A two-stage decision framework for inland nuclear power plant site selection based on GIS and type-2 fuzzy PROMETHEE II: Case study in China

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Abstract
Site selection is a critical strategic decision for inland nuclear power plants which have broad prospects of development. However, several shortcomings exist in current researches, such as the incomplete decision frameworks, the indiscriminately treated properties, and the information loss. To handle the above flaws, this study establishes a two-stage site selection framework. In the first stage, the geographic information system and preselection criteria are applied to identify suitable alternatives. And in the second stage, the interval type-2 fuzzy PROMETHEE II and suitability criteria are utilized to rank alternatives and select the optimal site, where different preference functions are selected accordingly. Therefore, the interval type-2 fuzzy numbers are adopted to describe the uncertainty and vagueness in calculation, without being transformed to exact value. Finally, based on the proposed two-stage decision framework, a case of Hunan, Hubei, and Jiangxi provinces is studied, to demonstrate its validity and practicability. The results show that S8 is selected as the optimal site for its strong government support, convenient fuel transport, and land availability. This study not only enriches the material databases for inland nuclear power plant site selection, but also offers theoretical reference for site selection studies of various objects.

KEYWORDS
geographic information system, inland nuclear power plant, interval type-2 fuzzy numbers, PROMETHEE II, two-stage decision framework

1 | INTRODUCTION

Due to global warming, energy security, and the demand for sustainable power development,¹ the share of clean energy is continuously expanding in the international market. Nuclear power is an indispensable part of the smart energy framework.² Compared to other clean energy, nuclear power has many advantages such as reliability of power supply, high
energy density, and low operation costs. As a consequence, the Chinese government gradually pays more attention to the development of nuclear power. At present, China’s nuclear power plants (NPPs) in the construction or operation period are all located in the southeast coastal regions. According to China’s Medium and Long-Term Development Plan for Nuclear Power (2005-2020), the installed capacity of nuclear power is planned to reach 88 GW by 2020. However, coastal nuclear power plants (CNPPs) alone cannot meet the planning needs. Compared with CNPPs, inland nuclear power plants (INPPs) are less likely to face natural disasters such as tsunamis and are closer to the load center, making electricity transportation more convenient. The Chapter 30 of the 13th Five-Year Plan, released during the two sessions in 2016, made it clear that preliminary work on inland nuclear power projects needs to be promoted more actively.

The site selection of INPPs, as a strategic decision, not only is critical throughout the life cycle, but also has a significant impact on sustainable development of the region. Natural factors, social factors, economic factors, environmental factors, and so on have a great impact on the power development, which INPPs site selection must take into account. On the one hand, NPPs have extremely stringent requirements for the site, and inappropriate site selection can seriously affect the safety and benefits. On the other hand, due to the Not-In-My-Back-Yard (NIMBY) effect, if the INPP site cannot meet the public demand, the nuclear power project will not start on schedule and even lead to the termination of the project.

At present, there is a certain research basis for the site selection of CNPPs, but studies on INPPs site selection are scarce. Meanwhile, existing decision-making frameworks for NPP site selection have several drawbacks, standing in the way to identify optimal INPP site scientifically and accurately. (a) The site selection framework is incomplete. INPP site selection is a two-stage decision problem, including identification of suitable alternative sites and selection of the optimal site. But most of the existing studies only focus on the second stage, and a few studies take only the first stage into account. (b) The properties of criteria are treated indiscriminately. Criteria with multiple properties are involved in INPP site selection. For some criteria, subtle value differences between alternatives point to strict superiority, while for others, once the criteria values reach a certain level, differences between alternatives can be ignored. However, existing studies applied the same kind of operator to different criteria. (c) The uncertainty and vagueness are not taken seriously. For one thing, INPP site selection is a forward-looking process, meaning that site conditions are uncertain at the start of construction. For another, the decision information of qualitative criteria depends on the judgment of experts, while imprecise and vague concepts exist in human language. However, fuzzy computation is transferred to deterministic environments in these literature on hand, which led to the loss of decision information.

Judging from aforementioned analysis, this paper proposes a two-stage decision framework for INPP site selection based on geographic information system (GIS) and interval type-2 fuzzy PROMETHEE II (IT2F-PROMETHEE II). Possible innovations are as follows: (a) A two-stage site selection framework, combining GIS and multiple criteria decision-making (MCDM) method, is firstly applied to identify suitable alternative sites and select the optimal site, respectively. Accordingly, this paper establishes a two-stage criteria system of INPP site selection, including preselction criteria and suitability criteria. (b) To treat the properties of criteria seriously, PROMETHEE II method with six preference functions is utilized for criteria calculation, in which the preference function and thresholds values are identified in accordance with the characteristic of each criterion. (c) This paper applies interval type-2 fuzzy numbers (IT2FNs), without being transformed to exact value, to reflect the uncertainty and vagueness of decision environment. To the best of our knowledge, this is the first time to propose a two-stage site selection framework for INPPs, and the IT2F-PROMETHEE II has not been applied to INPP site selection.

Main contributions can be concluded as four aspects. Firstly, the two-stage criteria system, identifying multiple factors, can provide a certain basis for scholars to carry out relevant researches on inland nuclear power, such as risk assessment, sustainability evaluation, and investment decision. Secondly, the method framework is improved into two stages, which not only enriches the INPP site selection material database, but also provides reference for site selection studies of various objects. Thirdly, two improvements are made on IT2F-PROMETHEE, including the application of different preference functions and throughout fuzzy calculation, to evaluate more scientifically and accurately. Last but not least, this paper provides valuable guidance and advice for the government and relevant departments in nuclear power construction planning.

