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Article

Innovative Nuclear Energy Systems: State-of-the Art Survey on Evaluation and Aggregation Judgment Measures Applied to Performance Comparison

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Abstract: This paper summarizes the experience gained in the application of multi-criteria decision making and uncertainty treatment methods to a comparative assessment of nuclear energy systems and related nuclear fuel cycles. These judgment measures provide a means for comprehensive evaluation according to different conflicting criteria, such as costs, benefits and risks, which are inevitably associated with the deployment of advanced technologies. Major findings and recommendations elaborated in international and national projects and studies are reviewed and discussed. A careful analysis is performed for multi-criteria comparative assessment of nuclear energy systems and nuclear fuel cycles on the basis of various evaluation and screening results. The purpose of this paper is to discuss the lessons learned, to share the identified solutions, and indicate promising future directions.

Keywords: multi-criteria decision making; nuclear energy systems; nuclear fuel cycles; multi-objective optimization; uncertainty treatment

1. Introduction

The future Nuclear Energy System (NES) should meet the following requirements: to be resource-sufficient producing low amounts of waste in the long run, to be cost effective, to maintain the necessary level of safety and reliability and to ensure effective resistance to nuclear weapon proliferation. While conducting an integrated analysis of the future NESs and related nuclear fuel cycles (NFC) performance, special consideration must be given to the full range of system factors and constraints.

In general, experts identify five significant problem areas associated with nuclear energy development: nuclear safety, risks of unauthorized proliferation of fissile materials and technologies, radioactive waste management, economic efficiency and limited natural fuel resources, which are deterrents to large-scale development. A conflict is evident, not only between various areas, but also for some measures within a certain area which may lead, for instance, to a reduction of long-term risks while increasing short-term ones. However, at present there are no universal, reliable and generally accepted quantitative criteria and methods for planning and assessing NES long-term development and principles for selecting promising technological solutions. Therefore neither a strategy combining NES and NFC deployment balanced on various costs, benefits and risks nor strategic and tactical tradeoff decisions in each related nuclear engineering area is yet possible.

Thus, the assessment of efficiency and sustainability of NES together with an optimization of the system performance is evidently of a multi-criteria nature. Besides conflicting criteria (which means that improving the value of one criterion may lead to a decrease in the values of another) a significant uncertainty of the judgment resulting from the assessment must be taken into account, making uncertainty analysis an inevitable step in order to create a sound basis for decisions. Uncertainty examination indicates the stability of results when making multi-criteria decision comparative assessments.

A lack of commonly applied proven methodologies for decision-making using multi-criteria techniques in the nuclear engineering field and, in particular, in the area of the NES (and NFC) performance assessments, makes the procedure of formulating a coordinated vision of a preferable technological and institutional solutions, either common to several countries or specific to a particular country, rather complicated.

Multi-criteria decision making (MCDM) techniques allow searching for compromises among the conflicting factors that determine the NES and NFC efficiency and sustainability by calculating corresponding trade-off rates and make it possible to carry out comparative analysis of alternatives and selection by ranking, and sorting of the best options.

This paper is organized as follows: Section 2 gives an overview on the experience of MCDM and the uncertainty treatment methods applied to a comparative assessment of NESs and NFCs capability (or potential) performance, Section 3 summarizes and discusses the major findings and recommendations elaborated in different projects and studies, finally in Section 4 lessons learned from existing studies are discussed and promising directions for the future are indicated.

2. Studies and Projects on Multi-Criteria Assessment of NESs and NFCs

The sustainability of NES operating commercially today is often questioned by the public and some decision makers, because of concerns related to safety, nuclear waste disposal and proliferation aspects. To address these concerns and ensure the sustainable development of nuclear energy international and national nuclear agencies and organizations regularly initiate studies and projects oriented to the topic of NES and NFC sustainability and efficiency assessments. Some representative illustrations of such endeavors are presented below, which at the same time do not pretend to cover all possible studies and projects having been realized by the nuclear community on that issue.

2.1. The IAEA/INPRO Related Studies and Projects

The International Atomic Energy Agency (IAEA) is the world's centre for cooperation in the nuclear field to promote the safe, secure and peaceful application of nuclear energy.

2.1.1. IAEA Nuclear Technology Basic Principles

Any integrated analysis on the NES and NFC options related to efficiency and sustainability assessments strives to be pluralistic, by coherently accepting different priorities, intentions, values, and norms, and simultaneously relying on a consensus about the established hierarchy of requirements and basic principles. A basic principle is a statement of a general goal that is to be achieved by nuclear technology and provides broad guidance for its deployment. An appropriate set of basic principles was proposed by the IAEA, which may be divided into three categories: beneficial, responsible, and sustainable [1]. The formulated eight basic principles are intended to provide a holistic approach to the use of nuclear technology to fulfill its potential, help to sustainably meet growing global energy needs.

The beneficial use category includes two basic principles: benefits and transparency, hence the nuclear energy should provide benefits that outweigh the associated costs and risks, and be based on the open and transparent communication of all relevant information. The sustainable use category includes two basic principles: resource efficiency and continuous improvement, wherein resource use and advances in technology and engineering to continuously pursued to improve safety, security, economics, proliferation resistance, and reduce environmental impact. Finally, the responsible use category encompasses four basic principles: the protection of people and the environment, security, non-proliferation, and long-term commitment in compliance with internationally recognized standards. Moreover, the IAEA proposed general nuclear and specific objectives for nuclear power, NFC and radioactive waste management and decommissioning to be achieved at different implementation stages. To adapt these general basic principles for a specific area the experts apply these concepts to elaborate problem- and practical-oriented principles.

2.1.2. INPRO Methodology

A methodology for assessing NES capabilities to meet national sustainability requirements was developed in the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) initiated by the IAEA in 2000 [2]. INPRO developed a set of basic principles, user requirements (UR) and criteria together, with an assessment method, which taken together, comprise the INPRO methodology for the evaluation of NESs, including those with innovative components. INPRO proposed a set of basic principles on which NESs should be based to meet the overall target of sustainable energy supply [3]. To achieve sustainable NES all basic principles shall be met in the area of economics, infrastructure, waste management, proliferation resistance, physical protection, environment and safety.

INPRO hierarchy of requirements to NES design for nuclear energy system assessment (NESA) is illustrated in Figures 1 and 2. At the top-level 14 basic principles are defined. The second level called 'user requirements' contains 52 URs which specify the conditions that should be met to achieve meeting the corresponding basic principle. In this way URs define a means of achieving the top-level goals. Finally, a set of metrics with 125 criteria with indicators and acceptance limits enable a judgment of NES potential. Each INPRO criterion consists of an 'indicator' and an 'acceptance limit'. Indicators may be based on single parameter, on an aggregated variable, on a status statement.

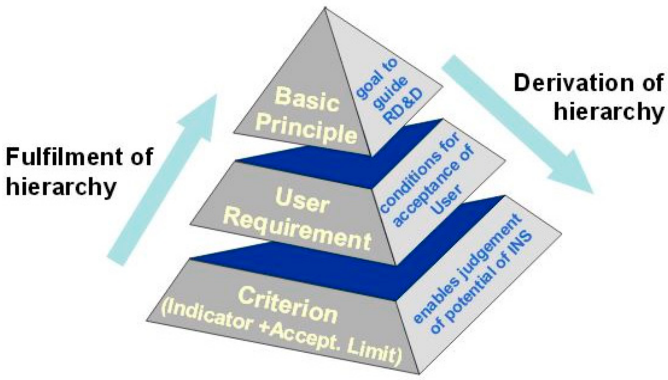


Figure 1. INPRO hierarchy of demands.

Two types of indicators of INPRO criteria are distinguished, numerical and logical. A numerical indicator may be based on a measured or a calculated value that reflects a property of an NES. Examples might be the estimated probability of a major release of radionuclides to the containment obtained from a probabilistic safety analysis or the number of intact safety barriers maintained after a severe accident. A logical indicator is usually associated with some necessary feature of an NES and usually is presented in form of a question.

In the INPRO areas (economics, safety, waste management, *etc.*) some indicators may be applicable to the overall NES, others are valid only for specific components (such as the reactor) or for specific nuclear technologies (e.g., light water reactors), they may relate to the functionality of a system or component or set out measures for implementation or methods ofanalyses. In addition, some indicators utilize 'evaluation parameters'. These parameters were introduced to assist the INPRO assessor in determining whether the acceptance limit for an indicator has been met. In some specific cases these evaluation parameters have their own acceptance limits, in which case they could be called sub-indicators. An example of evaluation parameters could be the use of parameters, such as some combination of design simplification, improved materials, increased operating margins, increased use of passive safety features and systems, increased redundancy, as an indicator for increasing the robustness of an NES component relative to an existing design as a means of enhancing defense-in-depth. In addition to the classification of indicators, another type of indicator, a so-called 'key indicator', may be defined in specific or in all INPRO areas, depending on the preferences of technology developers and Member States.

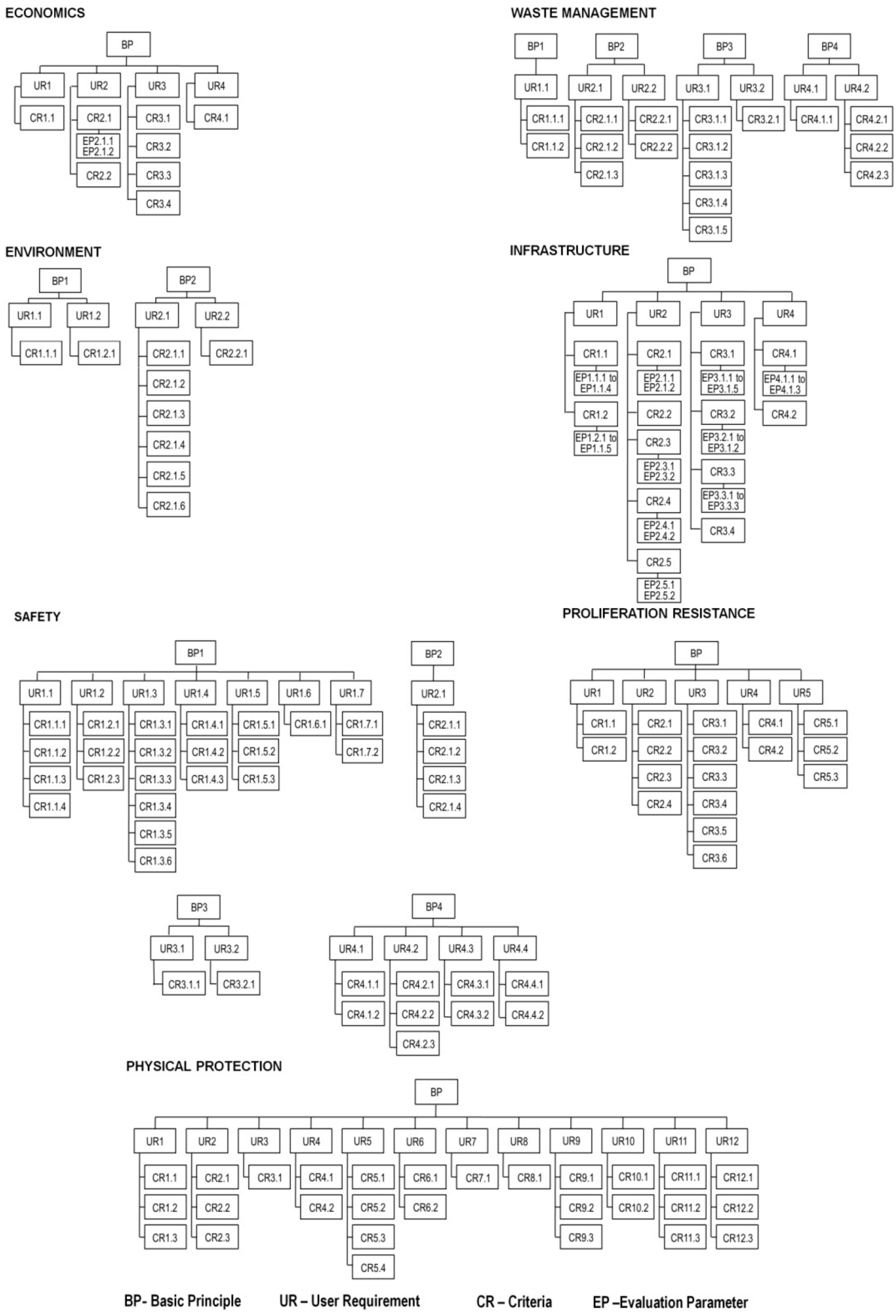


Figure 2. The INPRO hierarchies for each area.

