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Comparison of Innovative and Evolutionary NPPs in a Country-Specific Context for Bulgaria (Based on IAEA INPRO KIND – ET Methodology)

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Abstract. A comparison of two hypothetical Nuclear Energy Systems (NES) has been performed:

- NES-1 – GEN III/III + evolutionary design (LWR) and
- NES-2 – GEN IV – so called innovative design: LFR technology /SFR technology

Two cases for GEN IV NES have been considered: NES-2 (at present time) and NES-3 (in 10–15 years); for example, ALFRED demonstrator is expected to be commissioned by 2030. The comparison was done by means of INPRO KIND-ET (Evaluation Template) using country specific conditions for Bulgaria (small nuclear technology user country).

The paper includes the **Key indicators set** developed in the framework of IAEA INPRO KIND Project and also a brief description of KIND – ET methodology. The results of the before mentioned Nuclear Energy Systems evaluation, according to considered Key Indicators, have been presented and discussed. Benefits and risks of possible new nuclear energy system development in Bulgaria were addressed, using suggested judgment aggregation methodology based on the MAVT (Multi-Attribute Value Function) method.

Keywords: INPRO KIND Project, nuclear energy systems, key indicators set, multi-criteria comparative assessment, sustainable development of nuclear energy.

1 Introduction

In the frame of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and its Collaborative Project on Key Indicators (KI) for Innovative Nuclear Energy Systems (KIND), an excel template has been developed for the Innovative Nuclear Energy Systems (INES) multi-criteria comparative assessment in accordance with the methodology and recommendations as specified in the KIND project, based on the MAVT method [1,3] and a set of the KIND performance indicators – KIND-ET (KIND-Evaluation Template).

KIND methodology can be applied for comparative evaluations not only for innovative nuclear systems, but also for evolutionary nuclear systems and non-nuclear energy sources.

The objective of the INPRO Collaborative Project on Key Indicators for Innovative Nuclear Energy Systems (KIND), as it has been stated, is “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” [1].

2 Study of Key Indicators Set from the Point of View of Small Nuclear Technology User Country

Within the KIND project, a set of key indicators (KI) based on the INPRO Basic Principles [2] was developed and recommended for performing NES comparative evaluation. All indicators could be combined into the INPRO assessment areas (economics, waste management, proliferation resistance, environment, safety) and also maturity of technology and country specifics assessment areas were taken into consideration. Experts have the freedom to choose the key indicators set, the assessment areas and the high-level objectives to be used in the comparative evaluation. The objective is to achieve sustainable Nuclear Energy Systems (NES) when all basic principles are met in these INPRO assessment areas.

Comparative evaluations using KIND-ET tool have been performed considering a three-level objectives tree, including: 1) High-level objectives, HLOs (Cost, Performance and Acceptability); 2) Assessment Areas for each high-level objective, as follows: Economics for Cost; Waste management, Safety and Proliferation resistance for Performance; Infrastructure, Public acceptance and Maturity of technology for Acceptability; 3) Key Indicators in each assessment area. In the present study Environment assessment area has been replaced by other two areas: Infrastructure and Public acceptance, considered significant for Bulgaria’s country specifics in the assessment of the selected nuclear energy systems. Environment is included in other assessment areas. The results are shown in Figure 1.

The area of Economics is considered of high importance for Bulgaria. The Economic Basic Principle in INPRO Methodology states: “Energy and related products and services from Innovative NES shall be affordable and available”, [2].

High-level objectives titles	Areas titles	Indicators titles	Indicators abbr.	NES-1	NES-2	NES-3
Cost	Economics	Levelized energy product or service cost	E.1	3	3	3
Cost	Economics	Startup cost (itintial investment for construction of plant)	E.2	3	6	3
Performance	Waste management	Specific (long term) RAW inventory	WM.1	7	3	3
Performance	Safety	Design concept specific safety inherent and passive features and systems	S.1	5	2	2
Performance	Safety	Core damage and large early release frequencies	S.2	3	3	3
Performance	Safety	The potential to prevent release	S.3	5	3	3
Performance	Proliferation resistance	Attractiveness of nuclear material	PR.1	7	3	3
Acceptability	Infrastructure	Government policy	I.1	1	7	7
Acceptability	Infrastructure	Availability of human resources	I.2	3	8	8
Acceptability	Public acceptance	Survey of public acceptance	PA.1	1	8	3
Acceptability	Maturity of technology	Design stage	M.1	1	8	1
Acceptability	Maturity of technology	Degree of standardization and licensing adaptability	M.2	1	9	1

Figure 1. ‘Performance Table’ worksheet.

