 doi:10.20944/preprints201708.0104.v1

Peer-reviewed version available at *Sustainability* **2017**, *9*, 1623; doi:10.3390/su9091623

Article

Comparison and Screening of NFC Options in View of Sustainable Performance and Waste Management

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Abstract

Is it true that the nuclear technology applied to electric energy generation offers a clean, safe, reliable and affordable i.e. sustainable alternative? Yes it is, but its impact on the environment strongly depends on the implementation bearing residual risks due to a human factor, technical failures or natural catastrophes. A full response is therefore difficult and can first be given when the wicked multi-disciplinary problems get well formulated and "solved". These problems have multi-dimensional nature lying at the interface between: necessary R&D effort, the industrial deployment and the technology impact in view of the environmental sustainability including the management of produced hazardous waste. This enormous complexity indicates that just a description of the problem might represent a problem. The paper proposes a holistic approach to assess the nuclear energy systems potential with respect to sustainable performance applying Multi-criteria decision analysis with a suitable objective tree and a multi-level criteria structure and examines the trading-off techniques for ranking of the alternatives. The framework proposes a multi-criteria and multi-stakeholders treatment which can be used as a pre-decisional support towards an implementation of nuclear fuel cycles adapted to national preferences and priorities. Proposed approach addresses some aspects of the environmental footprint of nuclear energy systems. Advanced nuclear fuel cycles, previously investigated by the NEA/OECD expert group WASTEMAN, are analyzed as a case study. Sustainability facets of waste management, resource utilization and economics are in focus.

Keywords: advanced nuclear fuel cycles; waste management; resource utilization; economics; performance comparison; multi-criteria decision analysis; sensitivity/uncertainty analysis; environmental footprint

1. Background

Innovative electrical energy generating technologies should be sustainable that means clean, safe, reliable and affordable and moreover able to preserve resources and minimize liabilities [1]. The nuclear technology option might compete in this sense with other large-scale energy producing technologies as, for instance, those consuming the coal or oil resources [2]. However, similar to the other non-nuclear energy generation options, each nuclear option produces hazardous radioactive waste – called high-level waste (HLW) due to the contained long-living radionuclides. For this reason, HLW should be isolated from the biosphere by a disposal and an enclosure in special facilities, called HLW repositories [3]. Mainly for this reason, nuclear waste management causes in some countries a public concern due to a residual risk of radiotoxic fission products' or minor actinides' migration from casks containing HLW into the environment. This risk which is higher for waste radiotoxic components soluble in water is assessed in the R&D studies on repository safety cases. Another type of threads were: A severe accident of boiling water reactors after an earthquake and a tsunami, which lead in Fukushima Daiichi to the release of radionuclides into the ecosystem and impacted the citizens [4] and the catastrophic nuclear accident in Chernobyl where resulting steam explosion and fires released at least 5% of the radioactive reactor core into the atmosphere and downwind – some 5200 PBq (^{131}I eq. [5]).

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Despite these "dragon kings" which fall into the category of residual risk connected with a nuclear power plant operation, a nuclear power production is one of the options with both the strict safety provisions significantly enhanced after the above-mentioned worst-case accidents and the provisions made for including a priori the waste management costs into an effective electricity price in a business implementation plan. Of note, there are mature proven technologies, which, if implemented at each stage of nuclear fuel cycle (NFC), are able to safeguard the safe high-, or even intermediate- and low-level waste management [2,4]. Extensive and costly R&D programs on repository safety cases for HLW legacy disposal are carried out in many countries according to national legislation and rules of the local governance [for instance, 6]. R&D includes an assessment of different safety and performance indicators relevant to protect the human population and the ecosystem in the long term such as:

(1) radionuclide transfer times,

(2) concentration of radionuclide in the near field (to be monitored),

(3) characteristics of control dilution in time and space (e.g. waste form dissolution of release rates, canister failure rate, and porosities),

(4) profile of ground water.

Moreover, in safety oriented repository R&D studies a risk, a dose, possible environmental impacts, radionuclide concentration and fluxes outside the near field versus containment times are scrutinized [7,8].

Nowadays nuclear power plants operate in 31 countries around the world generating 2474 TWh of electric energy [9]. According to today's estimates, 48 further countries consider embarking upon nuclear power programs in the future. The experience from commercial use of nuclear energy gained over nearly six past decades has stimulated the R&D efforts towards a design of innovative NFCs, which are self-sustainable, but still affordable and thus offer improved resource utilization and the a reduced impact on the ecosystem [2,4].

Currently industrially implemented nuclear technologies are based mainly on an open or once through (uranium dioxide UOX) and a partly closed (mixed oxide MOX) NFCs, the latter recycling plutonium once [2]. However, severe accidents which happened during the past operation of nuclear power plants have drawn an attention and concern of the public and caused in several countries significant financial relocations in order to support a transition of energy production based on renewables. Is the financial effort necessary to follow this strategy a well-justified burden? The answer is ambivalent and depends on the local perspectives, the national criteria and overall priorities.

All NFC types, including the advanced closed NFC, multi- recycling fissionable components of the spent nuclear fuel (SNF) after SNF reprocessing, have in common that both the front- and the back-end fuel treatment stages generate radioactive waste [4]. In this context a decision making process at the national level targeting at a deployment of the most effective sustainable energy production technology and a selection of the mid- and long-term strategy might become very complex. In view of mature or maturing non-nuclear options utilizing coal, gas or regenerative energy production techniques it becomes even more difficult. Moreover, such processes have to cope frequently with the public opinion gaining on importance worldwide, especially in those countries having densely populated small geographic territories whereas in some other countries, having large territorial areas and more possibilities for safe HLW disposal, a governance plays a secondary role.

This paper screens advanced nuclear energy generating technologies and performs NFCs comparative evaluation in view of sustainability criteria and with focus on (1) identification of NFCs having the highest HLW minimization potential and (2) the enhanced ability to handle in a responsible way HLW management thus minimizing its radioactive inventory and an impact on environment due to reduced environmental footprint inclusive the footprint of repositories.

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2. Application Context

An implementation of each particular energy generation option requires usually an allocation of significant financial R&D resources and a development of effective business models supporting the decision makers towards an implementation of advanced technology. In general, many methodologies are available for comparison of NFCs in view of sustainable performance [10-14]. Using these methodologies nuclear versus non-nuclear options or even regenerative energy options like wind turbines against PV panels can be compared as well.

On the other hand, there is a lack of a common understanding and a consensus (among the experts, stakeholders and decision makers) on the impact of the results obtained from option screening studies on a final decision-making on R&D resource allocation necessary for the realization of a particular strategic choice [15-17]. Due to its intrinsic complexity, such a decision can be responsibly and consciously taken only after an application of a structured procedure. This procedure must include a judgement elicitation and aggregation. Judgement aggregation can be, however, first when all facets of the problem are taken into account and a set of criteria in different dimensions: technical, environmental, economic, societal, etc. is selected. This complexity is enhanced even more due to a wicked nature of the decision-making problem featuring often both conflicting criteria and multi-stakeholders perspectives. Wicked problems have no explicit solution therefore they have to be tackled by applying trading off techniques.

One of the targets of the paper is the comparison of nuclear energy generation alternatives (entire NFCs) within a suitable framework applying Multi-Criteria Decision Analyses (MCDA) methods [18-20]. The framework used here allows ranking of the NFC options according to their performance metrics on a set of chosen sustainability criteria which includes the waste management criteria. The paper demonstrates further the application of this framework to a comparative evaluation of the NEA/OECD NFCs. As the reference NFC, the current once-through i.e. open NFC deploying the pressurized water reactor (PWR) will be considered.

Herewith well-structured and thereby systematic comparative analysis between the conventional and the innovative NFC options is possible. The attention is focused on waste management, but NFCs are analyzed in a holistic way that is in a context of other sustainability criteria. Subsequent paper sections will show how MCDA performance can be screened in case both multi-criteria and multi-stakeholders participate to the decision making process. A generic case study using NEA/OECD data characterizing the performance of advanced NFCs will be discussed. This case study builds on the results of NFC options screening elaborated by the NEA/OECD expert group and published in the report on Advanced Nuclear Fuel Cycles and Radioactive Waste Management [21].

The performance of any set of alternatives; here the NFCs, can be compared within the MCDA-based framework in a structured way applying a multi-layer objective tree. Targeted high-level goal is located at the treetop. The selected objectives are placed at the intermediate-level, beneath the criteria necessary to fulfil the objectives are defined for each objective and finally, at the lowest level, the key performance indicators are accommodated which have to be assessed separately each alternative on each criterion.

This structure enables two approaches in order to rank the options: the top-down and bottom-up. The criteria are often conflicting. To handle them properly further information must be elicited on the preferences of decision makers. A utility/value function is a mathematical representation of preferences and maps the stakeholder utility/value measurement scale onto natural scale of key performance indicators, built of all indicator values assigned to a single criterion. Therefore, it is of primary importance to incorporate the suitable utility/value functions into the decision- making process. These functions might have different shapes: linear, exponential, stepwise etc. Further step requires an aggregation of judgements using assessed indicators and value/utility functions. One of the intermediate outcomes is the composed indicator score serving to deliver a ranking order indexes for considered options. In this procedure multiple categories of criteria might be involved. These categories may encompass different perspectives: economics, security of resources, environmental

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impact and proliferation resistance, waste generation and management, social attitude (public opinion) etc.

Advanced NFCs offer a possibility to design and implement safe and economic nuclear energy production systems efficiently addressing both the reduction of the natural resource consumption and the effective waste management. The latter two partly measure a degree of sustainability. It should, however, be kept in mind that innovative evolutionary and revolutionary nuclear energy systems exhibit different levels of maturity as compared to the conventional one thus requiring more R&D resources.

Without MCDA support strategic choices would therefore be difficult. Judgement aggregation should be based on the policy makers' priorities reflecting country specifics like, for instance, an access to uranium resources, an available storage capacity of facilities for waste management, possibility of interim fuel decay storages, site for the final high level radioactive waste repositories, affordable size of the nuclear power R&D efforts, social and economic standards to be achieved, etc. Obviously, different countries would tend to have different priorities because the criteria choice relies on the national preferences.

An important group of criteria reflects the engineers' or scientists' i.e. experts opinions based on the assessments having a technical origin. Such criteria were considered in the abovementioned technically oriented NEA/OECD study launched in 2004, which was mainly focused on an assessment of the impact of NFC options on the uranium consumption and the radioactive waste management problems [21]. An affordability aspect was only preliminarily tackled using the economic data available in 2004 biased by large uncertainties.

To be judged as sustainable, the NFCs should fulfil many requirements: preserve the resources, reduce Greenhouse Gasses (GHG) and other gaseous emissions in the entire life cycle of nuclear power plants deployed in NFC to irradiate the fresh fuel, minimize an inventory of generated hazardous waste and ensure the effective and safe waste management, reduce side impacts on the ecosystem, etc.. NFCs, if properly configured, have a potential to be sustainable.

NEA/OECD study analyzes:

(1) once-through NFCs and the extensions recycling fissionable nuclear material in the thermal reactors,

(2) sustained recycle of fissionable nuclear material in a mix of thermal and fast reactors, and

(3) sustained recycle of recovered fissionable nuclides in advanced fast reactors addressing both the maturing and the emerging NFCs.

The latter might still require extensive R&D efforts; nevertheless with a good prospect for the future due to steady technological advances in an enrichment and recycling (new separation processes) methods, a remote handling during reprocessing and the fresh fuel fabrication steps, maturing of the revolutionary reactor systems, advanced fuel rod designs including accident resistant fuels and an enhanced safety of both the reactors and the waste management and treatment.