The remainder of this paper is structured as follows: Section 2 analyzes the research status of NPP site selection and some related methods applicable to site selection research. In addition, the shortcomings in the existing researches are pointed out, which are improved in this study. Section 3 identifies and classifies the factors of INPP site selection. Section 4 elaborates the basic theory of the IT2FNs, interval type-2 fuzzy analytic hierarchy process (IT2F-AHP) and IT2F-PROMETHEE II, as well as the research framework of this paper. A case study of Hunan, Hubei, and Jiangxi provinces is illustrated in Section 5, while the sensitivity analysis about INPP site selection criteria is carried. Finally, Section 6 draws a conclusion.
2 | LITERATURE REVIEW

INPP site selection is a significant decision throughout the life cycle. So far, some valuable researches on NPP site selection have been done, as shown in Table 1.

2.1 | Site selection framework

Basri et al. comprehensively investigated the factors affecting nuclear power site selection, emphasizing the minimization of social and environmental impacts. Kassim et al. established a two-stage criteria system. Certain sites were removed by avoidance criteria in the first stage, and alternative ranking was carried out by suitability criteria in the second stage. Taking into account social, natural environmental, investment environment, and economic factors, Wu et al. applied gray comprehensive evaluation method to study the location of INPPs. Kurt contrasted the two MCDM methods that generalized Choquet fuzzy integral approach and fuzzy Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) were used to sort the alternative sites of NPPs, respectively. Ekmekcioğlu et al. combined SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis with MCDM methods, considering both internal and external influence factors. Erol et al. ranked the alternative NPP sites based on fuzzy Entropy and compromise programming.

In the above researches, scholars provided relatively scientific and effective site selection models. However, the application premise of the above models is that a limited number of relatively suitable alternatives have been identified. In practice, alternatives are not readily available but need to be determined through certain explorations. It is critical to identify suitable alternatives in wide areas, which directly affects whether the later MCDM stage can select the optimal site.

To solve the problem, GIS has been introduced for site selection. Importing population density and seismic geological

| Scholars          | Year | Methodology                  | Criteria                                                                 |
|-------------------|------|------------------------------|--------------------------------------------------------------------------|
| Ekmekcióğlu et al| 2011 | SWOT analysis                | Internal criteria and external criteria                                  |
| Wu et al          | 2013 | Gray comprehensive evaluation| Social factors, natural environmental factors, investment environment factors, and economic factors |
| Erol et al        | 2014 | Fuzzy Entropy and compromise programming | Population density, geological and seismological issues, atmospheric conditions, cost factors, and risk factors |
| Kurt              | 2014 | Generalized Choquet fuzzy integral and fuzzy TOPSIS | Geological factors, meteorological factors, socioeconomic factors, and geographical factors |
| Abudeif et al     | 2015 | Boolean logic and WLC        | Safety and health criteria, environmental and social criteria, and engineering and economic criteria |
| Barzehkar et al   | 2016 | Boolean logic and WLC        | Physical factors, biological factors, and socioeconomic factors          |
| Basri et al       | 2016 | A safety approach            | External factors, radiological impact, and feasibility of emergency plans |
| Kassim et al      | 2016 | AHP and expert judgment ranking method | Impact from the plant to the site, impact from the site to the plant, and cost impact |
| Yaar et al        | 2016 | GIS                          | Demographic criteria, seismologic criteria, and geologic criteria         |
| Baskurt et al     | 2018 | GIS                          | Exclusionary criteria, screening criteria, and discretionay criteria        |
| Shahi et al       | 2018 | GIS and DEMATEL              | Biological environment, socioeconomic environment, and physical environment |
conditions into GIS, Yaar et al.\textsuperscript{18} removed restricted areas and a nuclear power plant allowed area of 569 square kilometers is presented. Shahi et al.\textsuperscript{19} presented the indicator values in the GIS and overlaid the layers according to certain weights, which are calculated by fuzzy decision-making and trial evaluation laboratory (DEMATEL) method. And a conclusion was drawn that “access to shoreline” was the most important for nuclear power site selection. Abudeif et al.\textsuperscript{20} and Barzehkar et al.\textsuperscript{21} firstly applied Boolean logic to exclude the inappropriate areas, and then, the weighted linear combination (WLC) method was used to overlay each layer to present the priority of the potential nuclear power plant sites. Baskurt et al.\textsuperscript{22} screened out rejected areas based on exclusionary criteria and identified potential areas in GIS. Further, according to the performance of discretionary criteria in GIS, five preferred candidate sites for nuclear power plant were selected.

As shown in the above study, GIS can be applied to select several candidate sites in a wide area scientifically and effectively. However, the current application of GIS in nuclear power site selection is just to be combined with MCDM methods of weight calculation, such as analytic hierarchy process (AHP), in the stage of overlaying layers. And there is no further selection of the optimal site after identifying the candidate sites. Different from wind farms and photovoltaic power plants, nuclear power plants have strict requirements on the site and limits on their numbers generally. Therefore, it is very necessary to further sort the candidate sites to select the optimal one.

2.2 Multiple criteria decision-making approaches

Currently, some MCDM techniques have been applied in the selection process of alternatives successfully, such as WLC,\textsuperscript{23} TOPSIS,\textsuperscript{24} VIKOR (Vlsekriterijumska Optimizacija I Kompromiso Resenje),\textsuperscript{25} TODIM (an acronym in Portuguese for interactive and multicriteria decision-making),\textsuperscript{26} and ELECTRE (Elimination et Choix Traduisant la Realite).\textsuperscript{27} The characteristic analyses of the mentioned methods are shown in Table 2. Nevertheless, the above methods do not take the different characteristics of different criteria into account, which may cause some deviations in the calculations. Luckily, the PROMETHEE method, with multiple preference functions, provides a solution to this problem. To date, the PROMETHEE has been widely used in a variety of selection issues. Hernandez-Perdomo et al.\textsuperscript{28} executed the PROMETHEE approach to assess and rank multiple portfolios holistically. Petrovic et al.\textsuperscript{29} employed the PROMETHEE II to select the most appropriate project and refrigerant. Arikan et al.\textsuperscript{30} evaluated 10 disposal alternatives of solid waste via the PROMETHEE to select the most feasible one. Based on the PROMETHEE method, Wu et al.\textsuperscript{31} sorted the social sustainability of each small hydropower alternative. Regrettably, existing articles do not give full play to the advantages of the PROMETHEE method that only one preference function is used for evaluation. Thus, this paper tries to introduce the PROMETHEE II method, choosing different preference functions accordingly, to rank INPP candidates.