The first KI in the Area of Economics (E.1) – Levelized unit energy cost (LUEC) includes the cost of different factors, such as startup (initial investment for constriction of plant), operation, nuclear fuel, maintenance, administration, decommissioning, radioactive waste RAW disposal.

The second KI (E.2) – Startup cost is included in E.1, but the importance and specific conditions for providing initial funds for such big projects require additional consideration as they are a matter of high importance for Bulgaria.

As mentioned above, for the purpose of the assessment, two different areas (Infrastructure and Public acceptance) have been included additionally. The national energy policy issued by the government is a key point to establish and maintain the NESs. As the government policy on NESs exists, is reachable and understandable by the general public, a full score in this section can be obtained. What is also important for technology user countries is discussing and analyzing the availability of human resources – their sustainable and high level training and qualification in order to be able to face the challenges which pose the new innovative nuclear technology. The human resources need to be sufficient and qualified to be utilized when introducing a new energy system project.

The area of Waste management is also important to be included in the assessment of NESs. Based on the Waste management Basic Principle in INPRO Methodology [2] “Generation of radioactive waste in an INS shall be kept to the minimum practicable” the KI (WM.1) – Specific (long term) RAW inventory, was suggested. This KI is of great importance for Bulgaria due to the policy of the Republic of Bulgaria in the area of spent fuel SF and RAW management which is based on the moral principle of avoidance of undue burden on future generations. Bulgaria has no capability to conduct a full NFC. Concerning the SF, the National strategy does not exclude a prior discussion of any possible options. Keeping in mind the importance of SF and RAW management in taking decision of using nuclear energy there is a need to be considered this KI.

The area of Proliferation resistance is based on the Proliferation Resistance Basic Principle in INPRO Methodology [2]: “Proliferation resistance intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that INSs will continue to be an unattractive means to acquire fissile material for a nuclear weapons program”. It was proposed the KI: (PR.1) – Attractiveness of nuclear material (quality) and difficulty of diversion; is a concern for both technology user and technology holder countries. As long as most of the technology user countries do not have (for example) enrichment or separation technologies, the assessment is simplified.

After the Fukushima accident, the area of Safety became very sensitive, but strict regulations allow for a technology user country to accept or to refuse specific technology.

This assessment area is based on the Safety Basic Principle 1 (Defence in Depth) in INPRO Methodology [2] “Installations of an INES shall incorporate enhanced defence-in-depth as a part of their fundamental safety approach and ensure that the levels of protection in defence-in-depth shall be more independent from each other than in existing installations”; Safety User Requirement 1.5 [2]: Release into the environment: A major release of radioactivity from an installation of an INS should be prevented for all practical purposes and Safety Basic Principle 2 (inherent safety) [2]: “Installations of an INS shall excel in safety and reliability by incorporating into their designs, when appropriate, increased emphasis on inherently safe characteristics and passive systems as a part of their fundamental safety approach”. The proposed KIs used in assessment are:

- S.1 Design concept specific safety inherent and passive features and systems;
- S.2 Core damage and large early release frequencies,
- S.3 The potential to prevent release.

Safety requirements for design of NPP and plant systems should include at least the following: ?For all operational states and accident conditions, the NPP should be capable to perform the following fundamental safety functions:

1. Control of the reactivity;
2. Removal of the heat from the reactor core;
3. Confinement of radioactive substances should be within the established boundaries?.

For design basis and safety assessment should consider at least that for severe accidents the limit of cesium-137 in the atmosphere should be less 30 TBq that does not impose long term restrictions for soil and water use in the monitored area. In a long-term perspective starting three months after the accident, combined release of other radionuclides different from cesium isotopes should not provoke a greater hazard than the one identified for cesium release within the indicated limit. Here the environmental concerns were included.

3 Brief Description of KIND – ET Methodology

KIND-ET is an excel template based on multi-attribute value theory (MAVT) developed within the INPRO KIND project for comparative evaluation of the status, prospects, benefits and risks associated with the development of innovative nuclear technologies. KIND methodology could be applied for innovative nuclear systems, evolutionary nuclear systems and non-nuclear energy sources. Architecture and functional capabilities of the KIND-ET template allow it to be easily modified by users according to their preferences. Using KIND-ET, different nuclear technologies and their advantages and disadvantages could be compared under different conditions and also evaluated for their overall ranks taking into account experts' and decision makers' judgments and preferences.

