Nuclear Fuel Cycle Analysis by Integrated AHP and TOPSIS Method Using an Equilibrium Model

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1. Introduction

The Republic of Korea, since 2013, has been in the midst of decision making process regarding the urgent issues of nuclear spent fuel and lifetime extension of old NPPs. Determining whether to break away from domestic conflict surrounding nuclear power and step forward for public consensus can be identified by transparent policy making considering public acceptability. In this context, deriving the best suitable nuclear fuel cycle for Korea is the key task in current situation. Assessing nuclear fuel cycle is a multicriteria decision making problem dealing with multiple interconnected issues on efficiently using natural uranium resources, securing an environment-friendliness to deal with waste, obtaining the public acceptance, ensuring peaceful uses of nuclear energy, maintaining economic competitiveness compared to other electricity sources, and assessing technical feasibility of advanced nuclear energy systems.

This paper performed the integrated AHP and TOPSIS analysis on three nuclear fuel cycle options against 5 different criteria including U utilization, waste management, material attractiveness, economics, and technical feasibility [1]. The fuel cycle options analyzed in this paper are three different fuel cycle options as follows: PWR-Once through cycle(PWR-OT), PWR-MOX cycle, Pyro-SFR cycle. These fuel cycles are most likely to be adopted in the foreseeable future.

2. Method and Determining attributes

2.1 Methodology

There are two models utilized to assess the material flow. First model is the equilibrium model and second model is the dynamic model. The biggest difference between the equilibrium model and the dynamic model is whether time-dependent information is dealt with or not. The basic characteristics of an equilibrium model is “time-independent” based on the assumption that the whole system is in a steady state and that the mass flow as well as electricity production throughout the fuel cycle is in an ideal equilibrium state. [2]. This paper mainly focused on the equilibrium model to calculate the material flows based on 1TWh of electricity from current status to the advanced system in the long term. The reference reactors used to analyze in this paper are PWR and SFR. Main characteristics of reference reactor are shown on table 1.

Table 1. Characteristics of the reference reactors.

Parameters	PWR	SFR
Electric power (MWe)	1,000	400
Thermal efficiency (%)	34	39.4
Thermal power (MWt)	2941	1015
Load factor	0.85	0.85
Cycle length (EFPDa)	290	332
Number of batches	3	4
Conversion ratio	-	0.57

2.2 Determining attributes to be used in the analysis

Through the quantitative and qualitative analysis of nuclear fuel cycle options, attributes to be used in the analysis are determined as shown in table 2.

Table 2. Summary of Evaluation Attributes for fuel cycle options

Indicators	PWR-OT	PWR-MOX	SFR-Pyro
NU requirements(tU/TWh)	20.58	18.04	13.97
Spent fuel (tHM/TWh)	2.10	0.28	0.00
MA (kg/TWh)	4.60	2.31	0.04
HLW (m3/TWh)	0.00	0.21	0.05
Excavation volume (m3/TWh)	40.80	21.53	0.06
Recovered material composition	1.000	0.500	0.700
Pu inventory (kgPu/TWh)	26.66	15.73	0.08
Fuel cycle costs (mills/kWh)	6.21	7.69	6.68
Technical readiness level	1.00	0.80	0.40
Licensing difficulty level	0.50	0.60	0.85

3.Integrated AHP and TOPSIS analysis

3.1 Evaluation criteria

To assess nuclear fuel cycle options, the five criteria are selected: U demand (natural U requirements), waste disposal (spent fuel, minor actinides, high level waste, excavation volume), material attractiveness (spent fuel composition, PU to be disposed), costs (levelized fuel cycle cost), and technical feasibility (technical readiness, licensing difficulty). The hierarchical structure for the analysis is described in Fig 1.