Another target of the paper is a survey on selected environmental sustainability criteria and a performance comparison of nuclear versus non-nuclear technologies such as: Oil/gas, hydropower, wind and regenerative resources on these criteria. This discussion will however not be based on the results of the MCDA-driven study, but will use direct comparison of above-mentioned technologies on chosen sustainability criteria related to an environmental indicator cathegories as presented in Fig. 1 though an environmental footprint of all NFC stages will be addressed.

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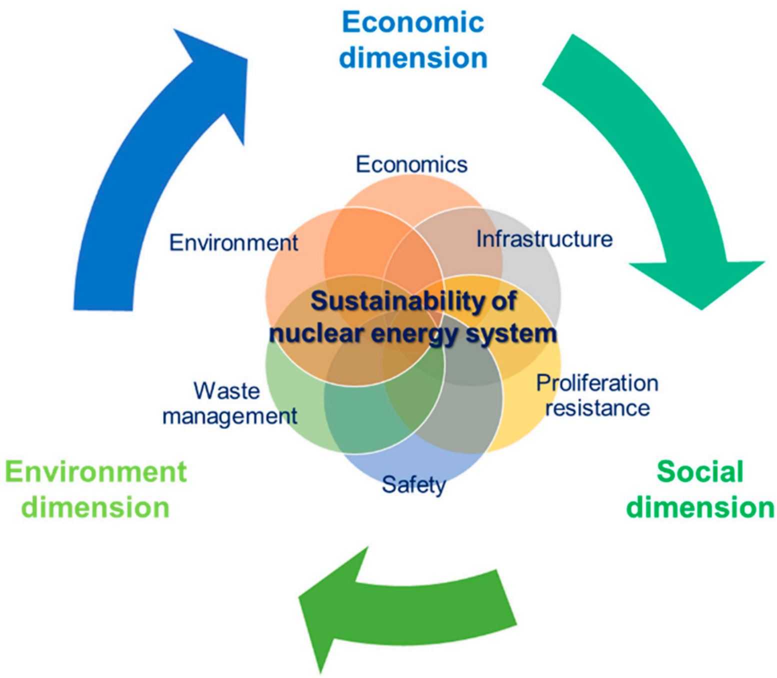

Figure 1. The INPRO/IAEA holistic approach to NFC sustainability [11].

3. Short Description of NEA/OECD Study on Performance Comparison of Nuclear Energy Systems and NFC Options

In the NEA/OECD study WASTEMAN twelve representative NFCs were analyzed [21]. The high-level objective was to identify those NFCs which have the highest potential to provide benefits to a repository program, to save the use of nuclear fuel resources and to improve prospects for sustainable deployment of a nuclear power. In order to be able to compare the performance of nuclear system options with different maturity levels the expert group developed a set of suitable technical NFC evaluation metrics. Evaluating metric data for each metric allowed judging how each nuclear energy system performs on each criterion and in a particular evaluation area. These metrics were adopted in the present framework as criteria/key indicators. Performance indicators for each nuclear energy system refer to a reactor in a "steady state" operation. Such an approach is sufficient for generic assessments because the conditions of transient phases in nuclear energy generation might widely vary between countries and are still biased with large uncertainties.

Nonetheless "steady state" evaluations of advanced NFC options open a perspective to different countries exposing both the opportunities and the challenges of particular strategic choices thus supporting future decisions concerning national research and development (R&D) programs on energy generating technologies. The study, although a generic one, can be easily adapted to national conditions and permits thereby the assessment of country specific scenarios even with large diversity of NFC types.

NEA/OECD metric data can be easily introduced into a multi-criteria framework provided a well-structured problem-dependent set of criteria is established. The paper considers a two-level objective tree with three high-level objectives:

(1) reduction of the resource utilization,

(2) minimization of the produced nuclear high level waste (benefit to a repository program) and

(3) economic competitiveness.

In the NEA/OECD study the nuclear energy systems are subdivided into three main groups characterized by the technical maturity level

(1) mature: current industrial practice and extensions,

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(2) maturing: partially closed NFCs and

(3) maturing or emerging: fully closed NFCs.

Table 1. NEA/OECD advanced NFC options.

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

These groups will be investigated here. A more detailed general description of all nuclear energy systems contained in Table 1 and the characteristics of each particular reactor type can be looked at more detail in [21]. A color code technique assigning each individual NFC option a different color is used in Table 1. This technique facilitates a presentation of the analyses results throughout next sections of the paper. NFCs represent a set of alternatives to be compared. Their performance indicators’ values are shown in Table 2. An approach proposed here is based on a problem formulation in form of a triplet consisting of:

(1) a set of potential alternatives (i.e. NFCs, see Table 1),

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(2) a set of criteria under which the alternatives are analyzed, evaluated (see Table 2), and will be compared for different future scenarios, and

(3) the problem statement.

Table 2. Criteria set.

Area	Criteria	Abbr.
Resource utilization	Natural uranium required per energy generated, kg/TWhe	Cr.-1
Nuclear waste management	Mass of TRU loss transferred to waste, kg/TWhe	Cr.-2
	Activity of SNF+HLW at 1000 years, TBq/TWhe	Cr.-3
	Decay heat loading of SNF+HLW at 50 years, Watt/TWhe	Cr.-4
	Decay heat loading of SNF+HLW at 200 years, Watt/TWhe	Cr.-5
	Volume of HLW + SNF (if it is declared a waste), m^3/TWhe	Cr.-6
Economics	Fuel cycle costs, mills/kWh	Cr.-7
	Costs of electricity at Equilibrium, mills/kWh	Cr.-8

4. Performance Comparison of OECD/NEA Advanced NFC Options with MCDA

4.1. Problem Statement

In order to support a national decision-making process targeted at the best choice of NFC for an industrial deployment, a hierarchical objective structure, which reflects the national specifics in the best possible way, should be established. Here generic case studies are intended thus a two-level objective tree depicted in Fig. 2 fits the problem. The high-level goal of the study is to compare NFCs options using judgement aggregation structure for eight key performance indicators per NFC option evaluated on eight criteria assigned to three high-level objectives (resource utilization, waste management, and economics), respectively. The expected outcome is the NFC options ranking according to the NFCs' overall performance scores.

Performance indicators Cr.-1, Cr.-2 – Cr.-6, and Cr.-7 – Cr.-8 should be respectively minimized. The priorities of stakeholders are taken into account assigning weighting to grade NFCs according to the high-level objectives. For the same purpose the lower criteria-level weights are selected and the weighting value/utility functions are properly chosen.

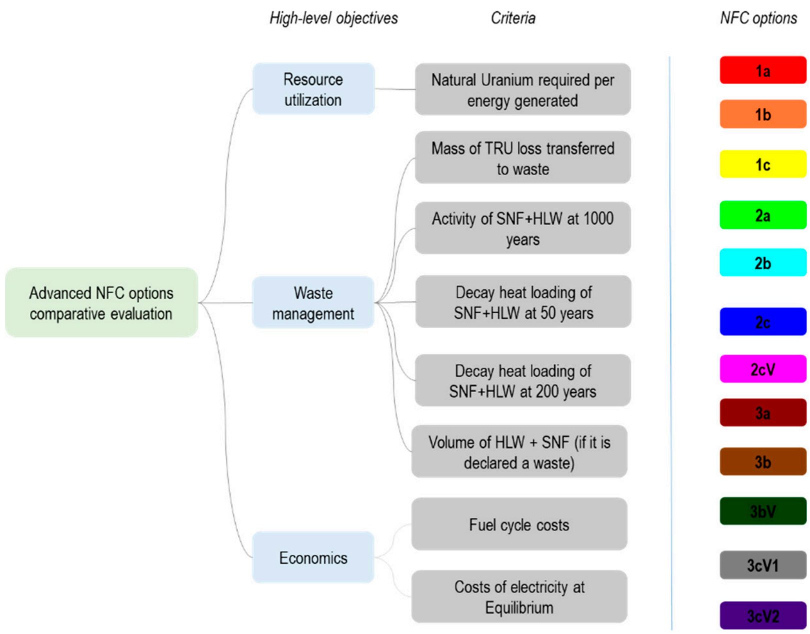

Figure 2. Hierarchical structure of the objective tree.

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4.1.1. Performance Table

As already mentioned, the NEA/OECD report [21] delivers indicator values for twelve NFC options grouped in families 1-3. These indicators are evaluated on the basis of the extensive physics-based studies carrying out calculations with well-established codes (such as DARWIN [22], CESAR [23] etc.). The material flows and the characteristics of the radioactive waste inventory generated in each NFC were calculated. The retrieved indicator values for each option from [21] are compiled here into the options performance table summarized as Table 3. The KI values are "point values" delivered in relation to both a particular reactor design and fuel composition. Uncertainties in KI assessment for Cr.1-6 were not assessed in [21] and will be not discussed here that means Table 3 contains best estimate for each KI values.

Table 3. Performance table.

Criteria	NFC options											
	1a	*1b*	*1c*	*2a*	*2b*	*2c*	*2cV*	*3a*	*3b*	*3bV*	*3cV1*	*3cV2*
Cr.-1	1	0.89	0.9	0.87	0.99	0.44	0.44	0.63	0.65	0.76	0.004	0.036
Cr.-2	29.78	20.34	21.04	8.87	4.6	1.63	3.93	0.1	0.11	0.14	0.17	0.15
Cr.-3	201	177	178	134	2.61	3.91	2.24	2.43	2.8	2.98	2.28	2.88
Cr.-4	2110	2030	2380	2000	979	888	852	934	963	1030	572	834
Cr.-5	591	506	619	337	31.7	32.1	26.7	29.6	31.9	34.1	19.3	27.5
Cr.-6	1	0.234	0.235	0.262	0.262	0.166	0.166	0.402	0.26	0.305	0.178	0.114
Cr.-7	3.55	4.53	4.66	5.13	6.71	3.84	4	4.69	5.25	7.45	4.41	3.98
Cr.-8	36.42	37.1	37.22	37.69	39.27	40.69	40.85	40.07	40.37	41.98	51.06	46.57

The performance of alternatives can be preliminary compared by drawing a value path diagram (Fig. 3). This diagram visually helps to identify the non-dominating options (those that do not provide improvement on one criterion at a sacrifice of another one). Fig. 3 demonstrates that the alternative 1c might be dominated by 1b, and the alternative 3bV might be dominated by 3b, respectively.

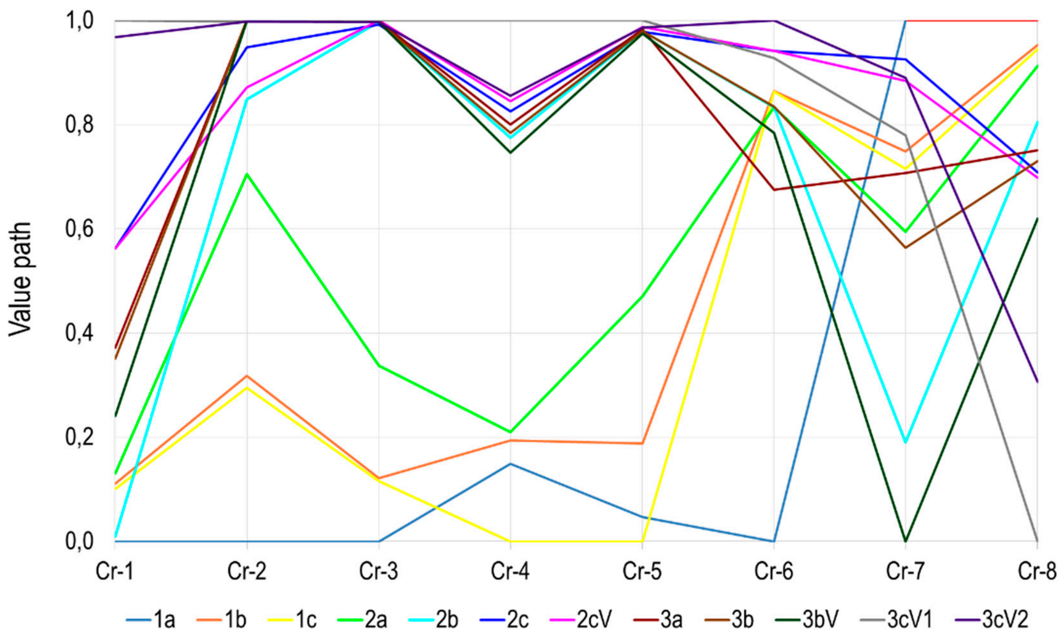

Figure 3. Value path.

