Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2023

A study of Gen III+ evolutionary reactor technologies: Bangladesh perspective (Based on IAEA INPRO KIND-ET methodology)

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Keywords : IAEA INPRO, KIND-ET, Gen III+

1. Introduction

Energy is considered as one of the main drivers of socioeconomic development for any nation. Access to affordable, reliable, sustainable, and modern energy for all is highlighted by United Nations in the Sustainable Development Goals (SDG) as one of the major aims to end poverty, protect the environment, and promote prosperity. As a developing nation, Bangladesh aspires to become a developed nation by 2041, but is experiencing an energy deficit issue. Currently, the majority of fossil fuel reserves, including local coal and natural gas, are being used in the country's energy sector. Due to extensive use of natural gas and technical difficulties in exploration of coal, Bangladesh is facing challenges in keeping pace with the increasing demand of electricity due to rapid industrialization and improvement of standard of living. Although renewable energy and oil imports were taken into consideration, their long-term application was not feasible due to their high costs and constrained generation potential.

In order to deal with this issue and maintain energy security, the government of Bangladesh is constructing a nuclear power plant (NPP) with two units of the VVER-1200 reactor (totaling 2400MWe). By 2025, these units are anticipated to be operational. In order to continue economic growth and in accordance with the recommendations of the country's Power System Master Plan 2016 (PSMP 2016), the government also plans to construct another nuclear power plant in the southern region of the country. [1]. Hence, a thorough analysis is needed to determine the suitable and feasible reactor technology for the southern region. The International Atomic Energy Agency (IAEA) has developed numerous tools to assess a suitable reactor technology for a country-specific context [2, 3]. Different countries have studied reactor technology assessment using such tools based on their country specific scenario [4,5].

In this paper, a study conducts an assessment of four advanced large pressurized water reactor (PWR) technologies, known as evolutionary (Gen III+) reactor technology, using the IAEA KIND-ET methodology. This paper also make recommendation for specific reactor technology that could be built in the southern region of Bangladesh.

2. Methodology

The development of this study has taken into account the analysis techniques and factors listed below.

***2.1** Consideration of evolutionary reactor technologies:*

The following evolutionary generation III+ PWR reactors are taken into consideration in our study since Bangladesh is already constructing two VVER-1200 reactor units, which fall within the PWR category, and because PWR reactor construction is increasing globally due to their advanced safety features:

- AP1000 (Designer: Westinghouse)
- APR1400 (Designer: KEPCO/KHNP)
- EPR (Designer: AREVA)
- VVER1200 (Designer: Gidropress)

2.2: Description of KIND-ET methodology

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, which is based on the Multi attribute value theory (MAVT) method under the collaborative Project on Key Indicators (KI) for Innovative Nuclear Energy Systems (KIND). A group of key indicators (KI) are taken into account for comparison analysis, according to the KIND project. Scores or natural units are used to analyze each indicator. All parameters have been grouped into relevant categories (economics, waste management, resistance to proliferation, environment, safety, technological maturity, etc.). At the highest level, it is recommended to assume two or three objectives. A multi-criteria comparative evaluation should be constructed and take the objectives tree structure into account. The organization's experience in evaluating weighting criteria should be simplified to guide the selection of the objectives tree structure [4,5]. The KIND goals tree template is shown in Figure 1 as a three-level hierarchical structure, with the orange figures representing performance indicators (key and secondary), the green figures representing evaluation regions, and the blue figures representing high-level aggregated objectives [5].