2.3 Uncertainty description

The traditional PROMETHEE method, with real numbers, cannot deal with uncertainty and vagueness in the INPP site selection process. On the one hand, site selection is a forward-looking decision-making, and INPP projects may take several years or even ten years to build, which means site conditions are likely to change in the future. On the other hand, there are multiple qualitative criteria of natural, social, economic, and environmental factors in the site evaluation, Table 2: Common MCDM methods and characteristic analyses

| Method     | Processes                                                                 | Characteristics                                                      |
|------------|---------------------------------------------------------------------------|-----------------------------------------------------------------------|
| WLC        | Get the global value of each alternative through the set aggregation operators | Combining different and even conflicting indicators which easily lead to loss and distortion of information |
| TOPSIS     | Sort according to the proximity of evaluation objects to idealized target | Impossible to specifically show the reasons why each alternative meet or not meet the conditions and not conducive to the improvement after sorting |
| VIKOR      | Compromise sort alternatives by maximizing group benefits and minimizing individual regrets | Unable to quantify the correspondence between the recession coefficient and the decision maker's risk aversion and loss |
| TODIM      | Obtain the overall perceived dominance based on the attribute values of other alternatives | Require many parameters and not fully utilize the information provided by the decision matrix |
| ELECTRE    | Eliminate inferior alternatives by constructing weak dominance relationships and gradually reduce the set of alternatives | Treat the properties of criteria seriously, avoid the loss of information during the process and the influence of decision compensation on the evaluation results |
whose value depends on the subjective evaluation of experts, while imprecise and vague concepts exist in human language. For the above considerations, it is important to collect information appropriately.

As an extension of type-1 fuzzy set, each element membership of type-2 fuzzy set in the domain is a type-1 fuzzy set instead of a single value. Therefore, it provides greater freedom and flexibility in expressing uncertainty. However, the computational complexity has affected its development in applications. Composed by two trapezoidal fuzzy numbers, IT2FNs are depicted by both primary and secondary memberships. For one thing, the calculation of IT2FNs is relatively simple compared with general type-2 fuzzy numbers. For another, IT2FNs are more accurate in uncertainty modeling compared with type-1 fuzzy numbers. In this work, IT2FNs are combined with PROMETHEE II to minimize uncertainty and vagueness, which have been applied to multiple studies. Ayodele et al used applied fuzzy sets to represent the language judgment of experts in wind farm site selection decisions. Xu et al used IT2FNs to explore supplier selection under. Ghorabaee et al used IT2FNs to address the uncertainty of information in green supplier evaluation. Xu et al executed IT2FNs to model language terms to reduce information leakage effectively. However, the above study prematurely defuzzifies the IT2FNs in the calculation, which may lead to information loss. Therefore, for a more complete and accurate evaluation, this paper attempts to rank the INPP candidates under purely fuzzy environment.

Based on this review, this study establishes a two-stage decision framework for INPP site selection. In the first stage, the GIS and preselection criteria are applied to identify suitable alternative sites. And in the second stage, the IT2F-PROMETHEE II and suitability criteria are carried out to rank alternatives and select the optimal site in the completely fuzzy environment, where different preference functions are designated accordingly.

### 3 | METHOD AND MATERIAL

#### 3.1 | Interval type-2 fuzzy numbers

**Definition 1**: Let \( \tilde{A} \) be a type-2 fuzzy set, then \( \tilde{A} \) is defined as follows:

\[
\tilde{A} = \{(x,u) | \forall x \in X, \forall u \in J_x, 0 \leq \mu_{\tilde{A}}(x,u) \leq 1 \}
\]

(1)

where \( X \) denotes the universe of discourse, \( J_x \) represents primary membership of \( x \), while \( \mu_{\tilde{A}}(x,u) \) means the secondary. In addition, \( \tilde{A} \) can be expressed as follows if \( X \) is endless:

\[
\tilde{A} = \int_{x \in X} \int_{u \in J_x} \mu_{\tilde{A}}(x,u) dx du, J_x \subseteq [0,1], 0 \leq \mu_{\tilde{A}}(x,u) \leq 1
\]

(2)

where \( / \) refers to not a fraction but the membership degree, \( \int \) refers to not integral calculus but the union of the corresponding relation between each element and the membership degree.

**Definition 2**: A bounded region is constituted by the uncertainty of the primary membership of \( \hat{A} \), of which the upper bound is composed of all maximum membership values and the lower is minimum. For convenience of expression, the upper membership function (UMF (\( \hat{A} \))) is defined to express the upper bound, while lower membership function (LMF (\( \tilde{A} \))) is for the lower bound.

\[
\text{UMF}(\hat{A}) = \sup \{ u | u \in [0,1], \mu_{\hat{A}}(x,u) > 0 \}, \forall x \in X
\]

(3)

\[
\text{LMF}(\tilde{A}) = \inf \{ u | u \in [0,1], \mu_{\tilde{A}}(x,u) > 0 \}, \forall x \in X
\]

(4)

**Definition 3**: If \( \mu_{\tilde{A}}(x,u) = 1 \) for any \( x \in X \) and \( u \in J_x \), then \( \tilde{A} \) is called a interval type-2 fuzzy set, which is shown as follows:

\[
\tilde{A} = \int_{x \in X} \int_{u \in J_x} 1/(x,u), J_x \subseteq [0,1]
\]

