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# National Options for a Sustainable Nuclear Energy System: MCDM Evaluation Using an Improved Integrated Weighting Approach

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**Abstract:** While the prospects look bright for nuclear energy development in China, no consensus about an optimum transitional path towards sustainability of the nuclear fuel cycle has been achieved. Herein, we present a preliminary study of decision making for China's future nuclear energy systems, combined with a dynamic analysis model. In terms of sustainability assessment based on environmental, economic, and social considerations, we compared and ranked the four candidate options of nuclear fuel cycles combined with an integrated evaluation analysis using the Multi-Criteria Decision Making (MCDM) method. An improved integrated weighting method was first applied in the nuclear fuel cycle evaluation study. This method synthesizes diverse subjective/objective weighting methods to evaluate conflicting criteria among the competing decision makers at different levels of expertise and experience. The results suggest that the fuel cycle option of direct recycling of spent fuel through fast reactors is the most competitive candidate, while the fuel cycle option of direct disposal of all spent fuel without recycling is the least attractive for China, from a sustainability perspective. In summary, this study provided a well-informed decision-making tool to support the development of national nuclear energy strategies.

**Keywords:** integrated evaluation; multi-criteria decision making (MCDM); sustainability; nuclear fuel cycle; dynamic model

## 1. Introduction

The world is moving towards a low carbon economy, which has brought "green energy" an integral part of the future energy mix [1]. Given the substantial dependence of many countries on fossil-fuel based electricity generation, substitution of fossil fuels with more $CO_2$-neutral sources of green energy will be challenging, but critical to accomplish in the near term. In past decades, nuclear energy became a well-established option making a prominent contribution to energy sustainability from the perspectives of economics, environment, and society [2]. The use of nuclear power is still controversial due to huge public concern about potential accidents, risk of proliferation, and nuclear waste management issues. Even so, many countries have openly declared their willingness to start generating nuclear power or to expand the scale of existing civilian nuclear programs [3].

Ultimate solution for completing an entire nuclear fuel cycle through an optimum transitional path towards sustainable development may one day be identified. Each nuclear country or newcomer interested in nuclear energy should carry out various and innovative Research and Development (R&D) programs in favor of their prevailing nuclear technologies and fuel cycle policy that may hasten that day. Therefore, it is significant to give the flexibility of the advanced nuclear fuel cycle under development, while addressing the nuclear waste management issues to support the development of the regional, national, and global energy strategies [4,5].

A complete and well-organized nuclear fuel cycle system is essential for nuclear sustainability, and also serves to exert considerable influence upon the decisions that must be made about distinctive energy strategies at a regional, national, or worldwide level [6]. In any case, there is an urgency not only to assess the interrelated benefits and risks of future advanced nuclear energy systems, but also to recognize the trade-offs that may be required among development goals to achieve nuclear sustainability.

In our past studies, a simulation code was developed for modeling the material flows and analyzing system complexity based on physical equations and system dynamics. It provides a quantitative performance analysis of a case study in China, and contains four proposed nuclear fuel cycle transition options through 2100 [7,8]. However, with regard to the general comparison associated with environmental, economic, and social impacts presented previously, this approach was not conclusive in suggesting an optimum transitional path towards sustainability in the nuclear fuel cycle. Consequently, there is still need for decision support to develop superior nuclear energy strategies in the near future.

Decision making for developing national energy strategies is a complex deliberative process based on integrated system assessment [9]. It is needed to consider extensive criteria and indicators to evaluate the different energy generation technologies, plans and policies. The Multi-Criteria Decision Making (MCDM) is a popular method for addressing the multi-dimensional and complex nature of sustainability encompassed the assessment of a finite number of sustainable energy options [10,11]. It enables conducting an integrated and operational evaluation for decision support that is applicable to solve complex problems featuring high uncertainty, conflicting objectives, a range of input data, and multiple interests and perspective. Given the broad range of processes involved in a complete nuclear fuel cycle, from cradle to grave, the MCDM study has become an important and convenient tool for the assessment of nuclear energy systems, nuclear facility site selection, and nuclear waste management issues. For instance, Keeney et al. [12] initially analyzed the suitable additional future sites for 1984's project of nuclear generating facilities in U.S. by using Multi-Attribute Utility Theory (MAUT) method. The same method was adopted in Keeney and Merkhofer's study [13], which was designed to aid the U.S. Department Of Energy (DOE) in its selection of three potential sites normalized for first geological repository of nuclear waste disposed of. An Evaluation and Screening Study (E&S Study) of nuclear fuel cycle options developed by U.S. DOE since 2011, which still selected MAUT as the basic analytical approach to provide the information about the potential benefits and challenges of a comprehensive set of nuclear fuel cycle options, as well as providing guidance for the R&D activities of fuel cycle technologies undertaken in U.S. [14]. A. Schwenk-Ferrero's studies [15–18] proposed a series of decision-making support work based on a complete MCDM framework for evaluating of nuclear waste management strategies and nuclear fuel cycle options in view of sustainability. They further applied the framework in the representative nuclear energy system studies previously investigated by International Atomic Energy Agency (IAEA) International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) Collaborative project [19] and Organization for Economic Cooperation and Development-Nuclear Energy Agency (OECD-NEA) [20]. These studies have provided a broad range of background information as well as insights on the decision making analysis of nuclear fuel cycle system, which made great contribution to the method and conduct of this case study of nuclear sustainability in China.

The decision results obtained from MCDM analysis generally depend on the identified criteria and indicators on which the different candidate options are to be evaluated, the criteria weighting, and the adopted MCDM techniques based on specific ranking methods. However, this input information underlying MCDM study is always associated with uncertainties. Notably, different countries might select different but suitable evaluation criteria and indicators from specific points of view for sustainable development [14,19,21]. Likewise, they might have opposite priorities relative to individual criteria owing to the country-specific primary context and national demands. Despite the importance of decision makers' (DMs') expertise and experiences in solving decision making problems for developing a national energy strategy, the subjective judgments should be combined with and supported by objective methods whenever possible [22]. For reliable and robust decision making, it is necessary to explicitly address the accuracy of the weighting system, analyzing in great detail how the distinctive weighting methods impact the resultant decisions, and what weighting methods are best suited for a given situation. However, given a high sensitivity of criteria weighting in most MCDM studies of nuclear energy system analysis, few studies have explicitly discussed how the different weighting methods (subjective/objective) could be used simultaneously and be combined effectively in a group decision environment.

To bridge this gap, this study intends to stress on the uncertainties caused by applying any single type of weighting method. Instead, we are of interested in the improvement of an integrated weighting approach, along with the application in a country-specific decision making analysis about future nuclear energy development. The main contribution of our work is to present a preliminary evaluation of decision making for China's future nuclear fuel cycle options from a sustainability perspective, with a particular emphasis on the strategic MCDM framework by adopting an improved integrated weighting method combined with the self-developed dynamic analysis model. Herein, a set of subjective and objective weighting methods were tested and compared against the weights of evaluation criteria for China-specific sustainability of nuclear energy. Then combined with the MCDM analysis, we provided a well-informed decision-making tool to support the development of national nuclear energy strategies. Particularly, we developed an improved integrated weighting method to effectively synthesize diverse weighting methods (subjective/objective) by which to evaluate conflicting criteria among the competing DMs at different levels of expertise and experience. This is the first time that this specifically tailored weighting method has been used in a nuclear fuel cycle evaluation study.

## 2. Methods

MCDM is a discipline aimed at supporting DMs faced with making numerous and complex evaluations [23,24]. It is capable of broadening the comprehensive understanding of the problem and its elaboration, encouraging deliberations among multiple and conflicting criteria/indicator tradeoffs, finally allowing selection of an optimum alternative in a scientifically rigorous manner. A typical MCDM framework is composed of four major stages: formulation of the criteria and evaluation metrics, determination of weights, MCDM techniques selection and execution. The evaluation process of the proposed MCDM framework and the details of the first stage have been addressed in another separated study. In this study, we selected two widely applicable techniques that represent different mathematical methods: the Technique for Order Preference with Preference by Similarity to Ideal Solutions (TOPSIS) method using a reference level model (distance) [25] and the Preference Ranking Organization Method for Enrichment Evaluation II (PROMETHEE II) method using an outranking model [26]. The methodological considerations and main implementation steps of TOPSIS and PROMETHEE II have been well developed and described, so we will not explain them in detail.