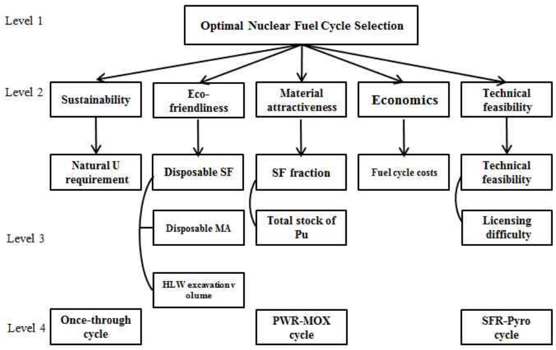

Fig 1.Hierarchic structure of fuel cycle evaluation criteria

3.2 AHP for calculating weighting factors

The criteria priority weights are derived by applying pairwise comparison of AHP method. By applying AHP method, 5 criteria being broken down into sub components make some relevant categories and levels in a hierarchic structure as shown in Figure 1.

Table 3 is the results of pairwise comparison of each criteria. The consistency index is 0.017. This is small enough to validate the consistency of the survey results. Final weights were determined by incorporating both pairwise comparison results and sub-weights as shown in table 4.

Table 3. Pairwise comparison results

Prioritization Matric	U demand	Wast disposal	Costs	Material attractiveness	Technical feasibility
U demand	1	1/5	1/4	1/3	1/2
Waste disposal	5	1	2	3	4
Costs	4	1/2	1	2	3
Material attractiveness	3	1/3	1/2	1	2
Technical feasibility	2	1/4	1/3	1/2	1

Table 4. Final weighting results

Criteria	Weighting	Metrics	Sub-Weighting	Final Weighting
U demand	0.062	Natural U requirements	1	0.062
Waste disposal	0.416	Spent fuel to be disposed of	0.25	0.104
		Minor actinides to be disposed	0.25	0.104
		HLW to be disposed of	0.25	0.104
		Excavation volume for HLW	0.25	0.104
Costs	0.262	Fuel cycle costs	1	0.262
Material attractiveness	0.161	Spent fuel composition	0.5	0.081
		Pu to be disposed of	0.5	0.081
Technical feasibility	0.099	Technical readiness	0.5	0.049
		Level of licensing difficulty	0.5	0.049

3.3 TOPSIS

TOPSIS is based on the idea that the chosen alternative should have the shortest distance from the Positive Ideal Solution and have the farthest distance from the Negative Ideal Solution [3]. The first step of TOPSIS is to construct the weighted decision matrix. Subsequently, we identified an ideal solution (A_b) and a negative ideal solution (A_b) from a set of weighted normalized decision matrix. And then the normalized distance of i -th alternative can be calculated by equation (1, 2). (1) is for calculating the distance from the positive ideal solution, and (2) is for the distance from the negative ideal solution.

$$d_{iw} = \sqrt{\sum_{j=1}^{n}(t_{ij} - t_{wj})^2} \quad (1) \quad d_{ib} = \sqrt{\sum_{j=1}^{n}(t_{ij} - t_{bj})^2} \quad (2)$$

The next step is to rank the alternatives according to the relative closeness to the ideal solution. The alternatives are ranked according to the similarity to the worst condition following equation (3).

$$s_{iw} = \frac{d_{ib}}{d_{iw} + d_{ib}} \quad (3)$$

From the normalized distances of the alternatives, the closeness coefficient of alternatives (CC_i) that is the relative closeness to the ideal solutions to derive ranking of the alternatives with respect to Ci are presented in table 5. According to the table, the highest grant for SFR-Pyro is turned out to be the most optimal option.

Table 5. Closeness coefficient(CC_i) and ranking of alternatives

Alternatives	CC_i	Rank
Once-through Cycle	0.39	3
PWR-MOX Cycle	0.46	2
SFR-Pyro Cycle	0.82	1

4. Conclusions

This paper analyzes four fuel cycle options using the Analytic Hierarchy Process (AHP) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution). The analyzed nuclear fuel cycle options include the once-through cycle, the PWR-MOX recycle, and the Pyro-SFR recycle.

The options were evaluated against five criteria: sustainability (i.e., natural uranium requirements), environment-friendliness (i.e., disposal of spent fuels, minor actinides, high level wastes, excavation volume), proliferation resistance (i.e., stock of plutonium), economics (i.e., the levelized fuel cycle cost), and technical feasibility (i.e., technical readiness, licensing difficulty). On the whole, the Pyro-SFR cycle is turned out to be the most promising option among the fuel cycle options.

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