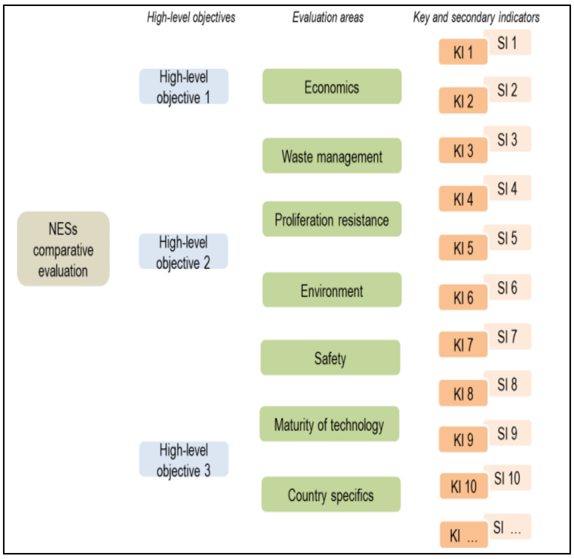

Figure 1: The KIND objectives tree

Calculating scores for the assessment areas or high-level objectives in line with the objectives tree's defined structure is important in order to interpret the ranking results.

2.3: Consideration of key indicators set of evolutionary reactor technologies:

In order to evaluate the four reactor designs in this study, the following high level objectives, evaluation areas, and key indicators are taken into account based on the country-specific scenarios [6,7,8,9].

High level objectives	**Evaluation areas**	**Key indicators**
Cost	Economics	Capacity factor
		Construction time
		Fuel cycle length
		Design life
Performance	Waste Management	Specific radwaste inventory
	Proliferation resistance	Link to physical protection
	Environment	Large early release frequency
	Safety	Core damage frequency
		Seismic design, SSE
		retention of molten core debris
		Safety injection systems ECCS
		Residual heat removal systems
		Operator Action Time
		stable and reliable plant operation
		Occupational radiation exposure
Acceptability	Maturity of technology	Share of proven technology

3. Multi-Criteria comparative evaluation using the KIND-ET

A comparative study among the four reactor technologies is conducted considering Bangladesh-specific parameters in the INPRO KIND-ET technique. The following presumptions are considered during the comparison: The assessment included the 17 KIs; each indicator scored on a scale of 05 points; all KIs should be minimized.

3.1 Performance table preparation

The titles of high-level objectives, areas, indicators, and indicator values are entered into the performance table worksheet (Figure 2) in line with the assumptions made regarding the objectives that should be attained by each indicator. The best possible value for an indicator is 1, while the worst possible value is 5. A screenshot of the Performance table worksheet is shown in Figure 2.

3.2: Structure of the objective tree and Weighting Factors

A hierarchical weighting technique to assess the weighting factors is developed using the multi-level structure of the KIND objectives tree. The key benefit of this strategy is that subject-matter experts in a certain field can evaluate related indicator weights in that field.

In order to calculate the final weighting factors for single-attribute value functions and the three-level KIND objective tree, three kinds of weighting factors (actual numbers from 0 to 1) are defined. The factors are weights for the high-level objectives (such as cost, performance, and acceptance), weights for each of the evaluation areas (economics, waste management, proliferation resistance, environment, safety, maturity of technology); and, finally, weights for the lowest level, i.e. the level of key indicators. The final weighting factors for each indicator are calculated by multiplication of the high-level objectives, evaluation areas, key indicators weights. A typical example of weighting factors calculations is shown in figure 3 [5]. Each branch of the objective tree, the sum of corresponding weighting factors must be equal to 1.

High-level objectives titles	Areas titles	Indicators titles	Indicators abbr.	MIN score	MAX score	AP1000	APR1400	EPR	VVER1200
Cost	Economics	Capacity factor	E2	1	5	1	2	2	1
Cost	Economics	Construction time	E3	1	5	1	2	2	4
Cost	Economics	Fuel cycle length	E4	1	5	2	2	1	3
Cost	Economics	Design life	E5	1	5	1	1	1	1
Performance	Waste management	Specific radwaste inventory	WM1	1	5	1	1	2	1
Performance	Proliferation resistance	Link to physical protection	PR1	1	5	1	1	1	1
Performance	Environment	Large early release frequency	ENV1	1	5	1	3	2	2
Performance	Safety	Core damage frequency	SP1	1	5	1	3	2	2
Performance	Safety	Seismic design, SSE	SP2	1	5	1	1	2	1
Performance	Safety	retention of molten core debris	SP3	1	5	1	1	2	2
Performance	Safety	Safety injection systems	SP4	1	5	1	2	2	2
Performance	Safety	Residual heat removal systems	SP5	1	5	1	3	3	1
Performance	Safety	Operator Action Time	Sp6	1	5	1	1	1	1
Performance	Safety	stable and reliable plant operation	Sp7	1	5	2	1	2	2
Performance	Safety	Occupational radiation exposure	Sp8	1	5	2	3	1	1
Acceptability	Maturity of technology	Share of proven technology	M1	1	5	1	1	3	2