### *2.1. Methods for Criteria Weighting*

In typical MCDM analysis, the weight of each evaluation indicator/criteria directly reflects an indicator/criteria's relative importance over others, which heavily influences the final decision making [15]. There are three factors to be considered for acquiring the criteria weights: the level of diversity among a range of criteria/indicators, the independency between criteria/indicators, and the subjective preference of DMs [11]. Generally, weighting methods are categorized into subjective and objective weighting methods. The subjective weighting method determines the relative importance of individual indicator/criteria in full accordance with the DMs' preferences or judgments. All the subjective information collected from the individual DMs are then calculated separately using some specific mathematic approaches (e.g., mathematical programming and eigenvector methods). In contrast, objective weighting is a data statistical method for determining the weighting values by solving corresponding mathematical models of evaluation matrices mechanically, without personal interference [27].

The individual weighting methods have diverse strengths and weaknesses. For instance, the subjective weights are determined by experts and the concordance of criteria values is checked by the DMs. Although the subjective weighting elicitation process is always time-consuming and difficult to execute, it is more satisfied and acceptable by the various experts/stakeholders involved in a given decision-making issue. However, the personal preferences and judgments from the DMs are frequently vague and hardly to be exactly evaluated by using numerical values in practice. In contrast, the objective weighting method may bypass potential uncertainties in human intuitive judgment, but might become debatable in terms of overreliance on the input evaluation indicator values (away from the group decision environment). Both subjective and objective methods are widely employed to elicit the criteria weights in the sustainable energy decision making research [10,11].

As will be discussed in Section 2, we first introduce some commonly used subjective (i.e., Fuzzy Analytical Hierarchy process (Fuzzy AHP)) and objective weighting methods (i.e., Entropy and Criteria Importance through Inter-criteria Correlation: CRITIC). Next, an improved integrated weighting method is recommended to combine different types of weighting methods in line with the conditions of individual DMs. In Sections 3 and 4, we applied the above weighting methods in the proposed MCDM evaluation model to rank the sustainability of future nuclear fuel cycle options in China.

### 2.2. Subjective Weighting Method

Thus far, a number of subjective weighting methods have been proposed, such as AHP [28–30], Delphi [31], Simple Multi-attribute Rating Technique (SMART) [32], Digital Logic Method [33], and Scorecard [34]. These methods respectively specify the weights taking account of the preference structure of each individual DM. Thus, the complexity of execution models increases with the quantity of criteria to be assessed, and the associated uncertainties increase as well. In addition, there are diverse stakeholders involved in energy strategy planning and execution, either directly or indirectly. For collecting accurate and complete judgment information from the related individuals, much tedious work associated with questionnaire surveys is supposed to be conducted. However, this takes a lot of time and money and will also introduce some mistakes owing to inadequate or false information, ambiguous judgments, and inevitable manual errors [35].

#### 2.2.1. Fuzzy AHP

A conventional AHP is a systematic decision-making method developed by Saaty [28–30] which has also been widely used for criteria weighting. It enables merging the experiences, heuristics, and intuition of diverse DMs in performing a process of pair-wise comparison, in which the relevance between any two criteria is measured and matched, in combination with a hierarchical structure. However, the conventional AHP is mainly applied in problems of crisp-information decision making without explicit consideration of the uncertainties regarding human subjectivity in judgment. Thus, to solve realistic problems involving non-crisp information, it was proposed to integrate fuzzy theory with the AHP method (i.e., Fuzzy AHP). It can be viewed as an advanced fuzzy analytical method developed from conventional AHP and associated with linguistic variables in terms of Triangular Fuzzy Number (TFN) (e.g., Chang's extent analysis method [36]). The literature review of the fuzzy set theory and the definition of linguistic variables of TFN can be found in Appendix A.

Let I be the total number of criteria at the same hierarchy level and $\widetilde{a}_{mn}$ be a set of TFN with the relative importance of the $m$-th over the $n$-th criteria judged by each maker, for $m,\ n = \{1,\ 2,\ \cdots,\ I\}$.

Here, $\widetilde{\mathbf{A}}$ represents the matrix of pair-wise comparison containing $I \times I$ sets of TFN as shown in Equation (1):

$$\widetilde{\mathbf{A}} = \begin{bmatrix} (1,1,1) & \widetilde{a}_{12} & \cdots & \widetilde{a}_{1I} \\ \widetilde{a}_{21} & (1,1,1) & \cdots & \widetilde{a}_{2I} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{a}_{I1} & \widetilde{a}_{I2} & \cdots & (1,1,1) \end{bmatrix}, \quad (1)$$

where each element $\widetilde{a}_{mn} = (l_{mn}, m_{mn}, u_{mn})$ in the matrix is assigned the lower, median, and upper bounds, respectively, of the TFN.

As for a total $X$ of DMs, to aggregate the individual judgments for each set of pair-wise comparisons into an "aggregated hierarchy", let $\widetilde{a}^{x}_{mn}$ represent a judgment TFN given by the $x$-th DM, for $x = \{1, 2, \cdots, X\}$. It is often assumed that the individuals are of equal importance. An aggregation of each individual's judgment can be computed using a geometric mean, thus the aggregated element $\widetilde{a}'_{mn}$ is given by:

$$\widetilde{a}'_{mn} = \left(\prod_{x=1}^{X} \widetilde{a}^{x}_{mn}\right)^{1/X}, \quad (2)$$

By adopting Chang's method, the major procedures to calculate the weight of each individual criteria at the same hierarchy level are given as follows:

Step 1: Find the fuzzy synthetic extent $\widetilde{S}_m$, a TFN with respect to the $m$-th criteria:

$$\widetilde{S}_m = \sum_{n=1}^{I} \widetilde{a}'_{mn} \otimes \left[\sum_{m=1}^{I}\sum_{n=1}^{I} \widetilde{a}'_{mn}\right]^{-1}, \quad (3)$$

Step 2: Defuzzify and determine the initial non-fuzzy weight $D_m$. This process is performed by seeking the minimum degree of possibility $V$ from the related $\widetilde{S}_m$:

$$D_m = V_{min}\left(\widetilde{S}_m \geq \widetilde{S}_n\right), \; for\ m \neq n, \quad (4)$$

For example, for any two TFN of fuzzy synthetic extents $\widetilde{S}_2$ and $\widetilde{S}_1$, $\widetilde{S}_2(l_2, m_2, u_2) \geq \widetilde{S}_1(l_1, m_1, u_1)$, the degree of possibility $V\left(\widetilde{S}_2 \geq \widetilde{S}_1\right)$ is determined by $\mu_{\widetilde{S}_1 \cap \widetilde{S}_2}(d)$:

$$V\left(\widetilde{S}_2 \geq \widetilde{S}_1\right) = \mu_{\widetilde{S}_1 \cap \widetilde{S}_2}(d) = \begin{cases} 1, \; m_2 \geq m_1 \\ 0, \; l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, \; otherwise \end{cases}, \quad (5)$$

where $\mu_{\widetilde{S}_1 \cap \widetilde{S}_2}(d)$ represents the ordinate value of the highest intersection point $d$ between $\widetilde{S}_1$ and $\widetilde{S}_1$, as shown in Figure 1.

Step 3: Obtain the final weight vector of criteria via normalization:

$$\boldsymbol{W} = \begin{bmatrix} w_1, & w_2 \ldots & w_I \end{bmatrix} = \begin{bmatrix} D_1 / \sum\limits_{m=1}^{I} D_m \\ D_2 / \sum\limits_{m=1}^{I} D_m \\ \vdots \\ D_I / \sum\limits_{m=1}^{I} D_m \end{bmatrix}^{T}, \quad (6)$$

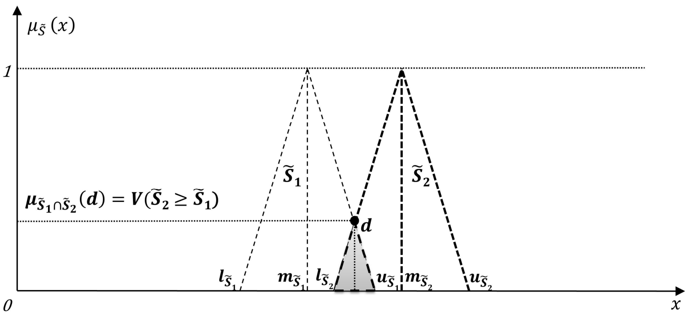


**Figure 1.** The intersection between the fuzzy synthetic extents $\widetilde{S}_1$ and $\widetilde{S}_2$.

2.2.2. Random Sampling Approach

In the conventional AHP method, one of the highlighted procedures is to build a pair-wise comparison matrix of judgments about the overall criteria given by the multiple DMs. Such a matrix is a bridge to link the linguistic variables of the individual criteria's priorities to the computable inputs of subjective preference scales. Instead of a real survey weighing process, here we applied a random sampling approach to simulate the questionnaire survey process among diverse DMs, and randomly sampled their judgments for the relative importance of the individual criteria from a symmetrical nine-level scale of $\left[\frac{1}{9}, \frac{1}{8}, \cdots, 1, 2, \cdots, 8, 9\right]$ with an equal probability. Next, all the sampling data were arranged to formulate several sets of simulated object matrices followed by a routine consistency check that effectively filters out the invalid weight coefficients (the same as the process in the conventional AHP method [28–30]). The random sampling simulation is conducive to eliciting and aggregating collective judgments in a transparent and efficient way for preliminary strategic assessment. It is also a good solution to account for the uncertain subjective preferences combined with objective appraisal method.

