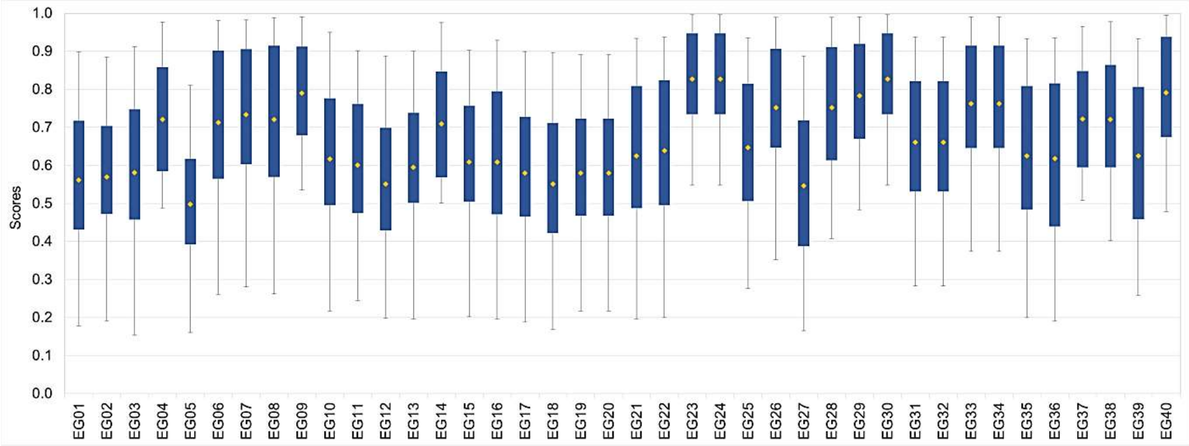
(*): the most promising fuel cycles; (**): additional potentially promising fuel cycles; (***): other potentially promising fuel cycles.

4.2.7. Sensitivity and uncertainty analysis

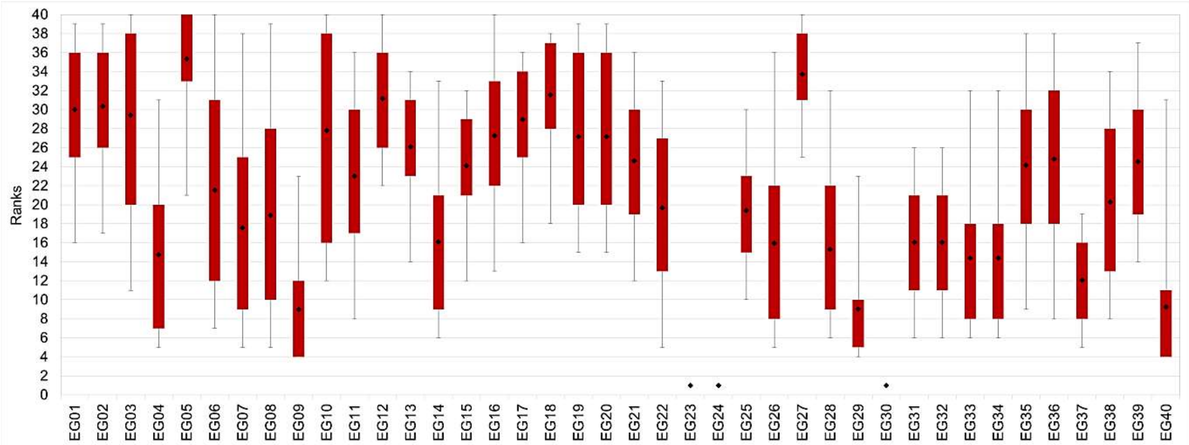
4.2.7.1. Global uncertainty analysis regarding weighting factors

A key feature of decision analysis is an iterative way of processing various preference information, which makes it possible to incorporate many different local perspectives into the decision support framework using different weight arrays. It could be noted that to consider the variety of perspectives from different stakeholders and to assess their impact on the overall scores and ranks of options, the weights are to be varied within the widest ranges that seems quite important for screening as well. This examination can be carried out through a detailed global uncertainty analysis with respect to weighting factors. The spreads in the overall scores and ranks of all the fuel cycle options due to uncertainties in the weighting factors are presented as box and whisker plots in Figs 4.16–4.18. Relevant evaluations were performed using the Overall Score Spread Builder extension of KIND-ET [4.1] for the case of the absence of any preference information about the relative importance of the benefit criteria (Fig. 4.16), the challenge criteria (Fig. 4.17), and both benefit and challenge criteria (Fig. 4.18).

A box and whisker plot graphically shows the centre and range or distribution of values for a single variable. The box and whisker plots presented below demonstrate mean values, 25th and 75th (box boarders) as well as 5th and 95th (whiskers) percentiles of the relevant statistical distributions of the overall scores and ranks for each alternative. The higher the overall score (and the lower the rank order), the higher the attractiveness of the option. The lower the spreads in the overall scores (or ranks), the more stable (robust) the overall score (and rank) for the relevant option with respect to the weighting factors.



(a)



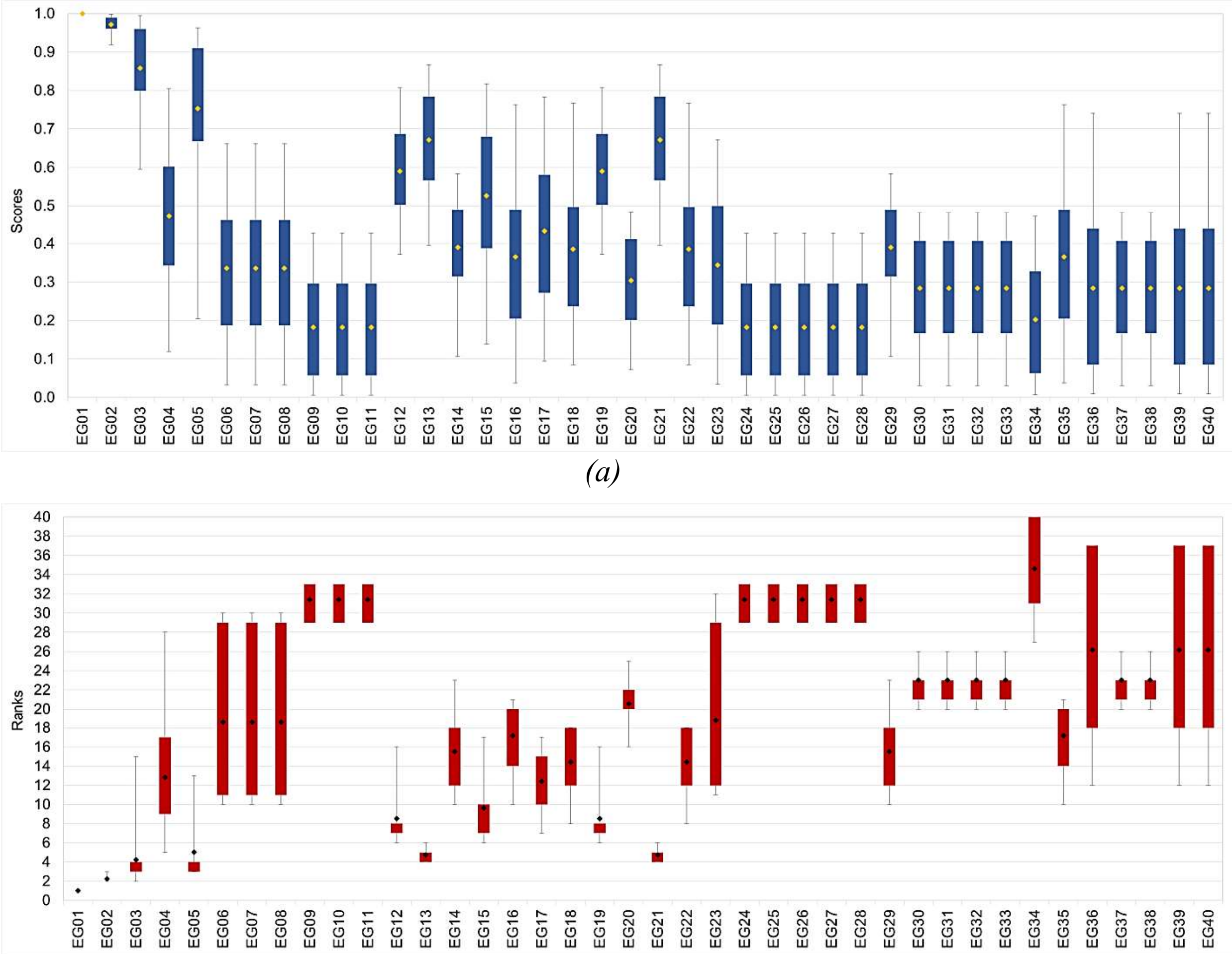
(b)

FIG. 4.16. Spreads in the overall scores (a) and ranks (b) due to uncertainty in the final weighting factors when the options are ranked on the benefit criteria.

The spreads in the overall scores and ranks due to uncertainty in the weighting factors presented in Figs 4.16–4.18 show statistical similarities and differences in fuel cycle overall performances associated with the fuel cycle options under consideration in the case of the absence of any preference information. This information generalises the analysis performed in the previous sub-sections demonstrating it in a condensed user-friendly form and can be used for assessing different characteristics of relevant statistical distributions (for instance, the probability that certain options may take given places in the ranking). Therefore, it is possible to use this information and associated statistical data for more refined screening.

The fact that EG23, EG24 and EG30, as well as EG01, are presented in Fig. 4.16(b) and 7(b), respectively, as simple points without any spreads, indicate outstanding performances of these options on the benefit and challenge criteria, as it was demonstrated early based on Pareto optimality-based screening. While considering both the benefit and challenge criteria (Fig. 4.18), one can notice that there are no options with superior performances for the whole set of criteria and the relevant spreads of the overall scores and ranks become more variable and volatile.

In general, the suggestions for screening out options based on the statistical analysis as a part of the screening framework do not contradict the suggestions obtained using the simple MAVT-based judgement aggregation with predefined sets of weights. However, statistical analysis provides additional information about the stability of rank orders (by means of spreads in overall scores and ranks) that can be applied for more refined screening, for instance, by setting thresholds for the maximum allowable rank that can be occupied by an option.



(a)

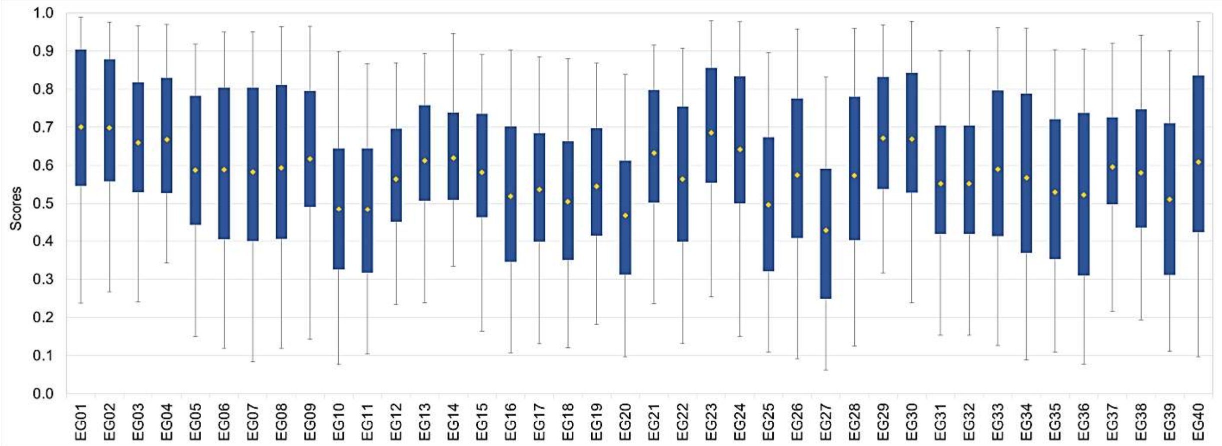
(b)

FIG. 4.17. Spreads in the overall scores (a) and ranks (b) due to uncertainty in the final weighting factors when the options are ranked on the challenge criteria.

