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Original Article

# An Integrated Multicriteria Decision-Making Approach for Evaluating Nuclear Fuel Cycle Systems for Long-term Sustainability on the Basis of an Equilibrium Model: Technique for Order of Preference by Similarity to Ideal Solution, Preference Ranking Organization Method for Enrichment Evaluation, and Multiattribute Utility Theory Combined with Analytic Hierarchy Process

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A B S T R A C T

The focus on the issues surrounding spent nuclear fuel and lifetime extension of old nuclear power plants continues to grow nowadays. A transparent decision-making process to identify the best suitable nuclear fuel cycle (NFC) is considered to be the key task in the current situation. Through this study, an attempt is made to develop an equilibrium model for the NFC to calculate the material flows based on 1 TWh of electricity production, and to perform integrated multicriteria decision-making method analyses via the analytic hierarchy process technique for order of preference by similarity to ideal solution, preference ranking organization method for enrichment evaluation, and multiattribute utility theory methods. This comparative study is aimed at screening and ranking the three selected NFC options against five aspects: sustainability, environmental friendliness, economics, proliferation resistance, and technical feasibility. The selected fuel cycle options include pressurized water reactor (PWR) once-through cycle, PWR mixed oxide cycle, or pyroprocessing sodium-cooled fast reactor cycle. A sensitivity analysis was performed to prove the

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Pressurized Water Reactor Pyro-processing Sodium-Cooled Fast Reactor
Sustainability

robustness of the results and explore the influence of criteria on the obtained ranking. As a result of the comparative analysis, the pyroprocessing sodium-cooled fast reactor cycle is determined to be the most competitive option among the NFC scenarios.



## 1. Introduction

Although nuclear power is considered to be a stable source of electricity with low carbon emissions, the public continually raises several critical questions about the sustainability of nuclear power. These serious contentions include multiple interconnected issues on efficiently using uranium resources, securing an environmentally friendly way to handle waste, ensuring peaceful use of nuclear energy, maintaining economic competitiveness compared with other electricity sources, and assessing the technical feasibility of advanced nuclear energy systems. Prior to developing a national policy regarding future fuel cycles, many countries are seeking plausible answers to these controversial issues as they are subjected to public scrutiny.

In a number of different fields, many scholars have developed multicriteria decision-making (MCDM) methods to explicitly evaluate several alternatives and make more informed and better decisions [1]. The MCDM methods include the analytic hierarchy process (AHP) [2,3], preference ranking organization method for enrichment evaluation (PROMETHEE) [4–6], technique for order of preference by similarity to ideal solution (TOPSIS) [7], and multiattribute utility theory (MAUT) [8]. Among these, MAUT has been applied to the widest range of decision-making problems in nuclear energy programs such as disposal site selection of nuclear wastes [9–11], nuclear emergency management [12,13], disposal of weapon-grade Pu [14,15], and decommissioning of nuclear reactors [16].

However, there are many shortcomings caused by the use of a single particular MCDM method. The results of a single method do not provide sufficient evidence to support policy decision making. The current research trend of MCDM is thus to combine two or more methods as part of an effort to compensate for the weakness caused by biased method usage. As a comparative study combining various MCDM methods with respect to nuclear fuel cycle (NFC) analysis has rarely been reported, such a study is expected to offer meaningful results converging to the optimal future fuel cycle.

This study selected three NFC options and evaluated them against five different criteria, which were broken down into 10 subcriteria: sustainability (natural uranium requirements), environmental friendliness [spent fuels, minor actinides, high-level waste (HLW) to be disposed of, and underground excavation volume], proliferation resistance (material composition of spent nuclear fuel and Pu inventory), economics (electricity generation costs), and technical feasibility (technology readiness level and licensing difficulty level) [17]. The fuel cycle options include the once-through cycle using a pressurized water reactor (PWR), the PWR mixed oxide (PWR-MOX) cycle, and the sodium-cooled fast reactor and pyroprocessing (PWR Pyro-SFR) cycle. This study has attempted to analyze three fuel cycle options using TOPSIS, PROMETHEE, and MAUT combined with AHP [18]. Although data uncertainties are still involved, this analysis allows us to produce a systematic evaluation of the options with multiple criteria.

## 2. Materials and methods

### 2.1. *Reference fuel cycle model and data: three scenarios*

We selected three fuel cycle options that would likely be adopted by the Korean government considering the current situation of nuclear power generation: the once-through cycle, the PWR-MOX cycle, and the PWR Pyro-SFR cycle. These options are differentiated in terms of treatment of spent nuclear fuels from PWRs as either dirty wastes or useful resources. Fig. 1 shows the simplified material flow between reactors and key fuel cycle facilities in the backend fuel cycle.

The same sets of data were used across these fuel cycle options. In the three fuel cycle options, there are two different types of reactors—PWR and SFR. Table 1 includes technical parameters of the two reactors required to analyze material flow. The data were adopted from commercial plants for PWR and prototype designs for SFR. As all fuel cycle options begin with the same steps, most processes in the frontend fuel cycle (i.e., mining, milling, conversion, and enrichment) are commonly applicable to all options. By contrast, each option has its own processes in the backend fuel cycle. Table 2 contains the performance data of the fuel cycle processes in the three fuel cycle options. In addition, the actinide compositions of spent nuclear fuels for each reactor are summarized in Table 3.

PWR spent fuels are directly transported to a repository in the once-through cycle. In the PWR-MOX cycle, U and Pu from PWR spent $UO_2$ fuels are recovered and then reused in MOX PWRs. In the PWR Pyro-SFR cycle, molten-salt pyroprocessing facilities fabricate fast reactor fuels from recovered U and transuranic elements (TRUs) from PWR spent fuels. For a fair comparison, all these options are assumed to produce the same amount of electricity, a total of 1 TWh, at the equilibrium state.

### 2.2. *Equilibrium fuel cycle model*

This study mainly concentrates on using the equilibrium model to calculate the material flows based on 1 TWh of electricity from the current status to the advanced system in the long term.

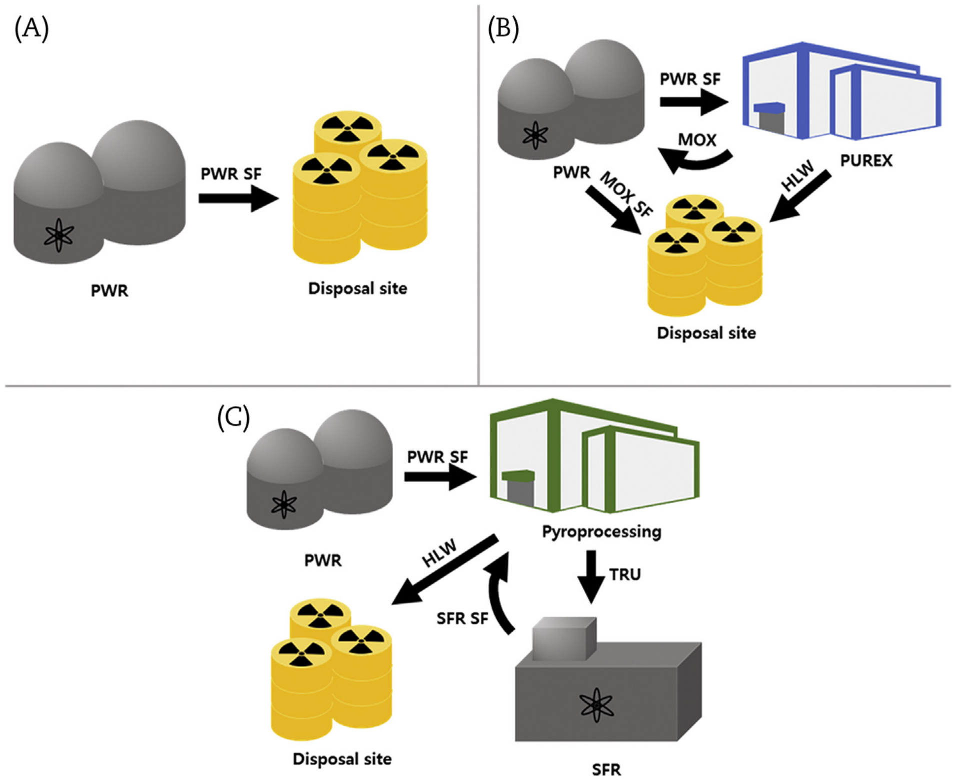



**Fig. 1 – Selected three different fuel cycle options. (A) Once-through cycle. (B) PWR-MOX recycling. (C) Pyro-SFR recycling. HLW, high-level waste; MOX, mixed oxide; PUREX, plutonium–uranium extraction; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor; SF, spent nuclear fuel; TRU, transuranic element.**

The basic characteristic of an equilibrium model is "time independent" based on the following assumptions: the mass balance, energy consumption rate, and optimal ratio of the reactor all remain constant during a perfect operation, and the global infrastructure is well organized.

What seems to be lacking with regard to an equilibrium model is certainty in the transition phase over decades or a century. This is because there is a series of generic issues related only to the current situation and the desired end point [19], omitting the transitional phase. Owing to the fundamental problem of impossibility to describe the transition phase, the results obtained by an equilibrium model tend to exclude the behavior in that period. Moreover, generic scenarios derived from the equilibrium model are less feasible in sociopolitical terms because country-specific environments are not considered. By contrast, the equilibrium model can help envisage an ideal option with a time-independent scope. Through the growth path in the long-term steady state, the optimal NFC option to be employed for the next few decades can be envisaged with an ideal scenario, which can help guide national policymakers. As the key issue of the equilibrium model is focused on the development of each generic scenario, country-specific data are not required to perform research. Hence, the model is easy to use, and the results can be applied globally. Clearly, it can help guide technological choices and raise awareness of performance features of chosen technologies, because the model will supply a mature technology as an optimized option [20]. Notwithstanding some weaknesses of an equilibrium model, it can incorporate the NFC scenarios and provide convincing evidence for nuclear policy decision making in the long term.