The acceptance limit of an INPRO criterion is a target, either qualitative or quantitative, against which the value of an indicator can be compared by the INPRO assessor leading to a judgment of acceptability (pass/fail, good/bad, better/poorer). In correspondence to the two types of indicators there are also two types of acceptance limits, numerical (for quantitative targets) and logical (for qualitative targets). Typically, a logical acceptance limit is a positive (yes) or negative (no) answer to a question raised by the indicator.

In addition, a 'desired target value' would usually be defined for a key indicator (KI) chosen to represent the ultimate KI value that could be achieved through development. The concept of desired target values can be further extended by defining a so called 'relative benefit index', and a 'relative risk index' for each KI. The risk may include the uncertainty in the desired target value of the KI determined to be achievable for a specific NES, but would also reflect the development effort required and the maturity level of the concept. Thus, a concept may be advanced that has a good possibility of achieving a very substantial improvement in the value of a KI, but at the same time the concept may require the development of specific technical features that are at an early stage of development, and may require significant investment of funds, staff, *etc.*

However, feedback from experts which have used the INPRO methodology for a comparison of different NES options indicates that the current INPRO methodology as described above does not seem to be well suited for comparing different NESs. In order to perform comparative NES assessments advanced methods should be proposed for judgments aggregation.

In elaborating national and international recommendations for the NES development there is need for a structured and objective evaluation of options including: (1) screening an NES (one or more than one), selected by Member State on a national, regional and/or global basis, to evaluate whether it is compatible with the objective of sustainable energy development; (2) comparison of different NESs or components thereof, e.g., to find a preferred or optimum NES tailored to the needs of a Member State; or to make a capability comparison on a global basis; (3) identifying necessary improvements which, in turn, will lead to research, development and demonstration to upgrade the performance. In performing an INPRO assessment, a reference energy scenario or scenarios driven by a projected total demand for nuclear energy as a function of time must be considered and the pace of NES (power plants with related NFC facilities) deployment must be modeled.

2.1.3. The GAINS Analytical Framework

The INPRO Collaborative Project "Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle" (GAINS) [4] developed an analytical framework for assessing transition scenarios from existing to future sustainable NESs.

The analytical framework (hereafter, the GAINS framework) is a part of the integrated services provided by IAEA to Member States which consider either an initial development or the expansion of their nuclear energy programs. The framework was understood as a common methodological approach based on the same assumptions and boundary conditions. The major framework components include:

- Scenarios for long term nuclear power evolution based on IAEA Member States' high and low estimates for nuclear power demand until 2050, and trend forecasts to 2100 based on projections of international energy organizations;

- A so-called 'heterogeneous' global model to capture countries' different policies regarding the back end of the NFC;
- Metrics and tools to assess the sustainability of dynamic scenarios for a NES deployment, including a set of KIs and EPs;
- An international database including characteristics of existing and future innovative nuclear reactors and associated NFCs for material flow analysis, which expands upon other IAEA databases and takes into account different preferences of Member States;
- Findings from analyses of scenarios of a transition from present nuclear reactors and NFCs to future NES architectures with innovative technological solutions.

The INPRO methodology was designed as a tool for assessing the capabilities of a national NES to meet requirements of sustainability, whereas the GAINS framework is aimed at comparing options and possible scenarios at the national, regional, and global levels. Accordingly, the GAINS framework relates to INPRO methodology primarily through the concept of 'key indicators' introduced in INPRO methodology reports.

The GAINS framework measures the transition from an existing to a future sustainable NES by the degree to which the selected targets (*e.g.*, minimized waste, minimized amounts of direct use materials in storage, or minimized natural resource depletion) are approached in particular evolution scenarios. The KIs and EPs are compared to determine the more promising options for achieving the selected targets.

The set of KIs and EPs for the GAINS assessments has been selected for global scenarios with different NES architectures after considering more than a hundred candidate indicators comprising all areas in the INPRO evaluation methodology. GAINS project participants sought to reduce the number of KIs to a minimum to facilitate implementation of a scenario-based approach. As shown in Table 1 these KIs/EPs quantify nuclear power production by reactor types, resource availability, discharged fuel mass, amount of generated radioactive waste, NFC services, costs and investment of a 'global' NES. This set of GAINS KIs and EPs, originally developed for global architectures, can be adapted for a more localized application.

2.1.4. Nuclear Reactor Technology Assessment for Near Term Deployment

Another IAEA guidance effort addresses 'newcomer' Member States which have embarked recently on initiatives to establish or reinvigorate nuclear power programs. The major challenge in this enterprise is the process associated with nuclear reactor technology assessment (RTA) for near term deployment. RTA permits the evaluation, selection and deployment of the best technology to meet the objectives of the nuclear power programme when choosing among various variable reactor designs.

The IAEA report [5] demonstrates the basic elements of the approach and technology that is recommended for use in performing RTA. Table 2 lists the key elements and numbers of features and sub-features that have been chosen as the base categories for the RTA within the context of the ad-joining major tasks of nuclear programme implementation, delivering the core technical evaluations for the project feasibility study, the bid invitation, the bid evaluation and contracting, and the reactor deployment phases. The report [5] describes the use of quantitative measures and metrics to evaluate the worth of design features so that the assessment team can develop a consistent approach for assigning the benefit derived from each required element. The study recommends for application in decision making processes the Kepner–Tregoe analysis and the multi-attribute utility theory techniques, and describes in detail how these approaches can be employed to improve current practices in selecting the best technology for application.

Table 1. The GAINS key indicators and evaluation parameters.

No	Key Indicators and Evaluation Parameters	INPRO Assessment Areas					
	Color coding indicative of relative uncertainty level in estimating specific quantitative values for future NES (can vary based on a particular scenario): **Low**; **Medium-Low**; **Medium-high**; **High**	**Resource Sustainability**	**Waste Management and Environmental Stressors**	**Safety**	**Proliferation Resistance and Physical Protection**	**Economics**	**Infrastructure**
	Power Production						
KI-1	Nuclear power production capacity by reactor type						X
EP-1.1	(a) Commissioning and (b) decommissioning rates		X				X
	Nuclear Material Resources						
KI-2	Average net energy produced per unit mass of natural uranium	X	X				
EP-2.1	Cumulative demand of natural nuclear material, *i.e.*, (a) natural uranium and (b) thorium	X	X				
KI-3	Direct use material inventories per unit energy generated	X			X		X
	Discharged Fuel						
KI-4	Discharged fuel inventories per unit energy generated		X				X
	Radioactive Waste Minor Actinides						
KI-5	Radioactive waste inventories per unit energy generated		X				X
EP-5.1	(a) radiotoxicity (b) decay heat of waste, including discharged fuel destined for disposal		X				X
EP-5.2	Minor actinide inventories per unit energy generated		X				X
	Fuel Cycle Services						
KI-6	(a) Uranium enriched and (b) fuel reprocessing capacity, both normalized per unit of nuclear power production capacity				X		X
KI-7	Annual quantities of fuel and waste material transported between groups		X		X		X
EP-7.1	Category of nuclear material transported between groups				X		
	System Safety						
KI-8	Annual collective risk per unit energy generation			X			
	Cost and Investment						
KI-9	Levelized unit of electricity cost					X	
EP-9.1	Overnight cost for Nth-of-a-kind reactor unit: (a) total and (b) specific (per unit capacity)					X	
KI-10	Estimated R&D investment in Nth-of-a-kind deployment					X	X
EP-10.1	Additional functions or benefits					X	

2.2. The NEA Related Studies and Projects

The Nuclear Energy Agency (NEA) is an intergovernmental organization which brings together 31 countries from North America, Europe and the Asia-Pacific region in a small, non-political forum with a mission to assist the member countries in maintaining and further developing nuclear energy for peaceful purposes. In particular NEA provides the authoritative assessments and forges common understandings on key issues in energy and sustainable development area.

Table 2. RTA key elements, features and sub-features.

Key Elements	A Number of Key Features	A Number of Key Sub-Features
Site specific considerations	7	7
Grid integration	5	5
Nuclear plant safety	18	47
Technical characteristics and performance	10	59
Nuclear fuel and NFC performance	13	13
Radiation protection	9	9
Environmental impact	4	4
Safeguards	1	1
Plant and site security	6	6
Owner’s scope of supply	7	7
Supplier/technology holder issues	18	18
Project schedule capability	6	6
Technology transfer and technical support	7	9
Economics	5	26

2.2.1. Trends in the Nuclear Fuel Cycle

Several studies pertain to an evaluation of the performance and to screening of advanced NES, employing only simplified comparative assessment techniques. Reference [6] provides a description of the developments and trends in the NFC examining their potential to improve the competitiveness and sustainability in the medium and long term and presents criteria and indicators for the future innovative NESs assessments (see Table 3). The study refers to two MCDM techniques: the multi-criteria method and the life cycle analysis without, however, applying them. The search was based on the available results taken over from the life cycle analysis performed in the past. As far as the multi-criteria analysis is concerned the expert group activities were focused on a definition and an analysis of the applicability of criteria (indicators) and the descriptive evaluation of the different NFC options along with developments according to these criteria. Experts have not attempted to quantify and use both criteria and indicators in a concrete selection and prioritization process. The aggregation judgment process would require the development of an adequate life cycle analyses framework, which was beyond the scope of the study. It can be stated that the objective was to provide a basis for a multi-criteria analysis without at aggregating the indicators for a decision making.

2.2.2. Advanced Nuclear Fuel Cycles and Radioactive Waste Management

The broad range and flexibility of advanced NFC under future development offer a possibility to design economic NES addressing efficiently both natural resource and waste management issues. The impact of various advanced NFC on the uranium consumption rate and on the radioactive waste management was analyzed in [7] relative to present industrial practices and current technologies.

Well established codes and tools (such as DARWIN, CESAR, MARNIE, TOUGH2, PORFLOW, see [7] for further details) were used to make numerical analyses of repository long term performance and to design the hypothetical repositories to be located in granite, salt and boom clay formations.

Table 3. Criteria and indicators.

	Criterion	Indicator	Measure
Economy	Economic competitiveness	Levelised NFC cost	USD/kWh (100%)
		Raw materials(U_3O_8 or Th)	USD/t (%)
		Separation work	USD/SWU (%)
		Conversion	USD/kgHM (%)
		Fabrication	USD/kgHM (%)
		Storage	USD/kgHM (%)
		Reprocessing	USD/kgHM (%)
		Transports	USD/kgHM (%)
		Encapsulation and conditioning	USD/kgHM (%)
		Disposal	USD/kgHM (%)
	Financial expenditure	Total cost	USD
	Technology availability	Research (govt.)	USD
		Development (non-govt.)	USD
		I: basic R&D	Years
		II: laboratory/process	
		III: pre-industrial	
		IV: industrial	
Environment and Public Health	Use of non-renewable resources	Energy recovered per kg U	TWh/kg U
	Energy intensity	Ratio of necessary energy input to obtained output	%
	Transportation	Range of ton-kilometers	t×km/kWh
		Energy intensity ratio	%
	Land occupation	Land area used	km^2/kWh
	Greenhouse gas emission	Amount of GHG emitted	t CO_2 eq./kWh
	Amount of waste	Total volume	m^3/kWh
		Volume at each life cycle step	m^3/kWh
		α-emitters	kg/kWh; Bq/kWh
		γ-emitters	kg/kWh; Bq/kWh
	Confinement time of waste	α-emitters	Years
		γ-emitters	Years
	Radiological impacts	Collective operational dose	manSv/kWh
	Human health effects: acute fatalities	Operational accidents	# of immediate fatalities per accident
Society	Human resources, work opportunities	Change in work opportunity	person × year/kWh
		Work opportunity	person × year/kWh
	Broad economic effects	Autonomy of resources	
		Induced industrial production	
	Social aspects	Acceptance and risk aversion	
	Proliferation resistance		

Three groups of fuel cycles were considered. The first group encompassed NFCs based on current industrial technologies and their possible extensions, namely the current once-through NFC in pressurized water reactors and NFC options with only one plutonium recycling path. The second group includes partly-closed NFC, multi-recycling plutonium, while neptunium has always been transferred to waste. The NFC options differ however with regard to the treatment of americium and curium. A main feature of the third group is the deployment of advanced NES which have necessary potential and flexibility for continuous transuranics (TRU) (plutonium and minor actinides) recycling until their fission.