4.1.2. Preliminary Judgement Aggregation

To perform the comparative evaluation of advanced and conventional NFCs a preliminary aggregation was done here adapting Multi-Attribute Value Theory (MAVT) method with the linear single-attribute value functions, because MAVT has found a wide application in MCDA-based frameworks supporting strategic choices in many areas including nuclear engineering [24-26]. Figure

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4 demonstrates NFCs' performance scores obtained applying MAVT with indicator values from the performance Table 3 and the objectives tree illustrated in Fig.1. Single-attribute value functions were defined over the local domain of each indicator type. A set of equal weights (locally normalized i.e. at each tree-level separately) was applied. The results: NFCs' scores obtained for each high-level objective are shown in Fig.4.

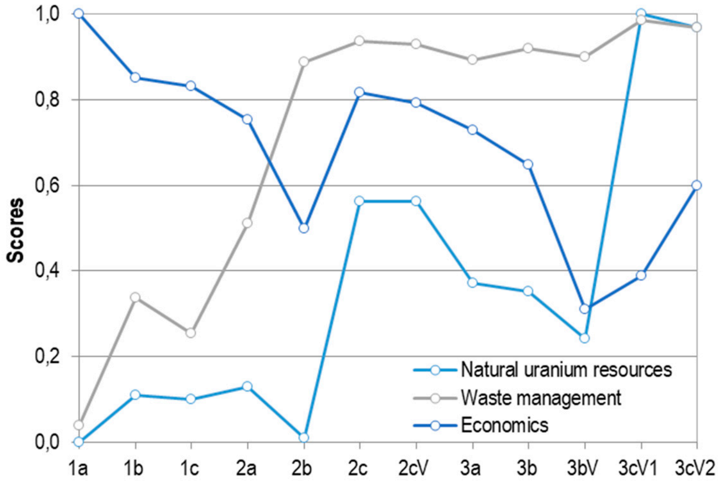

Figure 4. High-level objectives scores for NFC options (with a local equal weighting of criteria).

Note that for the high-level objective "resource utilization" only one criterion was selected therefore in this area there is no need to aggregate on different criteria. In the area of waste management and economics the aggregation of scores on relevant lower-level criteria must be performed first in order to deliver the overall scores for natural uranium resource utilization and economics, respectively. Fig. 4 shows these scores drawn over each NFC option. It can be easily recognized that the waste management score is high for the majority of evolutionary and all revolutionary nuclear energy systems. 'Open' NFC as well as NFC employing a 'single recycling' of plutonium in MOX fuel and the evolutionary NFC option-2a: 'Plutonium recycling in LWR once' using enriched ^{235}U (as a component of MOX-EU fuel) perform worse. As concerns the economical uranium resource utilization (objective 1) option-1a and option-2b have got the worst scores, the latter due to MOX-EU loaded to reactor cores i.e. a fuel type which consumes more uranium. The most economical resource utilization is provided by option-3cV1 and option-3cV2 i.e. NFCs based on fast sodium- or a gas-cooled critical reactor, respectively. NFCs' performance on high-level objective 'economics' exhibits a higher diversity, but is biased with large uncertainty. Current technology and its extension are obviously more economic than advanced NFCs of group 2 and 3. NFCs of group 2 seem to be more economic than NFCs of group 3 but with one exception: Option-2b which includes an Am-Cm separation process and requires a fabrication of two MOX-EU fresh fuel types.

Of note, the framework using MAVT requires a selection of appropriate criteria weights (representing the decision makers' preferences). These weights "measure" the relative importance of low-level criteria contributing to a fulfilment of a particular high-level objective and the relative importance of the latter. Here, a preliminary assessment was done using equal weights within each criteria group. An uncertainty in weighting factors leads to a statistical spread of scores. Spread of scores obtained for two high-level objectives (waste management and economics) while considering the impact of the weights' uncertainty are depicted in form of the scatter bars in Figs. 5a and b, respectively.

In general, NFC options- 2b, 2c, 2cV, 3a, 3b, 3bV demonstrate very similar performance on waste management criteria even for different balanced sets of weights. Waste management scores of options 3cV1 and 3cV2 are the highest; therefore these options seem to be the most attractive from the waste management perspective.

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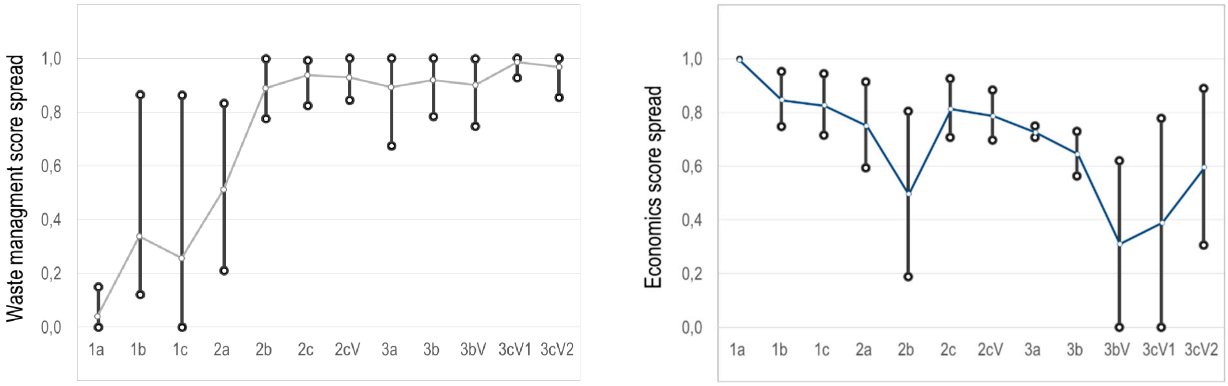
Option-3bV requires evidently the highest financial investments (worst score) whereas the best economic performance, i.e. the lowest costs, can be assigned to the option-1a which has the highest maturity level and does neither rely on the separation processes nor on the fuel recycling.



a) b)

Figure 5. Spread in calculated high-level objective scores due to uncertainty in waste management (a) and economics (b) weighting factors.

4.2. Preliminary Screening of the Options' Performance with Different Preferences-Weighting

Screening for dominance: A very useful preliminary stage in any performance comparison of options is an identification of non-dominated options which has been till now only visually done while studying the value paths in Fig.3. NFC option is 'dominated' if its performance indicators on an entire set of criteria are worse than those of an option that dominates it. Therefore, dominated options should be excluded from comparative procedure. This facilitates the comparison and makes the ranking more stable. More detailed analysis done here (see Table 4) confirms the preliminary observation that 1c is dominated by 1b, and 3bV is dominated by 3b. Recall, Fig. 3 reflects this domination relation in a visual way showing that the value path of the dominated NFC options lies below that of the dominating one. NFC-1b domination over 1c means that 1b will always have the higher rank when compared to 1c. The same holds for the 3b and 3bV options.

Table 4. Domination among NFC options.

Criteria	*1b dominates*) 1c*		*3b dominates*) 3bV*	
	1b	*1c*	*3b*	*3bV*
Cr.-1	0.89	0.9	0.65	0.76
Cr.-2	20.34	21.04	0.11	0.14
Cr.-3	177	178	2,8	2.98
Cr.-4	2030	2380	963	1030
Cr.-5	506	619	31.9	34.1
Cr.-6	0.234	0.235	0.26	0.305
Cr.-7	4.53	4.66	5.25	7.45
Cr.-8	37.1	37.22	40.37	41.98

*) option *i* dominates option *j* if all KI values on criteria for option *i* are more preferable then corresponding values for option *j*

The advantage of these preliminary analyses is that at this stage there is no need to determine the weighting factors yet. The disadvantage is that the identification of the set of non-dominated NFC options does not allow determining the ranking order. Therefore, it is necessary to define a decision rule and to integrate this rule in the proposed framework using elicited weights (representing the relative importance of criteria for singular experts, decision-makers and other stakeholder groups).

Preference-weighting: Other weight sets different from "equal weight option" discussed already in section 2.1.1, can be for instance selected as proposed in Table 5 with the enhanced emphasis on the economics, the resource utilization or the waste management objective, respectively. Such an approach suitable to examine the impact of different perspectives on options' ranking order is widely applied in many studies. A similar approach was followed within the US DOE supported study on evaluation and screening of NFCs [27].

The ‘equal weights’ method is thereby only a first approximation within the MCDA problem. It depicts a situation when nothing is known regarding experts’/stakeholders’ and decision-makers’ preferences. However, even if the detailed information regarding expert weightings is not available, the ‘equal weights’ ranking combined with a detailed weight sensitivity analysis provides a chance to make a general conclusions about the attractiveness of the options from many different perspectives [6].

A key feature of decision modeling is the iterative way of proceeding that allows local perspectives to be considered in the framework by means of diverse sets of weights. It is worth to notice that in order to simulate the perspectives of different interest groups and to assess their impact on the overall ranking scores just the base-case weights should be changed.

For the sake of demonstration a ratio 20:80 has been applied here for three weight variants, assigning a weight of 0.8 to an emphasized objective and weights equal a halve of 0.2 to the two remaining high-level objectives. Note that, the weight set chosen at each lower hierarchy level represents, due to the normalization condition, equal partial weight values.

The criteria weights can be as well changed. For instance, a country which considers fuel leasing option and does not intend to implement national HLW repository might assign zero to Cr.-3 weight, whereas the county which intends to multi-recycle fissionable material will care of minimizing loss of Transuranic element inventory (TRU) transferred to waste, etc.

Table 5. Weights options.

Criteria	Equal weighting		Economics emphasizing		Resource utilization emphasizing		Waste management emphasizing	
	High-level objectives weights	Criteria weights	High-level objectives weights	Criteria weights	High-level objectives weights	Criteria weights	High-level objectives weights	Criteria weights
Cr.-1	33,3%	100%	10%	100%	80%	100%	10%	100%
Cr.-2		20%		20%		20%		20%
Cr.-3		20%		20%		20%		20%
Cr.-4	33,3%	20%	10%	20%	10%	20%	80%	20%
Cr.-5		20%		20%		20%		20%
Cr.-6		20%		20%		20%		20%
Cr.-7	33,3%	50%	80%	50%	10%	50%	10%	50%
Cr.-8		50%		50%		50%		50%

4.3. Judgement Aggregation and Discussion on Ranking Results Stability

The ranking results, which are shown in Fig.6, were obtained using MAVT additive model with the multi-attribute value function:

$$u(x_i) = \sum_{i=1}^{n} k_i \, u_i \,(x_i) \qquad (1)$$

where u and u_i are multi- and single-attribute value functions, respectively, and k_i are the normalization constants equal to a product of all relevant level weights.