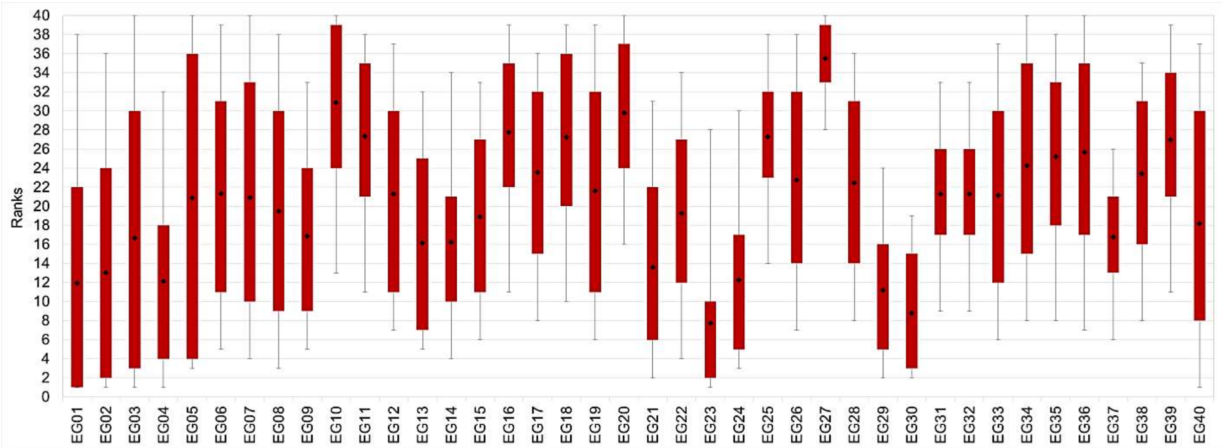
Thus, as can be seen from Fig. 4.16, some of the fuel cycle options from the additional potentially promising and other potentially promising fuel cycle groups demonstrate rather high spreads in their ranks (e.g., EG06, EG10 and some others) — such options can be screened out even with fairly attractive mean values of the overall scores and ranks.

Despite the fact that a separate and independent consideration of the benefit and challenge criteria can be valuable in terms of highlighting similarity patterns in the fuel cycle performances on different criteria groups, it will be more useful from a practical point of view to consider both groups of criteria together. This approach combining various groups of criteria makes it possible to specify fuel cycle options that can be considered cost effective, i.e., provide maximum benefits with minimal challenges. Focusing on the cost effective fuel cycle options can change the attribution of fuel cycles to different categories or give a chance to distinguish the options within the predefined groups. For instance, EG04 from the other potentially promising fuel cycle group despite its relative low attractiveness on the benefit criteria but quite attractive challenge performance demonstrates high overall performance for both benefit and challenge criteria (see Fig. 4.18). Considering the stability of the ranks of the options (minimal spreads in the ranks) due to uncertainties in the preference information (weights), it is possible to sub-differentiate the options within each fuel cycle group (see 4.28).

Summarising, it can be concluded that, since most of the screening procedures assume the absence or limitation of preference information, it seems reasonable to apply a stochastic approach in ranking options for different perspectives with follow-up processing of these data based on different screening criteria or requirements.



(a)



(b)

FIG. 4.18. Spreads in the overall scores (a) and ranks (b) due to uncertainty in the final weighting factors when the options are ranked on the combined benefit and challenge criteria.

4.2.7.2. Global sensitivity analysis regarding high-level objective weights

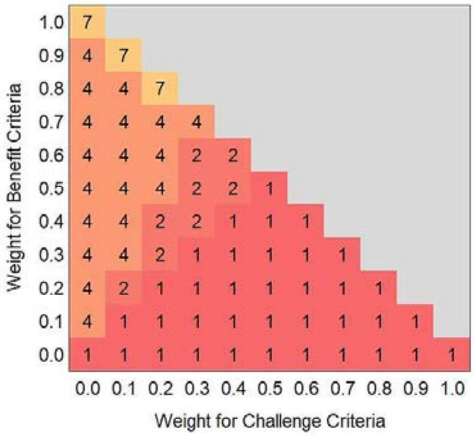
The statistical representation of the spreads in the overall scores and ranks illustrates potential performances and places of the options in the rating, allowing us to conclude about the stability of the relevant evaluations. However, it does not indicate which priorities are to be selected for a particular option to take a specific place in the ranking (for instance, the first one). A global sensitivity analysis regarding weights assigned to high-level objectives can complement this stochastic analysis by providing an answer to the question posed. This sensitivity analysis expands the original screening procedure based on the benefit criteria, by combining the criteria of benefit, financial risk and economics, development and deployment risk into an overall performance measure, which can be used for the final selection of the most promising option for real-life implementation.

The results of the global sensitivity analysis regarding weights assigned to the high-level objectives (namely, benefit, financial risk and economics, development and deployment risk) can be presented as heat-mapping techniques for each of the three groups of the high-level objective weights. This analysis makes it possible to demonstrate a set of options that may take the first rank, and the corresponding ranges of weighting factors providing this opportunity. The results are presented in Fig. 4.19 individually for once-through, limited recycle and continuous recycle fuel cycle options as well as for the whole set of fuel cycle options (Fig. 4.19 (a), (b), and (c) assume that only once-through fuel cycles, only limited recycle fuel cycles and only continuous recycle fuel cycles are available, correspondingly; Fig. 4.19(d) corresponds to the case when all the fuel cycle options are available; explanations for the colour codes used are given in Fig. 4.19(e). The Ranks Mapping Tool extension of KIND-ET was used to build these diagrams [4.1].

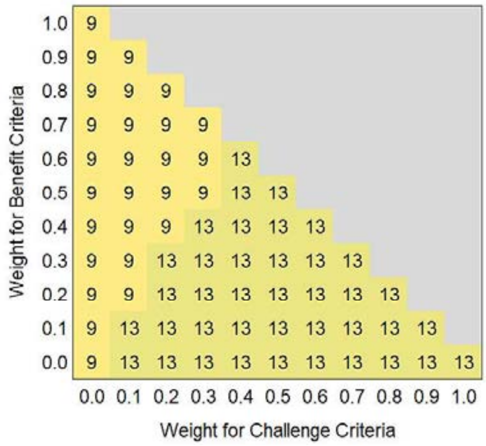
To obtain the corresponding diagrams, the weights for the three high-level objectives (benefit, financial risk and economics, development and deployment risk) were simultaneously varied in the range of 0 to 1. (The OX axis is for the development and deployment risk weight, the OY axis is for the benefit weight, and the OZ axis is for the financial risk and economics weight). As the weights are to fulfil the normalization condition constraining their sum to 1, only two high-level objective weights can be independently chosen. The most promising fuel cycle options, for the specific combination of weights, were identified with MAVT. The options located at the borders of the diagrams next to the grey areas correspond to the case when the financial risk and economics criteria are excluded from consideration and only the development and deployment risk and benefit criteria determine the overall performances of the options (the sum of the weights for the benefit and development and deployment risk criteria is equal to 1).

The coloured areas show the combinations of weights for which different fuel cycle options (indicated at the diagram) take the first rank. Thus, these diagrams show preference maps for different priorities and provide a better understanding of how promising each option is and what its rank robustness is in view of the weights of the high-level objectives. It worth noting, that despite the fact that 40 fuel cycle options are involved in the analysis, the number of options that may take the first rank is very limited, and most of them are stable (occupying large areas in the space of the weights of the high-level objectives). A similar analysis can also be performed for the weights of the evaluation area, which make it possible to highlight options that demonstrate superior performance in specific areas, such as safety, environment, non-proliferation, security, and sustainability. Due to the limited scope of the present study, such an analysis was not performed here.

It is interesting to note that aggregating the financial risk and economics, development and deployment risk along with the benefit criteria can bring the first ranks to more mature options that, for obvious reasons, can be screened out based on screening approaches used in the screening analysis focused on decision support in relation to R&D priorities (for instance, EG01, EG02). This clearly demonstrates the fundamental differences in approaches to screening studies that support the R&D prioritisation and screening studies that make it possible to select the most promising option for real-life implementation and deployment.



(a)



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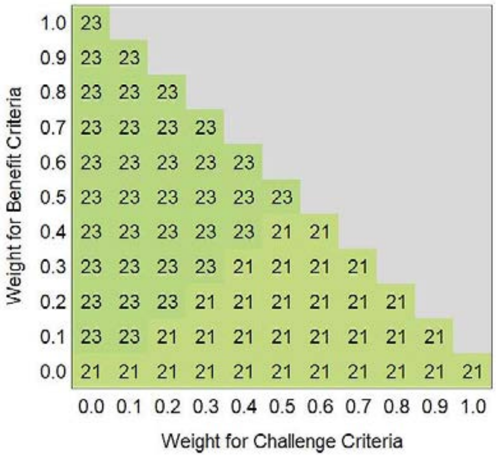

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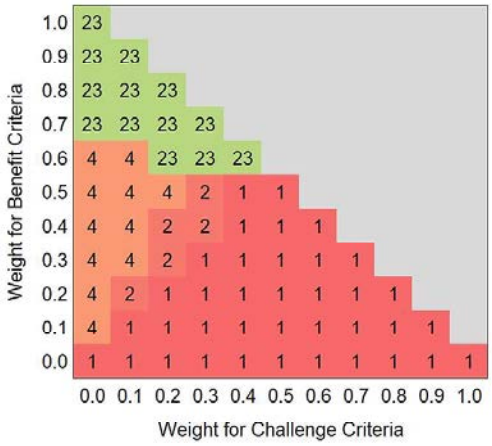

(d)

List of fuel cycle options

Once-through fuel cycles	EG01	EG02	EG03	EG04	EG05	EG06	EG07	EG08			
	1	2	3	4	5	6	7	8			
Limited recycle fuel cycle	EG09	EG10	EG11	EG12	EG13	EG14	EG15	EG16	EG17	EG18	
	9	10	11	12	13	14	15	16	17	18	
Continuous recycle fuel cycles	EG19	EG20	EG21	EG22	EG23	EG24	EG25	EG26	EG27	EG28	EG29
	19	20	21	22	23	24	25	26	27	28	29
	EG30	EG31	EG32	EG33	EG34	EG35	EG36	EG37	EG38	EG39	EG40
	30	31	32	33	34	35	36	37	38	39	40

(e)

FIG. 4.19. Fuel cycle options having the first rank for different fuel cycle groups and different high-level objective weights: (a) once-through, (b) limited recycle, (b) continuous recycle (c) the whole set of fuel cycle options(d), (e) explanation of the used colour codes.

4.2.8. Results and discussions

As was already mentioned, screening is an MCDA-based process that reduces a large set of alternatives to a smaller one that most likely includes the best option. Screening requires no or a limited information regarding decision-makers' preferences but, if appropriately applied, screening makes it possible to eliminate options that do not appear to warrant further attention. There are many approaches to screening out options from a large set — they are characterized by different efficiencies. The main methodological trend in this area is the use of sequential screening, consisting of the gradual application of various procedures.

In contrast to the original approach implemented in the U.S. DOE evaluation and screening study, which used an authentic screening procedure, this analysis implemented more formalized screening techniques, namely Pareto optimality-based screening and screening techniques based on trade-off weights (in its stochastic form). The latter techniques, due to the possibility of incorporating preference information, can improve the screening efficiency and provide more refined screening.

The original screening approach involved consideration of mainly the benefit criteria representing safety, environmental, non-proliferation, security, and sustainability goals to identify promising fuel cycle options, while financial risk and economics, development and deployment risk criteria were out of the MAVT-based judgement aggregation procedure. In the case of the implementation of the same assumptions, the INPRO comparative evaluation and ranking toolkit presented the evaluation results similar to those obtained in the U.S. DOE evaluation and screening study. In this regard, it can be concluded that both tools were cross-checked on the same performance and preference data and the calculation results obtained for such situations are in excellent agreement. This approach highlights the outstanding performance of Options EG23, EG24 and EG30, which are the only ones with identical performances on the benefit criteria dominating all the other options on these criteria.

Within the present study, in line with screening based on solely the benefit criteria, attempts were also made to involve the financial risk and economics, development and deployment risk criteria (Option EG01 provides outstanding performance and dominates all the other options on these criteria). This approach, combining various groups of criteria, makes it possible to determine fuel cycle options that can be considered cost effective, i.e., provide maximum benefits with minimal challenges. The focus on specifying the cost effective fuel cycle options may change the attribution of fuel cycles by different categories or gives a chance to distinguish the options within the predefined groups.

It was shown (see Table 4.18) that among the 18 options specified in the U.S. DOE study as promising fuel cycles only eight can be considered as satisfying the basic formal screening requirement if both benefit and challenge criteria are applied, i.e., screened options need to include the best option. Because the dominated options can never be the best ones, such options need to be excluded from further consideration. Considering the stability of the ranks of the options (minimal spreads in the ranks) due to uncertainties in the preference information (weights) (see Fig. 4.16–4.18), it is possible to sub-differentiate the options within each fuel cycle group (Table 4.20). Such reductions in the number of promising fuel cycles and sub-ranking of fuel cycles within the relevant groups can be considered as more refined screening results obtained based on the INPRO comparative evaluation and ranking toolkit that, as shown, can be effectively implemented for screening and classification studies as well.

Moreover, the direct involvement of the financial risk and economics as well as development and deployment risk criteria in the screening procedure is necessary when screening is considered as a pre-decisional phase before the decision analysis aimed at selecting the most preferable option for real-life deployment/implementation (instead of decision support related to the R&D prioritisation). Given these challenge criteria, the most preferable option for practical implementation may not belong to the groups of the most promising, additional potentially promising and other potentially promising fuel cycles specified in the U.S. DOE study to support the R&D prioritisation, in which only the benefit criteria were used for screening.