Multi-criteria decision analysis (MCDA) represents a group of approaches on decision evaluation methods to support decision makers to perform numerous and conflicting assessments to find the best alternative. MCDA is a process with the following phases: problem formulation, specification of alternatives, criteria identification, criteria assessment, selection of the MCDA method, uncertainty and sensitivity analysis, final conclusions and recommendations. A wide range of problems having multi-criteria character in the area of NESs assessments, makes the implementation of the MCDA methods recommended as appropriate and useful for evaluation of different options with a set of performance indicators taking into account experts' and the decision-maker's preferences [3].

Multi-attribute value theory (MAVT) is a MCDA method used for quantitative comparative evaluation, which combines different measures of costs, risks and benefits. The foundation of MAVT is the use of multi-attribute and single-attribute value functions. Multi-attribute value function represents a combination of indicators weighted according to the expert and decision-maker preferences into a total score (values of multi-attribute value function).

A single-attribute value function is created for each indicator. It should be linear or exponential, of increasing or decreasing type, etc. These value functions transform the diverse key 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. 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 [3].

To perform a multi-criteria comparison using the MAVT method according to the user instructions provided in the frame of the project [4] it is required to select a set of performance indicators; identify a structure of the objective tree; prepare a performance table; determine single-attribute value functions for each indicator; evaluate weighting factors; perform sensitivity analysis; interpret ranking results and formulate recommendations.

4 Multi-Criteria Comparative Evaluation Using the KIND-ET

A comparison of 2 hypothetical Nuclear Energy Systems (NES) has been made:

- NES-1 – GEN III/III+ evolutionary design (LWR) and
- NES-2 – GEN IV – so called innovative design: LFR technology /SFR technology

Two cases for GEN IV NES have been considered: NES-2 (at present time) and NES-3 (in 10–15 years); for example ALFRED demonstrator is expected to be commissioned by 2030.

The comparison was done by means of INPRO KIND-ET (Evaluation Template) using country specific conditions for Bulgaria (small nuclear technology user country).

Benefits and risks of possible new nuclear energy systems development in Bulgaria were addressed, using suggested judgment aggregation methodology based on MAVT (Multi-Attribute Value Function) method.

The comparison was performed taking into account the following assumptions: the 12 KIs were involved in the assessment; each indicator was evaluated in a 10-point scoring scale; all KIs should be minimized. The reason for using a broader scoring scale in comparing two alternatives is that it provides a more subtle differentiation of alternatives, reducing the probability of obtaining similar values of indicators.

4.1 Performance table preparation

The 'Performance Table' worksheet (Figure 1) requires the input of titles of high-level objectives, areas, indicators and indicator values for NESs considered. The values of all KIs for the two considered NESs are presented. In accordance with the assumptions made regarding the goals,

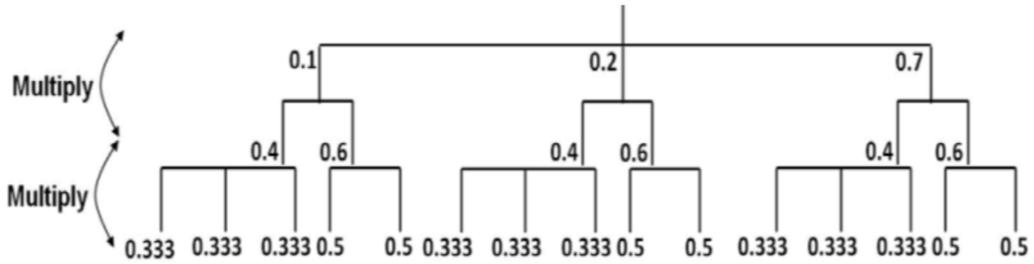

Figure 2. The structure of the objective tree.

which should be achieved by each indicator, the value 1 is the best possible value of an indicator, while the value 10 is the worst one. Figure 1 presents a screenshot of the 'Performance table' worksheet. The values of all KIs are considered by 2 experts in our Lab and are given as average values of the expert's perception.

4.2 Identifying a structure of the objective tree – 'Weighting Factors'

Selecting a structure of the objectives tree should be dictated by the simplification of expertise organization to determine the weighting factors and option based on arranging the indicators in the three-level objectives tree seems the most appropriate manner for global assessment. This is due to the simpler and more apparent procedure for weighting factors evaluation which may be organized by means of the subject matter experts' survey in different areas and, secondly, simplification of the procedure for the ranking results interpretation, which becomes more evident.