*2.3. Objective Weighting Method*

2.3.1. Entropy Weighting Method

The entropy concept has been adopted extensively in various scientific fields. For instance, in thermodynamics, it implies the extent of disorder in a system. In detail, it is used to determine the degree of homogeneity in the proportion of consumption among different alternatives, and informational entropy is applied to quantify the system complexity [37]. In MCDM analysis, entropy conveys the level of diversity within the evaluation metrics. That is to say, the smaller the entropy value is for a certain criterion, the more distinctive characteristics (also known as the contrast intensity) this criterion possesses to provide more available information. The procedures of the entropy weighting method are described in the following steps [38,39].

Step 1: Identify the entropy and the degree of diversity of the individual criteria. Because the different performance input data considering the total $I$ criteria for total $J$ options are quantified with distinctive units or scales, a given input metric should be normalized into a dimensionless form in advance (i.e., $r_{ij}$ represents a normalized element corresponding to the $i$-th criteria and the $j$-th alternative). The entropy for the $i$-th criteria, $e_i$ can be calculated by:

$$e_i = -\frac{1}{\ln(J)} \sum_{j=1}^{J} r_{ij} \cdot \ln(r_{ij}), \quad (7)$$

and the degree of diversity $d_i$ can be obtained from:

$$d_i = 1 - e_i, \quad (8)$$

Step 2: Calculate the entropy weights of all the criteria considered:

$$w_{i,\ entropy} = \frac{d_i}{\sum_{i=1}^{I} d_i}, \tag{9}$$

2.3.2. CRITIC Weighting Method

In addition to the application of the entropy concept used in MCDM study, another weighting method, CRITIC, proposed by Diakoulaki et al. [40] came into the spotlight recently. The CRITIC concept reveals that a higher degree of inter-dependency between criteria is more likely to result in errors in decision making. Compared to the contrast intensity considered in the entropy weighting method, the CRITIC method employs the Pearson product-moment correlation to determine the correlation weights as follows.

Step 1: Determine the correlation coefficients between criteria:

$$R_{im} = \frac{\sum_{j=1}^{J}\left(r_{ij} - \overline{r_i}\right)\left(r_{mj} - \overline{r_m}\right)}{\sqrt{\sum_{j=1}^{J}\left(r_{ij} - \overline{r_i}\right)^2 \cdot \sum_{j=1}^{J}\left(r_{mj} - \overline{r_m}\right)^2}},\ i,\ m = \{1,\ 2,\ \cdots,\ I\}, \tag{10}$$

where $\overline{r_i}$ and $\overline{r_m}$ are the average normalized values considering $i$-th and $j$-th criteria, respectively. $R_{im}$ reflects the correlation coefficient between criteria. When the value of $R_{im}$ approximates to "±1", the given two criteria are highly correlated, whereas no correlation is indicated by "0".

Step 2: Calculate the CRITIC weights of all the criteria considered:

$$w_{i,\ CRITIC} = \frac{\sum_{m=1}^{I}(1 - |R_{im}|)}{\sqrt{\sum_{i=1}^{I}\sum_{m=1}^{I}(1 - |R_{im}|)}},\ i \neq m, \tag{11}$$

### *2.4. Integrated Weighting Method*

An integrated weighting method was introduced to minimize the uncertainties that might exist in a single subjective or objective weighting method, which integrates the various weighting methods as a whole to represent a better solution [41]. Integrated weighting methods have been gradually applied in the energy projects in the recent years [42–44]. Because there are several kinds of weighting methods as noted above, we developed an improved integrated weighting method to integrate all the resultant weights as a whole. With consideration of the competing DMs at different levels of expertise and experience (namely the group members are not equally important), this improved method is capable of assigning the individual powers $\alpha_k$ to the $k$-th weighting methods (with the total number of $K$) in accordance with different DM conditions. The improved integrated weight is expressed as follows:

$$w_{i,\ IW} = \frac{\left(\prod_{k=1}^{K} w_{i,\ k}^{\alpha_k}\right)^{1/(\alpha_1+\alpha_2+\cdots+\alpha_k)}}{\sum_{i=1}^{I}\left(\prod_{k=1}^{K} w_{i,\ k}^{\alpha_k}\right)^{1/(\alpha_1+\alpha_2+\cdots+\alpha_k)}},\ \ k = \{1,\ 2,\ \cdots,\ K\}, \tag{12}$$

## 3. Description of MCDM Case Study in China

In our previous studies [7,8], we developed a dynamic model to analyze the quantitative performance of China's future nuclear fuel cycle transition from the existing to future advanced energy systems through 2100. The MCDM case study herein is based on the previous performance data combined with an integrated evaluation of the most promising nuclear energy system option for sustainable development in China. The four candidate options of nuclear fuel cycle transition presented are: (1) direct disposal of spent fuel discharged from Pressurized Water Reactors (PWRs) without recycling (hereafter abbreviated as PWR-DD); (2) single-recycling of PWR spent fuel in PWRs fueled with Mixed Uranium-Plutonium Oxide (PWR-MOX) fuels (hereafter abbreviated as MOX-DD);

(3) PWR-MOX followed by Fast Reactors (FRs) (hereafter abbreviated as PWR-MOX-FR); and (4) direct recycling of PWR spent fuel through FRs (hereafter abbreviated as PWR-FR). Each candidate option is therefore evaluated with respect to six criteria as follows: (1) resource utilization evaluated by Natural Uranium (NU) required per electricity generated; (2) nuclear waste management evaluated by accumulation of $UO_2$ spent fuel, High Level Waste (HLW) including spent fuel and reprocessing losses to be disposed, Low- and Intermediate-Level Waste (LILW) to be disposed, and Depleted Uranium (DU) per electricity generated; (3) economic competitiveness evaluated by levelized cost of electricity generation; (4) proliferation risk evaluated by plutonium inventory in the overall nuclear system and remaining separated plutonium in reprocessing facility per electricity generated; (5) environmental impact evaluated by land use, water use, and carbon emission per electricity generated; and (6) technological readiness evaluated by the deployment difficulty of First-Of-A-Kind (FOAK) commercial-scale facilities. These six criteria are associated with 12 detailed sub-criteria. Table 1 lists the above criteria and the overall evaluation metrics.

It should be noted that the last criteria of technological readiness was the only one determined qualitatively, unlike the other 11 sub-criteria which were directly derived from the material flow modeling output results, expressed as a quantitative value of energy per unit. Herein, we simplified the concept of technological readiness by evaluating the time necessary to deploy the involved nuclear technologies underlying the technology-neutral and market-preference assumptions. Thus, to maintain consistency with the selected criteria and overall evaluation metrics, the same deployment years for the corresponding FOAK commercial-scale facilities associated with the four fuel cycle options were likewise adopted (2015, 2020, 2040, and 2030, respectively) [7,8].

The hierarchical structure of this MCDM case study is shown in Figure 2. The overall hierarchy of preliminary evaluation of China's sustainable nuclear energy system can be easily visualized from Figure 2. From left to right, the problem objective is at the first level, the next level includes the criteria and sub-criteria affecting the decision making, and the four candidate options of nuclear fuel cycle transition are placed at the third level. Uncertainties analysis associated with the input data of the criteria and evaluation metrics, is not considered in the present study.