A trade-off between the financial risk and economics, development and deployment risk and the benefit criteria can bring upper ranks to more mature options that, for obvious reasons, can be screened out based on screening approaches used in the present analysis. This indicates the need for further development of the screening frameworks linking diverse perspectives, such as prioritizing R&D and selecting the most preferable option for real-life implementation. This screening procedure could represent a diversity of options that emphasizes different attributes (instead of options that are essentially similar) and give a set of options which is not in favour of a particular set of priorities [4.20]. This task, however, was not considered in the study, and only some preliminary results were presented to demonstrate the issue, i.e., the need to improve screening on the diversity dimension.

TABLE 4.20. THE REDUCED SET OF PROMISSING FUEL CYCLES WITH OPTIONS SUB-RANKING BASED ON ACCOUNTING FOR THE CHALLENGE CRITERIA

Fuel cycle groups		
The most promising	Additional potentially promising	Other potentially promising
EG23^{+}, EG29^{+++}, EG30^{++}	EG07^{++}, EG08^{+++}, EG40^{+}	EG04^{+}, EG14^{++}

+ - first grade option, ++ - second grade option, +++- third grade option

4.2.9. Conclusions

This case study presented illustrative results obtained using the INPRO comparative evaluation and ranking toolkit populated by the fuel cycle performance data from the U.S. DOE evaluation and screening study. It was shown that, for similar conditions, the fuel cycle evaluation and screening software (SET Tool) and KIND-ET (including its extensions) tools provide identical evaluation results, while the INPRO comparative evaluation approach leads to the conclusions similar to those presented in the U.S. DOE evaluation and screening study.

At the same time, the INPRO tools extends and complements the scope of the U.S. DOE study screening analysis through the lens of the INPRO comparative evaluation approach that can give some additional insights into overall performances of different fuel cycle options. This is achieved due to the possibility of the INPRO toolkit that implements the gradual screening procedure, which involves the sequential use of several different screening methods, such as Pareto optimality-based screening, screening techniques based on trade-off weights, etc. Depending on the availability of preference information, sequential screening makes it possible to filter out options that provide not only unacceptable, but also mediocre and volatile overall performances, considering the available preference data.

Moreover, sequential screening allows for follow-up sub-screening and sub-ranking of fuel cycle options in the specified fuel cycle groups with different levels of attractiveness, considering not only the benefit criteria but also financial risk and economics as well as development and deployment risk. Systematic accounting of financial risk and economics as well as development and deployment risk are necessary when, instead of the screening problem, in order to provide information for the R&D prioritisation, the problem of selecting the most preferable option for real-life deployment is considered. Given the criteria of financial risk and economics as well as development and deployment risk, the most preferable option for practical deployment may not belong to the groups of the most promising, additional potentially promising and other potentially promising fuel cycles specified in the U.S. DOE study, in which only the benefit criteria were used for screening.

In summary, the present study confirms that the more analytical instruments are involved in the decision analysis to support screening, ranking and selection of the most preferable alternative from a predefined set of options, the more multifaceted and exhaustive the analysis becomes.

The degree of validity of the main findings and conclusions can be significantly improved due to the thoughtful understanding that can be achieved in the case of the self-consistent use of various analytical tools. The follow-up improvement and sharpening of the considered decision support tools can be useful for expanding the application scope of relevant comparative evaluation and ranking frameworks, for instance, in order to improve screening on the diversity dimension.

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5. CONCLUSIONS

This section summarises the major findings and conclusions of the CENESO collaborative project and outlines possible applications of the comparative evaluation approach and the relevant Excel based tools. It also presents an insight on possible follow-up activities to the CENESO collaborative project.

5.1. SUMMARY OF DEVELOPED PRODUCTS AND SERVICES

Within the INPRO collaborative project "Comparative Evaluation of Nuclear Energy System Options" (CENESO) the following deliverables were provided:

(a) Based on the lessons learned from the case studies on the comparative evaluations of NES options performed under the KIND collaborative project as well as experience gained from similar case studies carried out by other research groups, it became possible to propose directions for extensions of the comparative evaluation approach by providing the capability to widen the scope of its application.

(b) The MAVT-based decision support tool – KIND-ET (KIND-Evaluation Tool) – was updated, including the incorporation of new features and improved user interface.

(c) New KIND-ET functional extensions were elaborated and tested; these extensions assist experts in performing sensitivity/uncertainty analyses in regard to weights, key indicators and single attribute value functions namely:

  (i) Domination Identifier – an analytical tool for identifying non-dominated and dominated options in a set of considered feasible options;
  (ii) Overall Score Spread Builder – an express tool for evaluating option overall score and rank spreads as well as probabilities for options to occupy certain places in the ranking caused by uncertainties in weighting factors and the objective tree structure;
  (iii) Ranks Mapping Tool – a visualisation tool for highlighting options taking the first rank for different combinations of high-level objective weights;
  (iv) Uncertainty Propagator – an instrument based on the traditional error analysis framework for evaluating uncertainties in option overall scores due to uncertainties in single attribute value function forms, key indicators and weights.

(d) Relevant supporting materials were elaborated to facilitate the toolkit implementation, including a set of user manuals, quick start guides, demo cases, country-neutral case studies, and self-education courses.

(e) A series of new and refined case studies of practical interest to the project participants were elaborated, suggestions for applying the comparative evaluation approach and lessons learned from its application were provided.

5.2. NATIONAL AND COUNTRY-NEUTRAL ANALYSIS: INSIGHTS FROM CASE STUDIES

Overall, within the CENESO collaborative project, 15 country case studies on comparative evaluations of NES options and deployment scenarios were provided by participants from Armenia, Bulgaria, Egypt, Indonesia, Kenya, Mexico, Pakistan, Romania (2 case studies), the Russian Federation (4 case studies), Thailand, and Ukraine (2 case studies). In addition, 2 country-neutral case studies were carried out in close cooperation of the INPRO secretariat with national experts from Germany and the Russian Federation.

The national case studies were focused on comparative evaluations of NES deployment scenarios, reactor technologies, evolutionary and innovative NES options, nuclear and non-nuclear energy supply options at the technological and scenario levels along with some other specific topics such as comparisons of different nuclear fuel fabrication processes and spent fuel management schemes. These case studies considered national specifics and priorities but were not deemed to adequately reflect any developments or official plans adopted in the corresponding Member States. In some cases, the results of these studies were presented to and discussed with decision-makers, in order to understand and clarify the role and place of the proposed comparative evaluation and ranking approach and tools to maintain the decision support process and corresponding dialogue.

In contrast to the national case studies, the country-neutral analysis was intended to demonstrate new potential application areas of the developed approach and tools, such as dynamic multi attribute decision support, multi-group decision support, multi-criteria classification and screening of a large set of NES and fuel cycle options. These studies were based on the performance data provided within the INPRO GAINS project and the U.S. DOE nuclear fuel cycle evaluation and screening study.

Both national and country-neutral analyses have demonstrated the applicability of the developed comparative evaluation approach, including its extensions and supporting tools for evaluating the merits and demerits associated with different fuel cycle and NES options, based on different types of evolutionary and innovative reactors, nuclear and non-nuclear energy systems, and NES evolution scenarios under consideration.

It is important to emphasise that each individual case study considered in this report provides an example of a different selection of evaluation areas and relevant key indicators to reflect the specific concerns and priorities of a particular country, the specifics of the problem requiring decision support, the availability of information, objective and subjective performance data and data on preferences. However, it proved impossible to unify the decision making process in regard to the selection of key indicators, as well as the procedures for their evaluation and the related databases required for making up performance tables due to the mentioned circumstances and factors. Nevertheless, the developed judgment aggregation procedure and approaches to the sensitivity/uncertainty treatment are quite suitable regardless of the specifics of the sets of key indicators and the rules used to evaluate them. Moreover, for similar problems in comparable conditions, even when different sets of key indicators are involved, similar trends can be observed with respect to the most preferable option from the set of the considered ones.

The basic requirements of the MCDA-based decision support process are that such a process is to be logical, transparent, comprehensive, reproducible and verifiable. In this regard, in order to support a productive dialogue and communication based on the comparative evaluation approach with decision-makers and different stakeholder groups, it is highly important to clearly describe and explicitly document all the assumptions that need to be made accurately to avoid misunderstandings in the interpretation of the results. Only in this case will this process bring transparency and added value to complex decisions involving multiple key indicators, objective and subjective judgments.

In general, the participants in the CENESO collaborative project confirmed that the proposed comparative evaluation/ranking approach and supporting tools could be effective in supporting practical decision making and maintaining an appropriate dialogue related to various topics in the area of nuclear energy planning and technology assessments. The developed toolkit can be used to streamline systemic activities and formulate specific local guidelines to improve the performance and sustainability of national nuclear energy.

In continuation of the KIND collaborative project, within the CENESO collaborative project, it was comprehensively confirmed that the MAVT based aggregation procedure is the most suitable for a given group of problems related to highlighting the merits and demerits of different NES options (including cases with a very large set of options) and ranking them according to their overall performances with the final objective — to select the most preferable one. This does not exclude the possibility that other MCDA methods may also be used for some specific problems, if a preliminary analysis involving the examination of such a context of the problem, including the availability of information provided by subject-matter experts and decision-makers, confirms that it would be reasonable to use alternative judgment aggregation frameworks.

The CENESO case studies also demonstrated that the proposed, tested and implemented extensions for the MAVT-based judgment aggregation framework allow users to consider problems with uncertainties in all key parameters of a decision support model (namely, weights, key indicators, single attribute value functions) because such uncertainties inevitably apply to most real-world problems. Uncertainty and sensitivity analyses can be helpful in determining how the final suggestions depend on different aspects and how they are affected by differences in the preferences of various decision-makers and stakeholders. The participants in the CENESO collaborative project established that such advanced uncertainty/sensitivity analyses can significantly increase the level of reliability of the results and conclusions, as this reinforces the judgments with information on the stability of the results. Due to this, the final suggestions can be reviewed and, if needed, reconsidered to reach robust conclusions regarding all the costs, benefits and risks associated with the considered options.

The KIND and CENESO experiences have shown that the increasing use of MCDA-based expertise provides valuable complementary insight and comprehension as well as balance of results of other approaches used for nuclear energy planning and technology assessment.

5.3. ENHANCING DECISION SUPPORT TOOLS

At the time of this publication, all the decision support tools were implemented on the MS Excel platform. Due to the platform’s architecture and functional capabilities, these tools can be easily modified by users according to their preferences for performing decision analyses, including sensitivity/ uncertainty treatment, as well as presenting the results of such studies on comparative evaluations and rankings of NES options and nuclear energy evolution scenarios.

Although the application of MS Excel was found to be very convenient and transparent for entering input parameters and ranks of the available options, certain additional improvements were considered appropriate. The key direction here is to increase the level of automatization of supporting calculations especially in performing sensitivity/uncertainty analyses. The path forward and future enhancement of the decision support toolkit can also include the user interface optimisation and Web application development. Other software development platforms can also be used for this purpose. Below are some additional comments on this subject.

It is important to note that the society of professional scientific software developers reached an agreement on the basic requirements for new generation calculation tools, such as that software is to be flexible, extensible, portable, and reusable. This refers to the ability of software to undergo modification, adaptability to new mathematical methods and possible changes in the research object, as well as the emergence of new information technologies.

This type of software could be developed in an appropriate architecture using state of the art information technology. For the effective development of such software, it is necessary to pay much attention to its preliminary design (ideally, its full life cycle is to be elaborated: from the design stage to installing the software on end-user computers) and involve a wide range of advanced instrumental information tools and technologies.

It is noteworthy that this type of software could encompass the fundamental changes in the software development technologies for scientific and technical applications that have taken place over the past decades: structural programming was replaced by object-oriented programming paradigms, relatively new programming languages became more popular in the development of the software tools for scientific and engineering applications. It is also meaningful to use generic markup/design level languages, structured query language (SQL) and specialized database management systems, technologies for creating distributed object systems that allow users to combine different levels into a single system.

It is very important to consider the trend towards a gradual transition to distributed object applications: the rejection from an entity in favour of a two-level client-server and distributed multilevel architectures. This trend arose quite naturally and was due to the widespread Web-ideology development. Consistent implementation of this concept can significantly increase the lifetime, expand potential user groups of software.

5.4. PATH FORWARD TO INTEGRATED DECISION SUPPORT FOR ENHANCING NUCLEAR ENERGY SUSTAINABILITY

The principles and routes for aggregating judgments in order to present and interpret the multicriteria assessment results can also be useful for integrating multiple quantitative data obtained using various analytical approaches applied to comprehensive assessments of the sustainability and effectiveness of NES options. The most widely used approaches in this area are as follows: material flow analysis; life cycle assessment; life cycle inventory analysis; cost–benefit analysis; geographic information systems (geospatial data analysis); probabilistic risk assessment; sociological research data, etc. (see Annex I). In this regard, aggregation of judgments can be useful not only for multi-criteria comparative evaluations and rankings of various options and selecting the best one among them (the main task on which the MCDA methods are focused) but also for such topics as the comprehensive performance assessment of the current state of the national nuclear energy sector in a broad sense (taking into consideration the technical, infrastructural institutional and social dimensions) or monitoring of the actual and expected performance of national nuclear energy sector over time. The issues mentioned above, which also require aggregated performance indicators and data, are important in strategic planning endeavours associated with the national nuclear sector and can be considered as a part of the systematic process of collecting, analysing and using information to track nuclear energy programme progress in achieving its objectives and to guide managerial decisions. Thus, the aggregation principles implemented in the MCDA methods can serve as an element in the implementation of integrated decision support to increase the sustainability of nuclear energy.