Figure 2: Performance table preparation worksheet

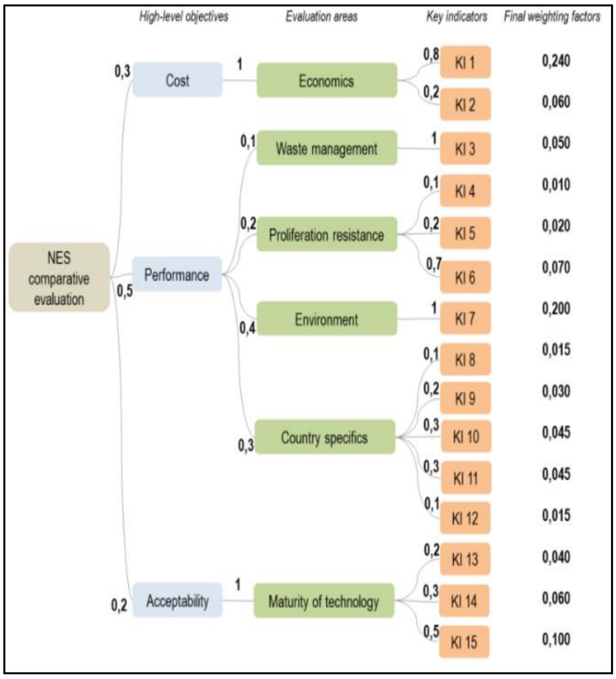

Figure 3: Example of the weighting procedure implementation [5].

Figure 4 illustrates the calculation and examination of the weighting components. The values of the weighting factor provide an assessment of the weight of each high-level objective, which are cost, performance, and acceptability from Bangladesh's point of view. The total of the associated weighting factors for each branch of the objective tree are equal to 1.
A snapshot of the Single-attribute Value Functions worksheet, which is used to determine the values of single attribute value functions, is shown in Figure 5. Considering to the instructions specified in KIND-ET methodology, the goal for each indicator is ‘min’ option and the linear /’lin’/ form of single-attribute value function from ‘Goal’ and ‘Form’ columns are selected.

4. Result

4.1 Ranking Result:

The ranking result spreadsheet is displayed in Figure 6(a), 6(b), 6(c), 6(d). The ranking result spreadsheet makes it clear that, among the four reactor technologies; the AP1000 reactor is the most favoured option, followed by the APR 1400 reactor technology. The least recommended alternative, with a score of 0.830, is the EPR reactor. The AP1000 achieves the greatest performance and cost score, in terms of high-level objectives. In terms of the technology maturity, APR1400 and AP1000 receives the highest acceptance score of 0.222. The analysis's key deciding factors are safety, economics, and technological maturity as the other sections show nearly identical results.

4.2 Weight sensitivity:

Realizing the impact of the assigned weights on the ranking outcomes requires the use of a weight sensitivity analysis, which is a crucial tool. Figure 7 displayed the alternate ranking outcomes for various weighting factor values, including the base case and modified weights alternatives. By assuming that all high-level objectives appear to be equally important, we have adjusted the weighting factors for the high-level objectives. Figure 7's weight sensitivity results reveal that the AP1000 receives the highest marks when compared to the other alternatives. The sensitivity results show that the APR1400 reactor has the second-highest score.