(5)

Combined with UMF (\( \hat{A} \)) and LMF (\( \tilde{A} \)), the set also can be expressed as follows:

\[
\tilde{A} = \int_{x \in X} \int_{u \in \text{LMF}(\hat{A})} \text{UMF}(\hat{A})/(x,u)
\]

(6)

**Definition 4**: If the LMF (\( \tilde{A} \)) and UMF (\( \hat{A} \)) are both trapezoidal fuzzy numbers, then the interval type-2 fuzzy set is called trapezoidal IT2FNs (Figure 1), denoted as follows:

\[
\tilde{A} = (\hat{A}, \tilde{A})
\]

(7)

where \( a_{\hat{L}}, a_{\hat{U}}, a_{\tilde{L}}, a_{\tilde{U}} \) related to LMF (\( \tilde{A} \)) take membership values of \( 0, h_{\hat{L}}(\hat{A}), h_{\hat{U}}(\hat{A}) \), respectively, and \( a_{\tilde{L}}, a_{\tilde{U}}, a_{\hat{L}}, a_{\hat{U}} \) related to UMF (\( \tilde{A} \)) take membership values of \( 0, h_{\tilde{L}}(\tilde{A}), h_{\tilde{U}}(\tilde{A}) \), respectively.

**Definition 5**: Suppose \( \hat{A}_1 \) and \( \tilde{A}_2 \) are two trapezoidal IT2FNs,

where

\[
\hat{A}_1 = (\hat{A}_1, \tilde{A}_1)
\]

(8)

(9)

(10)

and

\[
\tilde{A}_2 = (\hat{A}_2, \tilde{A}_2)
\]

(11)

The arithmetic rules between \( \hat{A}_1 \) and \( \tilde{A}_2 \) are defined as follows:
are nonzero positive real numbers and $k$ is a non-negative real value.

### 3.2 Interval type-2 fuzzy Analytic Hierarchy Process

The AHP is a method of hierarchical weight decision analysis proposed in the early 1980s by Saaty.\(^{40}\) For describing the uncertainty in decision-making process better, a variety of fuzzy AHP methods were proposed in a lot of literature. In this paper, the weights of criteria are calculated using the trapezoidal IT2F-AHP. The detailed operation steps are presented as follows.

**Step 1.** Establish the fuzzy judgment matrices, which represent the pairwise comparison of relative importance between elements in the hierarchical model. The pairwise comparison matrices are reciprocal matrices, defined as follows:

$$\bar{A} = \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{a}_{nn} \end{bmatrix},$$

where $\tilde{a}_{ij}$ are trapezoidal IT2FNs, denoting the relative importance of $C_i$ to $C_j$ and $1/\tilde{a}_{ij}$.

### Step 2.** Examine and correct the consistence of judgment matrices.

First, the improved center of area technique, defined as follows, is adopted to calculated the best nonfuzzy performance value of trapezoidal IT2FNs.\(^{41}\)

The linguistic variables used in this method and their corresponding trapezoidal IT2FNs scales are shown in the Table 3.
Extremely important \(\widetilde{\text{EI}}\), Moderate important \(\widetilde{\text{MI}}\), Quite important \(\text{QI}\) \((5.2,6.2,7.8,8.8;0.8,0.8)\), Exactly Equal \(\text{EE}\) \((S\text{I})\)

When CR is more than 0.1, the consistency of the judgment matrix is considered as unacceptable. The original values need to be modified until CR is less than 0.1.

**Step 3.** The geometric mean of each row \(\tilde{r}_i\) is calculated as follows.

\[
\tilde{r}_i = (\tilde{a}_{i1} \otimes \cdots \otimes \tilde{a}_{in})^{1/n}, i = 1, 2, \ldots, n
\]

**TABLE 3** The linguistic variables and trapezoidal IT2FNs scales

| No. | Linguistic variables     | Trapezoidal IT2FNs scales | Reciprocals |
|-----|--------------------------|---------------------------|-------------|
| 1   | Extremely important (\(\text{EI}\)) | \((7.2,8.2,8.9,9.0,8.0,8.8)\) | \((0.11,0.11,0.10,0.12,0.14,0.8,0.8)\) |
| 2   | Quite important (\(\text{QI}\))       | \((5.2,6.2,7.8,8.8,0.8,0.8)\) | \((0.11,0.13,0.16,0.19,0.0,0.8)\) |
| 3   | Moderate important (\(\text{MI}\))    | \((3.2,4.2,5.8,6.8,0.8,0.8)\) | \((0.15,0.17,0.24,0.31,0.8,0.8)\) |
| 4   | Slight important (\(\text{SI}\))       | \((0.1,0.2,0.3,0.4,0.8,0.8)\) | \((0.21,0.26,0.45,0.8,0.8,0.8)\) |
| 5   | Exactly Equal (\(\text{EE}\))         | \((1.1,1.1,1,1,1,1,1)\)    | \((0.2,0.25,0.5,1,1)\) |

**TABLE 4** The value of the mean random consistency index

| n   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RI  | 0.52| 0.89| 1.11| 1.25| 1.35| 1.40|

where \(\sqrt[n]{\tilde{a}_{ij}}\) = \(\left(\sqrt{a_{ij}},\sqrt{a_{ij}},\sqrt{a_{ij}},\sqrt{a_{ij}}\right)\), \(A_{\text{ij}}\) is the largest characteristic root of \(A\) and \(n\) is the number of rows (or lines).

**Step 4.** The fuzzy weights of \(C_j\) is obtained as follows.

\[
\tilde{w}_j = \tilde{r}_i \phi(\tilde{r}_1 \oplus \cdots \tilde{r}_i \oplus \cdots \tilde{r}_n), j = 1, 2, \ldots, n
\]

**3.3 | Interval type-2 fuzzy PROMETHEE II**

Built on outranking relation, the PROMETHEE is proposed by Ben in 1982 \cite{Ben1982} for ranking. This method is based on different preference functions to pairwise compare alternatives along each selected attribute. In this paper, IT2F-PROMETHEE II is applied to select the best site for nuclear power plants. The detailed steps are presented as follows.