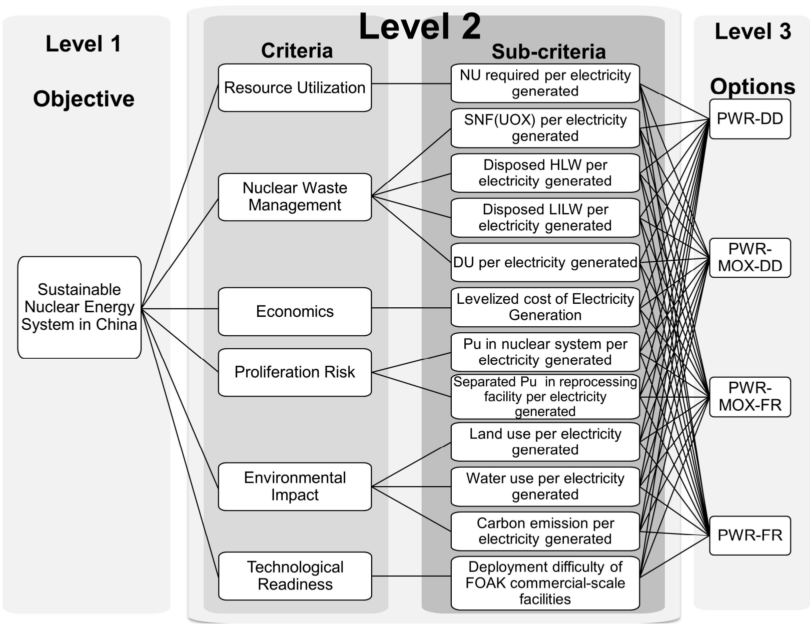


**Figure 2.** Overall hierarchical structure of the decision-making framework.

**Table 1.** Criteria and the overall evaluation metrics of China-specific sustainability combine with the four reference fuel cycle scenarios.

| **Criteria** | **Resource Utilization** | **Nuclear Waste Management** | | | | **Economics** | | **Proliferation Risk** | | **Environmental Impact** | | **Technological Readiness** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sub-criteria | NU [1] required per electricity generated | SNF(UOX) [2] per electricity generated | Disposed HLW [3] per electricity generated | Disposed LILW [4] per electricity generated | DU [5] per electricity generated | Levelized cost of electricity generation | Pu in nuclear system per electricity generated | Separated Pu in reprocessing facility per electricity generated | Land use per electricity generated | Water use per electricity generated | Carbon emission per electricity generated | Deployment difficulty of FOAK [6] commercial-scale facilities |
| Unit | tU/TWh | tHM/TWh | tHM/TWh | $m^3$/TWh | tHM/TWh | US mills/kWh | tHM/TWh | kgHM/TWh | $km^2$/TWh | ML/TWh | kg/TWh | - |
| Objective | Minimize | Minimize | Minimize | Minimize | Minimize | Minimize | Minimize | Minimize | Minimize | Minimize | Minimize | Minimize |
| PWR-DD | 25.267 | 2.362 | 2.362 | 7582 | 22.778 | 54.776 | 0.030 | 0.000 | 0.0114 | 3203 | 3,836,000 | 1.000 |
| MOX-DD | 23.314 | 0.931 | 0.192 | 6996 | 20.837 | 55.257 | 0.024 | 0.358 | 0.0090 | 2951 | 4,058,000 | 1.002 |
| PWR-MOX-FR | 18.924 | 0.533 | 0.038 | 5678 | 16.803 | 55.725 | 0.012 | 0.450 | 0.0069 | 2948 | 3,613,000 | 1.012 |
| PWR-FR | 17.112 | 0.496 | 0.011 | 5139 | 15.305 | 56.605 | 0.011 | 0.265 | 0.0063 | 3196 | 3,304,000 | 1.007 |

[1] NU: Natural Uranium. [2] SNF (UOX): Accumulation of Spent Nuclear Fuel of PHWR (Pressurized Heavy Water Reactor) and PWR (Pressurized Water Reactor) $UO_2$. [3] HLW: Accumulation of High Level Waste including spent fuel and reprocessing losses to be disposed. [4] LILW: Accumulation of Low- and Intermediate-Level Waste to be disposed. [5] DU: Accumulation of Depleted Uranium. [6] FOAK: First-Of-A-Kind.

## 4. Results and Discussions

### *4.1. Fuzzy AHP Weights*

In our study, the laborious work of random-sampling simulation, including consistency checking process are performed through a Matlab (R2015a, MathWorks, Natick, MA, USA) model. We finally stochastically selected 100 groups of simulated judgments and formulated them as 100 sets of valid pair-wise comparison matrices in line with the 12 sub-criteria at each individual hierarchy level. In principle, equal importance of the 100 simulated groups is unified. The corresponding 100 comparison matrices are well satisfied due to their high degree of consistency as well as to low repetition of diverse random elements. Table 2 presents the aggregated results of pair-wise comparison matrices in TFNs for evaluating the six high-level criteria combined with 100 groups of simulated judgments. This is followed by the aggregated TFN matrices for evaluating Criterion 2 (nuclear waste management), Criterion 4 (proliferation risk), and Criterion 5 (environmental impact) in Tables 3–5. Specifically, Criterion 4 is composed of only two sub-criteria, thus it is unnecessary to do the consistency checking on the related sampling data. For rationality, relative importance sampling was conducted based on the premise that Sub-criterion 4-1 (remaining separated plutonium in reprocessing facility) is more important than Sub-criterion 4-2 (plutonium inventory in the overall nuclear system).

Following Equations (1)–(6), the initial weights of individual criteria and sub-criteria at different levels were first calculated successively, and then were combined into the final overall weights. Table 6 lists the comparative results of overall weights calculated by conventional AHP and Fuzzy AHP. Notably, a result of zero can be obtained using Chang's Fuzzy AHP method (i.e., the weight of Sub-criterion 4-1), which means that the given criteria has an extremely small, or even a negligible influence, on the overall performance. It is largely a consequence of fuzzy synthetic extent logic for the defuzzification process to eliminate relatively nonessential criteria. For the conventional AHP method, by contrast, the related weighting value could be as low as near-zero, but nevertheless, reflecting a few individual opinions. It can be regarded that Fuzzy AHP is a natural result of the necessity for solving subjective uncertainties [36].

**Table 2.** Aggregated TFN matrices of pair-wise comparison for evaluating the six criteria.

| Criteria | Resource Utilization | Nuclear Waste Management | Economics | Proliferation Risk | Environmental Impact | Technological Readiness |
|---|---|---|---|---|---|---|
| **C** | **C1** | **C2** | **C3** | **C4** | **C5** | **C6** |
| C1 | (1.000, 1.000, 1.000) | (0.865, 1.110, 1.422) | (0.862, 1.146, 1.505) | (0.860, 1.146, 1.503) | (0.912, 1.186, 1.565) | (0.967, 1.219, 1.526) |
| C2 | (0.703, 0.901, 1.156) | (1.000, 1.000, 1.000) | (0.735, 0.933, 1.187) | (0.743, 0.924, 1.149) | (0.776, 0.999, 1.282) | (0.798, 1.050, 1.372) |
| C3 | (0.664, 0.873, 1.161) | (0.842, 1.072, 1.360) | (1.000, 1.000, 1.000) | (0.714, 0.933, 1.213) | (0.757, 0.968, 1.228) | (0.802, 1.006, 1.289) |
| C4 | (0.665, 0.873, 1.163) | (0.870, 1.082, 1.347) | (0.825, 1.072, 1.401) | (1.000, 1.000, 1.000) | (0.871, 1.113, 1.402) | (0.844, 1.099, 1.420) |
| C5 | (0.639, 0.843, 1.096) | (0.780, 1.001, 1.289) | (0.814, 1.033, 1.322) | (0.713, 0.898, 1.148) | (1.000, 1.000, 1.000) | (0.850, 1.118, 1.423) |
| C6 | (0.656, 0.820, 1.035) | (0.729, 0.953, 1.253) | (0.776, 0.994, 1.248) | (0.704, 0.910, 1.185) | (0.703, 0.894, 1.176) | (1.000, 1.000, 1.000) |