**Table 1 – Performance data of the reference PWR and SFR reactors.**

| | PWR | PHWR | SFR (CR 0.57) |
|---|---|---|---|
| Power(GWe) | 1,000 | 713 | 400 |
| Thermal efficiency (%) | 34 | 33 | 39 |
| Capacity factor (%) | 85 | 85 | 85 |
| Fuel types | $UO_2$ | $UO_2$ | U–TRU–10Zr metal |
| Discharge burn-up (MWD/MTU) | 55,000 | 7,500 | 128,000 |
| Uranium enrichment (wt%) | 4.5 | 0.711 | — |
| Lifetime (yr) | 60 | 50 | 60 |

CR, conversion ratio; MTU, metric ton uranium; PWR, pressurized water reactor; PHWR, pressurized heavy water reactor; SFR, sodium-cooled fast reactor; TRU = transuranic element.

### 2.3. *Equilibrium material flow of NFC options*

Fig. 2 shows the equilibrium material flows of the fuel cycle options. The material flows are based on the generation of 1 TWh of electricity. We evaluated natural uranium

**Table 2 – Fuel fabrication and reprocessing data for each cycle.**

| | Once-through cycle | PWR-MOX cycle | PWR Pyro-SFR cycle |
|---|---|---|---|
| Natural U requirements (wt%) | 0.71 | 0.71 | 0.71 |
| Depleted U enrichment (wt%) | 0.25 | 0.25 | 0.25 |
| U enrichment of PWR fuel (wt%) | 4.5 | 4.5 | 4.5 |
| Burn-up of PWR spent fuel (GWd/MTU) | 55 | 55 | 55 |
| Burn-up of MOX fuel (GWd/MTU) | — | 55 | — |
| Pu composition of MOX fuel (wt%) | — | 8 | — |
| Burn-up of SFR fuel (GWd/MTU) | — | — | 121 |
| TRU composition of SFR fuel (wt%) | — | — | 29.8 Pu, 3.7 MA |
| Loss of PWR spent fuel reprocessing (%) | — | 0.1 (PUREX) | 0.1 (pyroprocessing) |
| Major waste of PWR spent fuel reprocessing | | MA, FP | FP |
| Loss of SFR spent fuel reprocessing (%) | — | — | 0.1 |
| Major waste of SFR spent fuel reprocessing | — | — | FP |

FP, fission products; MA, minor actinide; MOX, mixed oxide; MTU, metric ton uranium; PUREX, plutonium–uranium extraction; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor; SFR, sodium-cooled fast reactor.

**Table 3 – Actinide composition of each type of spent nuclear fuel.**

| Types of spent fuel | Actinide | Weight (kg/TWh) | Composition (wt%) |
|---|---|---|---|
| PWR spent fuel | U | 2,071.1 | 98.51 |
| | Pu | 26.7 | 1.27 |
| | MA | 4.6 | 0.22 |
| MOX spent fuel | U | 257.6 | 93.47 |
| | Pu | 15.7 | 5.69 |
| | MA | 2.3 | 0.83 |
| SFR spent fuel | U | 42.0 | 66.56 |
| | Pu | 18.8 | 29.79 |
| | MA | 2.3 | 3.64 |

MOX, mixed oxide; PWR, pressurized water reactor; SFR, sodium-cooled fast reactor.

requirements, waste disposal, proliferation resistance, electricity generation costs, and technical feasibility for each fuel cycle option quantitatively and qualitatively, as shown in Table 4.

In the once-through cycle, PWR spent fuels are directly transported to a geological repository for permanent disposal after being temporarily stored in interim storage. There is no intermediate process for spent fuels between storage and final disposal. In the once-through cycle, there is no material loss within and between the fuel processes, whereas other cycles have 0.1% losses during spent fuel reprocessing steps. The assumption includes initial enrichment of 4.5 wt% and discharge burn-up of 55 GWd/metric ton uranium for PWR fuel.

In the PWR-MOX cycle, there are two types of PWRs; one loads $UO_2$ fuels, whereas the other uses MOX fuels. Pu is recovered from $UO_2$ spent fuels through plutonium–uranium extraction. The recovered Pu is mixed with depleted U, and then the mixture is fabricated into MOX fuels. MOX fuel is used in the PWR reactor again, and approximately 12.3% of the electricity is generated based on an output of 1 TWh of electricity. MOX spent fuels are disposed of without additional recycling.

In the PWR Pyro-SFR cycle, SFR produces 39.6% of the electricity at equilibrium. SFR uses metal fuels containing U and TRUs. U and TRUs are recovered from $UO_2$ and spent metal fuels through pyroprocessing. With repeated treatment through pyroprocessing, no spent fuel is transported for final disposal, whereas HLW from pyroprocessing is disposed in a final repository.

## 2.4. *MCDM methods*

### 2.4.1. *Analytic hierarchy process*

This study used AHP to obtain relative weighting factors for individual criteria. First, we defined a hierarchy structure with main criteria and associated attributes. Second, we evaluated the preferences of decision makers for criteria at each level by conducting a pairwise comparison matrix based on surveys. The relative preferences between two criteria were scored by a 9-point scale. In 1956, George A. Miller of Princeton University, Princeton, NJ, USA argued that people could clearly compare 7 ± 2 objects at the same time [2]. In addition, Professor T.L. Saaty [2], who invented AHP, at the University of Pennsylvania, Philadelphia, PA, USA suggested that using a nine-point scale could produce the most robust results for decision making. After a decision maker conducts ${}_nC_2$ times pairwise comparisons for $n$ criteria, the pairwise comparison matrix $A_{n\times n}$ can be obtained. Here, the $i^{\text{th}}$ row and $j^{\text{th}}$ column $a_{ij}$ of $A_{n\times n}$ is the relative score ratio of the $i^{\text{th}}$ and $j^{\text{th}}$ elements.

$$A = \begin{bmatrix} 1 & & \cdots & s_1/s_n \\ s_2/s_1 & \ddots & & s_2/s_n \\ \vdots & & \ddots & \vdots \\ s_n/s_1 & \cdots & & 1 \end{bmatrix} \tag{1}$$

Third, we used the eigenvector method that adopts the elements of eigenvector as the importance for the maximum eigenvalue. Multiplying matrix $A$ by the importance vector $w = (w_1, w_2, \cdots, w_n)$ one can obtain the following equations:

$$Aw = \lambda w \tag{2}$$

$$w_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \tag{3}$$

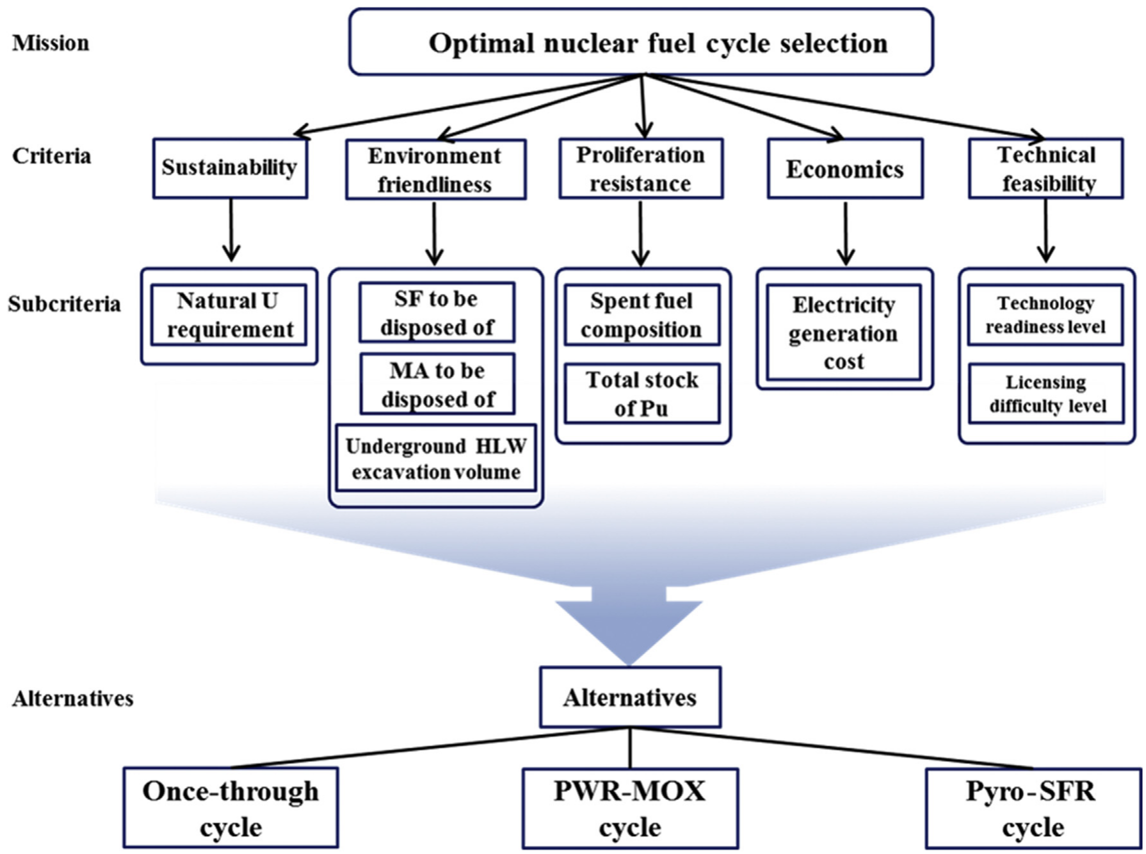



**Fig. 2 – Hierarchical structures of fuel cycle evaluation criteria. HLW, high-level waste; MA, minor actinide; MOX, mixed oxide; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor; SF, spent fuel.**

where $\lambda$ is the eigenvalue and $w$ the eigenvector corresponding to $\lambda$.