Cost estimations complete the study. The results show that advanced NFC with P&T of TRUs offer various possibilities for strategic choices regarding the efficient use of uranium resource and the optimization of waste repository sites and capacities, while keeping almost constant both: the radiological impact on the repositories and the financial impact on the complete NFC.

The metrics selected for assessment were: uranium consumption, TRUs loss/transfer to waste activity after 1000 years, decay heat after 50 years, decay heat after 200 years, high level waste (HLW) volume including spent nuclear fuel (SNF), maximum dose for repositories in granite, clay and tuff respectively, NFC cost and the total electricity generation cost. The study does not propose any multi-criteria method. Judgments are performed in a qualitative way. Final results (quantified metrics in form of indicators) depicting the NFC performance were synthesized as shown in Figure 3.

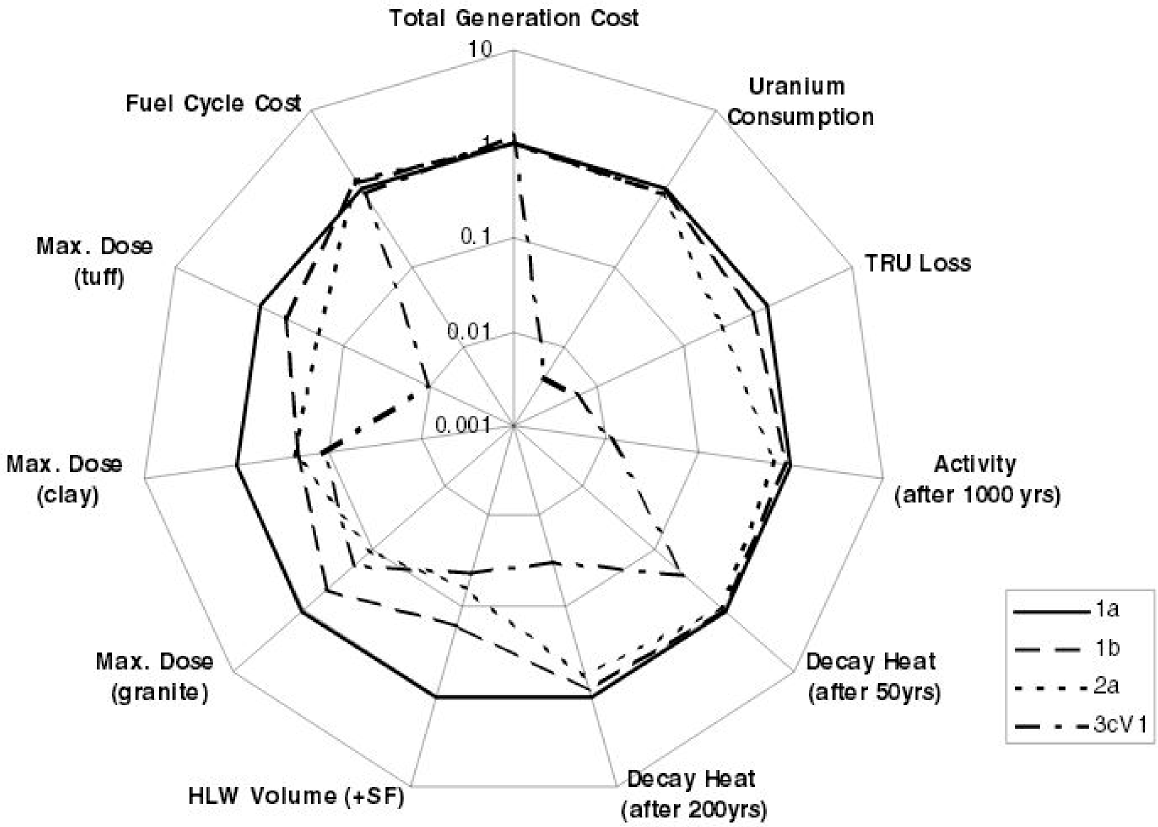


Figure 3. Comparison of eleven representative indicator values for various NFCs (**1a**: once-through NFC; **1b**: full LWR park, SNF reprocessed and Pu re-used once; **2a**: full LWR park, SNF reprocessed and multiple re-uses of Pu; **3cV1**: full fast reactor park and fully closed NFC).

Under the guidance of NEA Nuclear Science Committee and the mandate of Working Party on Scientific Issues of the Fuel Cycle comparative analyses of NFCs in view of resource and nuclear waste management were performed. Expert Groups assessed the impact of innovative NES including P&T on geological repository performance for different host formations [8,9].

2.2.3. Potential Benefits and Impacts of Advanced Fuel Cycles with Partitioning and Transmutation

In order to help promote closer collaboration across the fields of nuclear science and geological disposal the NEA Task Force on Potential Benefits and Impacts of Advanced Fuel Cycles with Partitioning and Transmutation carried out a comparative analyses of studies conducted in several international laboratories on the impact of advanced NESs with P&T on geological repository performance [10].

The outcomes of the analysis can be used to guide the development of appropriate P&T strategies in favorable combination with geological disposal design. The indicators selected for assessment purpose like peak dose rate, radiotoxicity, decay heat, waste form, volume and mass address mainly the repository performance evolution under normal and disturbed scenarios. The role of P&T in the management of uncertainty, which is an essential feature of safety case for geological disposal, was discussed as well as miscellaneous aspects such as proliferation and costs. No method was recommended for judgment aggregation.

2.2.4. Generation IV International Forum (GIF) Methodology

GIF offers a large R&D cooperation framework for preparing the development of six selected future NESs, called Generation IV (Gen IV) systems. Selected Gen IV designs are: Molten Salt Reactor, Super Critical Water Reactor, Gas-Fast Reactor System, Lead-cooled Fast reactor, Sodium-cooled Fast Reactor and High Temperature Reactor. These innovative reactor systems will have enhanced safety, competitiveness, proliferation resistance while using uranium in more efficient way and allowing the optimization of nuclear waste management, thus complying with the concept of sustainable development. A detailed evaluation of NESs may be performed by means of GIF methodology. The results allow the formulation of necessary R&D supporting NES future deployment.

GIF methodology focused mainly on advanced reactor technologies, rather than the overall NFCs, even though NFCs metrics are used in the assessments and does not give any guidelines regarding methods for integrated comparative assessments.

The GIF cost estimation methodology allows two approaches: a top-down method based on scaling and detailed information from similar reactor systems and the conventional bottom-up estimating techniques. To calculate aggregated costs following high level figures of merit are [11] applied:

- Costs to research, develop, and demonstrate the reactor system;
- Capital at risk;
- Annual non-fuel operation costs;
- Annual NFC costs;
- Levelized unit of energy cost and its components.

The GIF proliferation resistance and physical protection methodology is a systematic approach to evaluating vulnerabilities in design concepts. For comparison the IAEA/INPRO methodology for nonproliferation provides 'rules of good practice', therefore both methods together could provide users with overall approach to ensuring robust future design [12]. GIF Proliferation Resistance and Physical Protection measures are:

- *Proliferation technical difficulty*: The inherent difficulty, arising from the need for technical sophistication and materials handling capabilities, required to overcome the multiple barriers to proliferation;
- *Proliferation cost*: The economic and staffing investment required to overcome the multiple technical barriers to proliferation, including the use of existing or new facilities;
- *Proliferation time*: The minimum time required to overcome the multiple barriers to proliferation (*i.e.*, the total time planned by the Host State for the project);
- *Fissile material type*: A categorization of material based on the degree to which its characteristics affect its utility for use in nuclear explosives;
- *Detection probability*: The cumulative probability of detecting a proliferation segment or pathway;
- *Detection resource efficiency*: The efficiency in the use of staffing, equipment, and funding to apply international safeguards to the NES;
- *Probability of adversary success*: The probability that an adversary will successfully complete the actions described by a pathway and it will generate a consequence;
- *Consequences*—The effects resulting from the successful completion of the adversary's action described by a pathway.

The GIF-IV integrated safety assessment methodology consists of five distinct analytical tools or 'elements':

- Qualitative safety features review;
- Phenomena identification and ranking table;
- Objective provision tree;
- Deterministic and phenomenological analyses;
- Probabilistic safety analysis.

It is intended that each element be used to answer specific safety-related questions with different degrees of detail and at different stages of design maturity.

2.3. The U.S. DOE Related Studies and Projects

2.3.1. The Future of Nuclear Power and Nuclear Fuel Cycle

Two Massachusetts Institute of Technology (MIT) studies on the future of nuclear power and NFC were performed in 2003 and in 2011, respectively. The first interdisciplinary study assessed what is required to retain nuclear power as a significant option for reducing greenhouse gas emissions and meeting growing needs for electricity supply [13,14]. Three representative NFCs were considered and evaluated: (1) conventional light water reactor (LWR) operating in a once-through NFC; (2) thermal reactors with reprocessing in a partly-closed NFC with limited recycle; (3) fast reactors with reprocessing in a balanced fully-closed NFC where the fast reactors used to balance LWRs. The NFCs were rated using evaluation criteria including economics, waste management, nonproliferation, and reactor and NFC safety.

The second MIT Study on The Future of the Nuclear Fuel Cycle (2011) performed by MIT and other experts, considered relatively few NFC options for evaluation and was specifically focused on NFC dynamics and transition issues, using designs that would not require fast reactor technologies [15]. Both studies analyze performance characteristics of different NFC options and compare them to the current U.S. open NFC (containing only LWRs). These studies analyze data characterizing NFC material flows and requirements of NFC services peculiar to nuclear power economics, waste management efficiency, nuclear proliferation risks, nuclear safety which after aggregation in each performance area could be used in comparative assessments. Nonetheless these reports contain no recommendations regarding application of judgments aggregation method and tools for comparative assessments. All the conclusions are made based on expert opinions.

2.3.2. Nuclear Fuel Cycle Evaluation and Screening

In 2011, the U.S. D.O.E. Office of Nuclear Energy launched a study on the evaluation and screening of different NFC options, relevant to the U.S. national situation [16]. The study considers the entire NFC, from mining to disposal, including both once-through and partly or fully closed NFC with recycling of Pu or TRU recovered from used fuel. The goal is to identify a relatively small number of promising NFC options with the potential for achieving substantial improvements as compared to the current NFC. The results of this study are intended to strengthen the basis for prioritization of the R&D activities.