The 'Weighting Factors' worksheet evaluates the weighting factors for each indicator in accordance with the hierarchical weighting method. Figure 2 represents the structure of the objective tree, assumed by default. At each branch of the objective tree the sum of corresponding weighting factors must be equal to 1.

Figure 3 presents a screenshot of the 'Weighting Factors' worksheet. The weighting factor values reflect expert's evaluation for the importance (weight) of each high level objective /cost, performance, acceptability/ according to local conditions. At each branch of the objective tree the sum of corresponding weighting factors must be equal to 1.

Figure 4 presents a screenshot of the 'Single-attribute Value Functions' worksheet, where the values of single-attribute value functions are calculated. According to the instructions, we have chosen the goal for each indicator - 'min' option and the linear /'lin'/ form of single-attribute value function, by selecting them from 'Goal' and 'Form' columns.

5 Results

5.1 Ranking results

Figure 5 presents a screenshot of the 'Ranking results' worksheet. The ranking results show that NES-1 (Evolutionary design – Gen III+, LWR) is the most preferred alternative for Bulgaria, at present time, due to the limited resources and the importance of startup cost. Other

High-level objectives titles	High-level objectives weights	Areas titles	Areas weights	Indicators abbr.	Indicators weights	Final weights
Cost	0,500	Economics	1	E.1	0,5	0,250
Cost	0,500	Economics	1	E.2	0,5	0,250
Performance	0,200	Waste management	0,333	WM.1	1	0,067
Performance	0,200	Safety	0,333	S.1	0,333	0,022
Performance	0,200	Safety	0,333	S.2	0,333	0,022
Performance	0,200	Safety	0,333	S.3	0,333	0,022
Performance	0,200	Proliferation resistance	0,333	PR.1	1	0,067
Acceptability	0,300	Infrastructure	0,333	I.1	0,5	0,050
Acceptability	0,300	Infrastructure	0,333	I.2	0,5	0,050
Acceptability	0,300	Public acceptance	0,333	PA.1	1	0,100
Acceptability	0,300	Maturity of technology	0,333	M.1	0,5	0,050
Acceptability	0,300	Maturity of technology	0,333	M.2	0,5	0,050

Figure 3. 'Weighting Factors' worksheet.

High-level objectives titles	Areas titles	Indicators abbr.	Goal	Form	Exponent power	NES-1	NES-2	NES-3
Cost	Economics	E.1	min	exp	1	0,000	0,000	0,000
Cost	Economics	E.2	min	lin	1	1,000	0,000	1,000
Performance	Waste management	WM.1	min	lin	1	0,000	1,000	1,000
Performance	Safety	S.1	min	lin	1	0,000	1,000	1,000
Performance	Safety	S.2	min	lin	1	0,000	0,000	0,000
Performance	Safety	S.3	min	lin	1	0,000	1,000	1,000
Performance	Proliferation resistance	PR.1	min	lin	1	0,000	1,000	1,000
Acceptability	Infrastructure	I.1	min	lin	1	1,000	0,000	0,000
Acceptability	Infrastructure	I.2	min	lin	1	1,000	0,000	0,000
Acceptability	Public acceptance	PA.1	min	lin	1	1,000	0,000	0,714
Acceptability	Maturity of technology	M.1	min	lin	1	1,000	0,000	1,000
Acceptability	Maturity of technology	M.2	min	lin	1	1,000	0,000	1,000

Figure 4. 'Single-attribute Value Functions' worksheet.

Levels	NES-1	NES-2	NES-3
Multi-attribute value function	0,550	0,178	0,599
High-level objectives scores			
Cost	0,250	0,000	0,250
Performance	0,000	0,178	0,178
Acceptability	0,300	0,000	0,171
Areas scores			
Economics	0,250	0,000	0,250
Waste management	0,000	0,067	0,067
Safety	0,000	0,044	0,044
Proliferation resistance	0,000	0,067	0,067
Infrastructure	0,100	0,000	0,000
Public acceptance	0,100	0,000	0,071
Maturity of technology	0,100	0,000	0,100