### 2.4.2. *Technique for order of preference by similarity to ideal solution*

Around 1980, Hwang and Yoon [7] proposed the TOPSIS method that scores alternatives based on their multidimensional distances from positive and negative ideal solutions. Both positive and negative ideal solutions are imaginary alternatives respectively representing the best and the worst performance of all attributes. The selected alternative among a set of alternatives should have the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution [21]. TOPSIS creates a weighted normalized decision matrix consisting of $m$ alternatives and $n$ attributes:

$$T = \begin{bmatrix} t_{11} & \cdots & t_{1n} \\ \vdots & \ddots & \vdots \\ t_{m1} & \cdots & t_{mn} \end{bmatrix} \tag{4}$$

where $t_{ij} = w_j r_{ij} = \frac{w_j x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$, $\sum_{j=1}^{n} w_j^2 = 1$.

**Table 4 – Summary of evaluation indicators for fuel cycle options.**

| Criteria | Indicators | Once-through cycle | PWR-MOX cycle | PWR Pyro-SFR cycle |
|---|---|---|---|---|
| Natural U requirements | Natural U requirements | 20.58 | 18.04 | 13.97 |
| Waste disposal | Spent fuel (tHM/TWh) | 2.10 | 0.28 | 0.00 |
| | MA (kg HM/TWh) | 4.60 | 2.31 | 0.04 |
| | HLW (kg HM/TWh) | 2.10 | 0.28 | 0.00 |
| | Excavation volume ($m^3$/TWh) | 40.80 | 21.53 | 0.06 |
| Costs | Electricity generation costs (mills/kWh) | 65.73 | 67.40 | 75.24 |
| Proliferation resistance | Spent fuel composition | 1.00 | 0.50 | 0.70 |
| | Pu inventory (kg Pu/TWh) | 26.66 | 15.73 | 0.08 |
| Technical feasibility | Technology readiness level | 1.00 | 0.80 | 0.40 |
| | Licensing difficulty level | 0.50 | 0.60 | 0.85 |

HLW, high-level waste; HM, heavy metal; MA, minor actinide; MOX, mixed oxide; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor; tHM, ton heavy metal.

With this matrix, the positive and negative ideal solutions can be expressed as follows:

$$A_w = \{[\max(t_{ij} = 1, 2, \cdots, m) | j \in J_-], [\min(t_{ij} = 1, 2, \cdots, m) | j \in J_+]\} \equiv \{t_{wj} | j = 1, 2, \cdots, n\} \quad (5)$$

$$A_b = \{[\min(t_{ij} = 1, 2, \cdots, m) | j \in J_-], [\max(t_{ij} = 1, 2, \cdots, m) | j \in J_+]\} \equiv \{t_{bj} | j = 1, 2, \cdots, n\} \quad (6)$$

where $J_+ = \{j = 1, 2, \cdots, n | j$ associated with the attribute having positive impact$\}$ and $J_- = \{j = 1, 2, \cdots, n | j$ associated with the attribute having nagative impact$\}$.

The normalized distance of the i$^{th}$ alternative can be calculated as follows:

$$d_{iw} = \sqrt{\sum_{j=1}^{n} (t_{ij} - t_{wj})^2} \quad (7)$$

$$d_{ib} = \sqrt{\sum_{j=1}^{n} (t_{ij} - t_{bj})^2} \quad (8)$$

Then, alternatives are ranked according to the similarity to the worst condition:

$$s_{iw} = \frac{d_{ib}}{d_{iw} + d_{ib}} \quad (9)$$

Although TOPSIS still requires a method generating weighting factors for individual attributes such as AHP [22], this compensatory method allows tradeoffs among attributes.

Hence, a negative result in one attribute can be negated by a good result in another. In addition, TOPSIS can provide an intuitive principle based on the consideration of the normalized multidimensional distance from the best and worst solutions. At the same time, this method can reflect diminishing marginal rates of substitution [22].

### 2.4.3. *Preference ranking organization method for enrichment evaluation*

The PROMETHEE method developed by Vincke and Brans [4] during the early 1980s is an outranking method. Outranking method focuses on the degree of dominance of one option over another. This method is a well-suited approach for the evaluation and comparison of multiple criteria and various alternatives in terms of its ranking results on the decision options, and is applicable to other multiple criteria or alternatives [23]. The PROMETHEE method is based on the pairwise comparison of each alternative [24]. After determining the criteria, it is required to define an appropriate preference function among six types of generalized forms, as shown in Table 5. The preference function is utilized in the PROMETHEE method to readily make a distinction of preference variation between the alternatives. Alternative pairs *a* and *b*, presented as $P_j(a,b)$, are evaluated according to the preference functions. The preference function ($P_j$) presented into a degree ranging from 0 to 1 indicates the difference between the evaluations obtained by two alternatives ($a$,$b$) in terms of a particular criterion [25]:

$$p_{j(a,b)} = G_j\left[f_j(a) - f_j(b)\right] \quad (10)$$

$$0 \le p_{j(a,b)} \le 1 \quad (11)$$

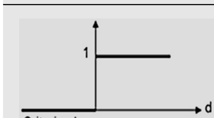
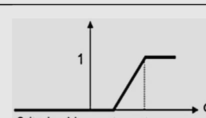
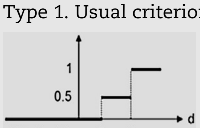
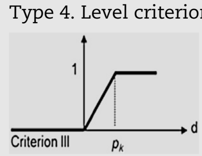
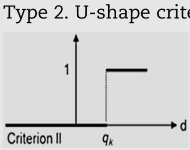
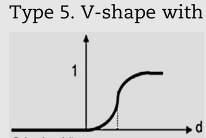
Here, a preference index of *a* and *b* is determined by Eq. (10).

Then, preference indices are calculated as follows:

$$\pi(a,b) = \sum_{j=1}^{k} p_j(a,b) w_j \quad (12)$$

Here, $P_j(a,b)$ implies a preference function value of the $j^{th}$ criterion, while $w_j$ implies weights of the $j^{th}$ criterion. In the PROMETHEE method, partial ranking is obtained from the leaving flow ($\varphi^+$) and entering flow ($\varphi^-$). Outranking flows are defined as Eqs. (11) and (12), using preference index $\pi(a,b)$:

**Table 5 – Six different types of the preference function.**

| Preference function | Definition | Parameter | Preference function | Definition | Parameter |
|---|---|---|---|---|---|
|   Type 1. Usual criterion | $P(d) = \begin{cases} 0 & d \le 0 \\ 1 & d > 0 \end{cases}$ | — |   Type 4. Level criterion | $P(d) = \begin{cases} 0 & d \le q \\ 0.5 & q < d \le p \\ 1 & d > p \end{cases}$ | $p$, $q$ |
|   Type 2. U-shape criterion | $P(d) = \begin{cases} 0 & d \le q \\ 1 & d > q \end{cases}$ | $q$ |   Type 5. V-shape with indifference criterion | $P(d) = \begin{cases} 0 & d \le q \\ \dfrac{d-q}{p-q} & q < d \le p \\ 1 & d \ge p \end{cases}$ | $p$, $q$ |
|   Type 3. V-shape criterion | $P(d) = \begin{cases} 0 & d \le 0 \\ d/p & 0 \le d \le p \\ 1 & d > p \end{cases}$ | $p$ |   Type 6. Gaussian criterion | $P(d) = \begin{cases} 0 & d \le 0 \\ 1 - \exp(-d^2/2\sigma^2) & d > 0 \end{cases}$ | s |

$$\varphi^{+}(a) = \frac{1}{n-1}\sum_{b\in A}\pi(a,b) \tag{13}$$

$$\varphi^{-}(a) = \frac{1}{n-1}\sum_{b\in A}\pi(b,a) \tag{14}$$

where A is a set of all alternatives $n$; $\varphi^{+}(a)$ indicates that alternative $a$ is outranking all the others, while $\varphi^{-}(a)$ indicates that alternative $a$ is outranked by all the others. The higher the $\varphi^{+}(a)$, the better the alternative, and also the lower the $\varphi^{-}(a)$, the better the alternative.

#### 2.4.4. *Multiattribute utility theory*

The MAUT model was developed in order to make optimal decisions by dealing with the tradeoffs of multiple objectives. This model enables the consideration of uncertainty, which is caused by the decision maker's preferences, in the form of a utility function. MAUT assesses alternatives based on utility functions developed by repeated question-and-answer processes with decision makers. There are several steps for MAUT. Step 1: Identify what attributes are important for decision making. Step 2: Drive a single utility function of each attribute. Step 3: Determine relative weighting factors of attributes. Step 4: Drive the multiattribute utility function. Step 5: Calculate how well each alternative performs on the multiattribute utility function.