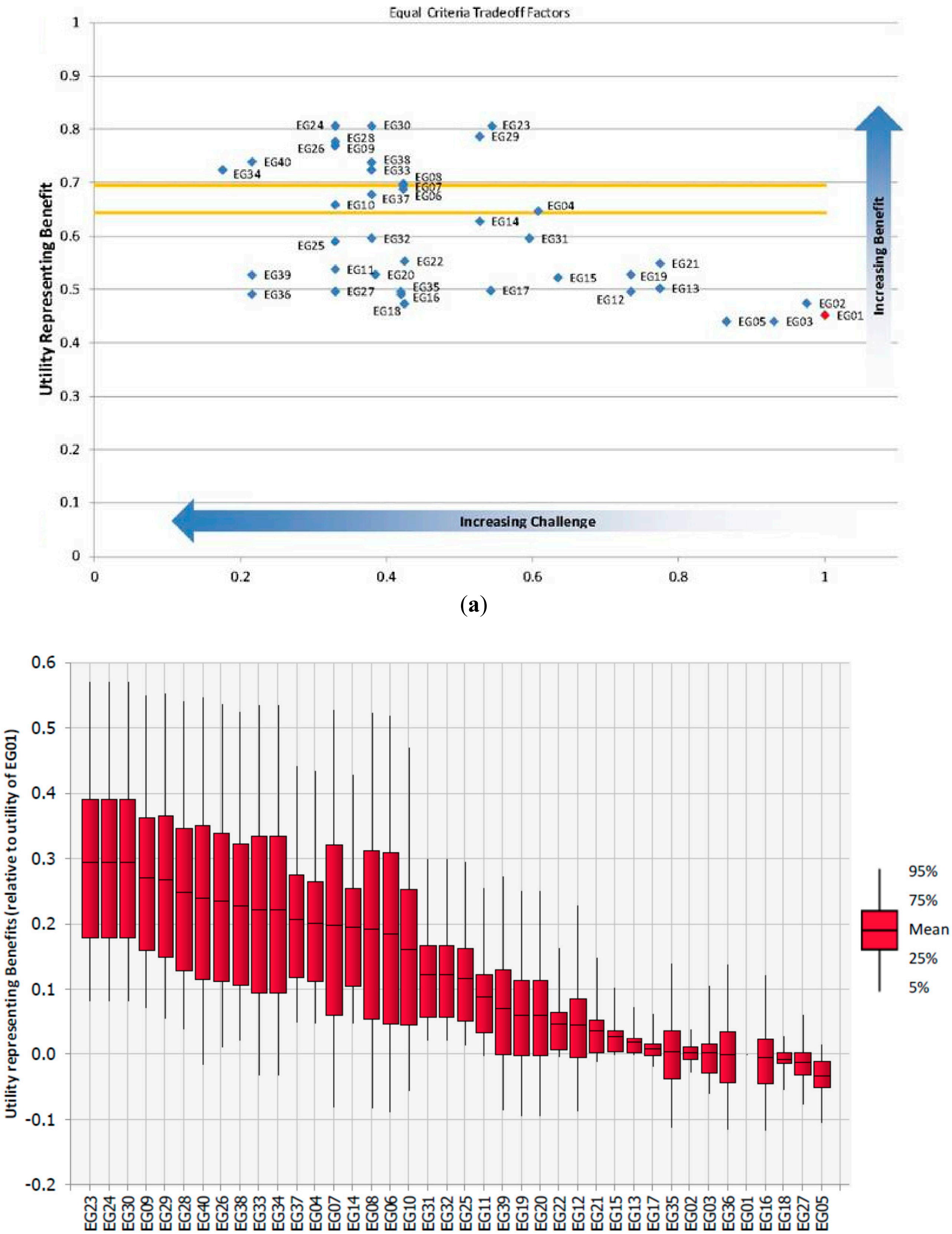
Nine evaluation criteria were specified, representing economic, environmental, safety, non-proliferation, security and sustainability goals to identify promising NFC options and measure improvements as compared to the current NFC in the U.S. The first six criteria related to the potential for benefit and the last three reflecting the challenges for developing and deploying a new NFC.

The 40 so-called 'evaluation groups' (EG) of NFC options were collected with similar physics-based performance. The set of NFC options was to be as comprehensive as possible with respect to potential NFC performance. An approach based on the fundamental characteristics of NFC rather than the specific NFC implementation technologies allowed creating a comprehensive set of options which included once-through and recycle NFC; thermal, intermediate and fast neutron reactors; critical and sub-critical reactors (ADS); uranium and/or thorium for fuel along with other distinguishing NFC features (Table 4 and Figure 4). Multi-attribute utility analysis with single-attribute utility step shaped functions for each metrics, proper tradeoff factors and criteria weights (determined using swing technique) were used to evaluate and compare alternative NFCs for multiple criteria simultaneously.

Table 4. NFCs in the Evaluation Groups.

EG	Short Description Indicative of NFCs in the Evaluation Group (EG)	NFC type
	Once-through	
EG01	Once-through using enriched-U fuel in thermal critical reactors	
EG02	Once-through using enriched-U fuel to high burnup in thermal or fast critical reactors	
EG03	Once-through using natural-U fuel in thermal critical reactors	
EG04	Once-through using natural-U fuel to very high burnup in fast critical reactors	***
EG05	Once-through using enriched-U/Th fuel in thermal or fast critical reactors	
EG06	Once-through using Th fuel to very high burnup in thermal 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	**
	Limited Recycle	
EG09	Limited recycle of U/TRU with new natural-U fuel to very high burnup in fast critical reactors	**
EG10	Limited recycle of ^{233}U/Th with new Th fuel in fast and/or thermal critical reactors	***
EG11	Limited recycle of ^{233}U/Th with new enriched-U/Th fuel in fast or thermal critical reactors	
EG12	Limited recycle of U/Pu with new natural-U fuel in fast and/or thermal critical reactors	
EG13	Limited recycle of U/Pu with new enriched-U fuel in thermal critical reactors	
EG14	Limited recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors	***
EG15	Limited recycle of U/Pu with new enriched-U fuel in both fast and thermal critical reactors	
EG16	Limited recycle of U/Pu with new enriched-U fuel in thermal critical reactors and fast ADS	
EG17	Limited recycle of Pu/Th with new enriched-U/Th fuel in thermal critical reactors	
EG18	Limited recycle of 233U/Th with new enriched-U/Th fuel in thermal critical reactors	
	Continuous Recycle	
EG19	Continuous recycle of U/Pu with new natural-U fuel in thermal critical reactors	
EG20	Continuous recycle of U/TRU with new natural-U fuel in thermal critical reactors	
EG21	Continuous recycle of U/Pu with new enriched-U fuel in thermal critical reactors	
EG22	Continuous recycle of U/TRU with new enriched-U fuel in thermal critical reactors	
EG23	Continuous recycle of U/Pu with new natural-U fuel in fast critical reactors	*
EG24	Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors	*
EG25	Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in thermal critical reactors	
EG26	Continuous recycle of ^{233}U/Th with new Th fuel in thermal critical reactors	**
EG27	Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in fast critical reactors	
EG28	Continuous recycle of ^{233}U/Th with new Th fuel in fast critical reactors	**
EG29	Continuous recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors	*
EG30	Continuous recycle of U/TRU with new natural-U fuel in both fast and thermal critical reactors	*
EG31	Continuous recycle of U/Pu with new enriched-U fuel in both fast and thermal critical reactors	
EG32	Continuous recycle of U/TRU with new enriched-U fuel in both fast and thermal critical reactors	
EG33	Continuous recycle of U/Pu with new natural-U fuel in both fast ADS and thermal critical reactors	**
EG34	Continuous recycle of U/TRU with new natural-U fuel in both fast ADS and thermal critical reactors	**
EG35	Continuous recycle of U/Pu with new enriched-U fuel in both thermal critical reactors and fast ADS	
EG36	Continuous recycle of U/TRU with new enriched-U fuel in both thermal critical reactors and fast ADS	
EG37	Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in both fast and thermal critical reactors	**
EG38	Continuous recycle of ^{233}U/Th with new Th fuel in both fast and thermal critical reactors	**
EG39	Continuous recycle of ^{233}U/Th with new enriched-U fuel in both thermal critical reactors and fast ADS	
EG40	Continuous recycle of ^{233}U/Th with new Th fuel in fast ADS and thermal critical reactors	**

ADS: subcritical reactors, ^{233}U/Th indicates recycle of uranium that is predominantly ^{233}U with thorium; (*): Most Promising NFCs; (**): Additional Potentially Promising NFCs; (***): Other Potentially Promising NFCs.



(**a**)

(**b**)

Figure 4. Considered NFCs and evaluation results. (**a**) Benefits *vs.* challenge; (**b**) Utility representing challenge.

2.4. Initiative Studies

2.4.1. Research Articles and Initiative Studies

An exhaustive set of research articles demonstrating results of initiative studies may be found in the journals and web-sites which give an overview on the experience gained with the MCDM methods and tools application in the nuclear engineering area (see, for example, [17–24]). Some of them will be discussed in the following section. The examples analyzed in these studies show that the application of MCDM methods may provide added value to conventional analysis techniques of possible options and increase a degree of clarity (better understanding). Moreover MCDM yields reasonable stable, well-interpreted and decision-making oriented results clarifying the pros and cons of the considered alternatives on quantitatively methodologically proven and well-elaborated foundations.

In a single paper it is impossible to reflect all available studies related to implementation of MCDM tools for nuclear engineering area and, in particular, for NESs and NFCs efficiency and sustainability comparative assessments which are becoming more popular day after day. For these reasons we limit our consideration to some general comments related to these studies.

2.4.2. Performance Indicators

The extensive set of different quantitative performance indicators (we use a 'performance indicator' term to combine in one notion such terms as 'figure of merit', 'key indicator', 'criteria', 'efficiency', *etc*., which are used in different studies to characterize performance of systems) are used in the studies related to NFCs and NESs efficiency and sustainability assessments which encompass economics, waste management efficiency, nuclear proliferation risks, nuclear safety aspects and cross-cutting issues. Some of these indicators which may be objectively evaluated characterize reactor technology performance, NFC material flows and requirements on NFC services, other one can be evaluated only qualitatively and are based on expert judgments. Different ways were proposed for aggregation of corresponding performance indicators into integrated performance indexes in order to assess the efficiency and sustainability associated with the corresponding options.

The lack of an agreement regarding the most representative set of performance indicators which could be generally used implies the need to continue activities on identification of the most informative performance indicators characterizing each of the problem areas. In dependence on the analyzed problem different types of performance indicators may be used such as: qualitative in form of descriptors and quantitative (binary, discrete, continuous, limited and unlimited, *etc.*). The type of indicators chosen determines the selection of appropriate MCDM methods for performing assessment.

Below some examples of the most popular performance indicators used in different studies:

- *Economics area*: net present value, discounted cost, internal rate of return, levelized cost, discounted payback period, overnight capital costs, *etc.*;
- *Non-proliferation area*: different aggregation of material flows (plutonium risk exposure, total amount of fissile materials in the NFC, *etc.*), fissile materials production capabilities, attractiveness of nuclear materials and facilities, time needed to produce a certain quantity of fissile materials, along with others;

- *Waste management area*: radiotoxicity, radioactivity, SNF and HLW amount and volume, peak dose rate, decay heat, time needed to reach a certain level of radiotoxicity of waste, *etc.*;
- *Resources area*: total uranium (thorium, plutonium) consumption, time needed to consume uranium reserves, and so on;
- *Nuclear safety*: events probabilities and consequences, collective radioactive exposure, *etc.*
- *Cross-cutting issues*: maturity of technologies, R&D needs and costs, infrastructural capabilities and others.

While forming a set of performance indicators for the NES and NFC efficiency and sustainability assessments, the authors intend to meet particular requirements, in general not every evaluation parameter may be considered and selected as a performance indicator. A generalized set of requirements should primarily obey completeness, informativeness, non-redundancy, independence, and decomposability rules. Let us briefly discuss these requirements.

1. *Completeness*. All parameters included in the set of performance indicators should provide adequate NES and NFC assessments, *i.e.*, the set should consist of all indicators that characterize the main aspects of both the problem area and the NES and NFC options under evaluation.
2. *Informativeness*. All performance indicators should be clearly understandable to both experts and decision-makers and facilitate the development and adoption of effective solutions. In parallel performance indicators should be analyzed to characterize the main aspects of developed scenarios and provide an opportunity to obtain their unequivocal quantitative assessments.
3. *Non-redundancy*. The set of performance indicators should be non-redundant to avoid duplication of information during the analysis of a problem in order not to complicate the evaluation process. At the same time the set should include all indicators necessary for qualitative assessment of the NES and NFC options.
4. *Independence*. The set of performance indicators should include only those indicators that neither overlap, nor are correlated with other indicators from the set.
5. *Decomposability*. If there are a large number of performance indicators, it is reasonable to divide them into smaller groups for convenience in simultaneous management. A set of performance indicators in this case may be built in the form of hierarchical structure (criteria or objective tree) reflecting hierarchical subordination level. In some cases, it may be necessary to implement several MCDM methods. Therefore the criteria tree construction requires additional work of expert team. It is obvious that in order to aggregate the values of indicators belonging to higher hierarchical level it is necessary to evaluate the indicators values at the lower hierarchical levels. The methods for calculating the values of indicators at the lowest hierarchical level are nowadays well developed.

2.4.3. Judgments Aggregation Procedures

The majority of the studies analyzed usually refer to multi-criteria techniques or methods, without applying them. Sometimes the results of multi-criteria studies performed by other groups are used or the studies demonstrate the implementation of one of the most known multi-criteria methods widely applied for supporting decision-making process in different subject areas. These approaches will be briefly described in the following section. Often experts limit themselves to a definition and analysis of the applicability of used performance indicators along with their evaluation for the different NESs and NFCs options. The aim is to provide a basis for a multi-criteria analysis without making an attempt to aggregate the indicators in a decision making process in the next step.