High-level objectives titles	High-level objectives weights	Areas titles	Areas weights	Indicators abbr.	Indicators weights	Final weights
Cost	0.333	*Economics*	1	*E2*	0.3	0.100
Cost	0.333	*Economics*	1	*E3*	0.4	0.133
Cost	0.333	*Economics*	1	*E4*	0.2	0.067
Cost	0.333	*Economics*	1	*E5*	0.1	0.033
Performance	0.555	*Waste management*	0.1	*WM1*	1.0	0.056
Performance	0.555	*Proliferation resistance*	0.2	*PR1*	1	0.111
Performance	0.555	*Environment*	0.2	*ENV1*	1	0.111
Performance	0.555	*Safety*	0.5	*SP1*	0.2	0.056
Performance	0.555	*Safety*	0.5	*SP2*	0.1	0.028
Performance	0.555	*Safety*	0.5	*SP3*	0.1	0.028
Performance	0.555	*Safety*	0.5	*SP4*	0.1	0.028
Performance	0.555	*Safety*	0.5	*SP5*	0.200	0.056
Performance	0.555	*Safety*	0.5	*Sp6*	0.100	0.028
Performance	0.555	*Safety*	0.5	*Sp7*	0.100	0.028
Performance	0.555	*Safety*	0.5	*Sp8*	0.100	0.028
Acceptability	0.222	*Maturity of technology*	1	*M1*	1.000	0.222

Figure 4: Weighting factors worksheet

High-level objectives titles	Areas titles	Indicators abbr.	Goal	Form	Exponent power	VF domain	MIN VF domain	MAX VF domain	AP1000	APR1400	EPR	VVER1200
Cost	*Economics*	*E2*	min	lin	1	global	1	5	1.000	0.750	0.750	1.000
Cost	*Economics*	*E3*	min	lin	1	global	1	5	1.000	0.750	0.750	0.250
Cost	*Economics*	*E4*	min	lin	1	global	1	5	0.750	0.750	1.000	0.500
Cost	*Economics*	*E5*	min	lin	1	global	1	5	1.000	1.000	1.000	1.000
Perfomance	*Waste management*	*WM1*	min	lin	1	global	1	5	1.000	1.000	0.750	1.000
Perfomance	*Proliferation resistance*	*PR1*	min	lin	1	global	1	5	1.000	1.000	1.000	1.000
Perfomance	*Environment*	*ENV1*	min	lin	1	global	1	5	1.000	0.500	0.750	0.750
Perfomance	*Safety*	*SP1*	min	lin	1	global	1	5	1.000	0.500	0.750	0.750
Perfomance	*Safety*	*SP2*	min	lin	1	global	1	5	1.000	1.000	0.750	1.000
Perfomance	*Safety*	*SP3*	min	lin	1	global	1	5	1.000	1.000	0.750	0.750
Perfomance	*Safety*	*SP4*	min	lin	1	global	1	5	1.000	0.750	0.750	0.750
Perfomance	*Safety*	*SP5*	min	lin	1	global	1	5	1.000	0.500	0.500	1.000
Perfomance	*Safety*	*Sp6*	min	lin	1	global	1	5	1.000	1.000	1.000	1.000
Perfomance	*Safety*	*Sp7*	min	lin	1	global	1	5	0.750	1.000	0.750	0.750
Perfomance	*Safety*	*Sp8*	min	lin	1	global	1	5	0.750	0.500	1.000	1.000
Acceptability	*Maturity of technology*	*M1*	min	lin	1	global	1	5	1.000	1.000	0.500	0.750

Figure 5:Single-attribute Value Functions worksheet

Levels	AP1000	APR1400	EPR	VVER1200
Multi-attribute value function	1.079	0.903	0.830	0.859
High-level objectives scores				
Cost	0.316	0.258	0.275	0.200
Performance	0.541	0.423	0.444	0.493
Acceptability	0.222	0.222	0.111	0.167
Areas scores				
Economics	0.316	0.258	0.275	0.200
Waste management	0.056	0.056	0.042	0.056
Proliferation resistance	0.111	0.111	0.111	0.111
Environment	0.111	0.056	0.083	0.083
Safety	0.264	0.201	0.208	0.243
Maturity of technology	0.222	0.222	0.111	0.167