MAVT is used here to assess the sustainability of a policy option by simultaneous treatment of indicators that refer to the three dimensions of sustainability: economic, social and environmental. Eq.1 shows that MAVT is able to combine information necessary for clarification of sustainable (weak) NFC development aspects. Moreover, MAVT is able to address de/coupling, adaptability and ir/reversibility (since separate criteria can be used to compare alternative policies). The MAVT

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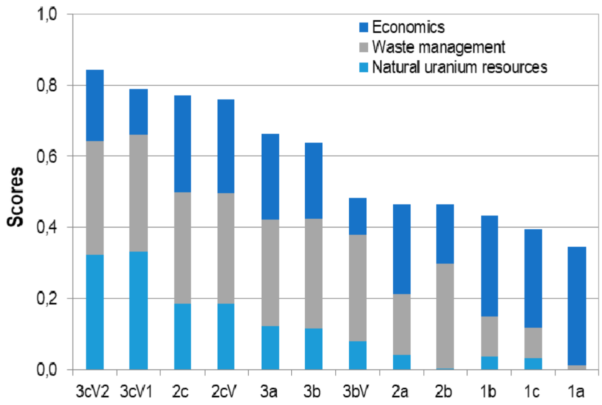
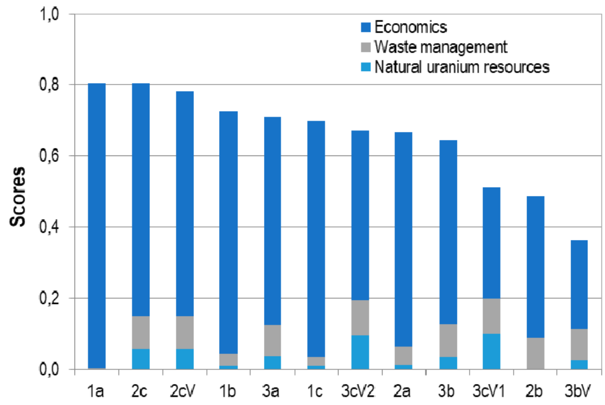
aggregation can include the impacts on different groups/sectors/regions on the ranking order and give a clear overview of the differences between preferences in these categories.

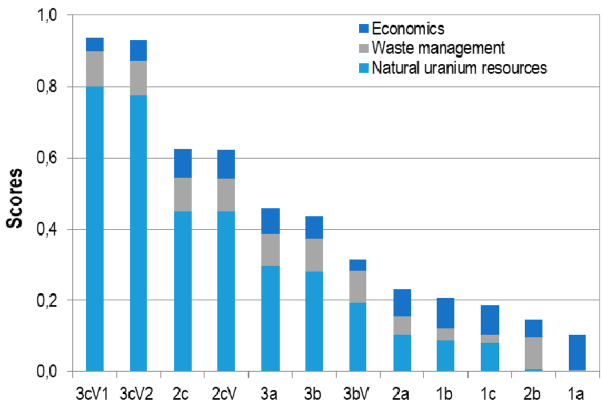
The ranking results obtained using MAVT-driven judgement aggregations are shown in Fig. 6. Included are: the overall score of each policy option (NFC) and three partial scores representing the contributions of each high-level objective to the total score value over NFC options.



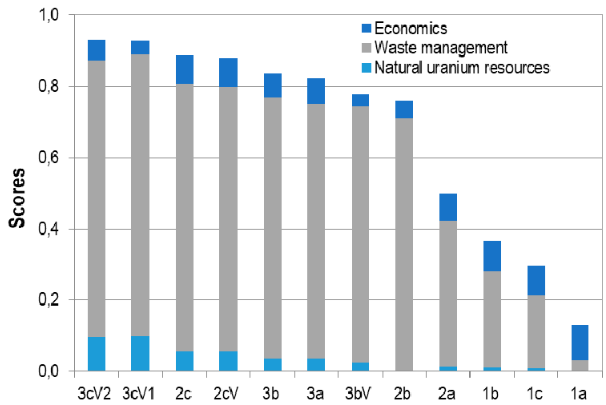
(a) Equal weighting



(b) Economics emphasizing



(c) Resource utilization emphasizing



(d) Waste management emphasizing

Figure 6. MAVT ranking results with breakdown of the overall scores into high-level objectives scores for different weights options.

Options: 3cV2 (NFC based on sodium-cooled European Fast Reactor) and 3cV1 (NFC based on Gen-IV gas-cooled reactor) perform best, followed by the options: 2c with heterogeneous americium recycling (in dedicated targets) in LWR and a variant 2cV representing NFC in which Am and Cm are transferred into a decay storage facility and their subsequent decay product are either disposed or recycled in the MOX fuel. The last (worst) ranking positions are occupied by NFC 1b, 1c and 1a mainly due to low waste management score (amount and characteristics of generated radioactive HLW inventory). Moreover, Figure 7 demonstrates very similar overall scores for several options suggesting another combination of NFCs than that done by the NEA/OECD experts namely into families providing similar trends. These "proxy" families are: 1b and 1c; 2c and 2cV; 2b and 3bV; 3a and 3b; 3cV1 and 3cV2. Options 1a and 2a have no corresponding partners.

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4.4. Sensitivity and Uncertainty Analysis

An uncertainty analysis presented here refers to the weights and value functions. The uncertainty in KI values Cr.1-Cr.8. is not addressed here because KI values represent best estimate for a given NFC deploying a particular reactor design with the fuel composition as described in [21].

4.4.1. Sensitivity and Uncertainty Analysis with Regard to Weights

The changes in a ranking order of NFC options belonging to one family may occur as a result of the modification of criteria weights (within the same high-level objective) or changes in the shape form for the single-attribute value function. The results of sensitivity studies in view of weights variation are illustrated in Fig. 7 for each of the three high-level weights assigned to the high-level objectives separately i.e. for resource utilization, waste management and economics, respectively.

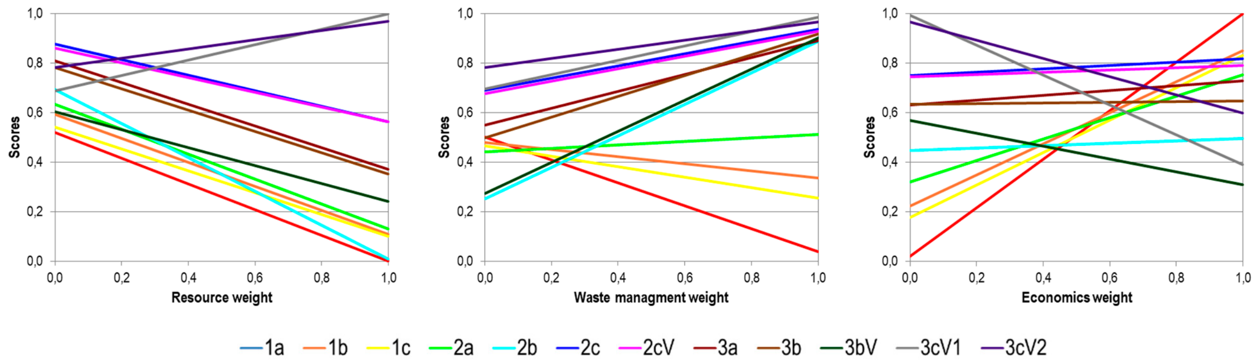
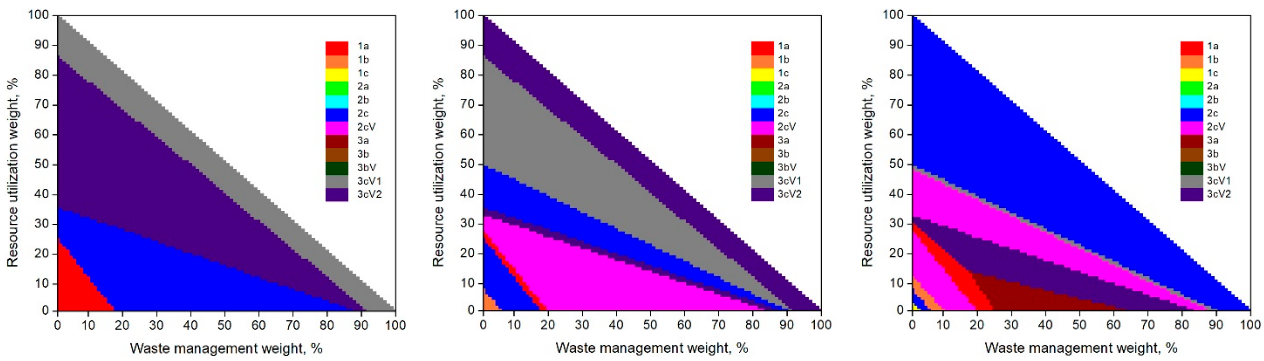


Figure 7. Score variation over value change of relevant high-level weight.

Sensitivity analyses demonstrate that the first rank can be taken only by options 1a, 2c, 3cV1 or 3cV2, respectively (Fig.8a). The ranking position of these options is very stable as compared to the options belonging to the second and the third family (Fig.8b and c). Note that according to a weight values combination only 4 NFC options can take the first position in ranking; while the second rank position can be taken by 6 options (1a, 1b, 2c, 2cV, 3cV1, 3cV2) see Fig.8b. The third rank position can be occupied by 8 options (1a, 1b, 1c, 2c, 2cV, 3a, 3cV1, 3cV2) as illustrated in Fig.8c.



a) b) c)

Figure 8. NFC options taking the first (a), second (b) and third (c) ranks due to different high-level-objective-weight combinations.

The spread of the overall scores due to uncertainty in waiting factors is presented as box-and-whisker plot in Fig. 9 on the base of evaluations performed using a stochastic multi-criteria acceptability analysis [28-30]). Box- and whisker-plots are a handy way to display numerical data breaking the entire data set down into four quartiles, each one with an equal number of data values. In order to generate the plot, the median of the lower half of the data set (quartile 1), the median of the entire data set (quartile 2), the median of the upper half of the dataset (quartile 3), and so on, i.e. 25th, 50th and 75th and 5th as well as 95th percentile, are used to represent the statistical distribution of obtained option scores. The stochastic sensitivity analysis shows that the rank one for option 3cV2 can be

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occasionally taken by the option 3cV1, the ranking position of options 2c and 2cV are rather stable and so on. Figure 9 confirms that options 3cV1 and 3cV2 persistently remain the most attractive one. This figure allows a dynamic interpretation of ranking and shows the inter-option competitions due to a weight variation.

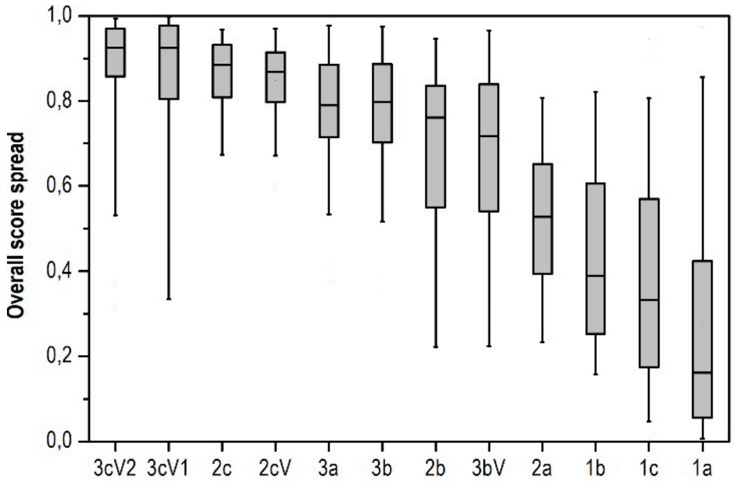

Figure 9. Spread of overall scores due to uncertainty in weighting factors.

It is interesting to observe that the performances of options 2c and 2cV are close to each other (2cV is a variant of 2c). In particular 2cV seems to be better than 2c for 3 criteria (Cr.-2,-7,-8), at the same time 2c is better than 2cV (Cr.-3,-4,-5) on 3 criteria whereas 2c and 2cV perform equally well on 2 criteria (Cr.-1,-6), see Table 6.