Integration of individual performance indicators into an aggregated indicator (also known as metrics, aggregated index, composite indicator) is carried out either by formulation of the universal decision rule, where the aggregated indicator is defined a priori, or by interactive (dialog) procedures, where the aggregated indicator will be defined a posteriori. Different types of aggregated indicators are addressed below:

- Arithmetical $F_a = \sum_{j=1}^{k} \mu_j \cdot (z_j / z_{jb})$;
- Geometrical $F_g = \prod_{j=1}^{k} (z_j / z_{jb})^{\mu_j}$;
- Quadratic $F_q = \sum_{j=1}^{k} \mu_j \cdot (z_j / z_{jb})^2$;
- Harmonic $F_h = 1 \Big/ \left(\sum_{j=1}^{k} \mu_j \cdot (z_j / z_{jb}) \right)$;
- General $F_o = \sum_{j=1}^{k} \mu_j \cdot \varphi(z_j / z_{jb})$, where φ is the differentiable function and z_{jb} is the reference value.

Here the k-tuples $z = (z_1, \ldots, z_j, \ldots, z_k)$ denote performance indicators, $z_i = (z_{i1}, \ldots, z_{ij}, \ldots z_{ik})$ – values of performance indicators for an alternative i, μ_j – weight of a performance indicator j, $\sum_{j=1}^{k} \mu_j = 1$.

All studies based on MCDM methods must formally reproduce all necessary stages of the decision support process: problem specification, formulation of alternatives, performance indicators identification, criteria assessment, selection and implementation of a MCDM method, uncertainty and sensitivity analysis, final conclusions and recommendations. Special attention has to be given to describe the most formal stages of the decision support process related to a specific mathematical method adopted like justification of a MCDM method applied, specification of the method parameters and assumptions, results representation, uncertainty and sensitivity analysis.

Given on one side a wide range of problems with multi-criteria character in the area on efficiency and sustainability assessments for NESs and NFCs and multiple objectives for consideration (at the levels of whole NES, a particular NFC or reactor technology, respectively), and the variety of existing judgment aggregation methods (with/without uncertainties, group/individual, discrete/continuous) on the other side it becomes evident that the application conditions for multi-criteria decision support methods and tools should be examined in view of NESs and NFCs comparative assessments.

3. Multiple-Criteria Decision-Making Framework

Multiple criteria decision making (MCDM) methods are a support tool aimed to help decision makers who are faced with numerous sometimes conflicting assessments to highlight conflicts and perform proper trading off during the decision making process [25,26]. Multi-Criteria Decision Analysis (MCDA) and Multi-Objective Decision Making (MODM) constitute the main components of MCDM. There are different classifications of MCDM problems and methods. The major distinction between MCDM problems is based on whether the solutions are defined explicitly or implicitly.

MCDA problems consist of a finite number of alternatives, explicitly known at the beginning of the decision support process. Each alternative is represented by its performance on multiple criteria. The problem may be defined as searching for the best alternative from the decision maker point of view or finding a set of acceptable trade-off among alternatives.

In general, MCDA will be applied to the following problem: given a set of M alternatives and N criteria for their assessment, where each of the alternatives has been evaluated by either by experts or through objective calculations. A decision rule must be found on the base of the experts' preferences, which will allow ranking all the alternatives according to their values and identifying the best among them.

In the MODM problems, the alternatives are not explicitly known. An alternative (solution) can be found by solving a mathematical 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).

Both of groups of methods may be applied to assess the sustainability and effectiveness of NESs and NFCs to quantitatively evaluate the most vulnerable areas of the considered options on one hand and to identify the cost-effective risk mitigation measures on the other hand in order to assess the effect from the implementation of these measures on risks minimization associated with the corresponding vulnerabilities. Although tasks, that can be solved using these groups of methods, are different their combined use seems appropriate to identify the most suitable and balanced NESs and NFCs deployment ways despite various controversial factors.

3.1. MCDA Application to Comparative Assessment of NESs and NFCs

3.1.1. The MCDA Paradigm

MCDA is a process which can be divided in the following main phases (Figure 5). At first, the problem should be formulated and structured. All parties interested in the analysis (decision-maker, experts, stakeholders, *etc.*) should find common attitude problem interpretation and understanding. This includes elaborating sets of alternatives, criteria, suitable constraints, involved uncertainties, *etc.*; and identifying goals and preferences, including factors and possible solutions as key points for further discussion and analysis.

The second phase implies construction of a model and its use. The basic MCDA characteristic is the formalization of all preferences involved in the analysis. Based on these preferences, decisions should be made by comparison of refined and elaborated sets of alternatives in a systematic and transparent manner.

Finally, based on the assessments performed and results obtained, including of the outcome of sensitivity and uncertainty analysis, a certain decision on a more preferable solution possible, otherwise it is necessary to turn back to one of the previous stages of MCDA process.

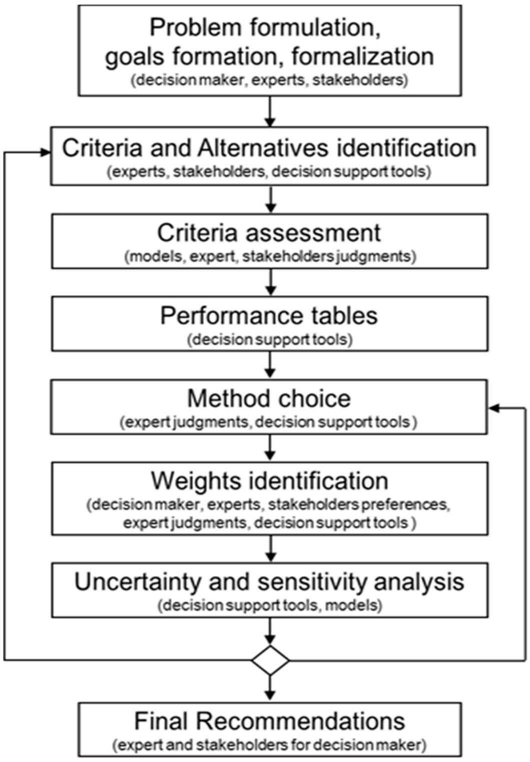


Figure 5. Flowchart of MCDA methods application.

Thus, properly organized studies based on the multi-criteria analysis represent a complex process not only formally operating with a set of mathematical methods and various analytical tools, but also leading to a comprehensive understanding of the problem and its elaboration.

MCDA does not provide a 'right solution'; in this regard it is appropriate to talk about a compromise or a trade-off solution, paying special attention to an analysis of the solution robustness to various methods used. It can be recommended to use an approach consisting of several MCDA methods application which can help all parties involved in the analysis process to understand, recognize and analyze the problem more thoroughly.

Many MCDA methods exist. Most of them were implemented in universal decision support software systems, which enable group analysis of decisions and uncertainty treatment. Choosing a unique solution or further reduction of a set of reasonable options may be performed by means of computer-aided decision-making tools based on different MCDA methods [25]; such as 1000Minds, Analytica, Criterium DecisionPlus, DecideIT, Decision Lab, Decision Lens, Expert Choice, Hiview3, Logical Decisions, MakeItRational, TreeAge Pro, *etc.* Usually the decision support software implements one or mostly two MCDA methods.

3.1.2. The Main MCDA Steps

The decision support process starts with identification of preferences for a given group of decision-makers, experts and the stakeholders (interested in a certain decision), passes through the following phases: problem formulation, specification of alternatives, criteria identification, criteria assessment, selection of MCDA method, uncertainty and sensitivity analysis, final conclusions and recommendations.

The ‘problem formulation’ step should provide a clear statement of the problem, reflecting both its current state and a vision of the preferred result. Consensus should be reached on problem formulation in order to avoid possible further misunderstandings during the decision support process. At this step it is necessary to specify clearly the requirements, conditions and restrictions that must be satisfied by any possible solution of the problem. The goal formulation is crucial issue specifying directions in a solution finding process.

The subsequent step ‘specification of alternatives’ provides an identification of possible ways to achieve the goals (a solution, alternative, *etc.*). Each alternative must meet all identified requirements, conditions and restrictions. The number of alternatives may be finite or infinite.

The ‘criteria identification’ step includes a formulation of quantitative parameters concretizing the goals against which each alternative is measured. Each goal must match one or more criteria. The criteria can be either qualitative or quantitative and, in some MCDA methods they must obey a certain set of requirements (not to be redundant, to be independent, *etc.*).

The ‘criteria assessment’ step should provide an evaluation of alternatives according to the proposed criteria and the development of the so-called performance table, which is an input data for any MCDA method. It is worth to mention that the assessments may be expressed quantitatively or qualitatively, they may be objective or subjective.

The ‘selection of MCDA method’ step should be accomplished with a selection of the most suitable method chosen according to the nature of the problem being solved. On the basis of the method chosen an assessment of the alternatives will be made.

The ‘uncertainty and sensitivity analysis’ step should provide justification for the solutions obtained, whichever method was used or whatever alternative was chosen. Such analysis helps to check stability and robustness of the solution under given uncertainties under considered criteria values and preferences, as well as to identify suitable ways to restructure the problem, including revision of the considered criteria, alternatives, and methods used.

The ‘final conclusions and recommendations’ step formulates recommendations to decision-makers regarding the more suitable trade-off solutions which were identified during implementation of the decision support process. If an outcome does not satisfy the decision-maker preferences, analysts should return to the previous steps.

In summary, given a wide range of problems having multi-criteria character in the area of NESs and NFCs efficiency and sustainability assessments with different possible range of assessment (e.g., complete NES level, a particular NFC level or reactor technology level, *etc.*), 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 taking into account experts and the decision-maker preferences on hand.

3.2. Review of Relevant MCDA Methods

3.2.1. The Most Commonly Used MCDA Methods

A large number of MCDA techniques have been developed able to deal with different kinds of problems. The assessments presented in different application studies to the nuclear engineering field were made using the following well-known MCDA methods: Multi-Attribute Value Theory (MAVT), Multi-Attribute Utility Theory (MAUT), Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS), ELimination Et Choix Traduisant la REalité (ELECTRE), Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE),Analytic Hierarchy Process (AHP) and Simple Scoring Model (SSM) [27–31] (see Figure 6).

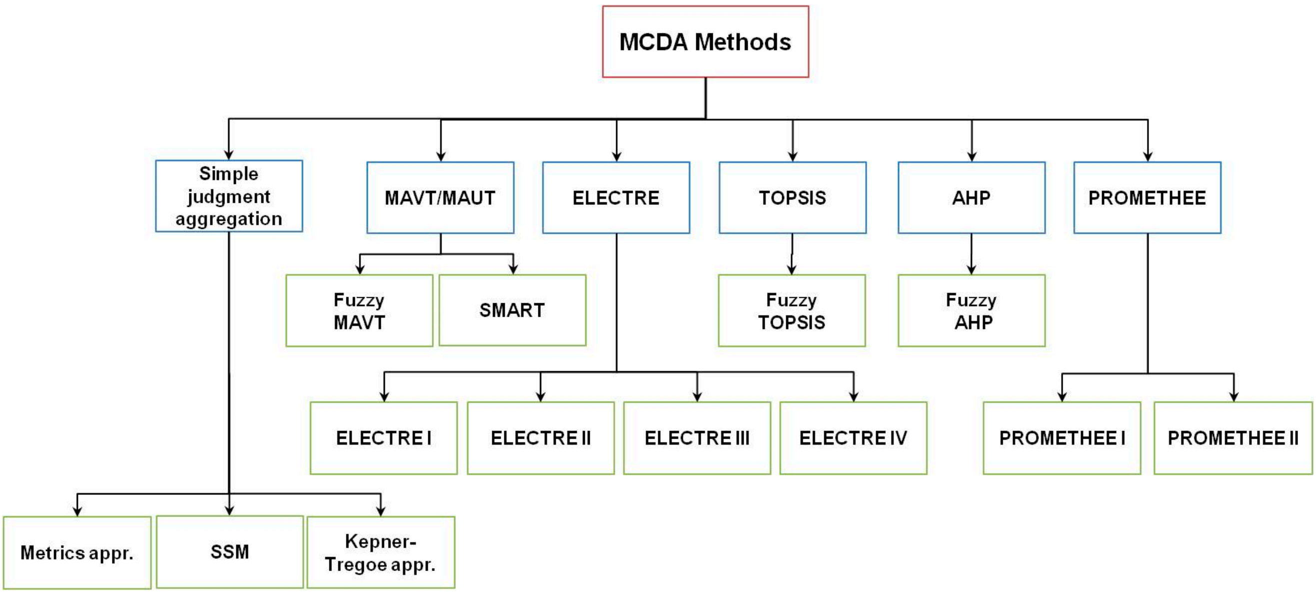


Figure 6. The most commonly used MCDA methods for NESs and NFCs assessments.