**Step 1.** Establish the fuzzy evaluation matrix.

Define the alternative set as \(\{z_1, \ldots, z_i, \ldots, z_n\}\) and the criteria set as \(X = \{x_1, \ldots, x_j, \ldots, x_n\}\), the fuzzy evaluation matrix is defined as follows:

\[
\tilde{A} = (\tilde{A}_{ij})_{m \times n} = 
\begin{pmatrix}
\begin{array}{cccc}
\tilde{x}_1 & \cdots & \tilde{x}_j & \cdots & \tilde{x}_n \\
\tilde{z}_1 & \tilde{A}_{i1} & \cdots & \tilde{A}_{ij} & \cdots & \tilde{A}_{in} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\tilde{z}_j & \tilde{A}_{i1} & \cdots & \tilde{A}_{ij} & \cdots & \tilde{A}_{in} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\tilde{z}_m & \tilde{A}_{i1} & \cdots & \tilde{A}_{ij} & \cdots & \tilde{A}_{in}
\end{array}
\end{pmatrix}
\]

where

\[
\tilde{A}_{ij} = (\tilde{A}_{ij}, \tilde{A}_{ij}) = \left[(a_{ij},a_{ij},a_{ij},a_{ij});(a_{ij},a_{ij},a_{ij},a_{ij})\right]
\]

denoting the performances of alternatives \(z_i\) on criteria \(x_j\).
The linguistic variables used in this method and their corresponding trapezoidal IT2FNs scales are shown in the Table 5.

Step 2. Normalize the fuzzy evaluation matrix.

Construct the normalized matrix $\tilde{B} = (\tilde{B}_{ij})_{mn}$

where

$$\tilde{B}_{ij} = (\tilde{B}_{ij}^L, \tilde{B}_{ij}^U) = \left(\frac{L_{ij}^L b_{ij}^L L_{ij}^R b_{ij}^R}{L_{ij}^L + L_{ij}^R}, \frac{U_{ij}^L b_{ij}^L U_{ij}^R b_{ij}^R}{U_{ij}^L + U_{ij}^R}, h_1(B_{ij}^L), h_2(B_{ij}^R)\right)$$

with

$$h_1(B_{ij}^L) = h_1(A_{ij}^L), h_2(B_{ij}^R) = h_2(A_{ij}^L), h_1(A_{ij}^L) = h_2(A_{ij}^R)$$

and

$$h_1(B_{ij}^L) = h_1(A_{ij}^L), h_2(B_{ij}^R) = h_2(A_{ij}^L), h_1(A_{ij}^L) = h_2(A_{ij}^R)$$

where

$$\bar{d}_{ij}^L = \min \left\{d_{ij}^L \mid l = 1, 2, \ldots, m\right\}, \bar{d}_{ij}^U = \max \left\{d_{ij}^U \mid l = 1, 2, \ldots, m\right\}$$

Step 3. The pairwise comparison programs are carried out among alternatives, and by that means, the performance differences concerning each criterion are calculated.

The performance difference between the alternative $z_i$ over $z_k$ concerning the criterion $x_j$ is defined as follows:

$$\bar{d}_{ij} (z_i, z_k) = \tilde{B}_{ij} - \tilde{B}_{kj}$$

Step 4. Selecting the preference functions.

IT2F-PROMETHEE II methodology describes the precedence of the alternative $z_i$ over $z_k$ with respect to the attribute $x_j$ by means of preference functions $\tilde{P}_j (z_i, z_k)$. When the function value is 0, there is no difference between $z_i$ and $z_k$; when it is close to 0, $z_i$ is weakly superior to $z_k$; when it is close to 1, $z_i$ is stronger than $z_k$; and when it is 1, $z_i$ is strictly superior to $z_k$.

In practical application, there are six preference functions commonly used.

Type 1. Usual Criterion, following the “more is better” principle.

$$\tilde{P}_j (z_i, z_k) = \begin{cases} 0, & \bar{d}_{ij} (z_i, z_k) \leq 0 \\ 1, & \bar{d}_{ij} (z_i, z_k) > 0 \end{cases}$$

Type 2. U-shape Criterion, setting $\tilde{q}$ as the threshold value to distinguish no difference and strict superiority.

$$\tilde{P}_j (z_i, z_k) = \begin{cases} 0, & \bar{d}_{ij} (z_i, z_k) \leq \tilde{q} \\ 1, & \bar{d}_{ij} (z_i, z_k) > \tilde{q} \end{cases}$$

Type 3. V-shape Criterion, setting $\tilde{p}$ to distinguish linear superiority and strict superiority.

$$\tilde{P}_j (z_i, z_k) = \begin{cases} 0, & \bar{d}_{ij} (z_i, z_k) \leq 0 \\ \bar{d}_{ij} (z_i, z_k) / \tilde{p}, & 0 < \bar{d}_{ij} (z_i, z_k) \leq \tilde{p} \\ 1, & \bar{d}_{ij} (z_i, z_k) > \tilde{p} \end{cases}$$

Type 4. Level Criterion, setting $\tilde{q}$ and $\tilde{p}$ to distinguish no difference, moderate superiority, and strict superiority.

$$\tilde{P}_j (z_i, z_k) = \begin{cases} 0, & \bar{d}_{ij} (z_i, z_k) \leq \tilde{q} \\ 1/2, & \tilde{q} < \bar{d}_{ij} (z_i, z_k) \leq \tilde{p} \\ 1, & \bar{d}_{ij} (z_i, z_k) > \tilde{p} \end{cases}$$