Such integrated decision support needs to assume the widespread use of modern analytical methods for evaluating various performance indicators together with relevant specialized databases, as well as the high-quality expert assessments in cases where there are no appropriate evaluation methods and/or related databases. If there are reliable, reproducible and substantiated quantitative data that can be obtained from verified information sources and databases, it is these data that are to be used further to evaluate performance indicators and various attributes. Otherwise, one can resort to expert assessments (in this case, it is advisable to elicit expert assessments of performance indicators and attributes in consultations with several independent subject-matter experts).

All the methods, information and data sources that are planned to be used for integrated decision support need to be clearly specified, justified and verified. It is desirable that the initial data as well as quantitative assessments of performance indicators and attributes are accompanied by evaluations of the associated uncertainties. The uncertainties can be caused by the objective difficulties in evaluating the exact values of performance indicators using the specific evaluation methods or the presence of uncertainty in the initial information and data source as well as by the fact that the performance indicators may vary or be volatile over time. The source of data is to satisfy the following basic requirements: to be complete; reliable; representative; internally consistent; relevant; and not contradictory. In this regard, the formation of appropriate information and methodological bases for high-quality assessments of performance indicators and attributes for their subsequent use in integrated decision support is an extremely crucial issue.

In contrast to the problems of modelling NES evolution scenarios, where only a set of technical, economic and scenario data is needed, for such integrated decision support, other data can additionally be required to characterise a variety of other aspects important for comprehensive evaluations of nuclear energy programmes, such as environmental impacts during normal operation and severe accidents, natural energy and rare resource consumption, taking into account the entire life cycle, multiple social aspects, including quality of life, social and individual risks in normal operation and severe accidents, human resource requirements, etc. Unfortunately, such comprehensive performance databases that could be applicable for integrated decision support do not practically exist at present. Many useful data can be found in various information sources and publications, posted on numerous internet resources and specialized databases. Thus, the collection, systematisation and verification of such data, as well as their processing in formats applicable for further use, is a very necessary task, the solution of which will help to increase the objectiveness of the assessments when individual performance indicators are aggregated into integrated performance metrics. Examples of useful information and data sources can be found in the outcome project materials: NEEDS (European Union); nuclear fuel cycle evaluation and screening (U.S. DOE), etc. (other studies in which experts can find useful data are included in the review presented in Annex I).

5.5. FINAL REMARKS

The anticipated users of the KIND approach and KIND-ET tool are national technical experts working in the areas of planning of a national nuclear power programme, innovative technology development for nuclear power and nuclear energy system analysis and assessment, and officers of ministries responsible for nuclear energy development programmes and international cooperation.

The KIND approach is intended for establishing a productive dialogue between energy-option proponents and decision makers regarding preferences for sustainable energy options. Therefore, to obtain meaningful results with KIND-ET, its user needs to have:

— Access to information and data on the status, plans and prospects of nuclear energy in the country including that on the status, plans and prospects of cooperation (nuclear trade) with other countries;
— In-depth knowledge of the discussion (debate) points regarding energy and/or nuclear energy system development in the country;
— Connection and communication to decision makers, who are assumed to be involved in problem formulation, definition of weights for high level objectives and evaluation areas and analysis of the ranking results including sensitivity analysis.

To make best possible use of the KIND approach and KIND-ET tool the user would need to be familiar with the technical details of correct approach application and the results of its verification as provided in Ref. [5.1].

REFERENCES TO CHAPTER 5

[5.1] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Multicriteria Decision Analysis Methods to Comparative Evaluation of Nuclear Energy System Options: Final Report of the INPRO Collaborative Project KIND, IAEA Nuclear Energy Series No. NG-T-3.20, IAEA, Vienna (2019).

ANNEX I

REVIEW OF THE EXPERIENCE OF APPLICATION OF THE MULTI CRITERIA DECISION MAKING AND OTHER DECISION SUPPORT APPROACHES IN NUCLEAR ENGINEERING AND RELATED STUDIES

I–1. INTRODUCTION

Within the INPRO collaborative project CENESO, interested INPRO Members systematically applied the comparative evaluation approach elaborated in the INPRO collaborative project KIND for comparisons of NES options (also applicable to comparisons of NES individual parts or constituents) to case studies of specific nuclear technologies and related issues. During the trial application of the comparative evaluation approach, they recognized the need to extend the scope of application of this approach to other topics and enlarge the spectrum of applied analytical patterns for performing decision analyses and representing results of comparisons.

It is advisable that such extensions be in line with the recent trends identified and used by other researchers in the area that facilitate applying the INPRO methodological achievements in the area of the comparative evaluation and ranking of NES options within other activities. This practice was already successfully applied within the KIND collaborative project [I–1, I–2]: the major findings and conclusions elaborated within international and national projects on various evaluating and screening results, aimed at decision support in nuclear engineering, including the multi-criteria comparative evaluation of NES options, were carefully reviewed and considered in order to elaborate the KIND approach and relevant decision support tools.

At the same time, a large number of papers in scientific journals or conference proceedings, articles and relevant presentations on websites, etc. are available, providing new ideas for performing comparative analyses and presenting their results. It could be mentioned that original research papers usually use more novel approaches to performing comparative analyses and presenting their results as compared to international and national projects tending to apply more familiar classical techniques. For this reason, a detailed consideration of original research papers may give additional concepts and proposals for extending the comparative evaluation approach and upgrading relevant tools along with enhancing patterns for presentation and interpretation of results.

This Annex outlines the experience gained from the application of the multi-criteria decision making framework along with relevant sensitivity/uncertainty analysis methods to comparative evaluations of NES options or their individual parts/constituents or any other topics related to nuclear engineering requiring relevant decision support tools.

Also, it seems reasonable to consider other promising decision support approaches used in some areas of nuclear engineering, which may be effectively combined with the multi-criteria decision making framework (life cycle assessment, system dynamics, group decision support, etc.). Such approaches and their links with the multi-criteria decision making framework were also studied in this Annex.

I–2. REVIEW OF PUBLICATIONS ON DECISION SUPPORT IN NUCLEAR ENGINEERING

Various multi criteria decision making (MCDM) methods, along with other advanced decision support tools for making comparative evaluations in nuclear engineering, have been successfully applied, and the relevant experience gained to date leads to a confident conclusion that such tools have become the main decision support means in different nuclear engineering areas. At the same time, there are practically no appropriate reviews to summarize relevant results and examine lessons learned from the MCDM application in nuclear engineering – this impedes the active and targeted use of MCDM-based tools for solving a great variety of practical problems.

The MCDM techniques (both multi-criteria decision analysis (MCDA) and multi-objective decision making (MODM)), along with other decision support techniques in nuclear engineering, make it possible to systematically search for trade-offs between the conflicting criteria for choosing, ranking, and sorting different options under consideration (from specific measures to improve the system performance to the complete NES options) in accordance with to the preferences of interested decision-makers, experts, and other stakeholders.

A great variety of decision support tools examined through solutions to different tasks in nuclear engineering has triggered the growing demand for the elaboration of integrated decision support concepts that implement different techniques most required for comparative evaluations of sustainability and performance of NES options.

A review of the publications on multi-criteria decision support techniques applied in nuclear engineering is presented below with the accent on issues related to the comparison and ranking of NES options or their parts/constituents. The most representative papers published in this field are considered.

I–2.1. The structure of the document

This Annex is organized as follows: Section I–2 provides general comments on the approach used to prepare the present review, including a description of the sources of publications. Section I–3 gives a general overview of the decision support methods, which have found extensive application in nuclear engineering with the focus on the MCDA and MODM frameworks. Section I–4 summarizes and discusses the best practices and relevant patterns used in the MCDM application along with relevant sensitivity/uncertainty analysis methods for comparative evaluations of NES options or their parts/constituents. Also, this section discusses the lessons learned, major findings and conclusions elaborated in different studies with emphasis on the identification of promising directions for the future.

For this review, one hundred publications were selected, where a specific MCDA or MODM method is applied to a certain decision support problem. The list of related publications that were used during preparation of this report can be found in the CENESO Collaborative Project Workspace at the INPRO Collaboration Platform. To get access to this workspace, it is necessary to contact the CENESO Contact Point[52]. All publications are arranged in chronological order. For each publication, indications are made as to its author(s), title, the title of journal or conference proceeding, volume and issue, pages, year of publication, and the MCDM framework used (MODM or MCDA).

Notwithstanding that the main focus in the document is on the MCDM techniques, Section I–3 also considers other approaches to decision support, which have found extensive application in different areas of nuclear engineering, such as cost–benefit analysis, life cycle and environment impact assessments, group decision making, geographic information system, and other

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approaches. Most of the approaches may be effectively coupled with the MCDM techniques in order to extend the area of their possible application.

The most representative examples of the MCDM framework application in nuclear engineering are considered and generalized in Section I–4, such as: decision support with regard to siting of nuclear power plants; comparison of different (including nuclear) energy options in view of the sustainable development perspective; comparison of NES deployment scenarios; comparison of nuclear technologies at the technological level; nuclear waste management decision support; nuclear emergency decision support; safety measures comparison; comparison of proliferation resistance measures; multi-objective optimization of nuclear reactor and related technology designs; and other tasks.

In addition, in Section I–4, the most commonly used MCDA patterns are described in regard to each step of the decision support process, i.e., identification of decision-makers, actors and stakeholders, identification of objectives and criteria, identification of alternatives, selection of MCDA method(s), assessment of attributes and criteria, weighting criteria, ranking the alternatives, and sensitivity/uncertainty analyses.

I–2.2. Sources of publications

An analysis has covered the most cited research papers indexed in the Web of Science, Scopus[53] published by Elsevier, Springer, Inderscience, MDPI, Hindawi, Taylor & Francis, Wiley Online Library, Atlantis Press along with some other publishers. Articles published in different journals prepared by these publishers form the core part of the process of scholarly communication and are an essential component of scientific research. The vast majority of the considered journals are available online (both in open access and downloadable immediately after purchase).

It is very difficult to cover all available printed matter on application of MCDM to nuclear related topics, including comparative evaluations of NES options that are becoming more popular. For this reason, only one hundred of the most representative and the most cited publications on the topic are considered, and this review is limited to some general comments and observed tendencies related to these studies.

I–3. DECISION SUPPORT IN NUCLEAR ENGINEERING

This section provides an overview of the most commonly used decision support methods, which have found extensive application in different areas of nuclear engineering, including comparative evaluations of NES options. The primary focus is on the MCDM (both MCDA and MODM) methods and toolkits.

I–3.1. Objectives of decision support in nuclear engineering

Broadly speaking, making a decision necessitates selecting one option or action from a set of feasible possibilities. To justify this selection, it seems reasonable to implement appropriate decision support techniques. Decision support involves data and information gathering

[53] Web of Science (previously known as Web of Knowledge) is a search platform, which combines bibliographic databases of academic journal articles and patents, including databases on inter-citations. It covers materials on natural, technical, biological, social sciences, arts and humanities, providing embedded capabilities for bibliographic information search, analysis, and management.
Scopus is a bibliographic and abstract database, which can be used as a tool for tracking citations of academic journal articles. It indexes over 18,000 publications in technical, medical and social sciences (including humanities), 5,000 publishers including academic journals, conference proceedings, and series books.

procedures, application of appropriate analytical tools and effective representation of data and analytic results that could jointly effectively assist a decision-maker.

The more complicated the topics considered (availability of multiple choices and involvement of different interested actors, objective and subjective evaluations, ill-structured cases, etc.), the more valuable decision support procedures are. In different areas of nuclear engineering, experts are facing situations that necessitate involving relevant decision support tools.

The decision support process is based on the concepts of efficiency, rationality and optimality. In this regard, decision support methods do not merely present relevant data but rather allow decision-makers to examine the impacts of their preferences within the confines of a certain decision along with highlighting trade-offs, which are inevitably present in any decision problem.

A proper and effective decision support framework needs to encourage broad participation of stakeholders, i.e., to actively involve representatives of different communities in dealing with a problem. It democratizes the decision support process, providing higher legitimacy to decisions made.

The decision support process is to be transparent especially in cases where making a decision involves multiple stakeholders that may lead to considerable gains or losses for individual actors. In the group decision making and especially in evaluating policy strategies, decisions have to be well justified and explained in detail. The transparent decision support process can reduce possible uncertainties and misinterpretations in relevant discourses and combine conflicting viewpoints. Interested stakeholders can be assured that their preferences and judgments are included in the decision support process.

Utilizing a well-structured and transparent approach, all actors involved in the decision support process will commonly reach a better understanding of associated trade-offs and preferences concerning a given decision support problem. Otherwise, unstructured decision processes may not provide an apparent added value.