In the framework of the classical deterministic MCDA methods, the criteria values and weights are real undistributed (*i.e.*, non-random) numbers. In such methods, uncertainties are examined by means of the sensitivity analysis, generally applying it to changes in the values of weights.

The approach consisting of using several different MCDA methods may facilitate thorough understanding, recognizing and analysis the problem, providing an additional sensitivity analysis of the obtained ranking results to the adopted methods that increase the confidence level to the study. Application of a wide landscape of different methods may have a significant influence on subsequent decision-making since it helps a decision-makers understand and analyze the problem more thoroughly, achieving a consistency in judgments and estimates with stable and robust ranking results. Although the ranks of alternatives may vary for different MCDA methods, the role such analysis plays is important, as it may demonstrate whether different methods may provide non-contradictory results.

3.2.2. The Features of the MCDA Methods

The Multi-Attribute Value Theory (MAVT) is a quantitative comparison method used to combine different measures of costs, risks and benefits into a high-level aggregated performance index—multi-attribute value function accounting for the expert and decision-maker preferences. Aggregated single-attribute value functions can be used, when quantitative information about each alternative is known. A single-attribute value function is created for each indicator. These value functions transform diverse indicators evaluated in their 'natural' scale to one common, dimensionless scale or score (from 0 to 1) in accordance with experts' and decision-maker's judgments. These scores are used in further calculations. The criteria are weighted according to their importance. To identify the preferred alternative, experts should multiply each normalized alternative's scores by corresponding weighting factors for all alternative's criteria, which reflect the experts' and decision-maker's preferences. The total scores (values of multi-attribute value function) indicate the ranks of the alternatives. The preferred alternative will have the highest total score that is the highest rank.

The Multi-Attribute Utility Theory (MAUT) is closely related to MAVT, but it is based upon the expected utility theory, therefore MAUT extends MAVT by using probabilities and expectations in order to deal with uncertainties. A criterion value uncertainty is represented in MAUT by a random variable with given probability density function. The overall utility function for each alternative can be consequently considered in as a random variable. The ranking of alternatives within MAUT is based on the comparison of expected utilities: one alternative exceeds the other if the mathematical expected value of a utility function for this alternative is greater than that the corresponding expected values of the other ones. Despite widespread use of the expected utility function treated as a universal tool to measure the preferences under uncertainties, its application to the choice of alternative ranking is not widely accepted. The MAVT and MAUT methods have been applied to many decision-making problems requiring multi-criteria comparative assessment of nuclear reactors, related NFCs, NESs and technology development areas.

The Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) is a method of compensatory aggregation that compares a set of alternatives by identifying weights for each criterion, normalizing scores for each criterion and calculating the geometric distance between each alternative and the ideal and anti-ideal alternatives, which are the best and worst scores in each criterion, correspondingly. Thus*,* TOPSIS is based on a concept that the chosen alternative should have the shortest distance from the most desirable (ideal, or positive ideal) solution and the longest distance from the less desirable (anti-ideal, or negative ideal) solution. Ideal solution is a solution which has the best level for all indicators considered. Negative ideal solution is a solution which has the worst indicator values. TOPSIS selects the solution that is the closest to the ideal solution and farthest from negative ideal solution.

ELimination Et Choix Traduisant la REalité—ELimination and Choice Expressing Reality (ELECTRE) is an outranking method of decision making assuming the construction of outranking relations aimed at comparing each pair of alternatives; and an exploitation procedure that elaborates on the recommendations depending on the type of problem being addressed (choosing, ranking or sorting) by means of two distinct sets of parameters: the importance coefficients and the veto thresholds.

The Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE) belongs to the so called outranking methods which imply forming an ordered relation of a given set of alternatives. Outranking methods are based on a pairwise comparison of alternatives for each criterion under consideration, with subsequent integration of the obtained preferences according to a chosen algorithm. In the PROMETHEE method it is required to choose preference function defined in the range from 0 to 1, with specified indifference and preference thresholds.

The Analytic Hierarchy Process (AHP) is a structured technique for organizing and analyzing complex decisions by means of decomposition of the decision problem into a hierarchy of more easily comprehended sub-problems. Once the hierarchy is built, the decision makers systematically evaluate its various elements by comparing them to one another two at a time, with respect to their impact on an element above them in the hierarchy. In making the comparisons, the decision makers can use concrete data about the elements or judgments about the elements' relative meaning and importance. The AHP converts these evaluations to numerical values that can be processed and compared over the entire range of the problem. A numerical weight or priority is derived for each element of the hierarchy, allowing diverse and often incommensurable elements to be compared to one another in a consistent way. In the final step of the process, numerical priorities are calculated for each of the decision alternatives. These numbers represent the alternatives' relative ability to achieve the decision goal.

3.3. Illustrations of Judgments Aggregations for the NESs and NFCs Comparative Assessments

A wide variety of problems can be solved using MCDM methods:

- Identification of optimal or more preferable parameters of reactor technologies comprising a related NFC and NES (type, technical and structural characteristics, *etc.*) Which are promising taking into account preferences of different decision-makers;
- Identification of costs, risks and benefits as well as the corresponding trade-off rates associated with the deployment of certain reactor technologies, related NFC and NES from the system viewpoint;
- Identification of cost-effective risk mitigation measures for reducing risks associated with the deployment of certain reactor technologies, related NFC and NES (technological innovations, diversification, *etc.*);
- Decisions about R&D resource allocation problem supported by an identification of a limited set of reactor technologies worth R&D budgets alignment to provide sustainable NES deployment.

Some application cases of judgments aggregation methods to the NESs and NFCs comparative assessments are discussed below.

3.3.1. Aggregated Indicator (Metrics)

This quite popular approach for judgment aggregation in nuclear engineering is based on using standards of measurement (metrics) by which efficiency, performance, progress, or quality of process or product can be assessed. Aggregated indicator method has been applied for comparative assessments of the nuclear material attractiveness.

Reference [32], for instance, delineates a set of metrics called figures-of-merit (FOM) that are intended to measure the attractiveness or preferences for a range of nuclear materials across a span of credible nuclear adversaries:

$$FOM = 1 - \log\left(M\left[\frac{1}{800} + \frac{h}{4500}\right] + \frac{M}{50}\left[\frac{D}{500}\right]^{\frac{1}{\log 2}} \right) \tag{1}$$

where M is the bare critical mass in kg, h is the heat content in W/kg, and D is the dose rate of 0.2·M evaluated at 1 m from the surface in rad/h.

Another approach, presented in [33] by Saito attempts to account for both spontaneous neutron emission and decay heat using a single attractiveness function. The concept of 'attractiveness' is based on analysis of the physical characteristics of nuclear fuel. Attractiveness may be used for categorization of different nuclear materials hazard. The fuel attractiveness criterion is the attractiveness function accounting for the potential power of a hypothetical explosive device and the technical difficulties arising from its production. The potential yield is determined by the α-Rossi coefficient (ratio of super-criticality to prompt neutron lifetime). The technological difficulties may be represented by the so-called protective barriers, including decay heat (DH) and spontaneously fissile neutron source (NS):

$$ATTR = \frac{\frac{\alpha}{\alpha^{239}}}{\frac{DH}{DH^{238}} + \frac{NS}{NS^{238}}} \tag{2}$$

3.3.2. Multi-Attribute Value/Utility Theory

The MAVT/MAUT methods are widely adopted for various decisions with multi-criteria objectives encountered in nuclear engineering applications. An approach based on the MAVT/MAUT was proposed by Charlton [22] for comparative analysis of diverse NFC for proliferation resistance.

This approach allows one to assess effectiveness of safeguards implementation at front- and at back-end NFC facilities and supports a choice technologies based partly on their effectiveness to deter the proliferation of nuclear materials. The method uses a series of attributes to determine a proliferation resistance measure for each step in a process flow sheet. Each attribute has a weighting that determines its relative importance in the overall assessment and is furnished with associated utility function which. This utility function is derived from both expert knowledge and physical characteristics that relate changes in the value of an attribute to its contribution to the integrated indicator. This approach can be used to estimate risks due to theft by an insider (host), or a threat from outsider (terrorist groups). A method was developed that aggregates proliferation resistance values for each NFC process into an overall nuclear security measure. The nuclear security (NS) measure for the system is determined by:

$$NS = \frac{\sum_{i=1}^{I} m_i \ \Delta t_i PR_i}{\sum_{i=1}^{I} m_i \ \Delta t_i} \tag{3}$$

where m_i is the significant quantity (SQs) of material in the process i, Δt_i is the time for which the material stays in the process i, and the coefficient PR_i determines the proliferation resistance value of the process i. Thus the total nuclear security measure represents the time- and mass-weighted average of the proliferation resistance measure. The mass values as defined by IAEA are: 8 kg for plutonium, 25 kg for high-enrichment uranium, 75 kg for low-enrichment uranium, 25 kg for neptunium-237 and americium (as an element), and 20,000 kg for thorium (as an element). The proliferation resistance for the process *i* is calculated using following expression:

$$PR_i = \sum_{j=1}^{J} w_j u_j\ (x_{ij}) \tag{4}$$

where w_j is the weight for the attribute j, u_j is the utility function for the attribute j and x_{ij} is the utility function argument for the attribute *j* in the process *i* (see Table 5 for attributes, their values and weighting factors).

Table 5. Measures, attributes and weighing factors.

Measures	*j*	Attributes	Weights
Attractiveness	1	Attractiveness level under the US DOE classification (from IB to IVE)	0.10
	2	Plutonium heat release (W/kg)	0.05
	3	Fraction of even plutonium isotopes	0.06
Concentration	4	Concentration (SQ/MT)	0.10
Handling of material	5	Dose rate (rem/h at a distance of 1 м)	0.08
	6	Size/weight	0.06
Type of accounting and control system	7	Measurement frequency	0.09
	8	Measurement accuracy (SQ/year)	0.10
	9	Purity of material	0.03
	10	Share of process operations using accounting systems	0.05
Accessibility	11	Probability of unidentified movements	0.07
	12	Physical barriers	0.10
	13	Inventory (SQ)	0.05
	14	Type of fuel charge	0.06

Fourteen utility functions for selected metrics were constructed as attractiveness level, heating rate from Pu, weight fraction of even Pu isotopes, concentration of fissile material in the process step, radiation dose rates size/weight of a single unit in the process (e.g., a fuel assembly), frequency of measurement of material inventory in the facility, measurement uncertainty in SQs/yr, separability (more separable more conductive for production of weapons), percentage of processing steps that use item accounting, probability of unidentified movement, physical barriers and inventory of fissile material in a facility and finally fuel load type.

3.3.3. Analytic Hierarchy Process

The AHP method has been extensively used for analyzing the issues related to national, energy and economic security. AHP was applied by Silvennonien, Krakowski and others in the nuclear engineering area, to perform comparative analysis of the advanced NFCs for planning of weapons material disposition and other problem. This parametric systems study utilizes a globally aggregated, long-term (~100 years) nuclear-energy model that interprets scenario consequences in terms of material inventories, energy costs, and relative proliferation risks associated with the civilian NFC. Results of pairwise comparison of various plutonium forms assessed in [34] are shown in Table 6. These results are used in comparative analysis of different NFC options in view of reduction capabilities of worldwide plutonium inventories by using conventional reactors and advance fuels.

Table 6. Pairwise comparisons of various plutonium categories.

Plutonium type	Plutonium in a Reactor	Plutonium in SNF	Separated Plutonium	Plutonium at a Reprocessing Facility	Weight
Plutonium in a reactor	1/1	1/4	1/8	1/6	0.05
Plutonium in irradiated nuclear fuel		1/1	4/8	4/6	0.10
Separated plutonium			1/1	8/6	0.55
Plutonium at a reprocessing facility				1/1	0.30

Presented examples are just an illustration reflecting an example of the application of MCDA tools for different judgment measures in nuclear engineering. Obviously the application example set might be expanded. This is however considered here beyond the scope since cases discussed are representative and reflect main common tendencies: diversity of performance indicators used, as a rule only a single MCDA method is applied, sensitivity analysis is performed in a limited scale; uncertainties of subjective and objective nature are not taken into account. These studies lack recommendations regarding applicability of the corresponding methods.