Type 5. V-shape with indifference Criterion, setting $\tilde{q}$ and $\tilde{p}$ to distinguish no difference, linear superiority, and strict superiority.

$$\tilde{P}_j (z_i, z_k) = \begin{cases} 0, & \bar{d}_{ij} (z_i, z_k) \leq \tilde{q} \\ \bar{d}_{ij} (z_i, z_k) / (\tilde{p} - \tilde{q}), & \tilde{q} < \bar{d}_{ij} (z_i, z_k) \leq \tilde{p} \\ 1, & \bar{d}_{ij} (z_i, z_k) > \tilde{p} \end{cases}$$

Type 6. Gaussian Criterion, used in cases where superiority and attribute values are nonlinear.

$$\tilde{P}_j (z_i, z_k) = \begin{cases} 0, & \bar{d}_{ij} (z_i, z_k) \leq \tilde{q} \\ 1 - e^{-(\bar{d}_{ij} (z_i, z_k) - \tilde{q})/\lambda}, & \tilde{q} < \bar{d}_{ij} (z_i, z_k) \leq \tilde{p} \\ 1, & \bar{d}_{ij} (z_i, z_k) > \tilde{p} \end{cases}$$

where

$$\lambda = \left(\frac{\tilde{e}_1, \tilde{e}_2, \tilde{e}_3, \tilde{h}_1(a^L), \tilde{h}_2(a^R)}{\tilde{e}_1, \tilde{e}_2, \tilde{e}_3, \tilde{h}_1(a^L), \tilde{h}_2(a^R)}\right)$$
Stage 5. Calculate the comprehensive priority values of each pair of alternatives.

The comprehensive priority values of the alternative $z_i$ over $z_k$ concerning all criteria are defined as follows:

$$\Pi (z_i, z_k) = \sum_{j=1}^{n} \hat{a}_{ij} \cdot \hat{P}_j (z_i, z_k)$$ (29)

Step 6. Calculation of net flows of each alternative.

The net flows of the alternative $z_i$ are defined as follows:

$$\Phi (z_i) = \Phi^+ (z_i) - \Phi^- (z_i)$$ (30)

where $\Phi^+ (z_i)$ and $\Phi^- (z_i)$ mean the outgoing flow and incoming flow, respectively, which are calculated as follows:

$$\Phi^+ (z_i) = \frac{1}{n-1} \sum_{z_j \in Z} \Pi (z_i, z_j)$$ (31)

$$\Phi^- (z_i) = \frac{1}{n-1} \sum_{z_j \in Z} \Pi (z_j, z_i)$$ (32)

3.4 Two-stage decision framework of inland nuclear power plant site selection

In this study, a two-stage decision framework for INPP site selection based on GIS and IT2F-PROMETHEE II is proposed, as shown in Figure 2.

3.4.1 Prestage: construction of criteria system

Firstly, an expert committee (EC) is organized to analysis on the decision factors and a committee leader is elected. The EC is composed of experienced experts with comprehensive knowledge and rich working experiences about nuclear power projects. Next, provided with previous projects information, literature material, relevant regulations and laws, committee members list the criteria of INPP site selection individually. The committee leader is responsible for collecting expert information, summarizing the influencing criteria and giving out the initial criteria system. Subsequently, the feedback is sent back to each member. Based on the feedback, experts compare own opinions with others’ and modify the criteria system. After multiround information collection, feedback, and modification, opinions of experts tend to be consistent. Finally, the two-stage criteria system of INPP site selection is established.

Stage I: Identification of alternative sites

Based on the criteria system obtained in the Prestage, the related data of designated areas is collected through national statistical yearbook, data of meteorological bureau, urban planning report, project report, and so on. Then, the collected data are imported into ArcMap 10.2 software and map layers for each preselected criterion are obtained. Next, overlay analysis based on GIS is employed to processing map layers. And the preliminary suitable areas can be figured out according to the result of map overlay. Since the construction of INPPs possesses many constraints like water sources, exclusion criteria are also considered in the ArcMap 10.2 software. After removing nonconstructive areas, the final suitable alternative sites are identified.

Stage II: Selection of the optimal site

First of all, data of suitability criteria are collected. The quantitative information is obtained from the authoritative database in the form numerical values, and the qualitative information, which are uniformly negotiated by EC, is in the form of linguistic values. Both types of information are converted into corresponding IT2FNs. Then, based on EC's comprehensive knowledge of nuclear power and experience of engineering projects, the relative importance of criteria and subcriteria is computed by IT2F-AHP. Next, preference functions and parameters are determined according to the expert opinions on the property of each criterion. Finally, IT2F-PROMETHEE II is utilized to calculate net flows of every alternative sites in purely fuzzy environment. Further, the ranking of alternatives is obtained and the optimal site is selected.

4 Analysis on the decision factors of the inland nuclear power plant site selection

4.1 Preselection criteria (P)

Preselection criteria are used to select candidate sites from study area based on GIS. There are 7 quantitative criteria, all of which are critical to the construction and operation of INPPs.

4.1.1 Seismic activity (P1)

Seismic activity is an essential factor affecting the safety of INPPs. Areas with minimal likelihood of deformation and defects on the ground are preferred, which can be evaluated by seismic fortification intensity and seismic acceleration.
Based on geological and historical data, and through scientific exploration and verification, China Earthquake Administration formulates technical indicators for major cities and regions. Seismic fortification intensity is divided into 6, 7, 8, and 9 degrees. And the range of seismic acceleration is 0.0-1.0 g (g is gravitational acceleration, 9.8 m/s²). The smaller the value is, the more suitable the area is to build INPPs.

4.1.2 | Topographic condition (P2)

Topographic condition directly affects not only the cost of INPP construction but also the safety of INPP. According to the requirements of the International Atomic Energy Agency and the National Security Agency of the United States, the area where the slope exceeds 12% or the slope exceeds 400 feet in the minimum area is the lightning protection zone.
for the nuclear power plant. The flatter the topography is, the more suitable the area is to build INPPs.