The utility function is a representation of the preferences of the decision makers over a set of attributes. The multiattribute utility function $u = (x_1, \cdots, x_n)$ indicates the level of utility if the $n^{\text{th}}$ attribute $X_n$ is $x_n$. An attribute set $X_i$ is utility independent from another attribute set $X_j$ if the utility for the attributes of $X_i$ does not change when the attributes in $X_j$ vary. If it works the other way around as well, $X_i$ and $X_j$ are mutually utility independent. In this case, the multiattribute utility function can be decomposed into a set of single-utility functions as a multiplicative form [26]:

$$\begin{aligned} u(x_1,\cdots,x_n) = {} & \sum_{i=1}^{n} k_i u_i(x_i) + \sum_{i=1}^{n}\sum_{j>i}^{n} k_{ij} u_i(x_i) u_j(x_j) \\ & + \sum_{i=1}^{n}\sum_{j>i}^{n}\sum_{l>j>i}^{n} k_{ijm} u_i(x_i) u_j(x_j) u_l(x_l) + \cdots \\ & + k_{12\cdots n} u_1(x_1) u_2(x_2) \cdots u_n(x_n) \end{aligned} \tag{15}$$

where $0 \le u(x_1, \cdots, x_n) \le 1$, $0 \le u(x_i) \le 1$, $k$ is a weight factor, $0 \le k \le 1$, and. $\sum_{i=1}^{n} k_i + \sum_{i=1}^{n}\sum_{j>i}^{n} k_{ij} + \sum_{i=1}^{n}\sum_{j>i}^{n}\sum_{l>j}^{n} k_{ijm} + \cdots + k_{12\cdots n} = 1$

When the decision makers are indifferent to the two attribute choices, the relationship of two attributes is additive independent. Then, the utility function can be simplified as follows [26]:

$$u(x_1,\cdots,x_n) = \sum_{i=1}^{n} k_i u_i(x_i) \tag{16}$$

where $\sum_{i=1}^{n} k_i = 1$.

A single-attribute utility function can be determined by using a set of lottery questions [7]. A complete form of a single-attribute utility function can be classified into three categories: risk averse as Eq. (17), risk neutral as Eq. (18), and risk prone as Eq. (19). The three data points are used to determine the unknown coefficients [8].

$$u(x) = a - b\exp(-cx) \tag{17}$$

$$u(x) = a + b(cx) \tag{18}$$

$$u(x) = a + b\exp(cx) \tag{19}$$

where $0 \le u(x) \le 1$, $a$ and $b$ are greater than 0, and $c$ is positive for increasing utility functions and negative for decreasing utility functions.

## 3. Implementation and its results

### 3.1. *Evaluation criteria*

#### 3.1.1. *Uranium requirements*

Recycling the nuclear materials remaining in spent fuels can reduce natural U requirements to generate the same amount of electricity. Compared with the once-through cycle, the PWR-MOX and PWR Pyro-SFR cycles save natural uranium by 12.3% and 39.6%, respectively. The PWR-MOX reuses $UO_2$ spent fuel once more, but the PWR Pyro-SFR cycle completely reuses $UO_2$ and spent metal fuel through continuous recycling and burning.

#### 3.1.2. *Waste disposal*

The burden of radioactive waste disposal can be lightened by reducing the volume of HLW to be disposed of. Radioactive wastes are classified as HLW if they have a heat generation rate higher than 2 kW/m$^3$ and an alpha emitter activity larger than 4,000 Bq/g (here, the half-life of isotopes is longer than 5 years). As the PWR-MOX cycle recovers Pu only, HLW from plutonium–uranium extraction still contains a large amount of fission products and minor actinides. Fission products and minor actinides dominate short- and long-term heat generation, respectively. Among the three fuel cycle options, the PWR Pyro-SFR cycle produces the lowest volume of HLW from pyroprocessing because high-heat-generating elements (i.e., Cs and Sr) are selectively stored, and TRUs are repeatedly used as SFR fuels. The disposal volume, including the waste itself and other casks or structures, depends on the decay heat generated from wastes. The Organization for Economic Cooperation and Development/Nuclear Energy Agency suggests a simple rule to calculate the excavation volume of waste disposal: the decay heat of wastes after 50 years of cooling is multiplied by the unit excavation volume rate of 20 m$^3$/kW [18]. This study does not consider the increased volume of low- and intermediate-level waste from spent fuel recycling.

#### 3.1.3. *Proliferation resistance*

Proliferation resistance is defined by International Atomic Energy Agency as “the characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material or misuse of technology by states in order to acquire nuclear weapons or other nuclear explosive devices" [27]. Moreover, proliferation resistance involves the establishment of impediments or barriers to the misuse of civil nuclear energy systems to produce fissile material for nuclear weapons [28]. These impediments include intrinsic and extrinsic barriers indicating technical and institutional measures, respectively.

Intrinsic barriers refer to the technical characteristics of nuclear facilities, such as design features, which increase technological difficulties for the diversion of fissile material and manufacture of nuclear weapons. Extrinsic barriers refer to institutional barriers, such as safeguards and international arrangements, which limit the availability of sensitive technologies and materials [27]. Intrinsic barriers are further classified into material and technical barriers of a nuclear energy system, which avoid production of weapon-usable material, avoid separation of plutonium, and are hard to access for the difficulties of diversion. Material barriers include isotopic, chemical, radiological, mass and bulk barriers, and detectability, whereas technical barriers include facility unattractiveness, accessibility, available fissile mass, detectability of and time required for diversion, and skills, expertise, and knowledge [27].

This study focuses on the intrinsic features of different fuel cycle alternatives. With respect to the material feature for the intrinsic barrier, spent fuel composition indicating the difficulty of the process required to extract weapon-usable materials is evaluated through a qualitative method in terms of chemical barriers. The higher chemical berrier is, the more difficult the diversion. Separating fissile materials from spent fuels increases the near-term proliferation risk. The PWR-MOX cycle recovers pure Pu, whereas the PWR Pyro-SFR cycle recovers Pu simultaneously with minor actinides and rare earths. Meanwhile, Pu inventory, based on the quantitative material flow study on the basis of 1 TWh of electricity, is applied to the long-term technical feature for the intrinsic barrier in terms of available fissile mass, which is closely related to the amount of plutonium to be considered potentially weapon-usable material. The amount of Pu to be disposed of is calculated because of the concern regarding Pu mining as a long-term proliferation risk. Over some decades, radiation levels with self-protection capability of nuclear materials will decrease, making spent fuel more accessible, and the Pu stockpiles will gradually become more suitable for use in weapons [28,29].

**Table 6 – Selected unit cost data for fuel cycle steps [32–34,36–39].**

| Step | Unit cost (2015 USD) | | | Unit | Remarks |
|---|---|---|---|---|---|
| | Low | Nominal | High | | |
| *Reactor unit cost* | | | | | |
| PWR reactor capital | 2,844 | 4,266 | 7,110 | $/kWe | INL report (2009) |
| PWR operation & maintenance, decommissioning & decontamination | 60 | 72 | 88 | $/kWe | INL report (2009) |
| SFR reactor capital | 3,719 | 5,032 | 9,298 | $/kWe | INL report (2009) |
| SFR operation & maintenance, decommissioning & decontamination | 66 | 77 | 93 | $/kWe | INL report (2009) |
| *Fuel cycle unit cost* | | | | | |
| Natural Uranium | 50 | 100 | 300 | $/kg U | Spot market prices as of Sep 2015 |
| Conversion | 5 | 10 | 15 | $/kg U | Spot market prices as of Sep 2015 |
| Enrichment | 93 | 120 | 150 | $/kg U | Spot market prices as of Sep 2015 |
| PWR fuel fabrication | 220 | 270 | 330 | $/kg HM | INL Report (2009) |
| MOX fuel fabrication | 3,282 | 3,500 | 5,469 | $/kg HM | OECD/NEA report (2006) |
| Interim storage of PWR spent fuel | 247 | 495 | 742 | $/kg HM | Ministry of Knowledge Economy 2012a |
| Interim storage of PHWR spent fuel | 108 | 217 | 325 | $/kg HM | Ministry of Knowledge Economy 2012a |
| Reprocessing $UO_2$ PUREX | 1,042 | 1,292 | 1,545 | $/kg HM | OECD/NEA report (2006) |
| Pyroprocessing for SFR spent fuel & SFR fuel fabrication | 5,310 | 5,930 | 7,975 | $/kg HM | KAERI 2010, Ko et al. (2014), conceptual KAPF |
| MOX SF dry storage | 230 | 346 | 577 | $/kg HM | OECD/NEA report (2006) |
| Cs–Sr decay storage | 66 | 131 | 196 | $/kg of (initial) HM | INL Report (2009) |
| Packaging & disposal of PWR spent fuel | 538 | 718 | 1,077 | $/kg HM | Ministry of Knowledge Economy 2012b |
| MOX SF packing | 1,000 | 1,400 | 2,000 | $/kg | OECD/NEA (2006) |
| Conditioning & disposal of pyroprocessing HLW (same as PUREX HLW) | 115,360 | 230,730 | 461,460 | $/m$^3$ | OECD/NEA report (2006) |
| Geological disposal (excavation) | 692 | 1,384 | 2,307 | $/m$^3$ | OECD/NEA report (2006) |
| PWR SF transport | 60 | 76 | 98 | $/kg HM | Hyundai Engineering report (2009) |
| MOX SF transport | 69 | 104 | 263 | $/kg HM | OECD/NEA report (2006) |

HLW, high-level waste; HM, heavy metal; INL, Idaho National Laboratory; KAERI, Korea Atomic Energy Research Institute; KAPF, Korea Advanced Pyroprocess Facility; MOX, mixed oxide; PHWR, pressurized heavy water reactor; PUREX, plutonium–uranium extraction; OECD/NEA, Organization for Economic Cooperation and Development/Nuclear Energy Agency; PWR, pressurized water reactor; SF, spent fuel; SFR, sodium-cooled fast reactor; tHM, ton heavy metal.