**Table 3.** Aggregated TFN matrices of pair-wise comparison for evaluating Criterion 2.

| Sub-Criteria of Criteria 2 | SNF (UOX) per Electricity Generated | Disposed HLW per Electricity Generated | Disposed LILW per Electricity Generated | DU per Electricity Generated |
|---|---|---|---|---|
| **SC 2** | **SC 2-1** | **SC 2-2** | **SC 2-3** | **SC 2-4** |
| SC 2-1 | (1.000, 1.000, 1.000) | (0.777, 0.990, 1.260) | (0.733, 0.940, 1.205) | (0.876, 1.158, 1.531) |
| SC 2-2 | (0.794, 1.010, 1.288) | (1.000, 1.000, 1.000) | (0.708, 0.893, 1.123) | (0.927, 1.168, 1.490) |
| SC 2-3 | (0.830, 1.064, 1.364) | (0.890, 1.120, 1.413) | (1.000, 1.000, 1.000) | (0.910, 1.159, 1.489) |
| SC 2-4 | (0.653, 0.863, 1.141) | (0.671, 0.856, 1.078) | (0.672, 0.863, 1.099) | (1.000, 1.000, 1.000) |

**Table 4.** Aggregated TFN matrices of pair-wise comparison for evaluating Criterion 4.

| Sub-Criteria of Criteria 4 | Pu in Nuclear System per Electricity Generated | Separated Pu in Reprocessing Facility per Electricity Generated |
|---|---|---|
| **SC 4** | **SC 4-1** | **SC 4-2** |
| SC 4-1 | (1.000, 1.000, 1.000) | (0.196, 0.233, 0.293) |
| SC 4-2 | (3.409, 4.298, 5.115) | (1.000, 1.000, 1.000) |

**Table 5.** Aggregated TFN matrices of pair-wise comparison for evaluating Criterion 5.

| Sub-Criteria of Criteria 5 | Land Use per Electricity Generated | Water Use per Electricity Generated | Carbon Emission per Electricity Generated |
|---|---|---|---|
| **SC 5** | **SC 5-1** | **SC 5-2** | **SC 5-3** |
| SC 5-1 | (1.000, 1.000, 1.000) | (0.723, 0.918, 1.184) | (0.730, 0.935, 1.182) |
| SC 5-2 | (0.730, 0.935, 1.182) | (1.000, 1.000, 1.000) | (0.761, 0.993, 1.284) |
| SC 5-3 | (0.761, 0.993, 1.284) | (0.779, 1.007, 1.314) | (1.000, 1.000, 1.000) |

**Table 6.** Comparative results of two subjective weights for the 12 sub-criteria.

| Criteria | Resource Utilization | Nuclear Waste Management | | | | Economics | Proliferation Risk | | Environmental Impact | | | Technological Readiness |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C | C1 | C2 | | | | C3 | C4 | | C5 | | | C6 |
| Sub-criteria | NU required per electricity generated | SNF (UOX) per electricity generated | Disposed HLW per energy generated | Disposed LILW Volume per energy generated | Disposed DU per energy generated | Levelized cost of Electricity Generation | Pu in nuclear system per electricity generated | Separated Pu in reprocessing facility per electricity generated | Land use per electricity generated | Water use per electricity generated | Carbon emission per electricity generated | Deployment difficulty of FOAK commercial-scale facilities |
| SC | SC 1-1 | SC 2-1 | SC 2-2 | SC 2-3 | SC 2-4 | SC 3-1 | SC 4-1 | SC 4-2 | SC 5-1 | SC 5-2 | SC 5-3 | SC 6-1 |
| Conventional AHP | 0.188 | 0.041 | 0.041 | 0.045 | 0.033 | 0.162 | 0.033 | 0.140 | 0.051 | 0.055 | 0.055 | 0.157 |
| Fuzzy AHP | 0.195 | 0.041 | 0.040 | 0.044 | 0.033 | 0.161 | 0.000 | 0.175 | 0.050 | 0.056 | 0.056 | 0.149 |

### 4.2. Entropy and CRITIC Weights

As discussed above, before calculating the entropy or CRITIC weights, we applied a common linear min-max normalization method. This was done to normalize the original data of evaluation metrics measured in different units or scales (Table 1) into a non-dimensional form with the unified monotonically decreasing utility. Then, the entropy, namely the degrees of diversity as well as the overall objective entropy weights (Table 7), were obtained through Equations (7)–(9).

Table 8 shows the Pearson correlation coefficients among the 12 sub-criteria calculated via Equation (10). The CRITIC weights were calculated using Equation (11). In Figure 3 are summarized the comparative results calculated by one subjective (Fuzzy AHP) and the two objective (Entropy and CRITIC) methods for illustrative purposes. However, it conceals large disparities among the calculated weighting results by using the individual subjective and objective methods. The variability in the results by adopting each of the weighting methods selected in this study (Fuzzy AHP, entropy and CRITIC) can be explained by the differences in the underlying factors respectively expressed in the above three typical methods: the subjective preference of decision makers, the level of diversity among a range of criteria, and the independency between criteria. Additionally, different normalization methods to pre-process the original input data of evaluation metrics as a common scale in the interval of "0–1" may also be one factor to result in weighting errors.

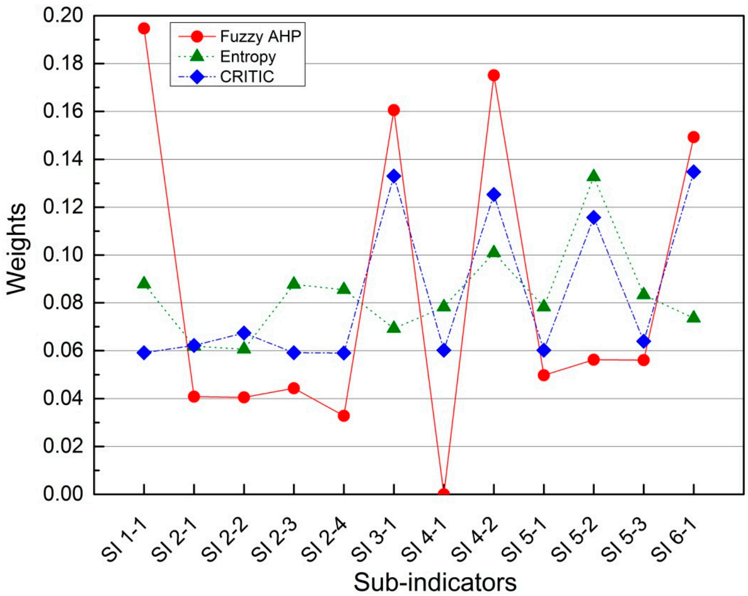


**Figure 3.** Comparative weighting results of the 12 sub-criteria by adopting four weighting methods.

**Table 7.** Calculated results of entropy weight for the 12 sub-criteria.

| Criteria | Resource Utilization | Nuclear Waste Management | | | | Economics | Proliferation Risk | | Environmental Impact | | | Technological Readiness |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C | C1 | C2 | | | | C3 | C4 | | C5 | | | C6 |
| Sub-criteria | NU required per electricity generated | SNF (UOX) per electricity generated | Disposed HLW per energy generated | Disposed LILW Volume per energy generated | Disposed DU per energy generated | Levelized cost of Electricity Generation | Pu in nuclear system per electricity generated | Separated Pu in reprocessing facility per electricity generated | Land use per electricity generated | Water use per electricity generated | Carbon emission per electricity generated | Deployment difficulty of FOAK commercial-scale facilities |
| SC | SC 1-1 | SC 2-1 | SC 2-2 | SC 2-3 | SC 2-4 | SC 3-1 | SC 4-1 | SC 4-2 | SC 5-1 | SC 5-2 | SC 5-3 | SC 6-1 |
| Entropy | 0.699 | 0.788 | 0.792 | 0.699 | 0.707 | 0.763 | 0.732 | 0.654 | 0.732 | 0.545 | 0.714 | 0.748 |
| Degree of diversity | 0.301 | 0.212 | 0.208 | 0.301 | 0.293 | 0.237 | 0.268 | 0.346 | 0.268 | 0.455 | 0.286 | 0.252 |
| Weight | 0.088 | 0.062 | 0.061 | 0.088 | 0.086 | 0.069 | 0.078 | 0.101 | 0.078 | 0.133 | 0.083 | 0.074 |