Table 6. Comparison between 2c and 2cV options

Criteria	Values		*Performance*
	2c	*2cV*	
Cr.-1	0.44	0.44	Equal
Cr.-2	1.63	3.93	2c better than 2cV
Cr.-3	3.91	2.24	2cV better than 2c
Cr.-4	888	852	2cV better than 2c
Cr.-5	32.1	26.7	2cV better than 2c
Cr.-6	0.166	0.166	Equal
Cr.-7	3.84	4	2c better than 2cV
Cr.-8	40.69	40.85	2c better than 2cV

4.4.2. Sensitivity and Uncertainty Analysis in regard to Single-Attribute Value Function Shape

The ranking order sensitivity to a change of the single-attribute value function shape is depicted in Fig.10 for the equal weighting option. Fig. 10 shows each option's rank position probability multiplied by 100%. The statistical approach was implemented to examine sensitivity of ranks to single-attribute value function shapes e.g. a random generation of a set of single-attribute value functions from a certain set of functions (in this case, from the set of exponential functions with different power being a parameter) . The outcome is an assessment of option ranks for each set of randomly generated single-attribute value functions. Based on this data, a probability of achieving certain rank may be evaluated for each option and its distribution determined and plotted.

Based on this analysis probability rank distributions can be assessed for each NFC option in order to determine the most probable ranks as well as the mean values, variance, etc. This data characterizes the degree of the option rank sensitivity to single-attribute value function shapes. Based on this information, it is possible to provide conclusions regarding the attractiveness of options taking into account uncertainties in single-attribute value function shapes.

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Fig.10 demonstrates that the most probable options occupying each rank position are the same as those which have been already identified while using ‘base case’ linear single-attribute value functions. The closest to the most probable options are the ones from relevant NFC families that were indicated in section 4.3. In general, this figure indicates that the ranking order is not very sensitive to the shapes of the single-attribute value functions. The same is true for other weighting options.

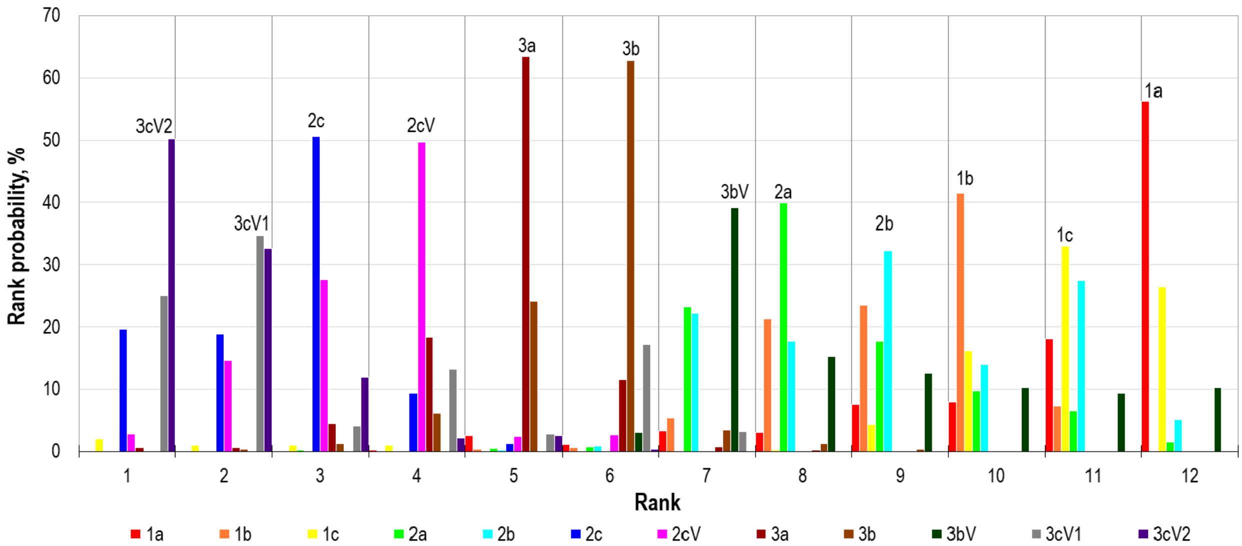

Figure 10. The rank distribution among NFC options due to uncertainty in single-attribute value function shape (equal weighting).

4.5. Robustness Analysis

The robustness of the ranking order obtained by the MCDA-based analyses can be examined using in the framework other methods instead of MAVT to perform the aggregation of judgements (Simple Scoring Model (SSM), AHP, TOPSIS, and PROMETHEE) [31-40]:

- Simple Scoring Model (SSM) [37] uses a linear additive model assuming that the overall score for a given alternative is evaluated as the total sum of the performance score on each criterion multiplied by the weight of that criterion.
- Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) [38] calculates the geometric distance between each alternative and the ideal and anti-ideal alternatives and assumes that the more preferable option should have the shortest distance from the most desirable (ideal) alternative and the longest distance from the less desirable (anti-ideal) alternative.
- Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) [39] is an outranking method which implies forming a partially ordered relation between each pair of alternatives.
- Analytic Hierarchy Process (AHP) [40] is based on pairwise comparisons of alternatives against each criterion using specialized AHP scale, determination of weights based on pairwise comparisons of criteria through hierarchy, determination of scores through eigenvectors for the maximum eigenvalue and evaluation of the overall score using a linear additive model.

These methods are based on different methodological foundations and implement different decision rules. An overview of an application of these methods to evaluation and aggregation judgment measures for performance comparison of nuclear energy systems can be found in [16]. Parameters for comparisons were selected in accordance with recommendations discussed in [12].

Table 7 demonstrates the comparison of ranking results (ranks of options) obtained using different MCDA methods for the ‘equal weighting’ case. It is evident that the use of different methods leads to well-coordinated and identical ranking results: minor differences in ranks order occurs only for NFCs families indicated in section 4.3 and can be explained by an impact of the specifics of the

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implemented decision rules. Of note, the same tendency is observed for other considered weighting options. As these methods are based on different methodological approaches, their application significantly contributes to conclusions on the stability of ranking results with respect to the selection of a decision rule.

Table 7. NFC options ranking results using different MCDA methods (equal weighting).

Rank	NFC options				
	MAVT	SSM	AHP	TOPSIS	PROMETHEE
1	3cV2	3cV2	3cV1	3cV2	3cV2
2	3cV1	3cV1	3cV2	3cV1	3cV1
3	2c	2cV	2c	2cV	2c
4	2cV	2c	2cV	2c	2cV
5	3a	3b	3b	3a	3a
6	3b	3a	3a	3b	3b
7	3bV	3bV	3bV	3bV	3bV
8	2a	2a	2a	2b	2a
9	2b	2b	2b	2a	2b
10	1b	1b	1b	1b	1b
11	1c	1c	1c	1c	1c
12	1a	1a	1a	1a	1a

5. Survey on Waste Characteristics and LCA Assessments of NFC Environmental Footprint

In this section, the waste inventories and important characteristics of the NEA/OECD NFC options 1a-3cV1 are addressed. To discuss the interfaces of nuclear energy systems with the ecosystem the literature survey was performed and, on this basis, the sustainability indicators, which allow comparing the environmental footprint of the nuclear to the non-nuclear alternative energy generating technologies, were selected. The global approach to sustainability requires the treatment of each technology option in at least four dimensions: technological, economic, environmental and social. Especially the multiple interfaces of the NESs with the environment are of concern and have been studied in the IAEA/INPRO document [41], the US DOE study [27] and Refs. [42-48].

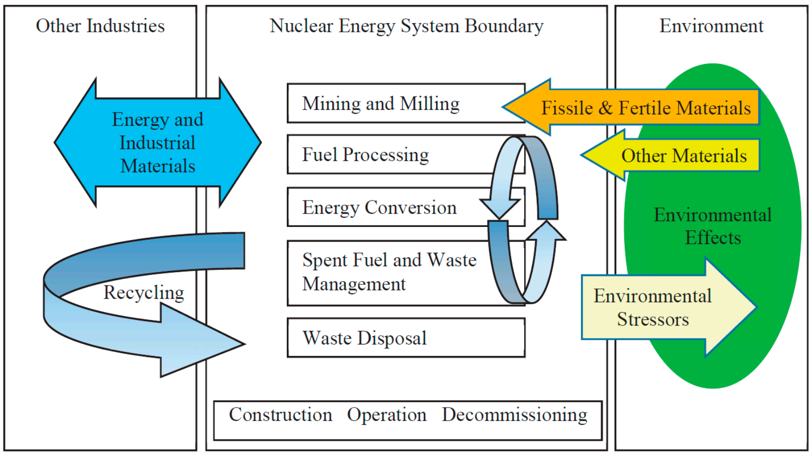

Figure 11. Interfaces of a nuclear energy system with the environment, taken from Ref. [41].

Here only the main results will be summarized.

1. Waste characteristics: In principle, the volume of nuclear waste produced by nuclear installations is relatively small compared to wastes from other large-scale energy-generating technologies. Annually, ca. 200 000 m^3 of low- and intermediate-level radioactive wastes (LLW or ILW, respectively) and ca. 10 000 m^3 or 12 000 tonnes of HLW (including SNF declared as waste) are produced worldwide [6]. The SNF inventories (in tonnes of heavy metal (tHM)) amounted in the

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reference year 2016 to 1833 (arising) and the cumulative inventory stored to 52359 in storage for all but three NEA/OECD member countries.

The operations in the front-end associated with the production of nuclear energy and the back-end (associated with production, decommissioning and disposal) generate waste, which has to be adequately managed. Wastes' arising at different NFC facilities and due to different NFC technical processes are usually subdivided in different classes and categories according to their characteristics. These classes determine further treatment of waste and ensure the safe management of radionuclides. The classification is based on the volumes, activity and radiotoxicity of waste arising at each stage of NFC including the reactor operation and decommissioning. The relative characteristics of wastes generated in a fuel cycle can be found in [21].

Table 8. Relative characteristics of waste generated in NFC (taken from [21]).

Generating process	Relative volume	Relative radioactivity	Relative radiotoxicity
Mining & milling	very large	low	low
Refining	small	low	low
Conversion and enrichment	small	low	low
Fresh fuel fabrication	small	low	low
Recycled fuel fabrication	small	low/medium	medium
NPP operation	large	medium	low
SNF management - reprocessing	small/medium	high/very high	high
SNF management - direct disposal	medium	high	high
Decommissioning	very large	low	very low

2. Waste categories: The radioactive wastes can be categorized according to various criteria. Nuclear power plant operator would, for instance apply a categorization based on the waste originating stream. A classification system which takes into account qualitative considerations affecting a disposal, adopts usually the IAEA classification groups: HLW, LILW-LL (Low and Intermediate Level Waste-Long Lived) and LILW-SL (Short-Lived), respectively. This classification system distinguishes radioactive waste based on the thermal hazard and a disposal type that is required. HLW requires geological disposal and comprises the inventory of fission products and actinides, separated during the reprocessing of used fuel. SNF if declared as waste belongs to HLW as well. Apart from this any waste which generates decay heat-load higher than ca. 2 kW/m^3 is classified as HLW. Wastes requiring shielding, but dissipating small amount of heat during their handling and transportation build the LILW category. This type of waste generates low heat (< 2 kW/m^3) and is usually broken down into two subcategories due to different type of containment required for long-lived radionuclides and alpha-emitters: both, LL with half-life times greater than 30 years and SL which requires geological disposal and SL being disposed in surface facilities, respectively. Some countries limit LL alpha-emitters to 400Bq/g in near surface disposal facilities considering also LL beta emitters ^{129}I and ^{99}Tc for geological disposal.

3. Waste volumes: The total amount of LLIW-SL, LLIW-LL and HLW assessed by NEA/OECD expert group for each fuel cycle option is shown in Fig.12, 13, and 14 respectively. Option-1d (DUPIC based NFC) was not considered previously in the MCDA framework because of lack of indicator values for 1d needed to perform the comparative study.