#### 3.1.4. Costs

The cost data of this study, shown in Table 6, have been converted to 2015 USD using an escalation of the gross domestic product deflator. The selected unit cost data in this study are mainly from the Organization for Economic Cooperation and Development/Nuclear Energy Agency (Paris, France), Idaho National Laboratory (Idaho Falls, USA), and Ministry of Knowledge Economy reports (Gwacheon-si, Republic of Korea) [32–34,36–39]. As most steps are under development or have market uncertainty, the unit cost data have a range of uncertainty from low to high. This study adopts a nominal unit cost only for calculating the leveled electricity generation costs of each fuel cycle considering the reactor costs.

#### 3.1.5. Technical feasibility

Technical feasibility is difficult to quantify, but this study attempts to measure it through expert surveys. Each fuel cycle is scored for the two aspects of technology readiness level and licensing difficulty level. Although a deep geological repository is still being developed, the once-through cycle is the most technologically proven cycle. The PWR-MOX cycle has been implemented restrictedly by some nations with a reprocessing policy, despite its commercialization. The PWR Pyro-SFR cycle is not commercialized yet and has many challenges to be resolved before commercialization. We assume that the licensing difficulty level largely relies on which reactors are used in each cycle. PWRs using $UO_2$ and MOX fuels have already been commercialized.

Fast reactor technology has been developed since the 1960s with experimental and prototype demonstrations in a number of countries including France, Russia, Germany, the UK, Japan, and the US [35]. Until now, SFR has one case of relatively successful demonstration in Experimental Breeder Reactor II.

### 3.2. Multicriteria evaluation

#### 3.2.1. AHP for calculating weighting factors

The group of experts consists of 17 nuclear experts who derived individual pairwise comparison matrices. The data were then aggregated by using geometric means supported by the experts' choice values to form a single pairwise comparison matrix. The criteria were prioritized by applying a pairwise comparison of the AHP method. By applying an AHP

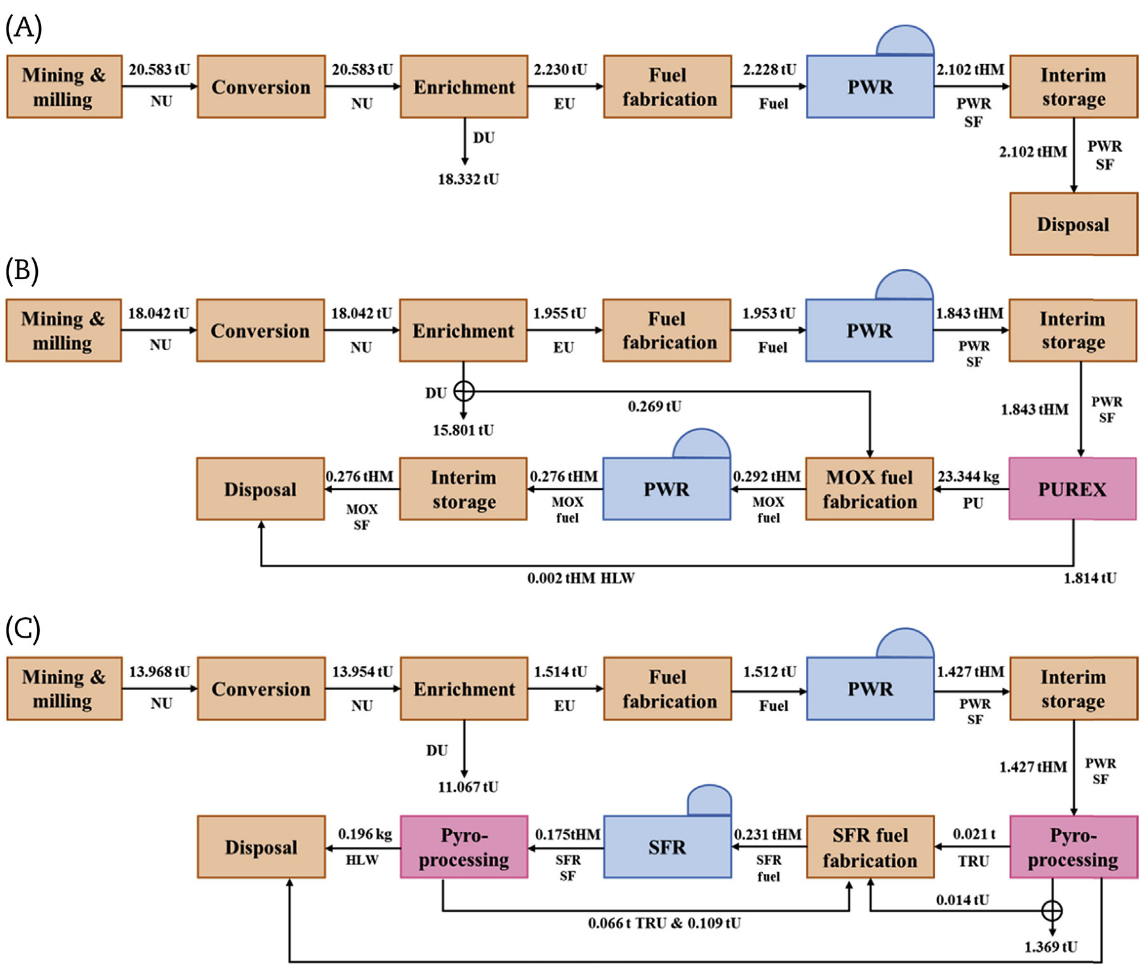



**Fig. 3 – Equilibrium material flows of fuel cycle options based on the electricity generation of 1 TWh. (A) Once-through cycle. (B) PWR-MOX cycle. (C) Pyro-SFR cycle. DU, depleted uranium; EU, enriched uranium; HLW, high-level waste; MOX, mixed-oxide fuel; NU, natural uranium; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor; SF, spent nuclear fuel; tHM, ton heavy metal; TRU, transuranic element.**

**Table 7 – Pairwise comparison results.**

| Prioritization matrices | Natural uranium requirements | Waste disposal | Costs | Proliferation resistance | Technical feasibility |
|---|---|---|---|---|---|
| Natural uranium requirements | 1 | 1/5 | 1/4 | 1/3 | 1/2 |
| Waste disposal | 5 | 1 | 2 | 3 | 4 |
| Costs | 4 | 1/2 | 1 | 2 | 3 |
| Proliferation resistance | 3 | 1/3 | 1/2 | 1 | 2 |
| Technical feasibility | 2 | 1/4 | 1/3 | 1/2 | 1 |

Consistency index = 0.017; consistency ratio = 0.015.

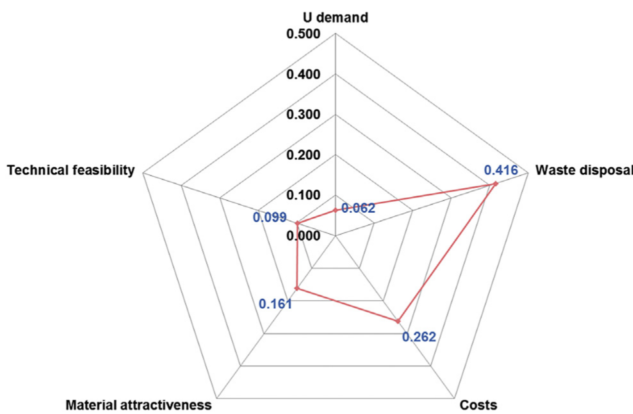



**Fig. 4 – Weights for five key evaluation criteria.**

approach, five criteria were broken down into subcomponents to create some relevant categories and levels in a hierarchic structure, as shown in Fig. 3. The results of the pairwise comparison obtained from this phase are provided in Table 7. Weights for five key evaluation criteria are assigned (Fig. 4), and the final weights are derived by multiplying the results of five pairwise comparisons and 10 subweights, as shown in Table 8.

The last step of the AHP method is to check the consistency of the data. Here, $\lambda_{max}$ is an estimation of $n$. Professor Saaty [2] showed that $\lambda_{max}$ is always greater than or equal to $n$ and that a small difference between the two indicates higher consistency. Thus, the consistency index (CI) is defined as follows:

$$CI = \frac{\lambda_{\max} - n}{n-1}, \lambda_{\max} \geq n \tag{20}$$

Professor Saaty [2] suggested that the survey is acceptable if the CI reaches zero. After determining the CI, the consistency ratio (CR) should be obtained as the ratio of CI to the average random index for the same order matrix. The random index is the CI of a randomly generated reciprocal matrix on a scale from 1 to 9 with reciprocals forced, and it can be applied to matrices with orders of 1–15 using a sample size of 100 [2]. When the CR value is < 0.1, it is considered to be acceptable. The CI is 0.017 and the CR is 0.015, which are small enough to validate the consistency of the survey results. According to the results of AHP, the waste disposal criterion is considered to be the most important factor in evaluating NFC.

### 3.2.2. *Multiattribute utility theory*

The focus of MAUT is to investigate the risk preferences of stakeholders and analyze them to identify the best fuel cycle scenario. The MAUT method, based on the expected utility theory, is comprehensive and makes it possible to consider and incorporate the preferences of each consequence at every step of the method [30]. In this study, a certainty equivalent utility assessment method and a standard lottery (50–50 gamble) were utilized to elicit the individual utility functions. These methods are preferred because probabilities of 0.5 are the most appropriate values to draw a clear understanding of uncertainty from the respondent [31]. To estimate utility functions, the boundaries of the utility function should be set at the worst and best possible attribute levels. For example, for the U requirement attribute, best and worst attribute levels of 20.58 and 13.97, equivalent to $p => 0.99$ and $p < 0.001$,

**Table 8 – Determined final weights.**

| Criteria | Weights | Subcriteria | Subweights | Final weights |
|---|---|---|---|---|
| Natural uranium requirements | 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 of | 0.25 | 0.104 |
| | | HLW to be disposed of | 0.25 | 0.104 |
| | | Excavation volume for HLW | 0.25 | 0.104 |
| Costs | 0.262 | Electricity generation costs | 1 | 0.262 |
| Proliferation resistance | 0.161 | Spent fuel composition | 0.5 | 0.081 |
| | | Total stocks of Pu | 0.5 | 0.081 |
| Technical feasibility | 0.099 | Technology readiness level | 0.5 | 0.049 |
| | | Licensing difficulty level | 0.5 | 0.049 |

HLW, high-level waste.