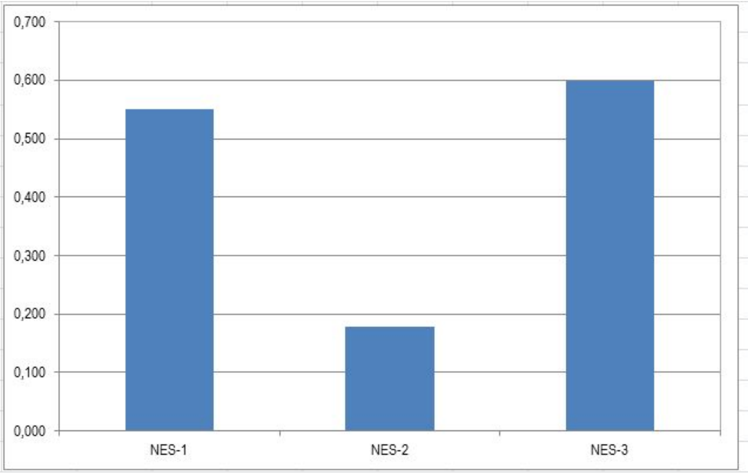

Figure 5. 'Ranking results' worksheet.

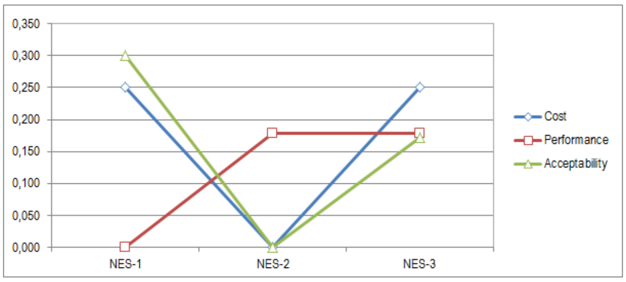

Figure 6.1. Multi-attribute value function decomposition into components of high-level objectives.

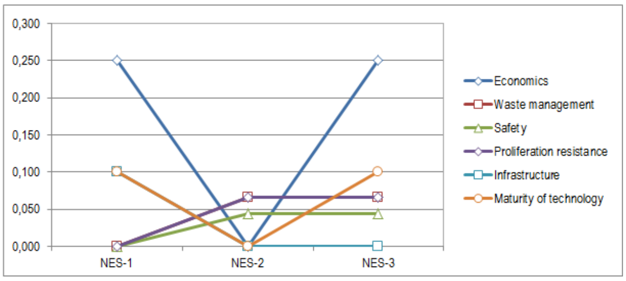

Figure 6.2. Multi-attribute value function decomposition into components of assessment areas.

important areas which reflect the decision for the new NES are Infrastructure, Public acceptance and Maturity of technology.

The values of multi-attribute value functions are 0.550, 0.178 and 0.599, respectively.

When we evaluate the case of GEN IV in the future (in 10–15 years) – NES-3, the results show that GEN IV technology has the highest overall score, due to the highest score for Performance high-level objective, in areas of Waste management, Safety and Proliferation resistance, respectively. This could be seen also from Figure 6.1 and Figure 6.2, which present multi-attribute value function decomposition into components corresponding to the considered high-level objectives and assessment areas.

High-level objectives titles	High-level objectives weights	Areas titles	Areas weights	Indicators abbr.	Indicators weights	Final weights
Cost	0,333	*Economics*	1	*E.1*	0,5	0,167
Cost	0,333	*Economics*	1	*E.2*	0,5	0,167
Performance	0,333	*Waste management*	0,333	*WM.1*	1	0,111
Performance	0,333	*Safety*	0,333	*S.1*	0,333	0,037
Performance	0,333	*Safety*	0,333	*S.2*	0,333	0,037
Performance	0,333	*Safety*	0,333	*S.3*	0,333	0,037
Performance	0,333	*Proliferation resistance*	0,333	*PR.1*	1	0,111
Acceptability	0,333	*Infrastructure*	0,333	*I.1*	0,5	0,056
Acceptability	0,333	*Infrastructure*	0,333	*I.2*	0,5	0,056
Acceptability	0,333	*Public acceptance*	0,333	*PA.1*	1	0,111
Acceptability	0,333	*Maturity of technology*	0,333	*M.1*	0,5	0,056
Acceptability	0,333	*Maturity of technology*	0,333	*M.2*	0,5	0,056