**Table 8.** Inter-criteria correlation factors according to the CRITIC method.

| Criteria | Resource Utilization | Nuclear Waste Management | | | | Economics | Proliferation Risk | | Environmental Impact | | | Technological Readiness |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C | C1 | C2 | | | | C3 | C4 | | C5 | | | C6 |
| Sub-criteria | NU required per electricity generated | SNF (UOX) per electricity generated | Disposed HLW per energy generated | Disposed LILW Volume per energy generated | Disposed DU per energy generated | Levelized cost of Electricity Generation | Pu in nuclear system per electricity generated | Separated Pu in reprocessing facility per electricity generated | Land use per electricity generated | Water use per electricity generated | Carbon emission per electricity generated | Deployment difficulty of FOAK commercial-scale facilities |
| SC | SC 1-1 | SC 2-1 | SC 2-2 | SC 2-3 | SC 2-4 | SC 3-1 | SC 4-1 | SC 4-2 | SC 5-1 | SC 5-2 | SC 5-3 | SC 6-1 |
| SC 1-1 | 1.000 | 0.858 | 0.771 | 1.000 | 1.000 | −0.958 | 0.989 | −0.591 | 0.989 | 0.032 | 0.857 | −0.840 |
| SC 2-1 | - | 1.000 | 0.988 | 0.858 | 0.869 | −0.810 | 0.909 | −0.891 | 0.909 | 0.477 | 0.474 | −0.796 |
| SC 2-2 | - | - | 1.000 | 0.771 | 0.784 | −0.737 | 0.833 | −0.915 | 0.833 | 0.558 | 0.341 | −0.715 |
| SC 2-3 | - | - | - | 1.000 | 1.000 | −0.958 | 0.989 | −0.592 | 0.989 | 0.033 | 0.857 | −0.840 |
| SC 2-4 | - | - | - | - | 1.000 | −0.954 | 0.992 | −0.612 | 0.992 | 0.058 | 0.844 | −0.850 |
| SC 3-1 | - | - | - | - | - | 1.000 | −0.919 | 0.462 | −0.919 | 0.127 | −0.856 | 0.652 |
| SC 4-1 | - | - | - | - | - | - | 1.000 | −0.700 | 1.000 | 0.178 | 0.780 | −0.895 |
| SC 4-2 | - | - | - | - | - | - | - | 1.000 | −0.700 | −0.820 | −0.102 | 0.765 |
| SC 5-1 | - | - | - | Symmetrical | - | - | - | 1.000 | 0.178 | 0.780 | −0.895 | - |
| SC 5-2 | - | - | - | - | - | - | - | - | - | 1.000 | −0.456 | −0.407 |
| SC 5-3 | - | - | - | - | - | - | - | - | - | - | 1.000 | −0.604 |
| SC 6-1 | - | - | - | - | - | - | - | - | - | - | - | 1.000 |

### 4.3. Integrated Weights

The original integrated weights equally assign the power for all the sets of weight and synthesize them by using a simple geometric mean. The above-mentioned weights (Figure 3) are integrated as a whole, namely improved integrated weight, which can be calculated through Equation (13) for the present case study.

$$w_{i,\ IW} = \frac{\left[\left(w_{i,\ Fuzzy\ AHP}\right)^{\alpha}\cdot\left(w_{i,\ Entropy}\right)^{\beta}\cdot\left(w_{i,\ CRITIC}\right)^{\gamma}\right]^{\frac{1}{(\alpha+\beta+\gamma)}}}{\sum_{i=1}^{I}\left[\left(w_{i,\ Fuzzy\ AHP}\right)^{\alpha}\cdot\left(w_{i,\ Entropy}\right)^{\beta}\cdot\left(w_{i,\ CRITIC}\right)^{\gamma}\right]^{\frac{1}{(\alpha+\beta+\gamma)}}},\ i = \{1,\ 2,\ \cdots,\ 12\}, \quad (13)$$

Given that the members of DM group might be from across sectors and industries with diverse levels of expertise/experiences in developing national energy strategies, as well as the complexity level of future nuclear energy system that the CDMs (Chief Decision Makers) would like to put forward, these could be reflected in the power assignment for the individual weighting methods. Herein, we proposed five potential cases underlying the roles of group composition and directly reflected the coefficient changes in the Equation (13), these DM cases are as follows.

Case 1: The DM group consists of the members from the nuclear-irrelevant fields; thus, they lack experience in giving credible subjective evaluation scores for nuclear projects. Hence, the CDMs have to select using only objective weights and assign equal power for each objective method, while discarding the subjective weights. Consequently, we have $\alpha = 0, \beta = \gamma = 1$.

Case 2: All the DMs possess a high level of expertise in nuclear technologies and typically have rich experiences in decision making. In view of the high level confidence, the CDMs simply adopted the subjective weights as the final weights, completely accepting the professional judgments from DM group. In this case, $\alpha = 1,\ \ \beta = \gamma = 0$, that is, the integrated weights are equal to the Fuzzy AHP weights.

Case 3: To maintain neutrality, the CDMs determined to adopt a relatively conservative approach. They assign an equal power to both objective and subjective weighting systems as follows: $\alpha = 1, \beta = \gamma = 0.5$.

Case 4: The DMs can assign subjective weights in light of their expertise and background. Upon the consideration that objective weights are somewhat persuasive, the CMDs elected to assign larger power (from one to two) to the DM judgments (i.e., $\alpha = 2,\ \ \beta = \gamma = 0.5$).

Case 5: The CDMs adopt the most conservative method regardless of the distinctions of subjective and objective weighting methods. An equal power was given to all the weights considered, thereby obtaining more fair and accurate integrated weights (i.e., $\alpha = \beta = \gamma = 1$).

The improvement in the integrated weighting method proposed here are therefore twofold: first, to flexibly adjust the preference coefficients on different weighting methods according to the practical application, and second, to directly reflect the real system complexity associated with the group decision support environments. The final integrated weighting results for the overall evaluation metrics in the five DM cases are listed in Table 9.

**Table 9.** Final integrated weighting results for the 12 sub-criteria in the five DMs' cases.

| **Criteria** | **Resource Utilization** | **Nuclear Waste Management** | | | | **Economics** | **Proliferation Risk** | | **Environmental Impact** | | | **Technological Readiness** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **C** | **C1** | **C2** | | | | **C3** | **C4** | | **C5** | | | **C6** |
| Sub-criteria | NU required per electricity generated | SNF (UOX) per electricity generated | Disposed HLW per energy generated | Disposed LILW Volume per energy generated | Disposed DU per energy generated | Levelized cost of Electricity Generation | Pu in nuclear system per electricity generated | Separated Pu in reprocessing facility per electricity generated | Land use per electricity generated | Water use per electricity generated | Carbon emission per electricity generated | Deployment difficulty of FOAK commercial-scale facilities |
| SC | SC 1-1 | SC 2-1 | SC 2-2 | SC 2-3 | SC 2-4 | SC 3-1 | SC 4-1 | SC 4-2 | SC 5-1 | SC 5-2 | SC 5-3 | SC 6-1 |
| Case 1 | 0.073 | 0.063 | 0.065 | 0.073 | 0.072 | 0.098 | 0.070 | 0.114 | 0.070 | 0.126 | 0.074 | 0.101 |
| Case 2 | 0.195 | 0.041 | 0.040 | 0.044 | 0.033 | 0.161 | 0.000 | 0.175 | 0.050 | 0.056 | 0.056 | 0.149 |
| Case 3 | 0.109 | 0.067 | 0.068 | 0.072 | 0.068 | 0.107 | 0.055 | 0.113 | 0.072 | 0.089 | 0.076 | 0.105 |
| Case 4 | 0.089 | 0.074 | 0.075 | 0.078 | 0.077 | 0.092 | 0.076 | 0.097 | 0.077 | 0.093 | 0.079 | 0.092 |
| Case 5 | 0.116 | 0.071 | 0.071 | 0.073 | 0.067 | 0.110 | 0.033 | 0.114 | 0.075 | 0.083 | 0.079 | 0.108 |

Figure 4 shows the comparative integrative weights directly. Under different DM cases, the obtained sets of weights to Sub-criteria 1-1 (NU required), 3-1 (levelized cost of electricity), 4-2 (separated Pu in reprocessing facility) and 6-1 (deployment difficulty of FOAK commercial-scale facilities) are obviously higher than the others. The question "Which weighting method is most suitable and fair to evaluate the importance of each criteria" is essential for the final decision making, but different to answer. Herein, the integrated weighting method has played a subtle role in influencing the final decision making by merging perfectly some extremely biased subjective preferences with the statistical objective correlation coefficients.