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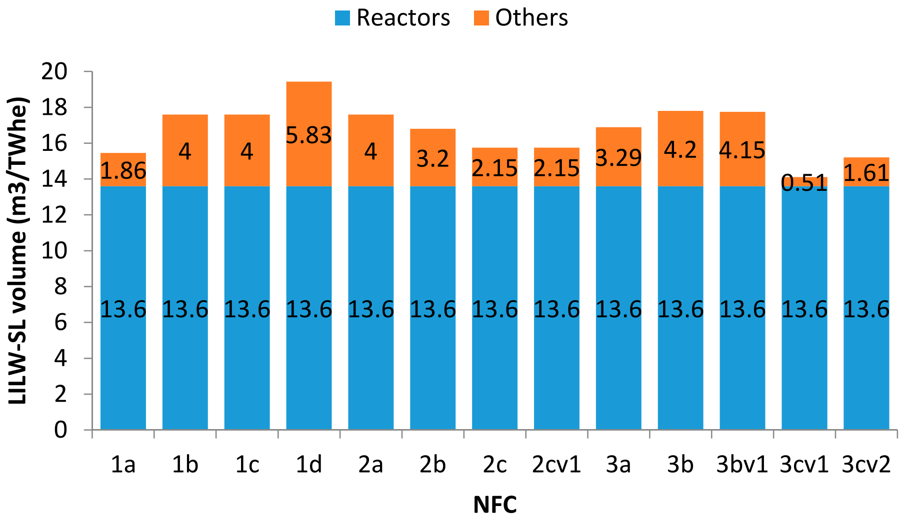

Figure 12. Total amount of short lived low- and intermediate-waste types; own elaboration of data used in [21].

The lack of data on the amount of LILW-SL caused that the NEA/OECD experts had to make similar assumptions for the waste streams of many NFCs. A small variability of waste volumes shown in Fig. 12 reflects these assumptions however this figure clearly demonstrates that the plant operation waste dominates the other waste generated by NFC facilities.

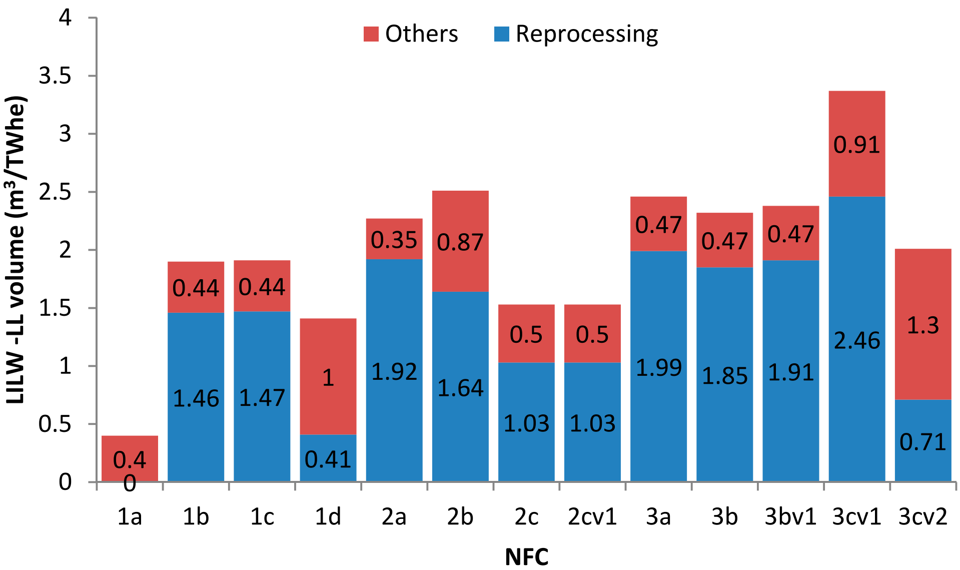

Figure 13. Volume of long lived low- and intermediate-waste types; own elaboration of data used in [21].

The amount of LILW-LL depends on the SNF reprocessing technology and a number of steps needed to separate fissionable materials. The waste volume depends on the conditioning technology; therefore the data presented in Fig. 13 has only an indicative preliminary character.

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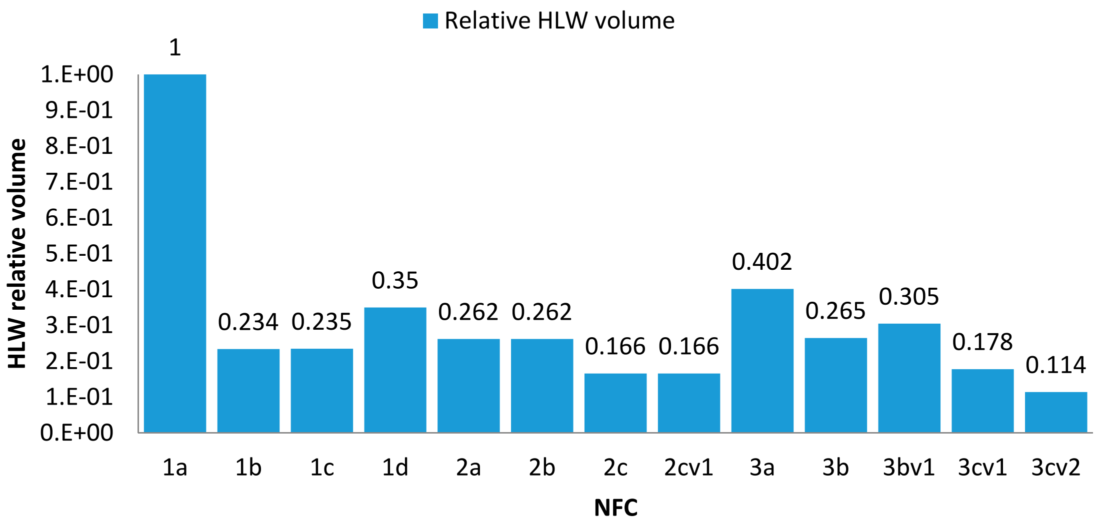

Figure 14. Volume of conditioned HLW (relative to NFC 1a); own elaboration of data used in [21].

The volume of HLW is mainly defined by the waste loading factor at conditioning which is, in many cases, limited by the amount of fission products. The inventory of minor actinides contained in the waste does not dramatically impact the HLW volume. The volume of waste in option 1a corresponds to the volume of the fuel sub assembly.

The amount of decommissioning waste shown in Fig. 15 and 16 is dependent on the number of decommissioning steps; thus reactors are the largest contributors for all NFCs.

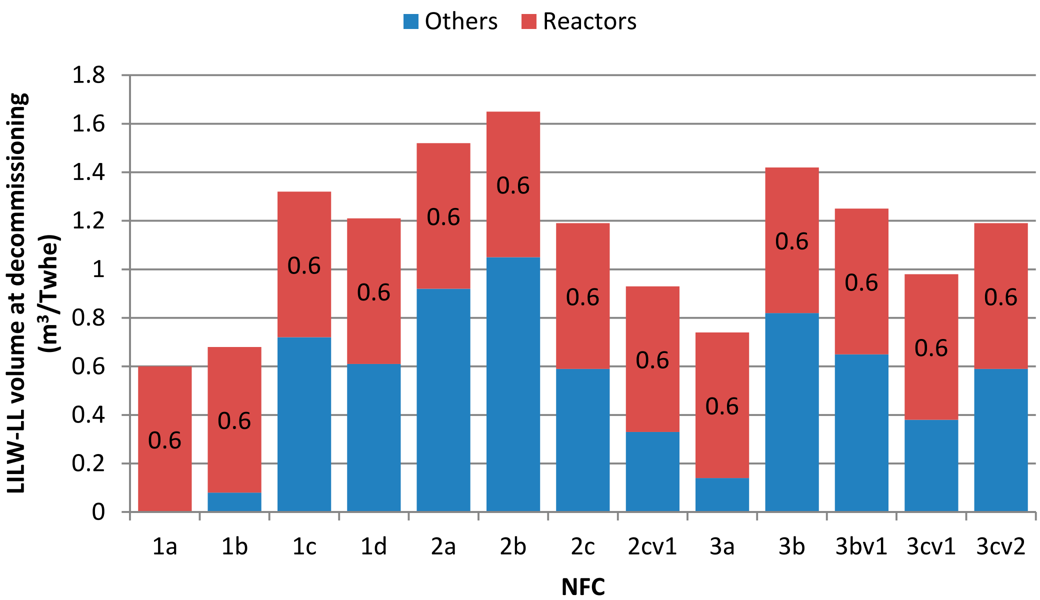

Figure 15. Volume of LILW-SL generated at decommissioning stage (uranium mining not included); own elaboration of data used in [21].

Of note, the current technologies are not yet optimized for the composition of waste streams produced by the advanced separation technologies, especially pyrochemical technologies and this fact has an impact on HLW volume. The majority of LILW-LL is attributed to reprocessing activities. The differences between the options are small but the data are biased with large uncertainties because of lack of available experimental data on secondary waste flows.

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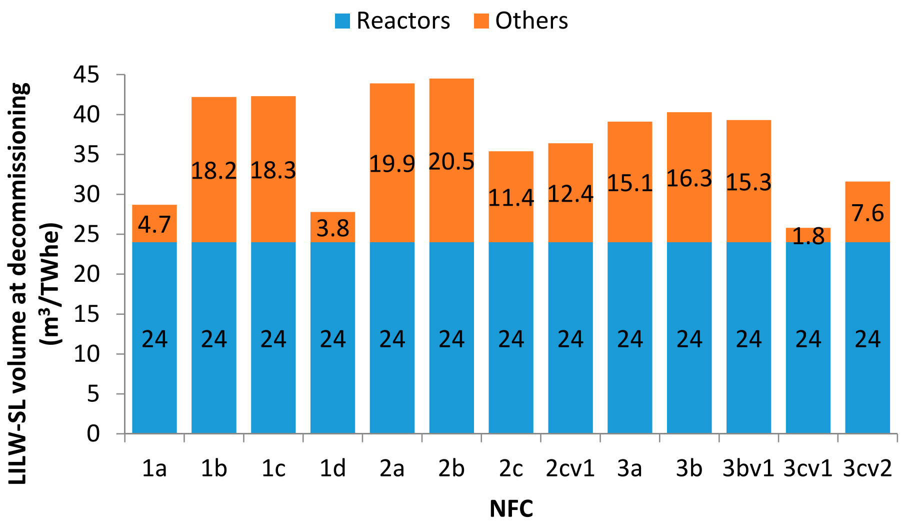

Figure 16. Volume of LILW-LL generated at decommissioning stahe (uranium mining not included); own elaboration of data used in [21].

4. Environmental footprint of NFC options: Results of extensive studies performed to assess the environmental footprint of nuclear energy systems can be found in Refs [41-47] and [37]. To perform Life Cycle Assessment (LCA) different methodologies can be applied. The methodology in [41] uses the classical PCA (Process Chain Analysis) approach. It considers

(1) the annual emissions,

(2) the environmental impact assessment penalty (EIAP) originating from the plant construction averaged on its whole lifetime,

(3) the EIAP due to cleaning and decommissioning (cradle to grave) and

(4) the EIAP from the transports between all fuel facilities.

For French reactor fleet only the "first order i.e. parent contributions" were assessed that means the technological chain was cut-off at the level of the sub-systems. Historical and published data were used. Indicators were normalized to the nuclear energy production in France in 2010 which amounts to 408 TWhe. Selected indicators which were evaluated are: GHG and atmospheric pollutions (SOx and NOx emissions), water pollution, land-use water consumption, water withdrawal and the technological waste generated.