Figure 6a: Ranking Result worksheet

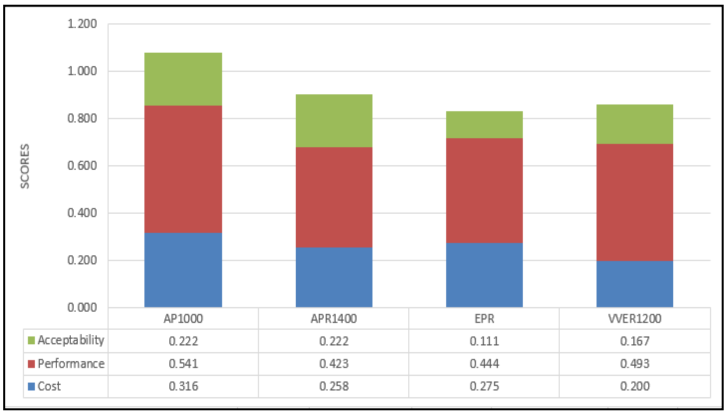

Figure 6b: Ranking Result worksheet based on high level objectives

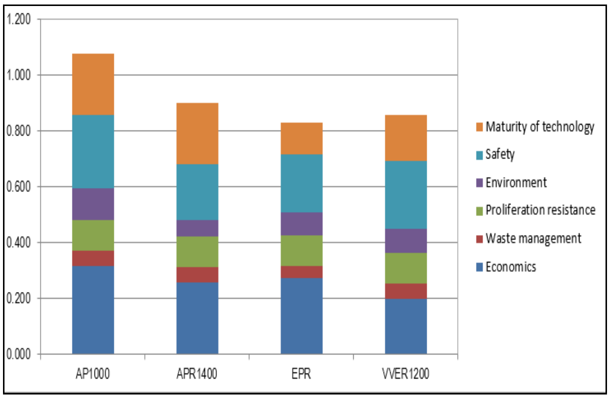

Figure 6c: Ranking Result worksheet based on evaluation areas.

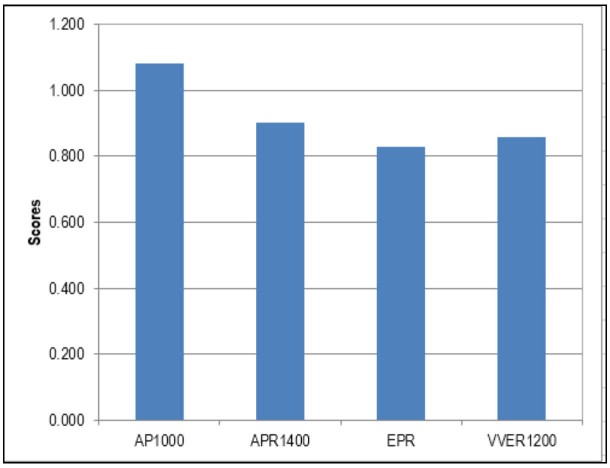

Figure 6d: Ranking Result worksheet based on final score.

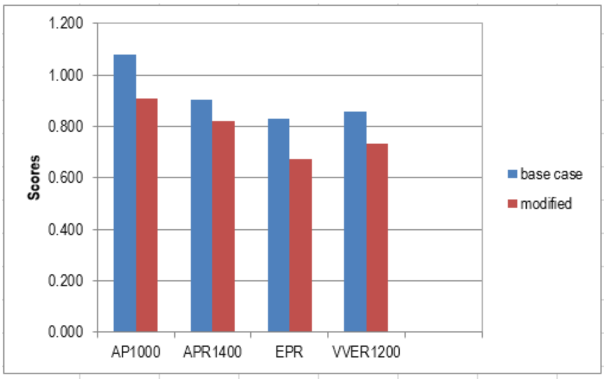

Figure 7b: Weight sensitivity analysis ranking result

5. Conclusion

The application of the Multi-Criteria Decision Analysis (MCDA) methodology gives a logical and strategy for comparing and judging various evolutionary nuclear reactor design. The benefits and drawbacks of various reactor technologies under various circumstances can be shown by using the KIND-ET template. In order to prepare accurate and logical input and interpret the generated scores for various evolutionary reactor technologies, the flexibility of the multi attribute value theory (MAVT) method demands qualified and knowledgeable specialists.