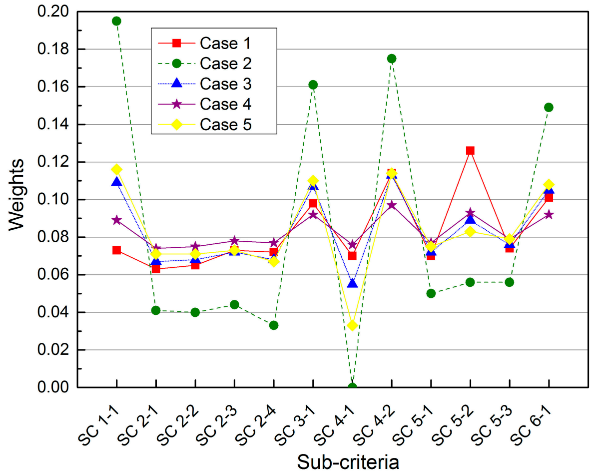


**Figure 4.** Comparative integrated weighting results of the 12 sub-criteria in the five DMs' cases.

## *4.4. Final Ranking Results of TOPSIS and PROMETHEE II*

The resultant integrative weights (Table 9) were then applied in the MCDM case study via the execution of both TOPSIS and PROMETHEE II methods, finally to obtain an overall ranking of the reference fuel cycle candidate options.

For the TOPSIS method, the TOPSIS scores, namely, the separation values of the four fuel cycle candidate options from both the positive and negative ideal solutions based on the five case assumptions, were calculated and are presented in Table 10.

For the PROMETHEE II method, an outranking model was built to calculate the net flow and obtain the final rankings of the candidate options. First, we applied the level preference function to evaluate the qualitative criteria (C6), and the V-shaped function to evaluate the quantitative criteria (C1–5, respectively) [45]. Second, in consideration that the values of the preference threshold in our study were not experimental values to be closely approximated, they might be somewhat arbitrarily specified for some specific values underlying the characteristics of individual criteria. Herein, we applied an objective method suggested by Rogers et al. [46] instead subjective assumption for assessing the appropriateness of the evaluation criteria. Accordingly, the calculation results of the overall net ranking flows for each nuclear fuel cycle option are listed in Table 10.

**Table 10.** Calculated results of TOPSIS and PROMETHEE under the five DMs' cases.

| Options | TOPSIS TOPISIS Scores | | | | | PROMETHEE II Net Outranking Flow Values | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
| PWR-DD | 0.462 | 0.650 | 0.452 | 0.390 | 0.450 | −0.254 | 0.027 | −0.244 | −0.319 | −0.228 |
| MOX-DD | 0.492 | 0.330 | 0.505 | 0.545 | 0.514 | −0.058 | −0.058 | −0.088 | −0.100 | −0.091 |
| PWR-MOX-FR | 0.526 | 0.329 | 0.536 | 0.598 | 0.538 | 0.156 | −0.107 | 0.133 | 0.196 | 0.120 |
| PWR-FR | 0.675 | 0.535 | 0.685 | 0.732 | 0.686 | 0.155 | 0.138 | 0.199 | 0.224 | 0.200 |

Figure 5 summarizes the comparative MCDM ranking results for China's sustainable nuclear energy system transitional path with respect to the five DMs' cases. The reference cases are located at the respective locations in the two-dimensional radar chart. This indicates that the overall ranking results using TOPSIS mostly agree well with the PROMETHEE II rankings regardless of the effects of different DM considerations. From a sustainability perspective, the first rank option is the PWR-FR fuel cycle while the last one is the PWR-DD fuel cycle, under the different DM cases. In addition, the rankings of the other reprocessing and recycling options (i.e., MOX-DD and PWR-MOX-FR) principally performed better than the PWR-DD option, the second-, or third-best option. The large exception noted was in Case 2: the rankings differ significantly from other cases in both TOPSIS and PROMETHEE II results. Case 2 was purely based on the subjective weights derived from the DM judgments. For enhancing the credibility and accuracy in subjective weights, we adopted a Fuzzy AHP application combined with random sampling method, which can reduce the subjective uncertainties caused by human perception, as well as of aggregating abundant conflicting opinions from the individual DMs. However, the methodological concerns could only help to strengthen the rationality of subjective weights consistently with the theoretical structure, rather than eliminating the inherent uncertainties of a certain technique. The large ranking variance in Case 2, on the other hand, is further proof of the importance of weighting system for decision making. The criteria weights directly influence the final ranking results of MCDM evaluation. It is necessary to stress the uncertainties caused by applying any single type of weighting method. Therefore, an integrated weighting method was recommended, to keep a balance between the subjective and objective weighting bias, and thereby increase the legitimacy of the outcome, as well as provide reliable and robust support for decision-making. Moreover, the proposed improved integrated weighting method based on the practical DM cases enabled us to assign more flexible powers to the specific objective/subjective weights, and to be more in line with the group decision support environments. Herein, we addressed the improvement of the integrated weighting approach, along with the application in a country-specific decision making analysis about future nuclear energy development.

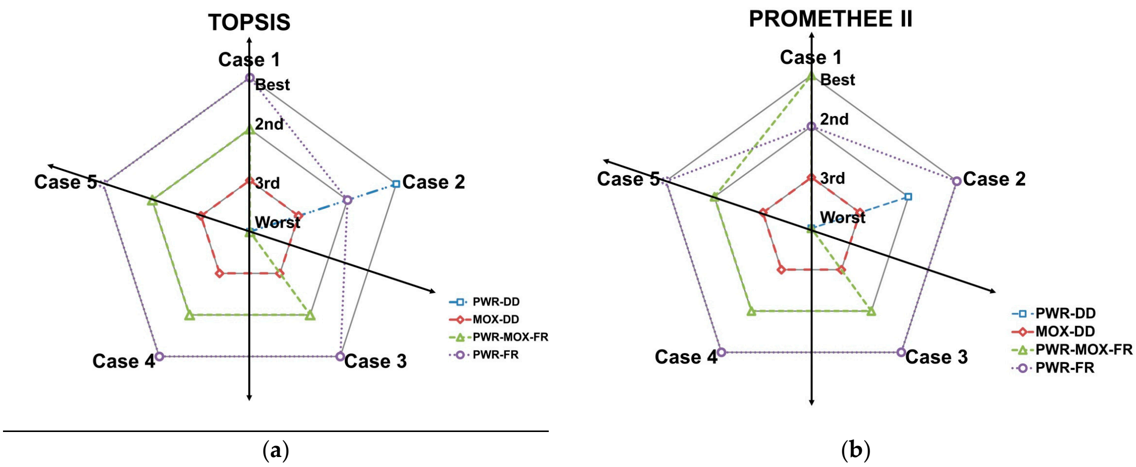


**Figure 5.** Comparative MCDM rankings for evaluating sustainable nuclear fuel cycle options under the cases of DMs: (**a**) TOPSIS; and (**b**) PROMETHEE II.

However, overall, each MCDM method has distinctive advantages and disadvantages with respect to the pursuit of preferable solutions. In this investigation, the comparative ranking results of both TOPISIS and PROMETHEE II methods applied in the MCDM case study of China's nuclear energy are proven robust and consistent. It is of great importance that various MCDM techniques are comparatively applied to evaluate and rank the transitional options of nuclear fuel cycle projects. The results of MCDM analysis are more rational and robust in the sustainable energy decision making.

## 5. Conclusions

While the prospects look bright for nuclear energy development in China, no consensus about an optimum transitional path towards sustainability in the nuclear fuel cycle has been achieved. The problem of decision analysis for national energy strategies can be characterized as dynamically complex, and which needs to anticipate the intended goal pursuits and unintended consequences of interventions in a dynamically evolving situation. A thorough set of decisions about China's future nuclear energy systems has been proposed here based on the self-developed dynamic simulation code. It enables: (1) quantification of a range of tangible and intangible effects of four nuclear fuel cycle options and assessment of their consequential benefits and risks from a multidisciplinary viewpoint; (2) identification of sustainability evaluation metrics for nuclear energy in the Chinese context; and (3) provision of decision support for analyzing the trade-offs involved in selecting a promising transitional path of nuclear fuel cycle toward sustainable development. This study is innovative in that it incorporates currently available modeling techniques into a strategic MCDM framework to perform a preliminary integrated assessment on the critical sustainability issues of nuclear energy in China. Above all, an improved integrated weighting method for MCDM was applied for the first time in a nuclear fuel cycle evaluation study. This integrated method synthesizes diverse types of weighting methods to evaluate the conflicting criteria among competing DMs at different levels of expertise and experience. It makes some technical contributions to address the gaps in effectiveness and reliability of any single weighting system, while making it more adaptable to group decision support environments.