### 4.1.3 Population distribution (P3)

Population distribution mainly refers to population density and population center. The International Atomic Energy Agency proposes that it is vital to study the distribution characteristics of the regional population density in the evaluation for nuclear power plant site selection. Staying away from densely populated areas reduces safety risks and the complexity of contingency planning. The less the population is, the more suitable the area is to build INPPs.

### 4.1.4 Water resource distribution (P4)

Sufficient water resources must be provided for the cooling systems of the nuclear power plant during the operation period and shutdown under normal condition. Distance from water resources will impact on the accessibility and cost of water. The closer to water resources, the more suitable the area is to build INPPs.

### 4.1.5 Traffic distribution (P5)

Traffic distribution mainly refers to the distribution of major highways and railways. In the construction and operation stages of the nuclear power plant, especially engineering construction, large quantities of materials and heavy equipment need to be transported. The traffic distribution near the region directly affects the convenience and cost of transportation. The closer to traffic facilities, the more suitable the area is to build INPPs.

### 4.1.6 Agriculture & Farming (P6)

Agriculture & Farming refers to the production value of Farming, Forestry, Animal Husbandry and Fishery. It is best to build INNP in areas with low output value to reduce the impact on agricultural activities. The smaller the value is, the more suitable the area is to build INPPs.

### 4.1.7 Conservation areas (P7)

Conservation areas refer to special zones such as natural reserve, scenic spots and historical sites, and military zone, where nuclear power plants are not allowed. Different from the other six, this one is an exclusionary criterion. Conservation areas are completely left out to build INPPs.

### 4.2 Suitability criteria

Suitability criteria are used for sorting candidate sites to select the optimal site. There are 4 criteria and 14 subcriteria, including qualitative criteria and quantitative criteria, as shown in Table 6.

#### 4.2.1 Natural factors (C1)

There are three natural factors.

- Average temperature (C11). The cooling water tower of INPPs depends on heat exchange with the outside. For every 1°C increase in atmospheric temperature, the thermal efficiency of the nuclear power unit drops by approximately 0.006%. Therefore, the candidate with lower temperature is more suitable.

#### Table 6 Suitability criteria of INPP site selection

| Criteria                | Subcriteria                                      | Properties |
|-------------------------|--------------------------------------------------|------------|
| Natural factors         | Average temperature                              | ★ ▽        |
|                         | Average wind speed                               | ★ ▽        |
|                         | Extreme weather risk                             | ○ ▽        |
| Social factors          | Public acceptance                                | ○ ▲        |
|                         | Support from the local government                | ○ ▲        |
|                         | Nearby hazardous facilities risk                  | ○ ▽        |
|                         | Regional development incentives                   | ○ ▲        |
|                         | Population center distance                       |            |
| Economic factors        | Construction cost                                | ★ ▽        |
|                         | Availability of the land                         | ○ ▲        |
|                         | Convenience of power transmission                | ○ ▲        |
|                         | Convenience of nuclear fuel supply               | ○ ▲        |
| Environmental factors   | Negative impact on terrestrial environments      | ○ ▽        |
|                         | Negative impact on aquatic environment           | ○ ▽        |
|                         | Pollutant emission reduction benefits (pm2.5)    | ★ ▲        |

Note: “★,” “○,” “▽,” and “▲” mean quantitative, qualitative, cost, and profit, respectively.
average temperature is more suitable.

- Average wind speed (C12). Wind speed affects not only the design load of INPPs, but also the dissipation of radioactive emissions under normal and accident conditions. The lower the wind speed is, the more suitable the candidate is.

- Extreme weather risk (C13). Extreme weather conditions refer to typhoons, hurricanes, floods, snowstorms, etc. The risk requires meteorologists to evaluate based on regional historical data and extensive experience. The smaller the risk is, the more suitable the candidate is.

### 4.2.2 | Social factors (C2)

There are four social factors.

- Public acceptance (C21). Considering the nuclear risks, people who live near nuclear power plants may show antinuclear attitudes. Public opposition is a major obstacle to the construction of INPPs. The candidate with higher public acceptance is more suitable.

- Support from the local government (C22). As the main decision maker in the region, government support is essential to the construction of INPPs. The candidate with more support is more suitable.

- Nearby hazardous facilities risk (C23). Nearby hazardous facilities refer to refineries, chemical plants, gas and petroleum product storage installations, and so on. Potential accidents could create dangerous substances such, which endanger the safety of INPPs. The smaller the risk is, the more suitable the candidate is.

- Regional development incentives (C24). The operation of the INPPs generates sufficient clean electricity, which attracts energy-consuming businesses, thus promoting the economic development and employment increasing. The degree of incentives is evaluated by economists. The higher the degree is, the more suitable the candidate is.

### 4.2.3 | Economic factors (C3)

There are four economic factors.

- Construction cost (C31). Construction cost mainly refers to land, labor, material, and other associated cost, which is different depending on the location. The less the cost is, the more suitable the candidate is.

- Availability of the land (C32). Land types are divided into agricultural land, construction land, and unused land.

Obviously, the availability of unused land is higher. The higher availability is, the more suitable the candidate is.

- Convenience of power transmission (C33). Power infrastructure is essential to the power transmission, while is the basis of INPP operation. The candidate with convenient transmission grid is more suitable.

- Convenience of nuclear fuel supply (C34). As a prerequisite for INPPs to operate, nuclear fuel supply affects the operation and maintenance cost of the INPPs. The candidate with convenient nuclear fuel supply is more suitable.

### 4.2.4 | Environmental factors (C4)

There are three environment factors.

- Negative impact on terrestrial environment (C41). Work such as site leveling is required during the construction of INPPs, which may cause damage. The candidate with less possible negative impact on terrestrial environment is more suitable.