The relative share (in %) of each stage of the fuel cycle to the overall environmental and technological indicators calculated for French Twice Through Cycle (TTC, corresponding to the option 1b) are illustrated in Fig. 17.

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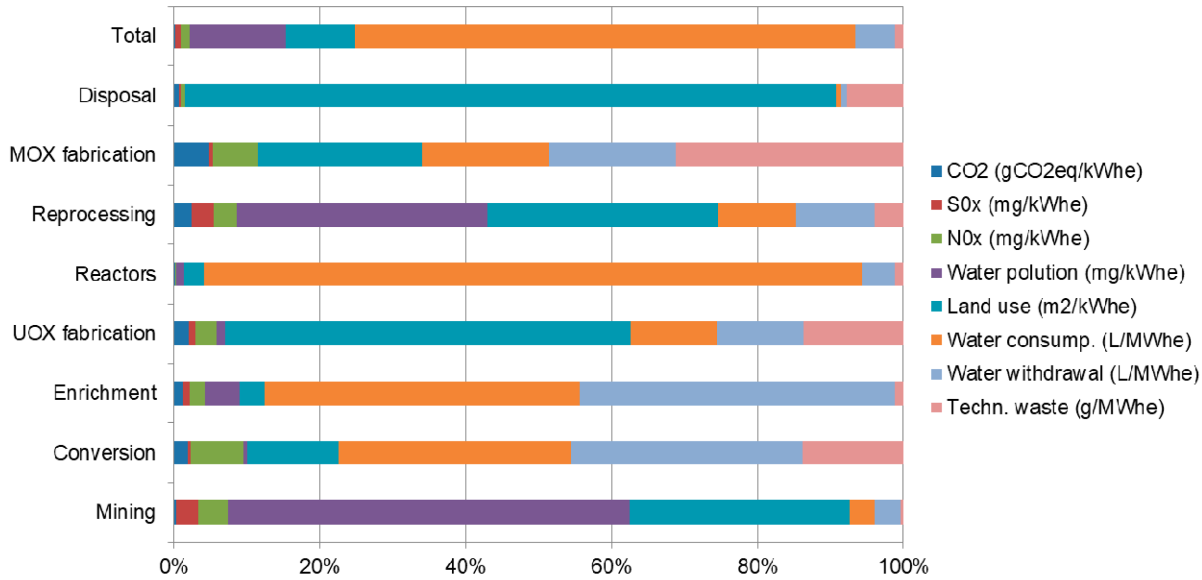

Figure 17. Relative share (%) of each NFC stage to the overall environmental and technological impact indicators for the option 1b (own elaboration on the base of the corrected data found in [42]).

During the operation of facilities involved in each NFC option, different radionuclides might be released into the atmosphere and into the aqueous media with the main contributors: radon and other noble gases, then tritium, ^{14}C and other radionuclides, see Fig. 18. These radioactive releases are well below the permissible threshold values (both authorization and regulation thresholds) and have a negligible heath impact (below 10μSV/year).

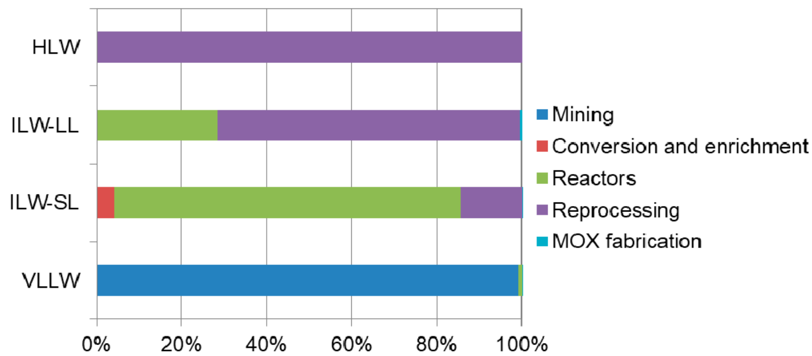

Figure 18. Share to the radioactive solid waste indicators for selected stages of NFC option 1b – own elaboration on the base of the corrected data found in [42] (VLLW indicates Very Low Level Wastes).

5. Environmental footprint of nuclear and non-nuclear energy-producing technologies: Data published in Ref. [48] allow comparing environmental footprint of nuclear technology with the footprint of other energy-producing sources as coal, oil/gas, hydro, wind, PV (photovoltaics), and biomass. Comparison of selected indicators for each technology is shown in Fig. 19.

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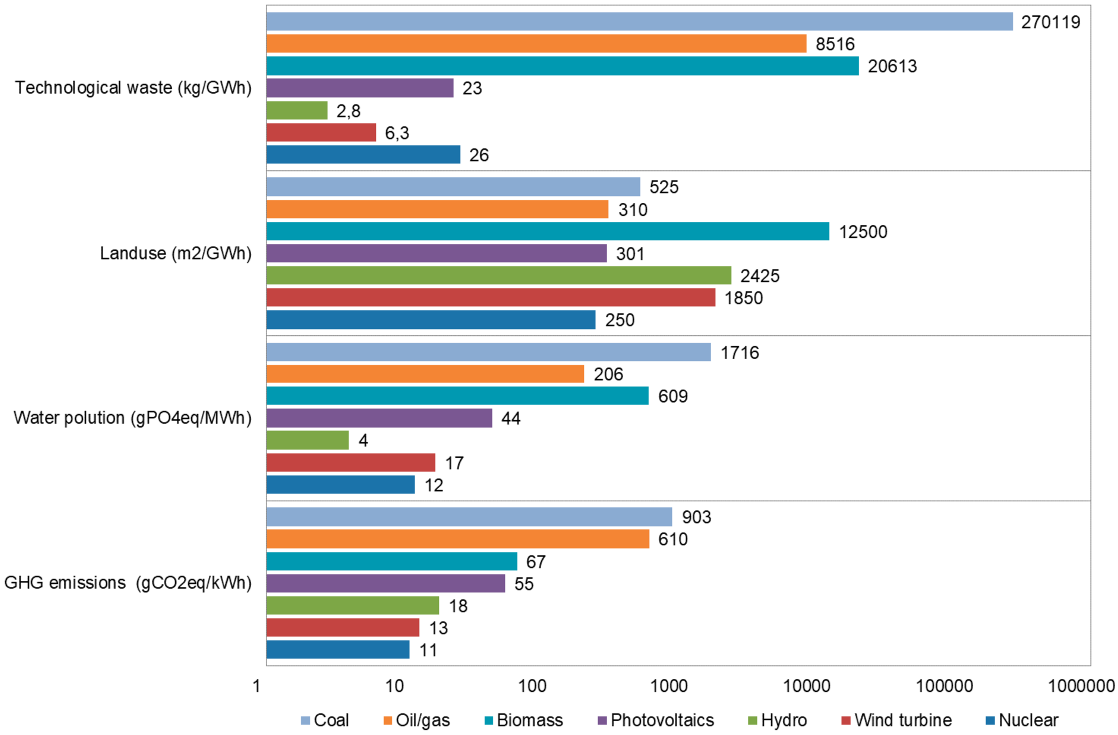

Figure 19. Comparison of selected environmental indicators values assessed for different energy-generating technologies adopted from [44].

In general, it can be demonstrated that the indicator values associated with the nuclear energy production reach in most cases the lower range limit of indicator local scales. Moreover, these values lay often very close to the values of the corresponding indicator for renewables. This underpins the significant potential of nuclear technology to minimize the impact of GHG emission (by two orders of magnitude) in comparison to fossil energy and by factor of 8 with respect to the PV energy. As concerns SOx and NOx emissions nuclear performs worse than hydro and wind options (see, for example [42], [44]), but better than PV and fossil options. In view of the potential impact indicators: Acidification and eutrophication, nuclear option occupies a second best position ([42]-[48]) after hydroelectricity, but well before any remaining options inclusive wind power and PV. The nuclear energy land-use is the lowest in spite the high impact of mining. Indicators connected to water pollution are well below the performance of coal, gas, PV, biomass and wind but worse than hydro. Technological waste indicator is ca. four orders of magnitude lower than the coal option indicator, lower by a factor $3{\cdot}10^{-2}$ than oil/gas indicator and a factor of $7{\cdot}10^{-2}$ as compared to biomass indicator and very close to PV, only hydro and wind options perform better.

6. General Discussion

The INPRO/IAEA holistic approach to sustainability of nuclear fuel cycles recommends that the nuclear technology should be feasible, viable, affordable, and safe, reduce resource consumption and liabilities, have small environmental footprint, minimal invasive impacts on both human beings and the ecosystem and offer an acceptable solution for the structural problems of our societies, economically, socially and ethically ([12]). As concerns the environmental impacts advanced NFCs strive for the waste reduction i.e. offer a reduced footprint of HLW repository due to a reduced waste volume to be disposed of. A remote handling of HLW and, if necessary the LILW, can be implemented in the majority of NFC facilities e.g. fuel fabrication and reprocessing of used fuel for recycling. A complete flow chart of the environmental stressor analyses is shown in Fig. 20 [41]. Some effects of stressors on the environment have been already discussed in Section 5.

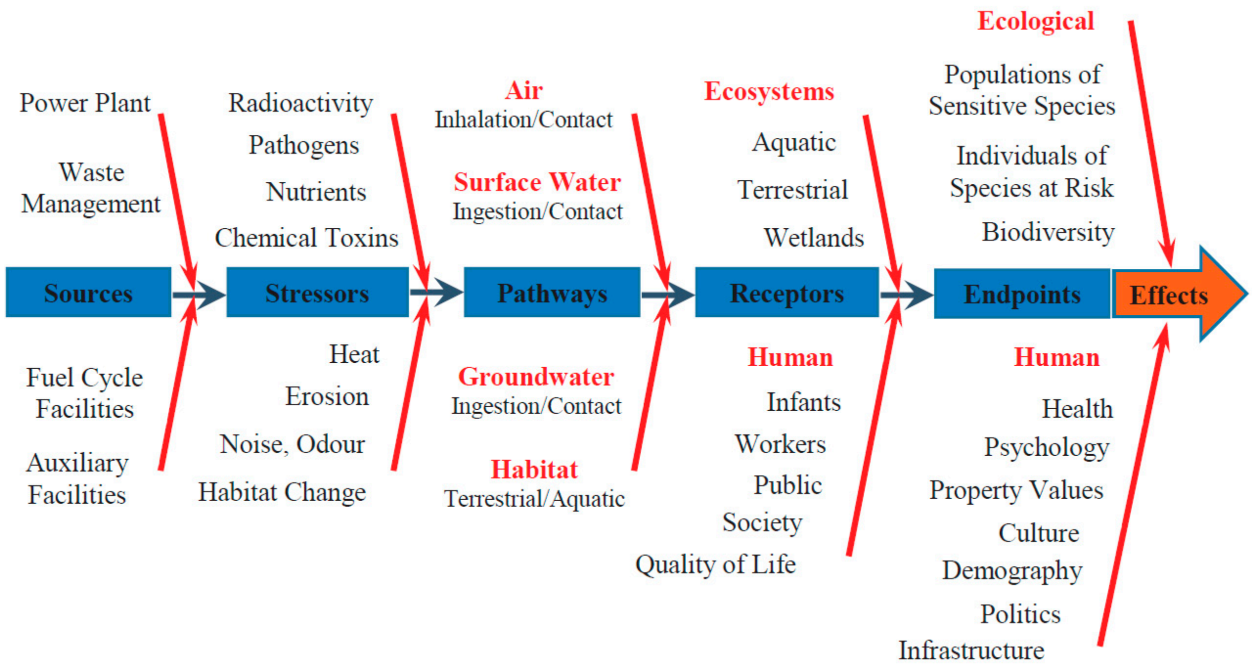

Figure 20 of An environmental stressor analysis: Flow chart [41].