4. Lesson Learned and Promising Directions of the Future Studies

4.1. New Projects and Endeavors

New projects arise which endeavor is to expand the application areas of advanced judgment aggregation tools with uncertainty treatment. The objective is to cope with the abovementioned deficiencies by developing an adequate framework, guidance and tools for comparative evaluation of nuclear technologies and their deployment with respect to the associated costs, benefits and risks.

4.1.1. Strategies for Sustainable Energy Development

Currently any long-term energy supply strategy is strongly focused on sustainable development. Therefore sustainable development indicators are used in conjunction with the MCDA methods. MCDA techniques allow aggregating single indicators and formulating comprehensive judgments about prospective development trends [35–37].

Indicators of sustainable development in a sector of energy production should substantiate the following facts: (1) in selecting energy carriers and relevant technologies for producing, delivering, and using energy products and services, it is required to consider economic, social, and environmental implications; (2) policymakers need methods for measuring and assessing the current and future energy use impact on human health and environment; (3) while using these tools, it is necessary to determine the degree of public energy consumption stability and identify the trends for increasing the degree of energy development sustainability. Actually, such quantitative indices called ‘sustainable energy development indicators’ intended to show to what extent an energy system complies with the three main components of the sustainable development concept, *i.e.*, economic, social, and environmental aspects.

Currently, it has become frequent practice to aggregate single sustainable energy development indicators into a composite index (integral metric) which allows assessing the quality and stability of energy system options. This aggregation is implemented with the use of the MCDA methods, among which the MAVT/MAUT family methods are most popular. A multi-attribute utility function, used as an integral metric, makes it possible to synthesize all the sustainable development aspects into a single aggregated composite index.

4.1.2. Supporting Studies on the Ethics of Nuclear Technology

The ethics of nuclear technology is a multidisciplinary endeavor to examine the problems associated with nuclear technology through ethical frameworks and paradigms [38]. The ethics of nuclear technology provides the analysis of ethical issues related to nuclear technology, so as to overcome nuclear dilemmas and structure nuclear debate.

In general, any professional ethics (such as bioethics, information ethics, *etc*.) provide for the problematization of challenging areas to identify possible trade-offs that balance the risks and benefits associated with conflicting factors. Thus, ethics may be considered a guide for practical decision-making that determines the most effective ways to optimize values. The effective optimization of values, if achieved in one area, does not guarantee its presence in other areas. Thus, advances in nuclear engineering may be incompatible with advances in ecology or economics. Ethics is focused on a general (holistic) optimization, and the search for a compromise between conflicting values.

The studies on the ethics of nuclear technology are a response to the aggravation of nuclear dilemmas and debates stimulated by the shortcomings of nuclear technology and provide a conceptual framework to overcome nuclear challenges. In the last decade, nuclear related contradictions loomed so large as to jeopardize not only the present status but the very future of nuclear technologies. The need for curbing associated challenges is stronger than ever, adding accordingly to the importance of comprehensive quantitative analysis of the nuclear technology ethics related problems, to which no alternative has presented itself yet.

In this regard, widening an application of advanced tools for judgments aggregation for supporting studies on the ethics of nuclear technology may provide solid basis for assessing the proposed ways of enhancing the efficiency and sustainability of technological and institutional measures being analyzed through the ethical frameworks and paradigms.

Contrariwise, consideration of nuclear related issues through the ethical frameworks and paradigms may also be useful for the further development and modification of corresponding comparative assessment and evaluation methodologies, to detail issues related to structuring and managing relevant information, organizing and performing assessments providing thereby conceptual background for such studies.

4.1.3. The IAEA/INPRO KIND Project

The new INPRO collaborative project on key indicators for innovative nuclear energy systems (KIND) has the objective to develop guidance and tools for comparative evaluation of the status, prospects, benefits and risks associated with development of innovative nuclear technologies for a more distant future. The urgent needs for such an activity is that the strong development of innovative technologies and the necessity to support future sustainable NESs deployment. Some IAEA Member States ask for support to evaluate the status, prospects, benefits and risks associated with development of particular technologies in comparison to other available, in order to prioritize/adjust within national programmes on innovative nuclear technology development the allotment of financing and some other resources. To achieve the KIND objective the project will:

- Develop a limited number of KIs for the status, prospects, benefits and risks associated with innovative technologies and NESs on their basis;
- Adapt advanced methods of expert judgment aggregation within the assessments involving also quantifiable data, to enable effective comparative evaluation of the innovative NESs based on the defined set of KIs;
- Using the developed KIs and the adapted methods of expert judgment aggregation, perform case studies on assessment of selected innovative nuclear technologies (NESs on their basis);
- Apply the adapted methods of expert judgment aggregation and uncertainty analysis to comparative evaluation of the transition scenarios to future sustainable NESs based on a set of KIs developed in the GAINS project.

In the framework of the KIND project a number of numerical examples were analyzed oriented to demonstration of MCDA method application for the support of decision making process in the NESs and NFCs efficiency and sustainability assessment. Expedience of application of some well-known MCDA methods for comparative assessment of NESs is presented in [39], for a set of KIs assessed for comparative evaluation of NES evolution scenarios in the INPRO GAINS project. This strengthens the applicability evidence to similar problems.

4.2. Advanced Methods and Tools

4.2.1. Multi-Objective Decision Making

Nuclear energy systems have the potential to contribute to growing energy demands in a sustainable way while playing an important role in economic and social development. However, it is extremely difficult to achieve a common view of an optimal pathway for their deployment and to determine *a priori* the most promising options since the selection of different alternatives for the expansion or deployment of new reactor systems where the environmental criterion is added to commonly used economic, technical and social criteria requires the adoption of powerful decision supporting techniques [40,41].

Therefore to make suitable decisions on the future policy concerning the NES and NFC deployment structure, it is necessary to allow discourse of unbiased experts, free of preferences on the specific modeling assumptions, and able to organize systematic research taking into account all possible NES and NFC options in context of the multi-objective character of the problem by using multi-objective optimization energy models and the MODM based advanced tools.

There is a growing understanding that the traditionally practiced single decision-making approach is no longer able to handle these problems. Optimization of NFC and NES structures has a multi-objective nature with various conflicting objectives characterizing different aspects associated with resource consumption, economics, proliferation risks and waste management. The energy sector and planning affect the interests and resources of multiple decision-maker groups. For this reason the development and application of state-of-the-art MODM tools for comparative NES and NFC deployment scenario assessment and optimization appears necessary because of their potential for highlighting conflicts and finding compromises in the decision making process.

Various MODM methods can be adopted for solving the multi-objective optimization problem: *a priori* or *a posteriori* methods, adaptive methods, methods based on the preliminary construction of the Pareto (efficient, non-dominated) set approximation. The alternatives in the MODM problems, are not explicitly known, thus an alternative (solution) is found by solving a mathematical model. The number of alternatives can be either infinite or not countable (when some variables are continuous) or if countable, typically very large (when all variables are discrete).

The family of MODM-based methods consists of the criteria constraint method, linear convolution method (linear programming case), combinatorial optimization problems, genetic algorithms (NSGA-II, MOCHC, *etc.*), reasonable goals method, *etc.*

Essential to this family is the concept of a set of non-dominated (effective) solutions (Pareto set). The Pareto set is informally defined as a set in 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 solution belonging to the Pareto set will not be improved by all the specific optimality criteria simultaneously. It is a difficult separate activity to form the Pareto set, and the information about the Pareto boundary may form the basis of multiple criteria interactive systems of decision making support. A decision maker consulted by experts will ultimately have to take a solution belonging to the Pareto set.

In the framework of numerous MCDM techniques any dominating alternatives must be identified and excluded before proceeding further. The concept of dominance is a relative concept however and much attention should be paid to the context in which it is used, but the identification of dominating and non-dominating alternatives provides additional information useful in the working out the final decision.

Formation of the Pareto set in multiple criteria optimization of dynamic systems necessitates repeated modeling of the system performance with different values of parameters varied. Modeling of a dynamic system is a problem per se and its solution requires the utilization of software systems. Pareto set in a multiple criteria case can be visualized and enables involving interactive decision maps, radar diagrams, and profiles of alternatives in the decision process.

The MODM methods able to solve the multi-objective optimization problem which are based on pre-approximation of the Pareto set have been recently gaining in popularity. The advantage is that using these methods a decision maker will find a trade-off solution on the Pareto front meeting his preferences. However, the main disadvantage of such methods, deterring their extensive application, is their high calculation complexity.

The interactive decision maps technique was developed for the exploration of multi-criteria decision problems with a more than two criteria. The interactive decision map is a graph displaying several overlapped differently colored slices of the envelope. Each slice contains reasonable values of the first and the second criteria for a certain value of the third criterion (in case when three criteria are considered). Values of the first and the second criteria are displayed on the vertical and horizontal axes. The value of the third criterion is related to the color of the slice and is given on the color scale in a slider of scroll-bar displayed on one side of the figure. Pictures of this kind are known as decision maps. The frontier of a slice displays efficient tradeoffs between two criteria for a given value of the third. Values of other criteria (fourth and fifth, if exist) can be changed by moving the additional sliders of the scroll-bars [42].

An interactive decision map is a tool allowing experts to explore different areas in the feasible alternatives space and to determine the closest alternatives to a given point (goal) in **n**-dimensional space (where n is the number of criteria). This goal is not an 'ideal' point, as used in the methods of ideal point family, but it is a 'reasonable' goal which may in principle be reached by the system. The approach does not require weights identification and may be classified as an interactive approach as illustrated in Figure 7 (taken from [43]) generated for evaluation of the attractiveness of highly enriched uranium production scenarios at a clandestine enrichment facility using centrifuge enrichment technology. The trade-off on NES and NFC structures obtained by means of such methods deliver balanced solutions in spite of conflicting indicators and satisfy the cost-effective requirement. These options are laying on the trade-off surface, which is a surface of non-dominated alternatives and allows identifying additional cost caused by an implementation of complex measures taken to increase the NESs efficiency due to reduction of uranium consumption, proliferation risks and SNF accumulation *etc.* (according to a specified objectives). The analysis of different areas on the trade-off surface supports a hypothesis about the potential of each considered NESs to achieve a specified goal by changing the deployment structure and offers a possibility to evaluate corresponding trade-off rates using indicators [44].

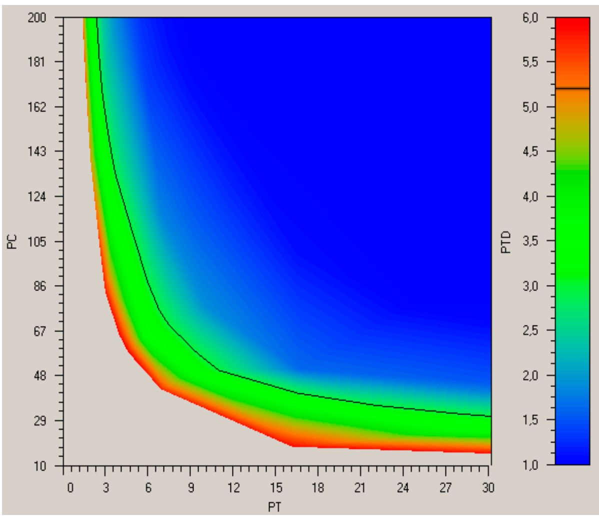


Figure 7. Marginal feasible proliferation scenario set (interactive decision map representation, PT (days): proliferation time, PC (c.u.): proliferation cost, PTD (kgSWU/yr): proliferation technical difficulty.

4.2.2. Uncertainty Treatment

An uncertainty analysis is an inevitable step providing better grounds for judgment and enables decision makers to estimate the stability of the achieved results. Studies related to the NESs and NFCs efficiency and sustainability assessment should contain uncertainty assessment calculations. Although an application of uncertainty analysis methods requires more information about system features and experts' preferences it may, at the same time, greatly enhance the quality of decision-makers' judgments since both the objective (in indicator values) and subjective (in weights) uncertainties can be taken into account [45].

Large uncertainties in initial parameters will not always lead to large uncertainties in performance indicators; thus, an accurate evaluation of uncertainties is needed for correct uncertainty treatment. In particular, a situation may arise when all alternatives due to utilized initial data will be statistically indistinguishable (for example, 90% confidence intervals of uncertainties in parameters are overlapping).