According to the analysis of four Gen III+ reactor designs in the context of Bangladesh, the base case analysis would favor the AP1000 reactor technology, followed by the APR1400 design, while the weight sensitivity analysis favor the APR1400 design.

In general, it might be said that the technique built on the MAVT approach is a sophisticated instrument that enables successfully carrying out comparative evaluation of the cutting-edge nuclear reactor technologies.

High-level objectives titles	High-level objectives weights	Areas titles	Areas weights	Indicators abbr.	Indicators weights	Final weights
Cost	0.333	Economics	1	E2	0.2	0.067
Cost	0.333	Economics	1	E3	0.2	0.067
Cost	0.333	Economics	1	E4	0.2	0.067
Cost	0.333	Economics	1	E5	0.2	0.067
Performance	0.333	Waste management	0.25	WM1	1.0	0.083
Performance	0.333	Proliferation resistance	0.25	PR1	1	0.083
Performance	0.333	Environment	0.25	ENV1	1	0.083
Performance	0.333	Safety	0.25	SP1	0.125	0.010
Performance	0.333	Safety	0.25	SP2	0.125	0.010
Performance	0.333	Safety	0.25	SP3	0.125	0.010
Performance	0.333	Safety	0.25	SP4	0.125	0.010
Performance	0.333	Safety	0.25	SP5	0.125	0.010
Performance	0.333	Safety	0.25	Sp6	0.125	0.010
Performance	0.333	Safety	0.25	Sp7	0.125	0.010
Performance	0.333	Safety	0.25	Sp8	0.125	0.010
Acceptability	0.333	Maturity of technology	1	M1	1.000	0.333

	AP1000	APR1400	EPR	VVER1200
base case	1.079	0.903	0.830	0.859
modified	0.911	0.823	0.673	0.735

Figure 7a: Weight sensitivity analysis result

REFERENCES

[1] "Key indicators for innovative nuclear energy systems as a guidance and tool to assess sustainability of innovations" draft report for the INPRO collaborative project on Key Indicators for Innovative Nuclear Energy Systems (KIND), 2017

[2] KIND-ET verification report. Report for the INPRO collaborative project on Key Indicators for Innovative Nuclear Energy Systems (KIND), 2017

[3] "Comparative assessment of hypothetical innovative nuclear energy systems based on the KIND methodology" report for the INPRO collaborative project on Key Indicators for Innovative Nuclear Energy Systems (KIND), 2014

[4] "Comparative evaluation of GAINS deployment scenarios based on the KIND methodology" report for the INPRO collaborative project on Key Indicators for Innovative Nuclear Energy Systems (KIND), 2014

[5] "USER INSTRUCTIONS FOR KIND-ET (KIND-EVALUATION TOOL)" A multi-attribute value theory based Excel-template for the INPRO project on Key Indicators for Innovative Nuclear Energy Systems (KIND), INTERNATIONAL ATOMIC ENERGY AGENCY, 2017

[6] Status report 81 - Advanced Passive PWR (AP 1000), International Atomic Energy Agency, 2011

[7] Status report 83 - Advanced Power Reactor 1400 MWe (APR1400), International Atomic Energy Agency, 2011

[8] Status report 78 - The Evolutionary Power Reactor (EPR), International Atomic Energy Agency, 2011

[9] Status report 108 - VVER-1200 (V-491) (VVER-1200 (V-491)), International Atomic Energy Agency, 2011