The results of the case study suggest that the PWR-FR fuel cycle is the most competitive candidate option while the PWR-DD fuel cycle is the least attractive option for China, from a sustainability perspective. This confirms the value of currently ongoing programs about reprocessing and recycling of spent nuclear fuel for sustainable nuclear energy development, and fully reflects the importance of the MCDM evaluation for developing national energy strategies as well. For R&D development in the long term, our study provides important support information for fuel cycle project prioritization. However, as the results showed, the promising transitional path of nuclear fuel cycle associated with FR recycling and the related reprocessing technologies could not meet all the evolving demands of nuclear energy development considering the country-specific dimensions. Likewise, such a preliminary study cannot conclude a determined decision on a certain preferred fuel cycle option at a national scale. There is still a long way for China to engage in the exploration of the nuclear energy R&D works for sustainability based on well-informed decision making.

In summary, the presented study provides a more reliable, effective, and systematic decision support tool based on an analytical MCDM framework. In a country-specific nuclear fuel cycle assessment study, the application of the integrated weighting method combined with the tangible case assumption of DMs, makes the overall evaluation more realistic and reliable. However, it should be noted that the MCDM study can only help the DMs to select a relatively preferable option from the existing candidate pool. The resultant option enables reflecting the DMs' timely preference priorities, rather than ensuring providing an absolutely correct or permanent solution to the problem [17]. Meanwhile, the input information of which MCDM study underlying is always associated with uncertainties (e.g., the identified evaluation criteria, the weights assigned to each criterion, and the selected MCDM techniques). Additionally, the limitation associated with each respective subjective or objective weighting method is perceived but inevitable. As a future direction, it should be added that the MCDM framework proposed herein is applied to a more appropriated sustainability evaluation metrics for assessing China's nuclear energy system transition incorporating the experts' judgment and DMs' preference. In addition, the robustness of uncertainty modeling and agility in the decision-making process deserve more in-depth discussion. As another direction, further application of the dynamic performance modeling and integrated analysis of more potential nuclear fuel cycle options involving the various current ongoing nuclear technology programs for developing national energy strategies is worthwhile.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

### *Appendix A.1. Fuzzy Set Theory*

For classical (crisp) set theory, the membership of elements in a set is assessed in a binary manner, according to a bivalent condition defined as an element that either belongs or does not belong to that set [47]. Zadeh's fuzzy set theory [48,49] is applied to model the imprecise and vague information conveyed by individual judgments. A fuzzy set is characterized by a membership function, which is utilized to assign each object a grade of membership ranging between "0" and "1". Likewise, a fuzzy set $\widetilde{A}$ in $\boldsymbol{X}$ is defined by:

$$\widetilde{A} = \{x,\ \mu_{\widetilde{A}}(x)\},\ x \in \boldsymbol{X}, \tag{A1}$$

where $\mu_{\widetilde{A}}(x)$: $\boldsymbol{X} \to [0,1]$ is the membership function of $\widetilde{A}$, namely, the degree of pertinence of $x$ in $\widetilde{A}$. When $\mu_{\widetilde{A}}(x)$ equals "0" or "1", $x$ does not or completely belongs to the fuzzy set $\widetilde{A}$ as in classical set theory, except for the difference that, in the case of $\mu_{\widetilde{A}}(x)$ assigned a value between "0" and "1", $x$ will partially belong to the fuzzy set $\widetilde{A}$ [50].

The fuzzy extension of Saaty's priority theory was proposed by Laarhoven and Pedrycz, and they defined it as "a fuzzy subset of real numbers, representing the expansion of the idea of the confidence interval" [51]. They introduced the TFN and applied it in the MCDM study. Generally, TFN is used to depict a certain DM's intuitive preferences among the individual criteria or candidate options by means of a reciprocal comparison matrix. The membership function of a TFN is represented as follows (Figure A1).

$$\mu_{\widetilde{A}}(x) = \begin{cases} \frac{x-l}{m-l},\ l \le x \le m \\ \frac{u-x}{u-m},\ m \le x \le u \\ 0,\ otherwise \end{cases}, \tag{A2}$$

in which $l$, $m$ and $u$ are the lower, median and upper bounds, respectively, of the fuzzy number $\widetilde{A}$. The TFN is denoted as $\widetilde{A} = (l,m,u)$, and the following Equations (A3)–(A7) are the main algebraic operations laws of two TFNs: $\widetilde{A}_1 = (l_1,m_1,u_1)$ and $\widetilde{A}_2 = (l_2,m_2,u_2)$.

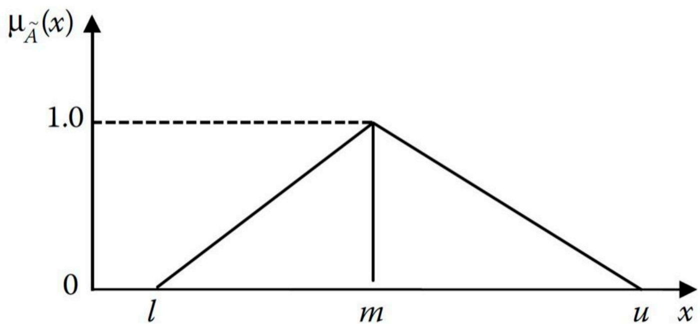


**Figure A1.** The membership function of the triangular fuzzy number (TFN).

TFN addition law:

$$\widetilde{A}_1 \bigoplus \widetilde{A}_2 = (l_1,m_1,u_1) \bigoplus (l_2,m_2,u_2) = (l_1+l_2, m_1+m_2, u_1+u_2),\ l,m,u \ge 0, \tag{A3}$$

TFN subtraction law:

$$\widetilde{A}_1 \ominus \widetilde{A}_2 = (l_1, m_1, u_1) \ominus (l_2, m_2, u_2) = (l_1 - l_2, m_1 - m_2, u_1 - u_2),\ l, m, u \geq 0, \tag{A4}$$

TFN multiplication law:

$$\widetilde{A}_1 \otimes \widetilde{A}_2 = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2), l, m, u > 0, \tag{A5}$$

TFN division law:

$$\widetilde{A}_1 \oslash \widetilde{A}_2 = \frac{(l_1, m_1, u_1)}{(l_2, m_2, u_2)} = \left(\frac{l_1}{l_2}, \frac{m_1}{m_2}, \frac{u_1}{u_2}\right),\ l, m, u > 0, \tag{A6}$$

TFN reciprocal law:

$$\widetilde{A}^{-1} = (l, m, u)^{-1} = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right),\ l, m, u > 0, \tag{A7}$$

*Appendix A.2. Linguistic Variables of TFN*

The conventional quantification of a fuzzy set is not competent to define situations that are extremely complex in any specific situation. Herein, the qualitative aspects of human thought are described in linguistic terms and converted to linguistic variables of a fuzzy set in the universe of discourse, combined with the respective membership function [50,51]. A linguistic variable is a variable with values expressed by words or sentences in a natural or artificial language. Each membership function (scale of fuzzy number) is defined by three elements of the symmetric TFN (i.e., the left, middle, and right points of the range over the above noted function in Equation (A2)). The linguistic comparison terms, with respect to a fuzzy nine-level scale utilized in this paper, are shown in Figure A2 and Table A1.

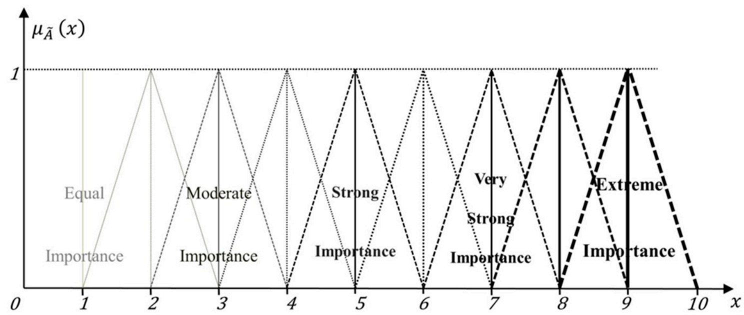


**Figure A2.** The linguistic scales of relative importance regarding TFN for pair-wise comparison of criteria.

**Table A1.** Membership function of linguistic and fuzzy number scale [51].

| Fuzzy Number | Linguistic Scales | Scale of Fuzzy Number |
|---|---|---|
| $\widetilde{1}$ | Equal importance | (1,1,1) |
| $\widetilde{3}$ | Moderate importance | (2,3,4) |
| $\widetilde{5}$ | Strong importance | (4,5,6) |
| $\widetilde{7}$ | Very strong importance | (6,7,8) |
| $\widetilde{9}$ | Extreme importance | (8,9,10) |
| $\widetilde{2},\widetilde{4},\widetilde{6},\widetilde{8}$ | Intermediate values between the above | |

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