An appropriate decision support model allows identifying the most preferred option out of a given set by means of corresponding analytical procedures: their value will increase if a decision analysis will be carried out in close collaboration between the decision-maker and decision analysts, using this model. Throughout the implementation of these procedures, the decision-maker can thoroughly examine and understand the decision problem. In this regard, the primary objective of decision support models it is not to rely on a formally selected ‘best’ decision, but, on the contrary, these models are an auxiliary tool that ensures full consideration and aggregation in a transparent manner of the most relevant preferences and judgments along with the information on the decision problem obtained from the decision-maker and other stakeholders.

Regarding nuclear engineering, it needs to be emphasized that the decision support process aimed at selecting the most preferred option (i.e., a specific measure to improve an individual system component performance or even a complete NES option, etc.) is to incorporate multiple criteria characterizing the resource consumption, waste accumulation in the long term perspective, cost effectiveness, safety and reliability level, efficiency of proliferation resistance measures and physical protection system, along with some others infrastructural and institutional measures. It means that, while performing comparative examinations of specific options, the full range of criteria and attributes are to be taken into consideration.

In this regard, comparative evaluations of NES options or their parts/constituents in terms of their performance and sustainability along with optimization of a relevant system design are of a multi-objective character with the conflicting criteria, which means that an increase in one criterion may decline the others.

This having been said, no universal principles for the selection of preferable (most promising) solutions in nuclear engineering are currently available. A lack of generally applied proven methodologies for multi-criteria decision making in nuclear engineering and, particularly, in the area of the NES performance comparison hinders efforts to identify the most preferred options balanced on various costs, benefits, and risks in a systematic and transparent manner.

I–3.2. Approaches to decision support in nuclear engineering

Decision support models facilitate decision making processes; they are elaborated within a variety of analytical frameworks by utilizing specific methods and tools. These models do not make decisions (it is the decision-makers' responsibility): they are simply means designed to assist and support the decision making process. The selection of an appropriate decision support tool depends on the decision to be made, available information and data to populate a decision support model and preferences and capabilities of the decision-makers along with other stakeholders. Decision support tools need to present information in a reasoned, consistent and well-behaved manner, interpretable for the decision-makers and interested stakeholders.

Several approaches to decision support have found extensive application in different areas of nuclear engineering, including cost–benefit analysis, life cycle assessment, group decision making, geographic information system and some others. They are considered below. Most of the approaches may be effectively coupled with the MCDM techniques to extend the area of their possible application.

I–3.2.1. *Cost–benefit analysis*

Cost–benefit analysis (CBA) is one of the most widely applied methods for evaluating decision options in different areas (including nuclear engineering) and assessing the positive and negative effects associated with a given set of options in monetary terms. It means that, if certain factors do not have a monetary value, they are also to be assessed in monetary terms. There are several techniques to carry out this conversion, for instance: to assess the costs of avoiding negative effects, to assess how much people are willing to pay for a reduction of negative impacts, etc.

The most generally applied method for comparing costs and benefits implies an evaluation of the present value (total discounted costs) and net present value for given options. The option with the greatest benefit and least cost is considered the most favoured. This approach implies that experts have to define a set of options, assess the monetary impacts of each option in terms of associated benefits and costs, rank the options based on the evaluated benefits and costs, converting them into a single net present value for each option, and perform a sensitivity analysis (if required).

The advantage of CBA is that the results are obtained in the clearest manner: all impacts summed up in a single monetary measure. Nevertheless, there is a great uncertainty in estimating the monetary value of some impacts (environmental, social, etc.) because they may usually have far-reaching consequences, which cannot always be expressed in monetary terms (or this assessment will be characterized by a great uncertainty). In addition, consideration of some decision making topics necessitates involving opposing interest groups having conflicting objectives. For such topics, CBA cannot be considered as an appropriate decision tool. For the abovementioned cases, MCDM, which allows options to be ranked, considering and aggregating different criteria without their conversion into the monetary units, is the most suitable analytical framework.

I–3.2.2. *Lifecycle assessment*

Lifecycle assessment (LCA) represents an all-enveloping environmental assessment method to examine the impacts of products, processes or services of relevance relative to each other across their entire lifecycle, i.e., 'from the cradle to the grave'. The LCA results broaden decision support without considering cost effectiveness issues.

For performing an LCA study, it is required to carry out an inventory analysis (i.e., an evaluation of material and energy balances of the system), impact assessment (i.e., a classification, characterization and evaluation of potential environmental impacts of the system) and improvement assessment (i.e., searching for the most promising possibilities to reduce the environmental burden).

The experience of LCA applications has demonstrated that this method is very effective for assessing total input and output material flows and energy forms from and to the environment for every step of the lifecycle of products/services (e.g., evaluations of environmental impacts of the fuel cycle options or whole NES).

Of note, LCA considers only environmental issues by providing a methodology for developing quantitative metrics for evaluation of potential environmental impacts of different options without aggregating individual metrics. If it is also required to consider other issues (e.g., social, economic, institutional, infrastructural, technological, etc.), LCA needs to be replaced by MCDM. At the same time, LCA (along with other similar methods, such as environment impact assessments and ecological footprint methods) is to be considered as a highly useful tool providing information on the environmental impacts in the form which is valuable for decision making and may be used in combination with other methods such as MCDA.

I–3.2.3. *Multi-criteria decision analysis*

MCDA is a framework widely used to assist decisions-making process with respect to a wide range of issues, including very different areas of nuclear engineering. MCDA provides an analytical support for subject-matter experts and decision-makers facing with conflicting assessments. Relevant instruments are intended to highlight conflicts, find compromises and balanced on different criteria solutions in the decision making process [I–3, I–4].

A properly organized expertise based on MCDA can also facilitate a comprehensive elaboration of decision making problems. Within the MCDA-based expertise, experts look for a compromise or a trade-off solution/alternative, the stability of which needs to be examined with sensitivity, uncertainty and robustness analyses with respect to the various methods used and their model parameters. MCDA evaluates costs, benefits and risks associated with a given option by means of ranking, sorting/classifying, and screening alternatives. A systematic MCDA application provides an insight into, and a better understanding of, the nature of conflicts among objectives and helps to reach a consensus among stakeholders.

MCDA provides a transparent and flexible approach applicable for a wide range of topics, such as:

- Comparative evaluation and ranking, screening and sorting options in terms of their performance with identification of merits and demerits associated with given options;
- Group (shared) decision support, which is a type of participatory process in which multiple individuals evaluate alternatives to select the most suitable one;
- Integrated with GIS, MCDA allows for consideration of spatial decision support problems;
- MCDA can serve as an integration tool combining results obtained by using other decision support methods (LCA, cost–benefit analysis, MODM, etc.).

The most commonly used MCDA methods are as follows (each technique has pros and cons and can be more or less useful as the case may be):

- Elementary methods (simple additive weighting, Kepner-Tregoe method, etc.);
- Value-based methods (MAVT, MAUT, AHP, etc.);
- Outranking methods (ELECTRE, PROMETHEE, QUALIFLEX, etc.);
- Reference point-based methods (TOPSIS, VIKOR, BIPOLAR, etc.).

In Chapter 3 of the main report, the most commonly used MCDA patterns are described with respect to each step of the decision support process: identification of decision makers, actors and stakeholders; identification of objectives and criteria; identification of alternatives; selection of MCDA method(s); assessment of attributes and criteria; weighting criteria; ranking the alternatives; and sensitivity/uncertainty analyses.

I–3.2.4. *Multi-objective decision making*

MODM is applied to problems, where "alternatives are not explicitly known. An alternative can be found by solving" a corresponding multi-objective "optimization problem. The number of alternatives may be either infinite or not countable (when some variables are continuous) or typically very large, if countable (when all variables are discrete)" [I–1]. This approach is oriented mainly to the multi-objective optimization of the system designs: a selection of design variables that provides the cost effective improvement of a system performance. In nuclear engineering, this approach is mainly used for optimizing the reactor and related technology designs, energy planning (including nuclear component), NES structures, and some others.

Essential for MODM is the concept of a set of non-dominated alternatives. It "is informally defined as a set" of alternatives for "which the value of any one among the specific optimality criteria may only be improved by degrading at least one of the remaining criteria. Thus, any" alternative "belonging to" this "set will not be improved by all the specific optimality criteria simultaneously" [I–1]. The formal definition of a set of non-dominated alternatives $P_{\mathbf{f}}(X)$ is as follows: if X is the set of feasible alternatives, $\mathbf{f}=(f_1,f_2,\ldots,f_m)$ is the set of optimality criteria, each of which, let us assume, is to be maximized), so that:

$$P_{\mathrm{f}}(X) = \left\{ x^* \in X \mid \text{there is no } x \in X \text{ for which } \begin{matrix} f_i(x) \geq f_i(x^*), \\ i = 1, \ldots m,\ \mathrm{f}(x) \neq \mathrm{f}(x^*) \end{matrix} \right\} \quad \text{(I–1)}$$

The totality of non-dominated alternatives shows the marginal capabilities of the system in terms of its possible performance improvements. The most appropriate compromise alternative is to be chosen from this set, considering additional information from subject-matter experts and the decision-maker's judgments and preferences.

For the two criteria problems, this set is displayed as a trade-off curve where one criterion degrades while the other improves. For the n-criteria problems, non-dominated alternatives belong to the n-dimensional trade-off surface. The shape of the trade-off curve or surface allows one to determine the extra costs caused by the improved system performance. Alternatives lying on the trade-off curve or surface offer the best compromise and satisfy the cost effective improvement condition of the system performance: they most of all contribute to improving the performance criteria at a minimum level of extra costs:

- The MODM methods to solve multi-objective optimization problems are various: "*a priori* and *a posteriori* methods; adaptive methods; methods based on the preliminary construction of the Pareto (efficient, non-dominated) set approximation" [I–1]: no preference methods (global criteria, goal programming, etc.).
- A priori methods (criteria constraints, achievement scalarizing function, weighted sum, etc.).
- A posteriori methods (ADBASE, normal constraint method, directed search domain, etc.).
- Adaptive and interactive methods (genetic algorithms (NSGA-II, MOCHC, etc.), feasible and reasonable goals methods, parameter space investigation (PSI) method, etc.).

Each technique has pros and cons and can be more or less useful as the case may be.

Summarizing the description of the MCDA and MODM frameworks, the following aspect needs to be discussed: while the topics that can be addressed with MCDA and MODM are different, the combined application of these two approaches facilitates finding the most preferable and balanced solution/alternative despite various contradiction criteria (Table I–1). A consistent application of the MODM and MCDA methods makes it possible to realize the full cycle of activities related to the identification of the most preferable options, which includes the following two major steps.

Firstly, it is necessary to identify the non-dominated (trade-off) options based on given sets of restrictions, projections, and other model assumptions. These options cannot be improved simultaneously on the whole set of performance criteria – absolutely unsatisfactory (worst) options will be excluded, and only non-dominated (trade-off) ones are to be kept for further consideration. The number of such options is usually in orders of magnitude less than that of options which can be improved.

Thus, MODM methods can provide a primary screening of all options, eliminating undoubtedly unsatisfactory ones that significantly narrow the space of possible options for the final examination and highlighting the cost effective directions for structural changes in the systems to increase their performance. It needs to be emphasized that these directions are cost effective (ensuring the maximum possible effect with minimum costs).

Secondly, it is required to make the final selection of the most suitable options from the primarily screened non-dominated ones by means of the MCDA methods considering experts' and decision-maker's judgments and preferences. It is worth noting that MCDA does not provide the totally 'best' option because an option can be more or less effective depending on the stated objective. This two-step procedure is used within the studies on comparative evaluations of the system performance.

TABLE I–1 COMPARISON OF MODM AND MCDA APPROACHES [I–4].

Criteria for comparison	MODM	MCDA
Criteria defined by	Objectives	Attributes
Objectives defined	Explicitly	Implicitly
Attributes defined	Implicitly	Explicitly
Constrains defined	Explicitly	Implicitly
Alternatives defined	Implicitly	Explicitly
Number of alternatives	Infinite (large)	Finite (small)
Decision maker`s control	Significant	Limited
Decision modelling paradigm	Process-oriented	Outcome-oriented
Relevant to	Design/search	Evaluation/choice

I–3.2.5. *Group decision making*

The most crucial decisions in different areas, including nuclear engineering, are to be made by groups of decision-makers with active participation of representatives of stakeholders who are impacted by the decision and have consequent interests in the decision outcome. The number of actors involved and their roles in the decision support process may vary significantly, but decision-makers and stakeholders' preferences are to be systematically considered. The group responsible for the decision has to choose the most preferred option out of several available alternatives, based on an examination of how the options are likely to perform with regard to multiple criteria considered to be important by the group representatives [I–5].

These group decision processes can be supported mainly by using relevant voting procedures considered in the social choice theories or appropriate extensions of the MCDA framework along with other possible approaches to support group decision making. It is assumed that the application of relevant MCDA extensions may help elaborate an advice offering the enhanced decision quality, improved dialog, and intensified decision implementation.