	NES-1	NES-2	NES-3
base case	0,550	0,178	0,599
modified	0,500	0,352	0,653

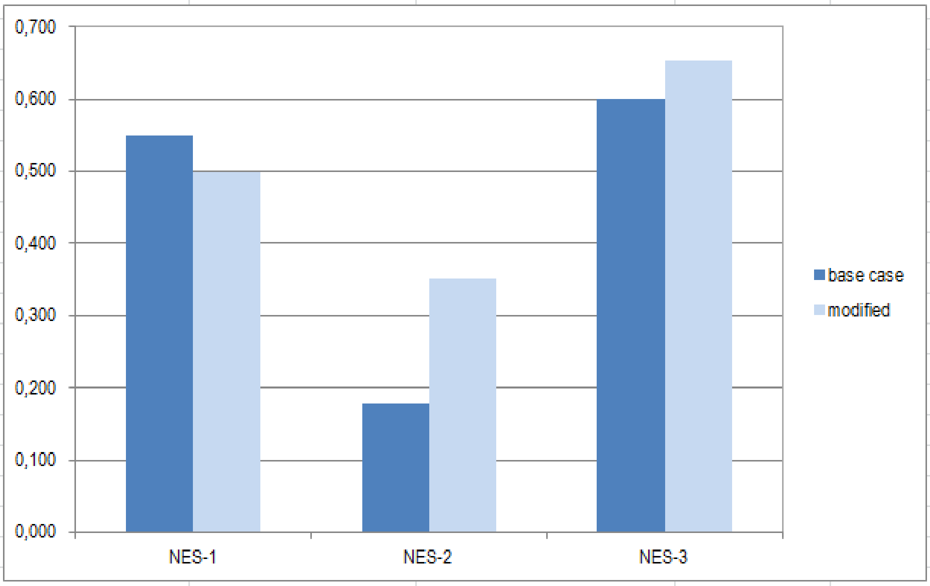

Figure 7. ‘Weights sensitivity” worksheet’: base case and modified option.

5.2 Weights sensitivity

A weight sensitivity analysis is a tool for understanding an influence of the assigned weights on the ranking alternatives. Figure 7 shows the alternative ranking results for different values of weighting factors: base case and modified weights options. We have changed the weighting factors on the level of high-level objectives by assuming that importance of all high-level objectives appears identical/equally important.

The modified case shows that by this change, NES-1 is still the preferred option at the time, but the difference between the two options becomes smaller – the values of multi-attribute value functions are 0.500 and 0.352, respectively, and NES-3 case becomes clearly the best option with the value of multi-attribute value function – 0.653.

5.3 Discussion of the results

For a small nuclear technology user country with limited resources such as Bulgaria, the cost and especially startup cost /initial investment for construction of plant/ appears the most important area and limitation at the same time when considering new nuclear energy system.

Other important areas which reflect the decision for new NES are also Infrastructure, Public acceptance and Maturity of technology. Results show that the global sustainable development of nuclear energy is a key factor for a small technology user country such as Bulgaria in developing a sustainable nuclear energy.

For a small nuclear technology user country, the international collaboration is directly connected with resolving the tasks and challenges in supporting of sustainability of their own Nuclear Energy Systems.

It should be noted the difference in achieving sustainable NES for countries who already use nuclear energy and new comers. For countries with significant experience in operation of specific Nuclear Power Plant type (such as LWR) it will be difficult to replace with an entirely new (GEN IV) or even different (as HWR) technology.

6 Conclusions

The Multi-criteria decision analysis (MCDA) methods application proposes reasonable and user friendly approach to judge and comparatively evaluate innovative nuclear systems, as well as evolutionary nuclear systems and non-nuclear energy sources.

The weighting factors evaluation is an issue that requires special attention. It should be taken into account the different importance of the criteria for comparative evaluation in order to support the optimization in the decision making. They should be selected in respect of possible changes during the long time of operation due to various reasons such as price fluctuations of resources or the development of a newer technology.

Performed assessment by using MAVT (multi attribute value theory) method demonstrates its flexibility. The method allows implementation of different approaches in comparing and differentiating alternatives as well as interpreting the ranking results. By using KIND-AT template, the advantages and disadvantages of NESs in different conditions can be demonstrated. The flexibility of MAVT method requires qualified experts in preparation correct input to avoid inappropriate results as well as for interpretation of the calculated scores for different NESs.

In general, it could be stated that the developed methodology based on MAVT method is an advanced tool that allows to perform successfully comparative evaluation of the innovative nuclear technologies, NESs and transition scenarios to future sustainable NES.

Comparative analysis performed should be considered only as an exercise for KIND-ET application to comparison of different NES.

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