**Table 9 – Single-attribute utility equations and risk attitudes of the individual criteria.**

| Attributes | Form of single-utility function | CE ($p = 0.5$) | Function form | Increase or decrease |
|---|---|---|---|---|
| Natural uranium requirements | $U_1(x) = -0.0126x^2 + 0.2847x^2 - 0.5178$ | 18.20 | Risk aversion | Decrease |
| Spent fuel to be disposed of | $U_2(x) = 1.0595e^{-x/0.694} - 0.0539$ | 0.45 | Risk prone | Decrease |
| Minor actinide to be disposed of | $U_3(x) = 1.3377e^{-x/3.219} - 0.3220$ | 1.60 | Risk prone | Decrease |
| HLW to be disposed of | $U_4(x) = -0.4272x + 0.893$ | 0.07 | Risk neutral | Decrease |
| Excavation volume for HLW | $U_5(x) = -0.0005x^2 - 0.0031x + 0.9992$ | 28.00 | Risk aversion | Decrease |
| Electricity generation costs | $U_8(x) = 45{,}681.56e^{-x/6.2715} - 0.2852$ | 69.00 | Risk prone | Decrease |
| Spent fuel composition | $U_6(x) = -2.4387x^2 + 5.6766x - 2.236$ | 0.68 | Risk aversion | Increase |
| Total stocks of Pu | $U_7(x) = 0.9735e^{-x/5.2714} - 0.0061$ | 3.50 | Risk prone | Decrease |
| Technology readiness level | $U_9(x) = 1.5592x^2 - 0.5557x - 0.0149$ | 0.80 | Risk prone | Increase |
| Licensing difficulty level | $U_{10}(x) = -3.8143x^2 + 3.7742x + 0.0653$ | 0.85 | Risk averse | Decrease |

CE, certain equivalent; HLW, high-level waste.

respectively, are first set. Consecutively, the certainty equivalent value for B can be elicited at the point where the respondent is indifferent between alternatives A and B. In other words, all attributes comprised the equivalent levels in the range from the best level probability $p$ to the worst level probability $1-p$. Among the three types of functional forms, the exponential and quadratic curves were used as utility functions according to the different risk characteristics of each attribute.

The utility equations and risk trends of each attribute were defined as shown in Table 9, and the graphs are shown in Fig. 5. The integrated evaluation of the alternative fuel cycles was conducted using the values of the combined utilities as shown in Table 10. In terms of utility function value, the top-ranked PWR Pyro-SFR cycle seems to be in the most favorable situation, followed by the once-through cycle. Reviewing the results of MAUT based on its utility values as shown in Fig. 6, it is observed that the PWR Pyro-SFR cycle shows outstanding performance for multilateral aspects, whereas HLW to be disposed of, spent fuel composition, and electricity generation costs are found to be the driving factors that contribute to the bottom-ranked PWR-MOX cycle.

### 3.2.3. *Preference ranking organization method for enrichment evaluation*

The first step of PROMETHEE is to choose the appropriate preference function shape for the criteria among six types of preference functions and then set the preference parameter of each criterion. Type 3, the linear function, is selected for the quantitative criteria (uranium demand, disposable spent fuel, disposable minor actinides, disposable HLW, underground excavation volume, total stock of Pu, and electricity generation costs), and type 4, the level function, is used for the three qualitative criteria (material composition of spent fuel, technology readiness level, and licensing difficulty level). Meanwhile, Table 11 presents the maximum and minimum values of each criterion through C1–C10, and these are reflected in either the preference thresholds ($p$) or the indifference thresholds ($q$).

With the derived weights of the criteria, the preference index is calculated as shown in Table 12. Using the calculated preference index, the positive preference leaving flow ($\phi^+$), denoting how much an alternative dominates the others, and the negative preference entering flow ($\phi^-$), denoting how much an alternative is dominated by the others, are calculated. From the values of leaving flow and entering flow (Table 13), the PROMETHEE I partial ranking, which provides incomplete ranking of alternatives, and the PROMETHEE II complete ranking of the alternatives from best to worst are derived by calculating the net flow ($\phi$); that is, the final ranking of the PROMETHEE method is decided by the net flow. Fig. 7 presents the net flow of each fuel cycle option, indicating that the PWR Pyro-SFR cycle occupies the top priority with a highly positive outranking flow, whereas the once-through cycle ranks last.

### 3.2.4. *Technique for order of preference by similarity to ideal solution*

The first step of TOPSIS is to construct a weighted normalized decision matrix as presented in Table 14. Subsequently, we identified an ideal solution ($A_b$) and a negative ideal solution ($A_w$) from a set of weighted normalized decision matrices. In other words, the positive ideal solution is a set of the ideal values of each criterion in the weighted normalized decision matrix, whereas the negative ideal solution is a set of the nonideal values of each criterion in the weighted normalized decision matrix.

The normalized distance of the $i^{th}$ alternative can then be calculated. From the normalized distances of the alternatives, the closeness coefficients of alternatives ($CC_i$), which represent the relative closeness to the ideal solutions for deriving the ranking of the alternatives with respect to $C_i$, are presented in Table 15. According to Table 15, the PWR Pyro-SFR cycle turned out to be the most optimal option in terms of relative closeness to the ideal solution. As shown in Fig. 8, it is observed that overall weighted normalized values of the first four criteria of the PWR Pyro-SFR cycle are the closest to the positive ideal solution. By contrast, the once-through cycle depicted in the graph shows the farthest distance from the positive ideal solution in most criteria rather than the PWR-MOX cycle. Fig. 9 describes the relative distance of each alternative with regard to the negative and positive ideal solutions, demonstrating that the PWR Pyro-SFR cycle has the biggest closeness coefficient. Accordingly, the PWR Pyro-SFR cycle is the leading option, whereas the PWR-MOX and once-through cycles ranked in the second and third positions, respectively.

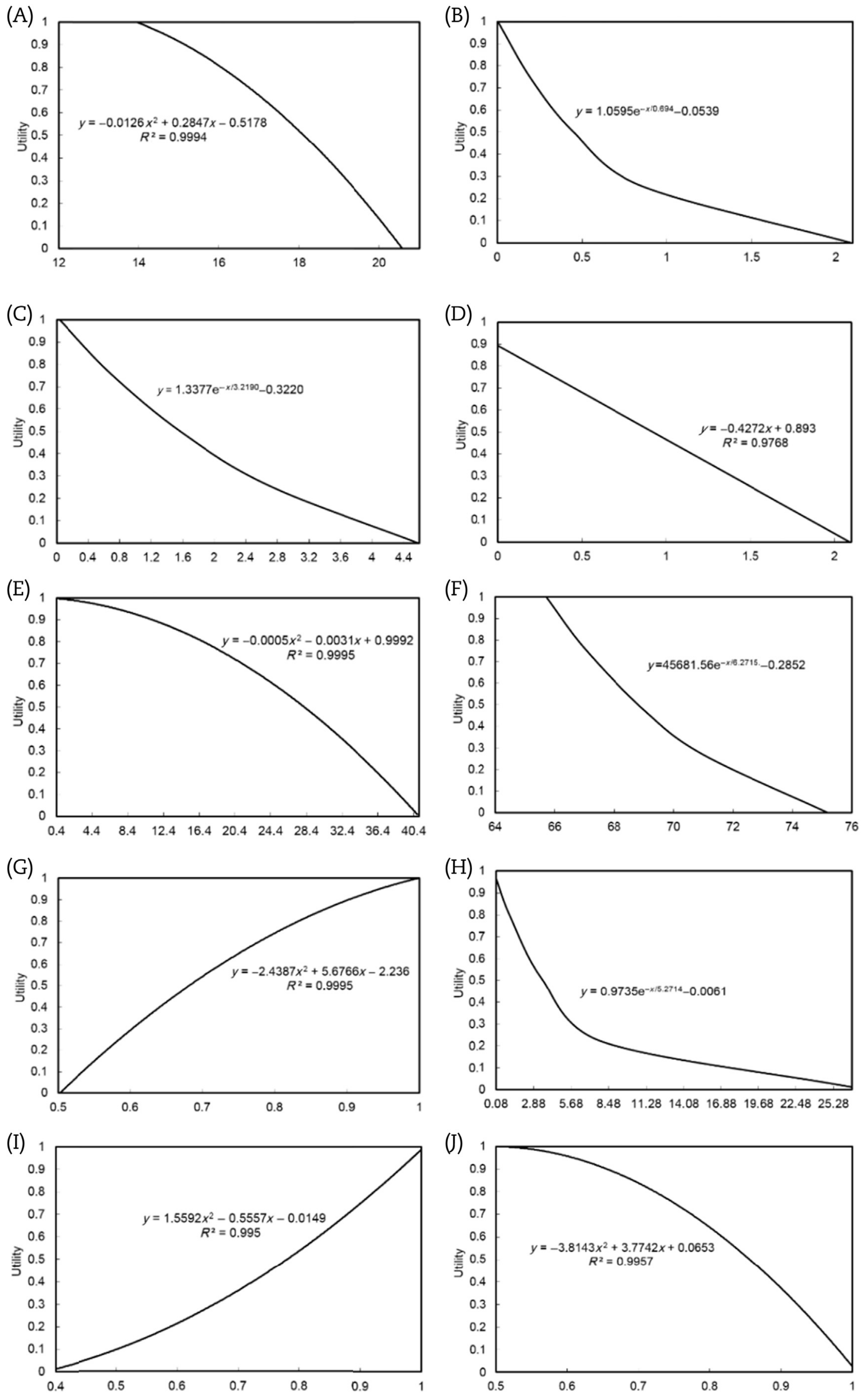



**Fig. 5 — Graphs representing utility equations and risk trends of the individual trends. (A) U requirements. (B) Spent fuel to be disposed of. (C) Minor actinides to be disposed of. (D) HLW to be disposed of. (E) Underground excavation volume. (F) Electricity generation costs. (G) Spent fuel composition. (H) Total stock of Pu. (I) Technology readiness level. (J) Licensing difficulty level. HLW, high-level waste.**