Extensions of the MCDA framework for group decision support make it possible to recognize and synthesize information regarding the group members' preferences and offer valuable insights into what options are preferred to others for each participant or the group as a whole. In some cases, the participants of the decision support process may use the same problem representation. Otherwise, individual actors may examine the problem using their own individual objective trees. Then suggestions for the group decision are to be generated by attributing importance weights to the group participants (of note, in group decision support, the aggregation of individual preferences and judgments into a group representation can be carried out through various procedures).

I-3.2.6. *Geographic information systems and MCDM*

In recent years, there has been extensive growth of theoretical and applied studies on real-world planning and management problems, which are analysed by tools integrating Geographic Information Systems (GIS) and the MCDM framework. The integrated GIS–MCDA framework consists of methods and tools for converting and coupling geographic data and preferences/value judgments to obtain relevant information for decision making [I–4].

GIS offer appropriate capabilities for storing, analysing, and visualizing geospatial data for decision making allowing subject matter experts and decision-makers to consider the spatial data in a more refined and user-friendly form. Integration with MCDA extends the decision support capabilities of GIS and related analytical technologies; as a result, MCDA is involved into new application areas, where the spatial factors are to be considered (particularly, in nuclear engineering, e.g., nuclear waste management and nuclear emergency issues, siting nuclear power plant and fuel cycle facilities, etc.). This integration appears to be beneficial for both GIS and MCDA.

I–3.2.7. *Other approaches (system dynamics, robust and stochastic optimization)*

System Dynamics.

System Dynamics is a simulation approach proposed by J.W. Forrester (MIT, Boston) [I–6]. It is a modelling instrument for addressing different socioeconomic issues. System Dynamics involves analytical reproduction of internal structures of the studied system, which under external influences allows understanding of its dynamic behaviour. System Dynamics as a simulation approach is based on the following concepts: feedback loops, influence diagrams (causal loop diagrams), which visualize the links between individual elements and components of a system. The following groups of variables are used in System Dynamics models: stocks – state variables represented by rectangular reservoirs, flows – the variation rates of stock per unit of time, which are represented as an in- or outgoing valve, according to the sign, other auxiliary variables can be added to the model to calculate the flows. Initial values are provided to calculate the stocks by numerical integration from initial time to current time.

System Dynamics is occasionally used for examining different energy planning issues (including energy systems with a nuclear component). This approach may be considered as an alternative option to the most commonly used simulation or optimization frameworks used for modelling NES deployment scenarios evaluating relevant performance metrics.

Any System Dynamics model considerably simplifies the real system, nevertheless, relevant insights into structural and causal links and mechanisms can be obtained from modelling, while the system are being elaborated and tested. System Dynamics models seek to predict qualitative changes in reference modes (i.e., to identify behaviour patterns and how they may change in course of time).

Along with other features, System Dynamics consider delays and time lags in the models and allow modelling non-equilibrium conditions and non-linearity of the functional links between variables. This approach is oriented mostly to modelling bounded-rationality processes with imperfect information and qualitative behaviours of system agents rather than normative optima being focused on causal relationships and fitting data to observations. Modelling of uncertainties due to imperfect foresight within System Dynamics may be carried out by means of scenarios and Monte Carlo simulations.

Robust and stochastic optimization.

These are complementary methods for treating data uncertainties in optimization models, which are actively applied in the models for energy planning (they are also used in studies focused on the optimization of NES structures and relevant deployment scenarios). Traditional optimization models for energy planning (incorporating different NES options) “are usually based on various deterministic methods adapted to large-scale optimization problem solutions (usually linear programming). The formulation of deterministic models and their solution requires the use of vast” amounts “of data assumed to be” exactly “known, which is often not the case” in practice [I–1]. In such models, data uncertainties are “caused by the fact that some exact data do not exist and are replaced by their evaluations”, others “cannot be measured exactly, and their values” are spread in a certain area [I–1]. “In many cases, even a small data uncertainty can make the nominal solution infeasible and practically meaningless” [I–1].

“Both robust and stochastic optimizations” help build “an uncertainty-immunized solution to an optimization problem with uncertain data. In stochastic optimization, uncertain numerical data are assumed to be random. In the simplest case, these random data obey a probability distribution known in advance. In robust optimization, it is not required to know the probability distribution of uncertain parameters. Instead of seeking to immunize the solution, in some probabilistic sense, to stochastic uncertainty, the decision-maker constructs a solution that is optimal for any realization type of the uncertainty in a given set” [I–1]. More active “development and implementation of the robust and stochastic optimizations functionalities for the uncertainty treatment seems to be very promising” [I–1].

I–4. MULTI-CRITERIA DECISION MAKING IN NUCLEAR ENGINEERING

The most representative examples of the MCDM framework applied to nuclear engineering includes as follows: decision support in regard to siting of nuclear power plants, comparison of different energy options (including nuclear) in view of the sustainable development perspective, comparison of NES deployment scenarios, comparison of nuclear technologies at the technological level, nuclear waste management decision support, nuclear emergency decision support, comparison of safety measures, comparison of proliferation resistance measures, and multi-objective optimization of nuclear reactor designs and related technology and other tasks.

In addition, the most commonly used MCDA patterns are described concerning each step of the decision support process, i.e., identification of decision-makers, actors and stakeholders, identification of objectives and criteria, identification of alternatives, selection of MCDA method(s), assessment of attributes and criteria, weighting criteria, ranking alternatives, and sensitivity/uncertainty analyses.

I–4.1. The main areas of the MCDM framework application in nuclear engineering

Examples presented below will clearly demonstrate that the MCDA framework provides an effective means for comprehensive evaluations according to different conflicting criteria, starting from specific measures to improve the performance of a certain NES component to comparisons of the whole NESs.

I–4.1.1. *Comparison of different energy options (including nuclear) in view of the sustainable development perspective*

At present, it is widely recognized that any long term energy supply strategy including a nuclear component needs to be elaborated in view of the sustainable development perspective. For this purpose, a set of different multiple sustainable energy development indicators have been proposed to measure the sustainability of certain energy supply options. These indicators are effectively used in combination with the MCDA methods for performing comparative evaluations of energy supply options. The MCDA framework aggregates single sustainable energy development indicators into a composite index (integral metric); thereby making it possible to assess the quality and sustainability of relevant energy system options and formulate advice regarding prospective development trends. The MAVT/MAUT methods are most popular in this regard and corresponding multi attribute value/utility functions are considered as integral metrics synthesizing all the sustainable development aspects.

When formulating indicators of sustainable energy development for comparisons of energy supply options with and without the nuclear component, special attention is given to the following basic requirements. The indicators used need to characterize in a similar manner the economic performance, social and environmental impacts of very different options, including fossil fuel, renewable, and nuclear energy generating options. The indicators need to be clearly defined, independent of each other and complemented with an adequate method for their calculation, measurement or assessment. The problem of comparing different energy options (including nuclear) in view of the sustainable development perspective is the most popular area for applying the MCDA toolkit at the national level and relevant publications on this topic can be easily found in numerous journals on the energy policy issues.

Finally, it needs to be noted that, along with MCDA, different MODM techniques are quite frequently used in the energy planning area (more often than in other areas considered in this review), which is quite naturally due to their specifics, including dynamic problems, infinite number of possible options to be considered, and multiple contradicting objectives characterizing economic, social and environmental aspects.

I–4.1.2. *Comparison of NES deployment scenarios*

Currently, one can observe an increasing number of publications on the use of the MCDA framework for comparison of NES deployment scenarios. These publications are very important because they provide an understanding of how a certain technological option will behave in different economic and infrastructural surroundings and these surroundings will affect the option performance.

When modelling NES deployment scenarios, experts consider the nuclear power deployment background, forecasts of its future development, accumulated stocks of nuclear material, and corresponding infrastructural capabilities. All this can be analysed at the national, regional and global levels for the short-, medium- and long term perspectives with a focus on how to evaluate the performance of NES options in terms of economics, utilization of resources, requirements for fuel cycle capacities, and accumulation of secondary fissile materials and radioactive waste. Equilibrium modelling (based on equilibrium and steady state models) and dynamic modelling (using simulation and optimization models) as well as their combined application can be equally used for evaluating the criteria.

Since different technological options may be combined into a system in different ways, when comparing the NES deployment scenarios, the number of comparable options may become rather large. In such cases, it may be required to involve not only the MCDA framework but also the MODM toolkit (along with the combination of both frameworks). It is worth noting that the majority of publications are based on the application of the MCDA framework and only a minor part of them is dedicated to the MODM framework.

I–4.1.3. *Comparison of nuclear technologies*

One of the important tasks is to compare NES options at the technological level. Different authors often use different sets of criteria, which are very context-dependent and formed considering the specifics of the decision support problem as well as available appropriate information, models and data. This has led to a common belief that it is impossible to formulate a universal set of criteria for comparative evaluations of different NES options. At the same time, there is a common understanding that relevant criteria have to characterize safety, economics, proliferation resistance and physical protection, waste management, environment, country specifics, and infrastructure aspects. For this reason, criteria are specified for a specific decision support problem, depending on available information and data. Special attention is given to the issue of technological readiness or maturity that is important to provide adequate judgments regarding the most promising option.

When comparing NES options at the technological level, all fuel cycle material flows are usually provided in the units per unit energy production in order to present them in a comparable form. NES comparisons at the technological level provide more details about peculiarities of the systems to be considered in selected evaluation areas. As a result, an evaluation of some criteria is possible only in scores (semi-quantitatively). In this regard, it is necessary to have an opportunity to interpret the corresponding criteria and their evaluations in terms familiar to decision-makers and stakeholders.

I–4.1.4. *Decision support on siting of nuclear power plants*

Siting of nuclear power plants is a process of finding a suitable location for a power plant with the aim of minimizing cost and maximizing the use of resources. It implies evaluating the following major issues: health and safety aspects, environmental effects, socioeconomic impacts, and financial considerations, and some others. Multiple criteria and attributes characterizing this process are as follows: investment cost, human resources, availability of required material, the environmental footprint, etc. To support the decisions to be made on siting a nuclear power plant, relevant decision support models are widely used to help the decision-makers select the most suitable plant sites. To deal with the siting problem, MCDA may be effectively combined with GIS along with different decision support methods, providing a primary screening of options.

I–4.1.5. *Multi-objective optimization of reactor designs and related technologies*

The MODM techniques are widely used for multi-objective optimization of reactor designs and related technologies. They involve selecting design variables to provide the cost effective improvement of the overall system performance. Traditionally, the design process is realized based on expert judgments and local parametric studies, assuming in-depth knowledge of physical phenomena that can help avoid an extensive number of simulations. If the study space is to be extended, relevant MODM-based computational models are elaborated for evaluating the multiple performances associated with a certain design as a function of design variables/parameters. The main result to be achieved is to identify and examine the Pareto front for the given performance measures using different MODM techniques (the most popular are the genetic algorithms and artificial neural network).

In nuclear engineering, there are many non-linear multi-objective optimization problems associated with nuclear reactor designs and related issues (optimization of nuclear fuel reloads, optimization of maintenance schedule of nuclear reactors, etc.), which may be effectively solved by using the genetic algorithms. These techniques have been successfully applied to different complex optimization problems, where the classical optimization approaches are more limited. In particular, when designing the nuclear reactor core, they may optimize the reactor cell parameters (array pitch, isotopic enrichment, dimensions and cells materials).

I–4.1.6. *Waste management decision support*

The MCDA-based decision support in nuclear waste management is another well-known, frequently encountered and rather important area of the MCDA application, due to the need to consider different technological, safety, environmental, institutional, and ethical issues as well as political feasibility and the overall benefits and risks related to the particular implementation process. Such studies encompass different technologies and safety aspects associated with research and power reactor fuel, its preparation for transport and storage, acceptance criteria for fuel subassemblies, envisaged storage time, and many others. Different waste management schemes may provide benefits to repository programmes.

The regional cooperation and approaches to nuclear waste management are one of the subareas of examination that may provide attractive and challenging prospects for Member States from the economic, safety, environmental, and security viewpoints. Such analyses involve considering technical requirements (safety criteria and standards, safeguards and physical protection, fuel acceptance criteria, long term stability of systems and stored fuel, site selection, infrastructural aspects, storage technology, licensing, operations, transport, decommissioning, and R&D), economic considerations (financial sources and conditions, economic evaluations, potential host countries, and customers), institutional considerations (organization and legal aspects), political and public acceptance considerations.

I–4.1.7. *Nuclear emergency decision support*

The management of severe accidents with radioactive releases is important from the very outset until many years or decades thereafter. For the last 30 years, different decision support tools based on the MCDA, MODM and GIS frameworks have been proposed, tested and applied to prevent and mitigate the effects of radiation accidents. They assist all the involved actors in working out more effective countermeasures against radiation accidents in regard to the formulation, evaluation and appraisal stages of the nuclear emergency management process.

For decision support for a nuclear emergency, MCDA is a more appropriate decision support framework, mainly for the accident response and recovery phases. In some cases, MCDA may be combined with GIS and complemented by the MODM techniques. Additionally, MCDA-based tools may be used for some other related problems, such as decision support at the planning phases, the threat and initial response phase, etc. One of the main benefits of the MCDA application for the nuclear emergency decision support is that it provides support for considerations between multiple stakeholders, establishing a common understanding of the issues and helping reach a consensus by combining tangible and non-tangible factors, objective and subjective attributes.