Table 6 summarizes the main findings regarding the overall performance of the considered NFC options for different stakeholders' preferences and other important circumstances. In particular, this table demonstrates that partly closed NFCs (2c, 2cV) represent in the mid-term the best trade-off among the other NFC options providing benefits to the SNF/HLW repository programs, improved use of the nuclear resource and affordable investment and NFC costs. However, in the long-term fast reactor based nuclear energy systems have, when they reach a deployment maturity, a higher potential to offer even better performances.

These results demonstrate that, from the technological perspective, nuclear technology itself is very flexible and if deployed properly may allow subject-matter experts, decision makers and stakeholders reaching different objectives. The challenge in the decision making process is to organize appropriate expertise on comparisons of NFC options in such a way that it would be possible to articulate and incorporate contradicting judgments, intentions, and capabilities of all concerned parties.

Due to the limited scope of the study, the results of the analyses obviously cannot form the basis for substantiation of management decisions; however, this paper is, in authors' opinion, quite sufficient to demonstrate the basic methodological aspects related to the application of MCDA methods for ranking of NFC options. The main benefit of aggregation of expert judgments based on formal mathematical methods is that they give a possibility of structuring the discourse and organize an efficient expertise. This procedure helps finding the most prospective among the NFC options and demonstrates, on a quantitative basis, the merits and demerits of the compared alternatives. Thereby, in spite of problem complexity, well-reasoned judgments on options' attractiveness are possible.

This type of analysis can form the basis for management decisions and contribute to the elaboration of a concerted (trade-off) position on the most prospective NFC options, if an expertise involving both proponents and opponents is elicited. Particular attention should be given to the discussion of issues related to subjective and objective uncertainties and risks which should be incorporated into the analyses. This is an important aspect since today both the new technologies and the scenario assumptions are still characterized by significant uncertainties.

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Table 6. Summary: challenges and opportunities of NFC implementation

Options	Challenges and opportunities
	Most preferable NFC options
3cV1 and 3cV2	These options provide in general fairly good overall performance and become the most preferable when the resource utilization and waste management criteria are of the highest priority (3cV1 is a little bit better than 3cV2 on the resource utilization criterion (but slightly more costly), while 3cV2 is a little bit better than 3cV1 on the waste management criteria).
2c and 2cV	These options provide similar overall performance and take the highest ranking if a cost-effective reduction of resource consumption and burden decrease of nuclear waste are desired.
1a	This option performs the best when the requirement to provide good economics is of the highest priority. This option stays the best in ranking even when the importance of the resource utilization and waste management criteria (corresponding weighting factors) is changed up to 20%.
	Potentially preferable NFC options
3a and 3b	These options may be considered as appropriate choice in view of waste management and resource utilization perspectives instead of 2c, 2cV, 3cV1 and 3cV2 when the latter options cannot be selected because there are some reasons not to deploy them. Option 3a and 3b have the similar waste management but the worst resource utilization performance score in comparison with 2c, 2cV, 3cV1 and 3cV2, 3a is a little bit better than 3b on the resource utilization criterion and slightly cheaper, while 3b is a little bit better than 3a on the waste management criteria. In addition, 3b dominates over 3bV, which excludes 3bV from consideration when 3a and 3b options are available. 3a and 3b may be competing with 2c, 2cV, 3cV1 and 3cV2 if 3a and 3b economics performance will be improved up to the level of 'current industrial practice and extensions'-options and there are no requirements to provide a good resource utilization performance.
	LWR-based NFC options
1b, 2a and 2b	The comparison between 1b, 2a and 2b performances is worthwhile if options deploying FR are not considered at all: 1b can be preferable in case of economics emphasizing (1b dominates over 1c, which excludes 1c from consideration if 1b option is available), 2b can be preferable in case of waste management emphasizing, 2a will be preferable in case of resource utilization emphasizing, respectively. Of note, the overall sustainability performance of these options is significantly worse than that of NFC options with FR and ADS.

7. Conclusions

Electrical energy generation based on nuclear technologies can compete with the other energy generating technologies because of its constant capacity factor, low GHG emissions and the provisions taken on the management of hazardous waste generated as a byproduct. In each country, management of radioactive waste (as of any other industrial waste) is subject to the general legal framework. Practice shows that the majority of nuclear power-holding countries, first accumulates the inventory of high-level wastes that cannot be accepted directly in near-surface or subsurface disposal facilities to dispose them later, in the mid- or long-term, in a deep geological repository for the final safe enclosure. This strategy is technically feasible and permits a complete waste isolation from the biosphere in the future. However, it might impose considerable economic burden if the surface interim storage duration had been several times prolonged.

In practice, the range of R&D efforts towards the safe waste disposal is dependent on national conditions like, for instance, available geological formations, and on specific characteristics of nuclear waste legacy determined by its isotopic composition. The latter must be assessed in order to develop a detailed HLW repository design (both with retrievable or non-retrievable options). Therefore, long time ago the technology-holding countries have established the expert organizations and authorities responsible for a design and licensing of the final HLW disposal. These organizations conduct and coordinate the R&D activities on safety assessment studies, on minimization of the impact on the environment, and on site robustness tests for predictable performance response to uncertainties.

The vulnerability of nuclear technology cannot be attributed to its intrinsic features but is rather caused by its implementation and joint to NFC exploitation specifics in combination with a human factor and natural catastrophes. However, the risk of nuclear power accidents over time since 1952 amounts 0.003 events per plant per year [49].

All NFC types, including the advanced closed NFCs with multiple recycling of fissionable materials, have in common that both the front- and the back-end- fuel production stages generate radioactive waste. Nevertheless, nuclear power production is among others the only large-scale energy-generating technology which assumes full responsibility for all its waste forms with the provision made for including a priori the waste management costs into the total final electricity price. Moreover, there are mature proven technologies, which, if implemented at each stage of NFC, are able to safeguard the safe high-, intermediate- and low-level waste disposal. Advanced nuclear energy systems have a potential to minimalize the impact of nuclear technology on the environment and human beings hence innovative nuclear energy systems would be able to fulfil the goals of sustainable development.

The comparative evaluation of nuclear energy system options can be performed even by non-experts applying the MCDA-based frameworks provided the experts give a support to this process. The expert groups should make the technical assessment of the performance indicators on the selected criteria for each considered option. The MCDA framework includes screening, prioritizing, selecting and ranking of the alternatives on the basis of human judgement i.e. multi-criteria approach with often conflicting criteria. Thereby, this framework has to encompass the construction of the objectives hierarchy structure, selection of the performance indicators, choice of the preference/value functions, the weights and a judgement aggregation rule. The evaluation procedure delivers scores for each option implying an overall ranking order of NFC options. NFC ranking may iteratively support a decision-making process on the base of a trading-off between both alternatives and weights (swing weight technique).

The generic case study performed here by means of MCDA methodology and the discussion of study results put in evidence the benefits of MCDA-based framework application to the policy/strategy selection process. In practical situations however, the laborious stage of preference elicitation must precede the evaluation stage because the preferences and priorities are significant and country specific elements of analyses. Moreover these parameters determine both the single attribute

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preference/value function shape and the high-level-objective-weights. In the situation a multi-group, "democratized" decision–making process is strived for, opinions of different stakeholders, experts, or decision-makers groups can be easily incorporated into the framework using various sets of elicited weights. However, before attaching the "true" weights to the criteria, a consensus within each group has to be obtained. In this way the stakeholders/experts valuations can be combined with the technical performance indicators of options and both of them constitute the most significant part of input for the MCDA-driven method.

In the paper a finite set of explicitly defined NFC options with key indicators assessed by NEA/OECD expert group "WASTEMAN" was used and a judgement aggregation was done applying the MAVT-based method. The MAVT approach includes mapping of each local attribute/indicator scoring/value scale into a common scale and the employment of multi-attribute judgement aggregation rule combining the indicators, the value functions and the low- and high-level-objective weights to the overall NFC score. Linear single-attribute value functions were chosen here because the constant slope (first order derivative value) implies an indifferent attitude of a decision maker towards the changes of the rate of function values versus the incremental change of an indicator value.

The ranking results show, that options belonging to the group-3 offer the most attractive waste management strategy, and have the highest potential to fulfil the sustainability goals. This ranking result is rather stable. The NFCs of group-2 are a good trade-off. NFCs belonging to group-1 exhibit the worst performance in view of sustainability criteria.

Extensive sensitivity analysis was additionally performed to examine the robustness of ranking results with respect to the value function shape's and the weight assignment's variations. It was proved that embedding other MCDA methods in the proposed framework instead of MAVT had no dramatic impact on the ranking order. Additionally, extensive stochastic analyses based on the Monte Carlo method have been performed in order to treat the uncertainties in weight values and investigate their impact on the ranking order. The generated box- and whisker-chart demonstrates the dynamic variation of NFC ranking order established w.r.t. the "base-case" i.e. the equal high- and low-level-objective weights, respectively. Moreover, this box provides additional information on ranking robustness by estimating the preference value probabilities.

The framework applied in this paper offers a high degree of flexibility. The base case weights and the indicator scale ranges can be adapted to the particular needs. A key feature of decision modeling is, however, the iterative way of proceeding. Feedback from participants contributing to a decision-making process at each iteration step is an essential issue refining the model.

In summary, the presented study confirms that nuclear technology might be clean, safe, reliable and affordable provided the proven technologies available to safeguard the operation of both the power plants and the NFC facilities reprocessing/storing the generated wastes are respected rigorously. The weak point seems to be not a technology but a human factor i.e. a technology implementation due to its specifics and risk, and a way of realization and operation which sometimes might violate the experts' recommendations.

Acknowledgments

The authors would like to acknowledge the international organizations' NEA/OECD expert groups and IAEA projects whose results were cited in the paper, especially the INPRO/IAEA section coordinating the KIND/INPRO project on "MCDA application to comparative evaluation of nuclear energy systems". A. S-F is the NEA German expert and contributed to the NEA Expert Groups: WASTEMAN and Transition Fuel Cycle Scenario Studies launched by the Working Party on Nuclear Fuel Cycle. Both authors (A.S-F and A. A) contributed to the KIND/INPRO project.

Abbreviations

ADS: Accelerator Driven System

AHP: Analytic Hierarchy Process

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EIAP: Environmental Impact Assessment Penalty
EU: Enriched Uranium
EFR: European Fast Reactor
FR: Fast Reactor
IAEA: International Atomic Energy Agency
ILW: Intermediate Level Waste
INPRO: International Project on Innovative Nuclear Reactors and Fuel Cycles
GHG: Greenhouse Gasses
HLW: High-level Wastes
OECD: Organization for Economic Cooperation and Development
KIND: Key Indicators for Innovative Nuclear Energy Systems
LCA: Life Cycle Analysis
LL: Long Lived
LLW: Low-level Waste
LILW-LL: Low Intermediate Level Waste-Long Lived
LILW-SL: Low Intermediate Level Waste-Short-Lived
LWR: Light Water Reactor
MAVT: Multi-attribute Value Theory
MCDA: Multi-criteria Decision Analysis
MOX: Mixed Oxide fuel
NEA: Nuclear Energy Agency
NFC: Nuclear Fuel Cycle
PCA: Process Chain Analysis
PROMETHEE: Preference Ranking Organization Method for Enrichment Evaluations
PWR: Pressurized Water Reactor
R&D: Research and Development
SL: Short-Lived
SNF: Spent Nuclear Fuel
SSM: Simple Scoring Model
TOPSIS: Technique for Order Preference by Similarity to the Ideal Solution.
tHM: tonnes of Heavy Metal
TRU: Transuranium elements
TTC: Twice Through Cycle
VLLW Very Low Level Wastes
WASTEMAN: WASte MANagement acronym of the NEA/OECD study

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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