**Table 10 – Values of single-utility and multiattribute utility functions.**

| Attributes | Weights | Once-through cycle | PWR-MOX cycle | PWR Pyro-SFR cycle |
|---|---|---|---|---|
| Natural uranium requirements | 0.062 | 0.0041 | 0.5173 | 1.0005 |
| Spent fuel to be disposed of | 0.104 | −0.0027 | 0.6584 | 1.0056 |
| Minor actinide to be disposed of | | −0.0020 | 0.3298 | 1.0000 |
| HLW to be disposed of | | −0.0051 | 0.7744 | 0.8923 |
| Excavation volume | | 0.0404 | 0.7008 | 0.9991 |
| Electricity generation costs | 0.262 | 0.9969 | 0.6976 | −0.0036 |
| Spent fuel composition | 0.081 | 1.0019 | −0.0074 | 0.5427 |
| Pu to be disposed of | | 0.0001 | 0.0431 | 0.9527 |
| Technology readiness level | 0.049 | 0.9886 | 0.5384 | 0.0123 |
| Licensing difficulty level | | 0.9988 | 0.9567 | 0.5175 |
| Utility function value | | 0.4432 | 0.5472 | 0.6135 |
| Ranking | | 3 | 2 | 1 |

HLW, high-level waste; MOX, mixed oxide; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor.

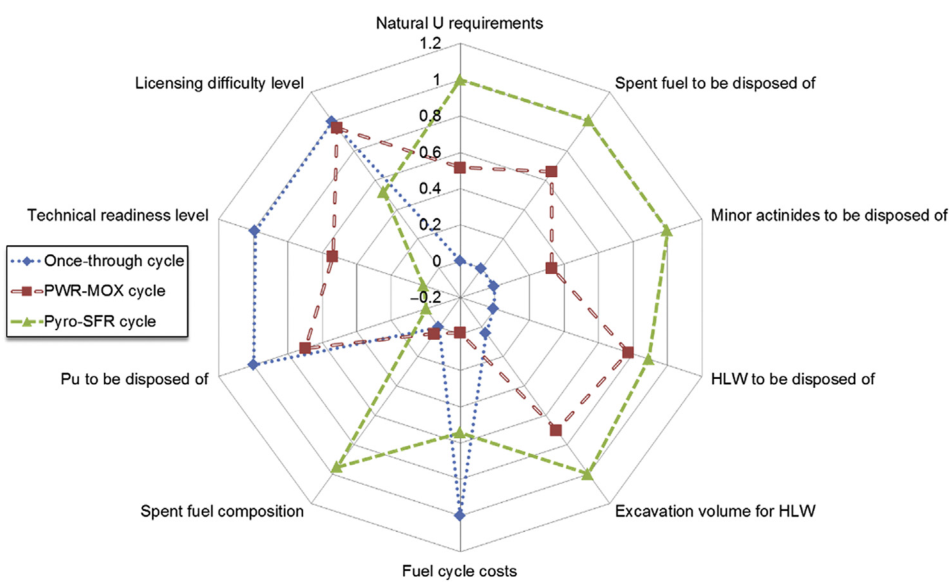



**Fig. 6 – Utility values of each criterion. HLW, high-level waste; MOX, mixed oxide; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor.**

**Table 11 – Determined preference function shapes and thresholds.**

| Preference function type | C1 (min) | C2 (min) | C3 (min) | C4 (min) | C5 (min) | C6 (min) | C7 (max) | C8 (min) | C9 (max) | C10 (min) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Linear (III) | Linear (III) | Linear (III) | Linear (III) | Linear (III) | Linear (III) | Level (IV) | Linear (III) | Level (IV) | Level (IV) |
| MAX | 20.58 | 2.10 | 4.60 | 2.10 | 40.80 | 75.24 | 1.00 | 26.66 | 1.00 | 0.85 |
| MIN | 13.97 | 0.00 | 0.04 | 0.00 | 0.04 | 65.73 | 0.50 | 0.08 | 0.40 | 0.50 |
| $p$ | 2.20 | 0.70 | 1.52 | 0.70 | 13.59 | 3.17 | 0.50 | 8.86 | 0.60 | 0.35 |
| $q$ | — | — | — | — | — | — | 0.30 | — | 0.30 | 0.30 |

$p$, preference threshold; $q$, indifference threshold.

**Table 12 – Aggregated preference index (outranking degree).**

| | C1 (min) | C2 (min) | C3 (min) | C4 (min) | C5 (min) | C6 (min) | C7 (max) | C8 (min) | C9 (max) | C10 (min) |
|---|---|---|---|---|---|---|---|---|---|---|
| Πj(a, b) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 13.784 | 4.050 | 0.000 | 0.000 | 0.000 |
| Πj(a, c) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 26.200 | 4.050 | 0.000 | 2.450 | 0.000 |
| Πj(b, a) | 6.200 | 10.400 | 10.400 | 10.400 | 10.400 | 0.000 | 0.000 | 8.100 | 0.000 | 0.000 |
| Πj(b, c) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 26.200 | 0.000 | 0.000 | 2.450 | 0.000 |
| Πj(c, a) | 6.200 | 10.400 | 10.400 | 10.400 | 10.400 | 0.000 | 0.000 | 8.100 | 0.000 | 2.450 |
| Πj(c, b) | 6.200 | 4.089 | 10.400 | 4.100 | 10.400 | 0.000 | 0.000 | 8.100 | 0.000 | 0.000 |

**Table 13 – Flows of alternatives and PROMETHEE II ranking.**

| Alternatives | $\varphi^+$ | $\varphi^-$ | $\varphi$ | Ranking |
|---|---|---|---|---|
| Once through | 0.5053 | 1.1425 | −0.6372 | 3 |
| PWR-MOX | 0.8455 | 0.6112 | 0.2343 | 2 |
| PWR Pyro-SFR | 1.0164 | 0.6135 | 0.4029 | 1 |

MOX, mixed oxide; PROMETHEE, preference ranking organization method for enrichment evaluation; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor.

**Table 15 – Rating of alternatives in terms of relative closeness to ideal solution.**

| Alternatives | $d_{ib}$ | $d_{iw}$ | $CC_i$ | Ranking |
|---|---|---|---|---|
| Once through | 0.208 | 0.046 | 0.180 | 3 |
| PWR-MOX | 0.087 | 0.147 | 0.627 | 2 |
| PWR Pyro-SFR | 0.038 | 0.208 | 0.845 | 1 |

MOX, mixed oxide; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor.

## 4. Discussion

The results of ranking are obtained by the integrated MCDM approaches, as shown in Table 16. All the methods applied in this study yield similar ranking results. The outcomes of its stability were investigated by performing sensitivity analysis under given uncertainties in the data. We implemented Latin-hypercube analysis 5,000 times, considering a variation of ± 10% with triangular distribution for the attributes of the 10 criteria using @Risk software developed by PALISADE. The rankings with a large range of intervals indicate that the obtained results are robust and reliable, as shown in Fig. 10. The complete rankings in PROMETHEE II, TOPSIS, and MAUT were stable while varying the weights. Namely, the top-ranked PWR Pyro-SFR cycle in all the three methods was observed to be robust and reliable. From the above evidence in the integrative

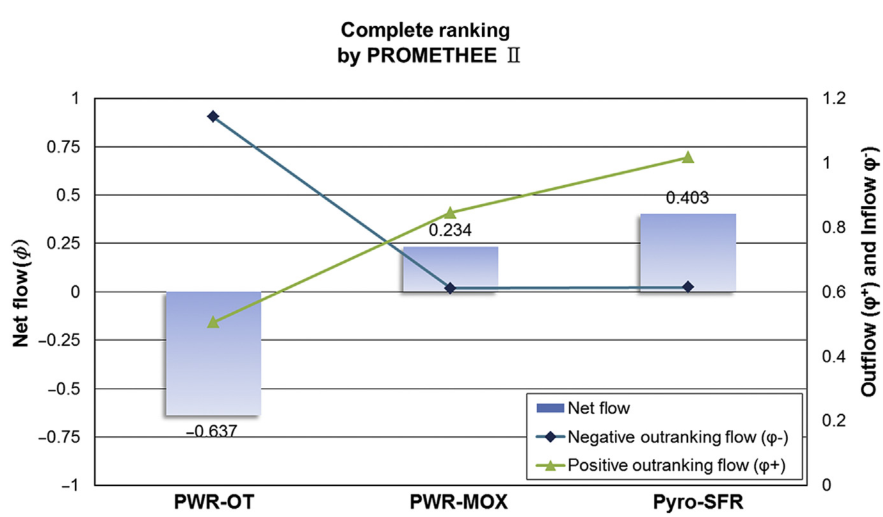



**Fig. 7 – Complete ranking by PROMETHEE. MOX, mixed oxide; OT, once-through; PROMETHEE, preference ranking organization method for enrichment evaluation; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor.**

**Table 14 – Weighted normalized decision matrix.**

| Alternatives | C1 (min) | C2 (min) | C3 (min) | C4 (min) | C5 (min) | C6 (min) | C7 (max) | C8 (min) | C9 (max) | C10 (min) |
|---|---|---|---|---|---|---|---|---|---|---|
| Once through | 0.042 | 0.103 | 0.093 | 0.103 | 0.092 | 0.143 | 0.061 | 0.070 | 0.037 | 0.021 |
| PWR-MOX | 0.036 | 0.014 | 0.047 | 0.014 | 0.049 | 0.147 | 0.031 | 0.041 | 0.029 | 0.025 |
| PWR Pyro-SFR | 0.028 | 0.000 | 0.001 | 0.000 | 0.000 | 0.164 | 0.043 | 0.000 | 0.015 | 0.036 |

MOX, mixed oxide; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor.