I–4.1.8. *Comparison of safety measures*

Nuclear safety characterizes the capacity to prevent accidents either by limiting their potential impact or reducing their likelihood. Although nuclear safety regulation practices various forms, operators and regulators discuss different possible technical improvements (or even portfolios of modifications) to increase nuclear power plant safety. Comparing different modification options and allocating the associated resources involves applying advanced decision support methods to balance costs and safety performance, and relevant decisions on the safety performance improvement is to be made by trading-off between costs and safety choices in nuclear power plants.

MCDA can also facilitate practical implementation of the integrated risk informed decision making (IRIDM) process, which is a systematic process aimed at integrating the major considerations influencing and criteria or attributes specifying nuclear power plant safety.

I–4.1.9. *Comparison of proliferation resistance measures*

Since the proliferation resistance potential of NES strongly depends both on intrinsic features and extrinsic measures, which can be characterized by different performance criteria, it is evident that comparative evaluations of possible measures to improve proliferation resistance require the applications of both MCDM frameworks – MODM and MCDA. Different metrics are proposed to characterize proliferation technical difficulty, proliferation cost and time, quality of fissile material type, detection probability and required resources, the probability and consequences of adversary success, and many other metrics.

The MAVT/MAUT methods are the most widely adopted for various decision support problems related to proliferation resistance issues especially for performing a comparative analysis of different fuel cycle options with regard to proliferation resistance. They allow comparison of the effectiveness of different measures (technological, safeguards, etc.) implemented at the fuel cycle front-end and at back-end and support a selection of the most promising measures based on their effectiveness to prevent the proliferation of nuclear materials and related technologies. These approaches are mainly based on attributes, which determine an overall proliferation resistance measure for each step in a process flow sheet. Each attribute has to be weighted to determine its relative importance in the overall evaluations. A corresponding utility function assigned to each attribute can represent either professional expertise of the assessor or a relationship binding changes of an attribute to changes in the overall performance measure.

I–4.1.10. *Comparison of economic performance and risks associated with nuclear technologies*

Within studies on comparisons of the economic performance and competitiveness of different nuclear technologies, the discounted cash flow analysis is becoming a frequently used means for selecting more attractive options. Performance criteria such as net present value, discounted cost, internal rate of return, discounted payback period, and different economic risk measures (value at risk (VaR), tail value at risk (tVaR), expected shortfalls, etc.) are thought to be the prime decision support criteria and serve as effective complementation of the levelized cost methodology that have practical sense mainly at the project level considerations.

The need for such complementation is related to that fact that, unfortunately, the levelized cost methodology (which includes all the aspects affecting the total cost and views them over a system commissioning, operation and decommissioning) does not address the role of economic risks and uncertainties involved. Assessment approaches are required to consider the variety and diversity of risks associated with investments in nuclear power. The problem becomes more urgent in the case of liberalized energy markets where different business entities have obtained a high decision making autonomy and, first of all, seek to maximize their profits. In such situations, it seems quite natural to apply the MCDM framework to provide aggregative judgments regarding economic costs, risk and benefits.

I–4.1.11. *Other tasks*

The presented examples are to be considered as the most representative illustrations of the most frequently met application areas of the MCDM tools for aggregating different judgment measures in nuclear engineering. Obviously, some other areas may be also found (such as multi-criteria selection and adjustment of nuclear data for neutronic calculations, comparison of neutronic codes and selection of the most efficient one, comparison of decommissioning strategies, etc.), which have not been covered, because they are more specific and less representative and, therefore, beyond the scope of this review.

It needs to be noted that this topic has provoked growing interest recently: new projects and studies are being launched to elaborate advanced judgment aggregation tools coupled with advanced uncertainty treatment. The main objectives of these endeavours are to cope with the limitations of classical decision support methods by developing improved analytical framework, guidance and tools for comparative evaluations of NES options or their parts/constituents in view of the associated costs, benefits and risks.

Nevertheless, the abovementioned examples reflect the main common trends in the MCDA application in nuclear engineering: a diversity of performance indicators are involved; the number of MCDA methods used in the analysis is more often than not limited to 1, sensitivity and uncertainty analyses are overly simplified with no in-depth investigation of all possible uncertainty sources. In general, there are no relevant discussions regarding the applicability of the corresponding decision support area methods.

Summarizing, it is worth noting that multi-criteria examination of NES options or their individual parts/components is a trend to be extended, thereby allowing the MCDM frameworks and their different modifications to be applied both to solving new problems and re-examining the already considered ones. By applying the MCDA and MODM techniques, it is possible to effectively search for compromises between conflicting criteria that determine the performance and sustainability of NES options or their individual parts/components within different decision support problems. Different MCDM methods provide added values to a comparative analysis of the NES options or their individual parts/components.

I–4.2. Practices used within the MCDA based decision support process in nuclear engineering

MCDA typically includes several stages known as the MCDA process: identification of decision makers and stakeholders; articulation of objectives and criteria; identification of alternatives; selection of MCDA method(s); assessment of attributes and criteria; weighting criteria; ranking the alternatives; and sensitivity/uncertainty analyses. The most commonly used MCDA patterns in the different areas including nuclear engineering are described below.

I–4.2.1. *Identification of decision makers and stakeholders*

When initiating the decision support process, it is necessary first to identify those who are interested in the decision to be made, i.e., decision makers, stakeholders and other groups of society representatives. The advantages of a broader public involvement in decision making have been well recognized because it helps a wider community understand and recognize the decision concerned and, therefore, its legitimization.

The number of actors involved in the decision support process varies for each decision problem and depends on available time and resources as well as the level of importance of the decision to be made. Depending on their preferences, different actors will protect their own interests in promoting certain options and objectives that may cause conflicts among different actors abiding the opposing interests and contradicting values.

Having specified the groups of actors involved in the decision support process, it is required to articulate the final set of criteria to be used to support decision making, the most appropriate

MCDA and sensitivity/uncertainty analysis methods, and approach to weights assignment, because all these steps are the context-dependent in regard to participants concerned.

I–4.2.2. *Specification of objectives and criteria*

An essential stage of the MCDA-based decision support process is the articulation of the objectives and specification of the criteria (or attributes) and their arrangement, which are strongly context dependent. The criteria need to be recognized and accepted by all actors participating in the decision support process. It is apparent that a set of criteria, providing the most crucial impact on the ranking results, has to be related to the overall objectives of the decision making problem.

The criteria are directly used for evaluating performance values for each option, making it possible to format a base for comparing each considered option with others. The major requirements to a set of criteria are as follows: it needs to be legible, representative and complete but not redundant (i.e., the number of criteria is to be as small as possible, so that double counting can be avoided). Very different kinds of criteria (and their combinations) can be applied within the MCDA framework: measurable, ordinal, probabilistic, fuzzy criteria, and some others.

Identifying the final set of criteria may require several iterations of relevant considerations and discussions within interested groups. An inductive approach may be applied when articulating the criteria assuming a detailed analysis of all characteristics of the options followed by grouping and aggregating the main features that may help identify real key criteria or attributes. Due to the cognitive limitations of the human mind and difficulties related to the need to gather data for evaluating performance values for each option, the number of criteria in most studies is not higher than 15 (nevertheless, some specific studies may use more criteria).

Different nuclear engineering areas involve different criteria characterizing economic (including economic performance and risk measures), technical (safety, waste management, proliferation resistance, maturity of technology), social (public acceptance, institutional issues), sustainability (resources, environmental impact, infrastructure) aspects.

I–4.2.3. *Formation of options*

Forming and articulating a set of options for comparison is a very important step in the decision support process, which may require a degree of responsibility and more efforts than ranking and choosing among the options. The group participation and structured brainstorming may facilitate identifying alternatives. In addition, new options may arise progressively, as long as the information is being introduced and examined throughout the decision support procedure.

Options under consideration need to be specified explicitly and articulated rather clearly. The number of options is extremely context-dependent and may vary significantly: from several to many ones. It seems practical to initiate the decision support process with a relatively roughly defined but rather representative and diverse set of options, among which it is potentially possible to find the more promising variant. In group decision making, it may be required to include a variety of options in which all stakeholders are interested with the aim of creating trust among the stakeholders.

Different specialized software tools can be helpful in generating and formulating options. If the set of options is rather long, it can always be reduced by eliminating dominated options through relevant screening procedures and the remaining options can be examined in detail. Screening for dominance is an effective tool for identifying non-dominated options.

I–4.2.4. *Assessment of criteria and attributes*

Relevant performance values or scores (in ordinal, interval and ratio terms) are to be assigned to each criterion for each option, using qualitative expert judgments or results of the advanced models' application. If reliable, replicable quantitative data are available, they are to be used for assessing criteria instead of an expert opinion. Otherwise, it is reasonable to gather data by consulting with several experts. The sources of performance values are to be expressly stated.

In general, any performance value is characterized by an uncertainty because of the objective difficulties of determining the exact value by means of applied evaluation method, the value may vary in course of time as well as due to many other reasons. This obstacle is to be considered while interpreting ranking results, because the performance values have a strong impact on the final results. Of note, uncertainties associated with the performance values have been rarely accounted for in decision support models in nuclear engineering.

I–4.2.5. *Selection of the MCDA method*

This step involves selecting the most appropriate MCDA method according to the nature of the decision support problem to be examined. Based on the method chosen, a comparative evaluation of the options will be made. MCDA is applied as follows: given a set of M options and N criteria for their assessment, one needs to assume that each of the options has been evaluated by each of the criteria either by experts or through objective calculations. It is then necessary to create an appropriate MCDA-based decision support model proposing a certain decision rule and incorporating the experts and decision makers' preferences to rank the options according to their values and identify the most promising one among them. The following MCDA methods have found wide application for considering different decision support problems in nuclear engineering (see Ref. [I–1] for more details):

- "Simple Scoring Model (SSM) uses a linear additive model assuming that the overall score for a given alternative is evaluated as the total sum of the performance score on each criterion multiplied by the weight of that criterion" [I–1].
- Multi attribute Value Theory (MAVT) is a value-based MCDA method assuming judgement aggregation in terms of measured/evaluated criteria into an overall score using multi attribute value functions and considering the experts and decision-makers' preference strength.
- "Multi attribute Utility Theory (MAUT) is related to MAVT", which "is based" on "the expected utility theory" and "extends MAVT" in "using probabilities and expectations to deal with uncertainties" [I–1]. The option's ranking "within MAUT is based on the comparison of expected utilities: one" option surpasses "the other if the mathematical" expectation "of a" multi attribute "utility function" for the certain option "is greater than that" for the other [I–1].
- "Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) calculates the geometric distance between each alternative and the ideal and anti-ideal alternatives and assumes that the more preferable option is to have the shortest distance from the most desirable (ideal) alternative and the longest distance from the less desirable (anti-ideal) alternative.

— Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) is an outranking method, which implies forming a partially ordered relation between each pair of alternatives.
— Analytic Hierarchy Process (AHP) is based on pairwise comparisons of alternatives against each criterion using specialized AHP scale, determination of weights based on pairwise comparisons of criteria through hierarchy, determination of scores through eigenvectors for the maximum eigenvalue and evaluation of the overall score using a linear additive model" [I–1].

Numerous studies have shown that different MCDA methods (such as MAVT, MAUT, TOPSIS, PROMETHEE, AHP etc.) in nuclear engineering provide well-coordinated results, despite some differences in ranking alternatives.

Any MCDA method requires additional data, functions, parameters to be defined (for instance, single attribute value/utility functions, preference function, indifference and preference thresholds, etc.). In general, it may require additional information from the decision-makers and subject-matter experts, which will certainly complicate and extend the analysis. At the same time, as the first approximation, it is possible to apply the simplest model assumptions when selecting these additional parameters (for instance, to linear value, utility and preference functions) followed by performing a detailed sensitivity analysis of these parameters. Of note, this approach is most commonly used in decision support processes in nuclear engineering.

I–4.2.6. *Weighting criteria*

Weights assignment within the MCDA framework is a necessary step, as ranking results strongly depend on weighting factors that make weights assignment the most challenging task. The main purpose of weights assignment is to indicate the relative importance of performance criteria; then these weights are directly used within the aggregation procedure realized in a certain MCDA method for the comparative evaluation of options. Different methods for weights assignment have been suggested and currently widely used in different areas, including nuclear engineering, which may be combined into the following groups: subjective weighting methods, objective weighting methods and combination weighting methods [I–7, I–8].

The subjective methods for assigning weights are based on the preferences of the decision-makers and stakeholders: due to this the elicitation process can be explained more clearly. These methods are most commonly used for MCDA in nuclear engineering. The most popular weighting methods are as follows: direct rating method, ranking method, pairwise comparison, ratio method, swing method, and some others.

The objective weighting methods are based on the idea that weights may be formally assessed using specific mathematical methods applied to performance tables containing criteria values for given options. In this case, decision-makers along with other stakeholders do not participate in evaluating the relative importance of criteria. Usually, the relevant objective weight assignment procedures are not highly transparent and are not intuitively obvious; nevertheless, they are applicable. The most commonly used methods are Criteria Importance Through Inter-criteria Correlation (CRITIC) method, entropy weight method, mean weight method, statistical variance procedure method, and the standard deviation method.