The following methods are available among those for uncertainty evaluation in performance indicators: sensitivity coefficients method, Monte-Carlo methods, quantile uncertainty estimates, GRS-methods, *etc.* The correct implementation of these methods requires however, a modification of corresponding calculation tools to overcome the major shortcomings of the conventional approach to the NESs and NFCs efficiency and sustainability assessments in which only point estimates for the technology characteristics and parameters are required and must be used.

An uncertainty of the decision-makers preferences (weights uncertainty) may be taken into account utilizing, for example, the concepts of the fuzzy numbers, probability theory or interval algebra. The applications of the MCDA methods which allow incorporating uncertainties are, for example, Fuzzy MAVT, Fuzzy AHP, *etc.*

Within a multi-criteria problem, the application of fuzzy numbers may be considered in many cases as justified and more natural than utilization of probability distributions. The use of fuzzy sets can assist with uncertainty assimilation both for criterion values and weight coefficients [46]. The Fuzzy MAVT is intended for uncertainty treatment when solving multi-criteria problems using the 'value function' concept. Within this method, criterion values, scores, and weights are considered as fuzzy numbers, single-attribute value functions are usually considered as given by experts in the forms of usual/crisp functions. Ranking alternatives in the Fuzzy MAVT is based on comparison of overall fuzzy values by means of visual analysis. Several techniques for ranking fuzzy numbers are based on different defuzzification methods and methods for comparison of fuzzy numbers.

Case studies on multi-criteria assessment of the NES and NFC options taking into consideration uncertainties may provide robust judgment aggregation and form a base for well-founded recommendation as compared to the one using deterministic MCDA methods.

For the optimization energy planning models (such as MESSAGE, FCOPT *etc.*), which can be used for studies focused on the optimization of NES and NFC structures, the development and implementation of the robust and stochastic optimizations functionalities for the uncertainty treatment seems to be very promising. Such models 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 amount of data which are assumed to be known exactly, which in practice is often not the case. In the optimization of NES and NFC models data uncertainty is caused by the fact that some exact data do not exist and are replaced by their evaluations, another one cannot be measured exactly, and their true values flow around the measured values. In many cases, even small data uncertainty can make the nominal solution infeasible and practically meaningless.

Stochastic and robust optimizations are complementary approaches for treatment of data uncertainty, both of them having however their own advantages and drawbacks [47]. Both robust and stochastic optimizations enable building an uncertainty-immunized solution to an optimization problem with uncertain data. In stochastic optimization the 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 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.

4.3. Discussion

4.3.1. General Comments

The MCDM methods can handle judgment problems and may be adapted to the assessment of NESs' and NFCs' efficiency and sustainability. Multi-criteria decision-making techniques are valuable tools in policy formulation. A multi-criteria judgment approach can deliver quantitative information about how much a certain option is more effective and sustainable then another. These methods also provide an opportunity to identify the most vulnerable areas of considered NES of NFC and the cost-effective risk mitigation measures. Moreover, MCDM application allows assessing the impact of measures implementation and optimal risk management associated with corresponding vulnerabilities.

The intrinsic difficulty in NESs' and NFCs' efficiency and sustainability assessment is that there is a large number of performance indicators describing the characteristics of different deployment options. Moreover, indicators of binary, qualitative and quantitative type have to be used. Therefore, there is a strong tendency to develop both a proper framework including the basic concept and a prototype practice-oriented software to be integrated in the decision making process. This advanced software-supported approach has the potential to replace the traditional analytical procedure associated with the application of MCDA methods. Current activities dedicated to the adaptation of advanced methods of expert judgment aggregation in the area of NESs and NFCs performance efficiency and sustainability are focused on the development of methodologies for overall, integrated assessments. As the NES and NFC potential performance must, in some cases, be assessed using a set of conflicting indicators, MCDA are the method of choice. They allow experts to recognize and implement various trade-off based judgments on conflicting alternatives to reach a compromise and to balance solutions on costs, benefits and risks, taking into consideration different decision maker groups involved in the decision process. Each group—decision makers, experts, stakeholders, environmental protection activists—brings along different criteria and point of view (preferences) which must be resolved by applying the multi-criteria decision framework to support overall judgments. Revising possible performance indicators of NESs and NFCs in each problem area, approaches and tools can be developed for performing multi-criteria analysis and on their basis and a structured and practically oriented toolbox can be implemented along with detailed recommendations on its applications.

Framework application of both software and MCDA method should be examined on case studies in order to demonstrate their potential for performing effective comparative evaluations of NFCs and ranking of NESs based on a defined set of evaluated performance indicators.

As concerns the MCDM application framework and tools it seems rational to split the problem into parts and to proceed according to the logic 'from simple to complicated'. This pathway will simplify the analysis providing a clear understanding of results which may be obtained making first the simplest assumptions and, then increase the complexity of the problem and the methods. This approach will benefit from 'learning by doing' effect and give an opportunity to analyze the use of more sophisticated MCDM methods *versus* the simpler ones.

Special attention should be given to both mathematical and application boundaries of the MCDM tools for and to a particular problem. General recommendations for the application in multi-criteria assessments without a reference to specific methods, performance indicator sets, objects of evaluation, *etc.*, should be avoided. Application framework test process should include elaboration of specific test cases, case studies, numerical examples which show the application limits of the MCDM tools in numerous problem areas preferably, on the basis of well-known studies in order to clearly demonstrate the added value resulting from application and to formulate recommendations for decision–maker groups.

It seems more appropriate to emphasize not only the specific method or software, but to consider an expanded landscape of different MCDM tools (*i.e.*, the more representative ones), which can be applied to perform a specific assessment. Particular attention should be paid to the comparative analysis of the results obtained while using the similar model assumptions but the different tools. It is important to get consistent, not conflicting results.

4.3.2. Recommendations on the MCDM Application

Despite the different theoretical frameworks, tools and calculation algorithms, various methods usually lead to a similar final ranking of alternatives. Selecting the best MCDA method suited for a given problem is a separate task. If the selection will be made based on choosing one among all the possible methods, the questions may rise as far as the completeness of the research and the confidence of the expert who proposed the method to solve multi-criteria problems is concerned.

In the general case, if two different expert groups will analyze a multi-criteria problem, the final ranking of the alternatives may not overlap even while using the same method. This is caused by different viewpoint regarding weights, types and parameters of value functions, utility and preferences functions *etc.* A similar situation is to be expected if two expert groups perform their research under the supervision of different experts skilled in using different methods. In this case, the probability that the same ranking will result, even if these groups have similar judgments about the problem, is even smaller. Moreover, the results of weight identification by means of different methods (for example, by swing and pair-wise procedures) may significantly differ, even in case of their implementation within the same MCDA framework.

Differences in rank order may occur due to different representation of a performance table, showing qualitative and quantitative assessments of alternatives on criteria, in case the experts use principally different MCDA methods. Unfortunately, there are no specific rules for conversion between different variants of the performance table into a universal form suitable to be used in different methods. This is especially true for the AHP method which is based on pair wise comparisons. Although the pair wise comparison of alternatives with regard to quantitative criteria seems useful, an automatic conversion of quantitative assessment to pair wise comparison ratios may differ from the coefficients that experts may give directly in the scale of the AHP method.

In numerous studies it was shown that application of the MCDA methods (MAVT, MAUT, TOPSIS, PROMETHEE, AHP *etc.*) for multi-criteria comparative assessments of the NESs or NFCs give, despite some differences in the ranking alternatives, well-coordinated results even while using different methods. The multi-criteria approach provides more detailed differentiation of the alternatives, for specific costs, benefits and associated risks criteria and allows different trade-off options.

For a particular problem it is recommended to make the final choice of the most appropriate method on the basis of the problem context analysis and the initial quality of information provided by experts in the subject matter. In dependence on whether the precise assessment of all indicator values without uncertainty will be done or, on the contrary, the consideration will be limited by qualitative judgments regarding indicator values, different methods should be used. MAVT, TOPSIS, PROMETHEE methods are more appropriate in the former case whereas the AHP method is more suitable in the latter. If it is necessary to consider the uncertainty in indicator values, the MAUT method is more suitable as compared to, for instance MAVT or others. Obviously, a content of relevant method set should not be limited to those considered previously. Experts may express their preference to other ranking/aggregation methods, but in this case, it is essential to make a verification of their applicability and results. Moreover, it should be checked if under comparable conditions, the results obtained using different methods are well coordinated and consistent.

It is recommended to perform an additional sensitivity analysis of the obtained ranking results which obviously will significantly increase the confidence level. MCDA methods applied to a multi-criteria assessment of the effectiveness and sustainability of NESs or NFCs deployment options should respect following recommendations. Despite the fact that the results of ranking alternatives are affected by the expert preferences with respect to certain criteria, there exist stability regions in which for a wide range of variation of the preferences, the ranking order is preserved. On the base on the sensitivity analysis results, on additional analysis of alternatives using expert judgment and on the total set of graphical and attribute information the best alternative may be chosen.

One of the important areas for further development is an extension of MCDA method implementation to problems with uncertainties. In such problems, the weights are not determined by their average values, but are distributed within certain intervals. This is relevant for and in demand of most practical multi-criteria problems. In spite of the fact that in the considered studies the uncertainty analysis was not performed at a full scale, the conditions necessary for extension with uncertainty calculations should be identified not least because it is an inevitable step providing better grounds for judgments with conclusions on the stability of results.

5. Conclusions

The successful development of the application framework of the MCDM methods and of advanced tools dedicated to a comparative assessment of NESs and NFCs achieved so far along with the experience gained to date lead to a confident conclusion that the problem understanding and conceptualization phase has come to a closure. The next phase needed in order to progress is an active and targeted application of the developed toolkits to practical problems addressing possibly a great variety of test cases.

Wide application of the MCDM (both: MCDA and MODM) techniques allows searching for compromises between the conflicting factors that determine the efficiency and sustainable deployment of nuclear reactors and related NFC, calculating corresponding trade-off rates according to expert knowledge based judgments and the decision-makers preferences. To support a decision-making a great deal of alternative comparative multi-criteria analyses should be performed for choosing, ranking, and sorting of the different options.

Growing demand for reliable assessing frameworks for NESs and NFCs potential, efficiency and sustainability requires R&D work to be actively embarked upon building integrated calculation concepts. These are expected to form the basis for dedicated software development featuring flexibility, upgradability and an availability of advanced user interface which still require implementation efforts. In order to upgrade the elaborated framework to a broad application range new case studies analyses and an intensive educational process via specialized training courses should be envisaged.

The MCDA toolkit shall be used to streamline systemic applied activities, to formulate specific guidelines with respect to approaches, in order to increase the NESs and NFCs efficiency and sustainability at technological, institutional and political levels, respectively. If successfully implemented, this bundle of efforts will lay down a firm foundation for the development of the MCDM tools application culture in nuclear engineering area which, in turn, will contribute to raising the overall nuclear energy sustainability.

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Author Contributions

All authors equally contributed to the development of the concepts presented in this paper.

Abbreviations

AHP	Analytic Hierarchy Process
ADS	Accelerator Driven System
BP	Basic Principle
CR	Criteria
DOE	Department of Energy
ELECTRE	Elimination Et Choix Traduisant la Realite
EP	Evaluation Parameter
EG	Evaluation Group
GAINS	Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle
GIF-IV	Generation IV International Forum
HLW	High Level Waste
IAEA	International Atomic Energy Agency
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
KI	Key Indicator
KIND	Key Indicators for Innovative Nuclear Energy Systems
LWR	Light Water Reactor

MAVT	Multi-Attribute Value Theory
MAUT	Multi-Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
MCDM	Multiple Criteria Decision Making
MIT	Massachusetts Institute of Technology
MODM	Multi-Objective Decision Making
NEA	Nuclear Energy Agency
NES	Nuclear Energy System
NESA	Nuclear Energy System Assessment
NFC	Nuclear Fuel Cycle
PROMETHEE	Preference Ranking Organization METHod for Enrichment Evaluations
P&T	Partitioning & Transmutation
R&D	Research and Development
RTA	Reactor Technology Assessment
SNF	Spent Nuclear Fuel
SSM	Simple Scoring Model
TOPSIS	Technique for Order Preference by Similarity to the Ideal Solution
TRU	Transuranic Actinides
UR	User Requirement

Conflicts of Interest

The authors declare no conflict of interest.

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