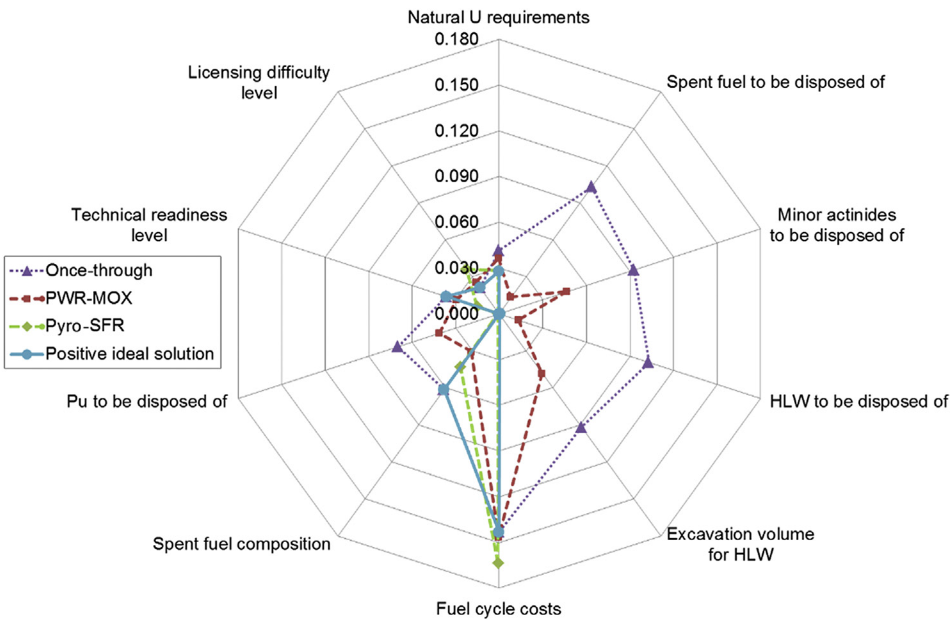



**Fig. 8 – Relative closeness to the positive ideal solution of each criterion (TOPSIS). HLW, high-level waste; MOX, mixed oxide; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor; TOPSIS, technique for order of preference by similarity to ideal solution.**

perspective approach of this study, some conclusions can be stated: the results of the sensitivity analyses on weights and parameters imply that the derived rankings are reasonably stable, the PWR Pyro-SFR cycle turned out to be the most promising fuel cycle option, and the once-through cycle is the least feasible option.

## 5. Conclusions

In this study, the screening and ranking analysis of the viable national NFC alternatives were evaluated quantitatively and qualitatively by developing an equilibrium model for material flow analysis and by performing integrated MCDM method analyses with the aim of identifying the most suitable NFC option for the foreseeable future. Considering the fact the there is no silver-bullet MCDM method for NFC evaluation, various methods combined with AHP were utilized in this study. In spite of their different characteristics and theories, the results obtained from the MCDM method were similar and the sensitivity analysis on the relative weights using the Latin-hypercube simulation demonstrated its robustness. The most important point is that most of the MCDM methods used in this study are required to be organized well to yield appropriate and reliable thresholds affecting the results directly, especially for the TOPSIS and PROMETHEE methods. Meanwhile, MAUT procedures are somewhat time-consuming to form the single-utility functions with proper risk-taking curves. Since the four MCDM methods belong to a different classification of the traditional MCDMs, other methods can also be utilized for screening out.

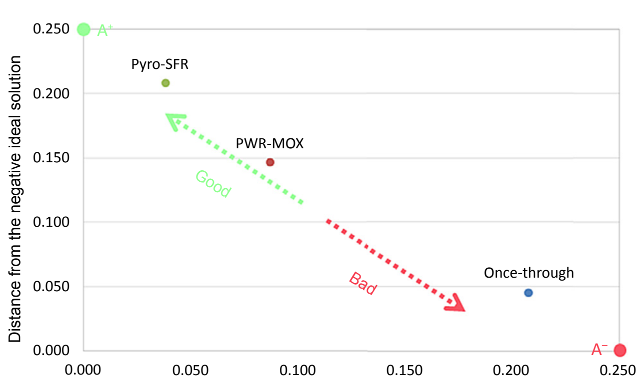



**Fig. 9 – Relative distances from positive and negative ideal solutions (TOPSIS). MOX, mixed oxide; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor; TOPSIS, technique for order of preference by similarity to ideal solution.**

**Table 16 – Results of three different MCDM methods.**

| Alternatives | TOPSIS ranking | PROMETHEE ranking | MAUT ranking |
|---|---|---|---|
| Once through | 3 | 3 | 3 |
| PWR-MOX | 2 | 2 | 2 |
| PWR Pyro-SFR | 1 | 1 | 1 |

MAUT, multiattribute utility theory; MCDM, multicriteria decision making; MOX, mixed oxide; PROMETHEE, preference ranking organization method for enrichment evaluation; PWR, pressurized water reactor; Pyro-SFR, pyroprocessing sodium-cooled fast reactor; TOPSIS, technique for order of preference by similarity to ideal solution.

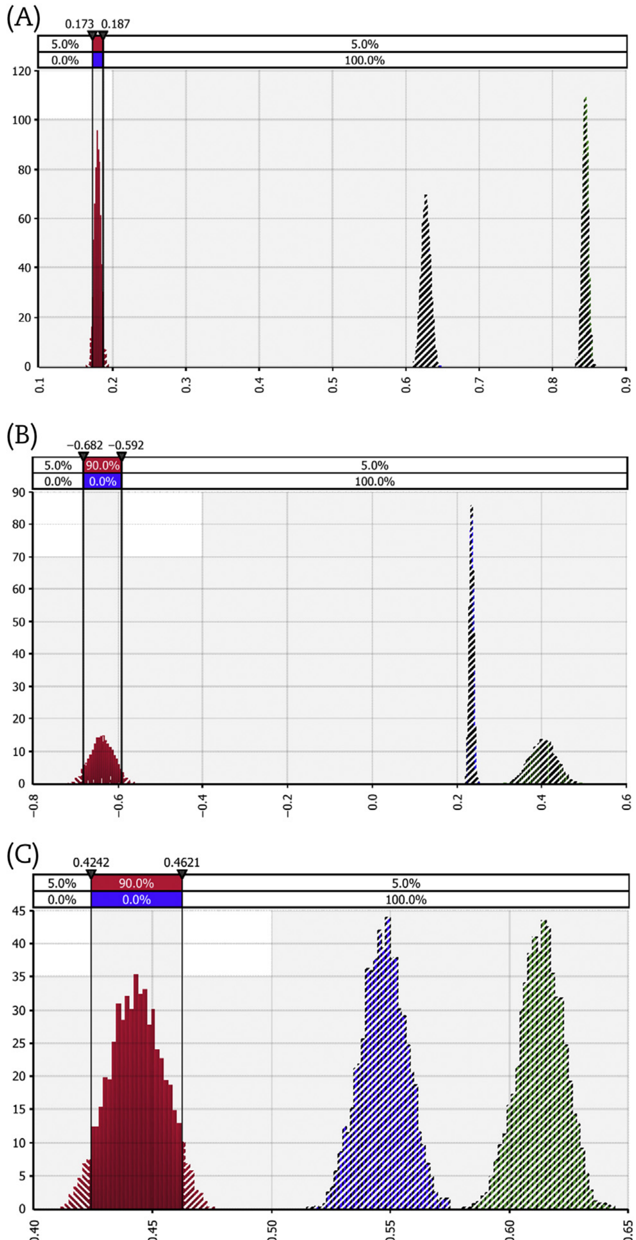



**Fig. 10 – Sensitivity analysis on the MCDM ranking of each alternative using the Latin-hypercube simulation. (A) TOPSIS. (B) PROMETHEE. (C) MAUT. MAUT, multiattribute utility theory; MCDM, multicriteria decision making; PROMETHEE, preference ranking organization method for enrichment evaluation; TOPSIS, technique for order of preference by similarity to ideal solution.**

While maintaining growth in nuclear power in Korea, as noted in the national energy plans, the findings of this research demonstrate that the PWR Pyro-SFR cycle shows its outstanding performance and benefit with regard to long-term sustainability and environmental friendliness. The integrated approach in this study can provide decision makers and stakeholders with insights into NFC policy making. What remains to be accomplished by future research is to scrutinize the transition phases for centuries through a dynamic model to indicate how to realize the optimal fuel cycle with country-specific characterizations for long-term prediction and sustainability.

## Conflicts of interest

All authors have declared no conflicts of interest.

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