Within the integrated (combined or hybrid) weighting methods, weights are derived from the combination of subjective and objective information on weights obtained by the subjective and objective weighting methods. These methods are based on multiplication and additive synthesis.

Finally, it needs to be remarked that the simplest way to assign weights to criteria is to use the 'equal weights method' (mean value) that distributes weights equally among all the criteria. This approach has been widely applied as a starting point in many decision support problems.

I–4.2.7. *Ranking of options*

Applying any MCDA methods, it is possible to obtain the ranks (a complete order or a partial order) of the options from the most to less preferred ones. The most attractive option allows achieving the most promising trade-off balance concerning criteria in terms of a decision rule used in the applied MCDA method.

Since different uncertainties are inevitably present in any decision support model, special attention is to be given to the ranking results interpretation – the recommendations gained by use of the method and its parameters need to be stable and robust.

I–4.2.8. *Sensitivity, uncertainty and robustness analysis*

Sensitivity and uncertainty analysis is a necessary step in any multicriteria decision analysis, as only after such an analysis has been performed it becomes possible to rate the comparative evaluation results stable and, therefore, trustworthy. A sensitivity analysis is performed in order to specify how sensitive the outcome functionals are to variations of individual input parameters. An uncertainty analysis is performed in order to understand how uncertainties in input parameters affect the outputs of a MCDA treated topic.

The sensitivity/uncertainty analysis methods used in MCDA based studies (including nuclear engineering) are as follows: deterministic and probabilistic (stochastic) analyses (most commonly used); fuzzy set theory; and other possible approaches and frameworks like interval arithmetic, grey theory, etc. Although applying uncertainty analysis methods requires more information about system features and experts' preferences, it substantively improves the validity and trustworthiness of the provided support to decision makers by proving stability of the analysis outputs to a variety of uncertainties related to both objective and subjective factors.

The robustness of the ranking order can be examined by simultaneously using different methods for performing judgments aggregations (for instance, Simple Scoring Model, MAVT/MAUT, AHP, TOPSIS, PROMETHEE, etc.). These methods are based on different methodological foundations and implement different decision rules. The ranking results are rated robust if the observed difference from application of different methods can be explained by different decision rules used when applying these methods. High robustness of the ranking results is also a proof of their stability.

I–5. CONCLUSIONS

The presented bibliometric analysis outlines the application scope of decision support toolkits applicable (with a focus on the MCDA and MODM frameworks) for a multi-criteria comparative performance evaluation and optimization of NES options or their separate components as well as summarizes the experience gained, major findings and lessons learned from the application of this toolkit in various evaluation and screening studies along with the indication of the most promising directions for further elaboration.

The multi-criteria comparative evaluation and multi-objective optimization of NES options and their parts/constituents have become a regular practice involving appropriate decision making support toolkits for designing and selecting the most promising trade-off variants. In spite of rather wide and effective application of MCDM techniques in nuclear engineering, it is currently recognized that the scope of possible applications of relevant decision support tools is nowhere near exhausted. Due to a wide spectrum of criteria characterizing technical performance, resource consumption, economic performance along with other performance measures, the MCDM framework makes it possible to systematically determine the most promising solution/alternative out of a set of feasible ones, considering the conflicting nature of the criteria.

It is worth noting that, in nuclear engineering, the specific patterns (best practices) of MCDM have been recognized as rather suitable due to the fact that they consider the nuclear engineering background for the targeted audience interested in the decision support analysis results. These patterns include criteria selection, weighting, evaluation, and final aggregation. In particular, all performance criteria are combined into individual areas to clearly characterize technical, economic and social aspects associated with the given options. The most commonly used weighting methods are subjective ones. However objective and hybrid weighting methods are also of certain interest. It is observed that the 'equal criteria weights' is still the most popular weighting method and MAVT/MAUT are the most popular MCDA methods. Several other methods based on the weighted sum, reference point, outranking, fuzzy set methodology, and their combinations are also exercised for decision making in nuclear engineering.

Furthermore, due to the combined use of various multiple criteria decision support methods and tools, it is possible to examine the stability and robustness of relevant options with respect to applied methods and parameters. This provides comprehensive evaluations and optimization of design variables according to different conflicting criteria characterizing technological and economic performance, availability and acceptability of relevant options, as well as associated risks. Also, it is evident that the demand for integrated decision support concepts in nuclear engineering necessitates combining different methods for considering more complicated decision support problems in order to increase the NES performance and sustainability from the technological, institutional and social perspectives.

The experience gained to date in adapting and applying the MCDM framework, especially combined with other relevant decision support tools in nuclear engineering, make it possible to effectively search for compromises between the conflicting criteria that determine the performance of NES options and their components, evaluating trade-off rates according to the experts and decision-makers' judgments and preferences, sorting and ranking alternatives, and selecting the most preferable options.

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ANNEX II

CONTENTS OF THE SUPPLEMENTARY ELECTRONIC FILES: KIND-ET TOOL/EXTENSIONS, USER INSTRUCTIONS

The electronic version of this publication provides a decision support toolkit developed, verified and applied within the KIND and CENESO collaborative projects for comparative evaluations and ranking of nuclear energy system options by interested INPRO Members in support of decision analyses and prioritisation in programmes of nuclear technology research and development.

This decision support toolkit includes relevant Excel files and user instructions for the following analytical instruments that facilitate performing the basic ranking of options under consideration and uncertainty/sensitivity analyses with respect to key factors important for decision making:

(a) KIND-ET (KIND-Evaluation Tool) – a focused decision support tool representing a MAVT-based Excel template for multi-criteria comparative evaluations of NES options in accordance with the approach and suggestions elaborated in the INPRO/KIND collaborative project (version v.2.0, updated within the INPRO/CENESO collaborative project). There are two user instructions to support the KIND-ET tool:

- User Instructions for KIND-ET – provides (1) a brief description of the MAVT method implementation in the KIND and CENESO collaborative projects; (2) KIND-ET functionalities and capabilities; and (3) guidelines for using KIND-ET to complete all necessary steps related to the development of the decision support model based on the MAVT method. It also provides some examples demonstrating the implementation of this tool for comparative evaluations and rankings of nuclear energy system options/scenarios.
- User Instructions for the Extensions of KIND-ET – a description of the four functional extensions for KIND-ET, namely, (1) KIND-ET Extension-1: Domination Identifier; (2) KIND-ET Extension-2: Overall Score Spread Builder; (3) KIND-ET Extension-3: Ranks Mapping Tool; and (4) KIND-ET Extension-4: Uncertainty Propagator. Examples are provided to illustrate how these tools can be applied to perform advanced sensitivity/uncertainty analyses.

(b) Domination Identifier – an analytical tool for identifying non-dominated and dominated options from a set of considered feasible options (KIND-ET extension 1);

(c) Overall Score Spread Builder – an express tool for evaluating option overall score and rank spreads as well as probabilities for options to occupy certain place in the ranking caused by uncertainties in weighting factors; it consists of the following three components (KIND-ET extension 2):

(i) *Weight Generator* (this component generates 10,000 combinations of weighting factors uniformly distributed in the range from 0 to 1, constrained only by normalisation conditions, and provides the capability to select weight combinations satisfying some restrictions);

(ii) *Randomizer* (this is an accessorial component of Overall Score Spread Builder allowing one to change conditions for weights randomisations);

(iii) *Score Evaluator* (this component evaluates overall scores and ranks of options for each weight combination and builds the resulting box and whisker charts, demonstrating the spreads of overall scores and ranks for all options considered along with probabilities for options to occupy certain place in the ranking due to uncertainties in weighting factors).

(d) Ranks Mapping Tool – a visualisation tool for highlighting options taking the first rank for different combinations of high-level objective weights (KIND-ET extension 3);
(e) Uncertainty Propagator – an instrument based on the traditional error analysis framework for evaluating uncertainties in option overall scores due to uncertainties in single attribute value function forms, key indicators, and weighting factors (KIND-ET extension 4).

These instruments are provided as individual Excel-based analytical tools in separate Excel files and may be used by experts independently or in any combinations to deepen the analysis/expertise and enhance the quality of presented results. The data input formats in the KIND-ET extensions are consistent with the formats used in KIND-ET and it is assumed that, for the effective application of extensions, a relevant KIND-ET model is to be elaborated beforehand.

The KIND-ET extensions expand the KIND-ET capability and assist experts in performing sensitivity/uncertainty analyses in regard to weights, key indicators and single attribute value functions. In particular, these tools provide a preliminary screening of options under consideration (in terms of highlighting dominated/non-dominated options), local and global uncertainty/sensitivity analyses regarding weighting factors (at the highest and lowest levels of the objective tree), key indicators, single attribute value functions and presentation of results in a suitable and understandable form to experts specialising in issues related to nuclear energy planning and technology assessment.

The supplementary files for this publication can be found on the publication's individual web page at www.iaea.org/publications.

LIST OF ABBREVIATIONS

ADS	accelerator driven system
AHP	analytic hierarchy process
ALWR	advanced light water reactor
BAU	Business as-usual
BN-1200	sodium cooled fast reactor of 1200 MW(e) of the Russian design
BR	breeding ratio
BWR	boiling water reactor
CBA	Cost–benefit analysis
CC	combined cycle
CENESO	the INPRO/IAEA collaborative project “comparative evaluation of nuclear energy system options”
CFE	federal commission of electricity
CPP	coal-fired power plants
CR	conversion ratio
EFR	European fast reactor
EG	evaluation group
ELECTRE	Elimination et Choix Traduisant la Realite
EPU	energy planning unit
ERIRAS	the energy research institute of the Russian academy of sciences
ESBWR	Economic Simplified Boiling Water Reactor
ETL	energy transition law
FOAK	first of a kind
FP	fission product
FR	fast reactor
GAINS	INPRO collaborative project “Global architecture of innovative nuclear energy systems based on thermal and fast reactors including a closed fuel cycle”
GHG	greenhouse gases
GIS	geographic information system
GLCC	general law on climate change
HLM	heavy liquid metal
HLO	high-level objective
HLW	high level waste
HM	heavy metal
HWR	heavy water reactor

IAEA	International Atomic Energy Agency
IGCC	integrated gasification combined cycle
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
IRIDM	integrated risk informed decision making
JSC "SSC RF-IPPE"	Joint Stock Company "State Scientific Centre of Russian Federation Institute of Physics and Power Engineering"
KI	key indicators
KIND	INPRO collaborative project "Key Indicators for Innovative Nuclear Energy Systems"
KIND-ET	KIND-Evaluation Tool
KNEB	Kenya Nuclear Electricity Board
LCA	life cycle assessment
LFR	lead cooled fast reactor
LNG	liquified natural gas
LWR	light water reactor
LUEC	levelized unit electricity cost
MA	minor actinide
MAUT	multi attribute utility theory
MAVF	multi attribute value function
MAVT	multi attribute value theory
MCDA	multi-criteria decision analysis
MCDM	multiple criteria decision making
MESSAGE	calculation tool for planning and evaluation of nuclear energy systems
MNUP	mixed nitride uranium-plutonium fuel
MODM	multi-objective decision making
MOX	mixed oxide fuel
MSR	molten salt reactor
MW	Megawatt
NCCS	national climate change strategy
NDCs	nationally determined contributions
NEA	Nuclear Energy Agency
NEMix	The National Energy Mix (the mix of proven technologies capacities used to fit the annual national electricity and heat demand on the period 2011 to 2050)
NES	nuclear energy system
NESA	Nuclear Energy System Assessment, using IAEA INPRO Methodology
NEPIO	Nuclear Energy Programme Implementation Organisation
NFC	nuclear fuel cycle
NFCSS	nuclear fuel cycle simulation system

NGPP	natural gas power plant
NOAK	N_{th}-Of-A-Kind
NRC “Kurchatov Institute”	National Research Centre “Kurchatov Institute”
NRNU “MEPhI”	National Research Nuclear University Moscow Engineering Physics Institute
OECD	Organisation for Economic Co-operation and Development
PM	particulate matter
PROMETHEE	preference ranking organization method for enrichment evaluations
PRODESEN	national electric system development programme of Mexico
Pu	Plutonium
PWR	pressurized water reactor
R&D	research & development
RGP3	Russian Group Power model
RTA	reactor technology assessment
SAVF	Single attribute value function
SBO	station blackout
SD	standard deviation
SENER	Mexican Secretariat of Energy
SET	Screening and Evaluation Tool
SFR	sodium cooled fast reactor
SI	secondary indicator
SMR	small modular reactor
SNF	spent nuclear fuel
SSM	simple scoring model
SWU	separative work unit
TOPSIS	technique for order preference by similarity to the ideal solution
TRU	transuranium element
UOX	uranium dioxide fuel
UNAM	National Autonomous University of Mexico
UNFCCC	United Nations Framework Convention on Climate Change
U.S. DOE	U.S. Department of Energy
WENRA	Western European Nuclear Regulators' Association

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