- Negative impact on aquatic environment (C42). INPPs need a lot of cooling water during operation. Therefore, changes in the temperature and substance of the aquatic environment may be caused to different degrees. The candidate with less negative impact on aquatic environment is more suitable.

- Pollutant emission reduction benefits (pm2.5) (C43). Nuclear power is almost zero emissions, which can alleviate the pollution problem from current coal-fired power plants. This criterion value can be calculated by the amount of particulate matter 2.5 (pm2.5 for short) emission reduction as

\[
S_{PM2.5} = (H \cdot C) \cdot k \cdot m
\]

where \( S_{PM2.5} \) is the amount of particulate matter 2.5; \( H \) is the generating equipment availability hour; \( C \) is the installed capacity of INPPs; \( k \), measured by g/kWh, stands for the average coal consumption; and \( m \), measured by t, represents the quantity of particulate matter 2.5 produced by burning a ton of standard coal. At the present stage of China, the appropriate value of \( k \) and \( m \) is about 335 g/kWh and 0.01 t.

### 5 | CASE STUDY

In recent years, Hunan, Hubei, and Jiangxi provinces (as shown in Figure 3) have witnessed rapid economic development and gap between energy demand and supply has been widening. There are poor primary energy resource endowment and high degree of external dependence. Located at the end of China’s energy transmission, electricity is scarce
almost every year in these provinces. Based on various considerations, the government is steadily promoting the preliminary work of the INPP construction. Several experts and researchers are invited to select the ideal site.

5.1 | Stage I: Site identification based on geographic information system

After a series of investigation and surveys, the information of preselection criteria in Hunan, Hubei, and Jiangxi provinces is collected. To guarantee the accuracy of data, all the information is derived from authoritative databases and data sources are shown in Table 7.

Then, the data are imported into ArcMap 10.2 software based on GIS by researchers for data processing and spatial analysis, as shown in Figure 4. The geological condition in Hunan, Hubei, and Jiangxi provinces is generally good. Seismic activity was slightly higher in some areas, but it is not so bad. In Figure 4B, the more obvious the color contrast is, the greater the terrain changes. The northwest regions have higher altitude and larger slope. The population is mainly distributed in the central part, especially in the provincial capitals, while the western region is sparsely populated. And the same is true for agriculture. Rivers are widely distributed in the study area, while the lake is mainly distributed in the southeast of Hunan, northeast of Hubei, and north central of Jiangxi. Natural reserve, scenic spots, and historical sites in Hunan, Hubei, and Jiangxi provinces are shown in the Figure 4G. Due to the data are not available, military zones are not presented.

Further, overlay analysis is carried out to evaluate suitability of INPP construction. According to the suitability map obtained by GIS, as shown in Figure 5, restricted areas are excluded and four regions (R1, R2, R3, and R4) are identified as the preferable sites for INPPs. However, the color contrast of R2 is relatively obvious, which means that the slope of this region is relatively large, so the region is excluded.

### Table 7 Data sources of preselection criteria

| Preselection criteria          | Data sources                                                                 |
|-------------------------------|-----------------------------------------------------------------------------|
| Seismic activity              | China Earthquake Administration                                             |
| Topographic condition         | Geospatial Data Cloud                                                       |
| Population distribution       | National Bureau of Statistics                                              |
| Water resources distribution  | The Ministry of Water Resources of the People’s Republic of China          |
| Traffic distribution          | Ministry of Transport of the People’s Republic of China                    |
| Agriculture & Farming         | National Bureau of Statistics                                              |
| Conservation areas            | Ministry of Ecology and Environment of the People’s Republic of China       |
FIGURE 4  Layers of preselection criteria in Hunan, Hubei, and Jiangxi provinces (A)-(G)
Considering plenty of water is critical during the operation of INPPs, potential feasible sites are identified at the confluences of rivers where there is more water. As shown in Figure 6, two alternatives (S1 and S2) are identified in R1, two alternatives (S3 and S4) are identified in R3, and five alternatives (S5 to S9) are identified in R4.
5.2 Stage II: Site selection based on interval type-2 fuzzy PROMETHEE II

In the second stage, suitability criteria include both qualitative and quantitative information. For quantitative criteria, the data are calculated or obtained from authoritative databases, as shown in Table 8. The information of C11 (Average temperature) and C12 (Average wind speed) is derived from China Meteorological Administration. And the data of C43 (pollutant emission reduction benefits (pm2.5)) calculated by formula (1). For qualitative criteria, EC is invited to evaluate the performance of each alternative site. The researchers collect relevant materials about alternative sites and provide them to EC. In addition, a sociologist and an environmentalist are involved in providing expertise in their respective fields to assist decision-making. For each criterion of each site, four experts reach consistent evaluation after discussion in the form of Linguistic terms, as shown in Table 9.

Then, the relative importance of criteria and subcriteria is evaluated by EC, according to their comprehensive knowledge and experience of nuclear power. Further, the IT2FAHP is carried out to calculated the weights of suitability criteria, and the results are shown in Table 10.

Next, EC determines different preference functions according to the characteristics of different criteria and determines their thresholds. Hazardous facilities (C23) directly affect safety which is the most important issue of INPPs, and thus, the higher evaluation strictly prefers to the lower. Therefore, the EC selects the Usual Criterion for the criterion. It cannot make a difference until the differences in evaluation of public (C21) and government (C22) reach certain levels. Therefore, the corresponding preference function is designated as U-shape Criterion. For other criteria, before evaluation differences get to certain levels, the higher is linearly superior to the lower, while temperature (C11), wind speed (C12), and cost (C31) are considered superior only if the differences reach certain levels. In consequence, the preference function is selected as V-shape Criterion and V-shape with indifference Criterion, respectively. The designated preference functions and thresholds are presented in Table 11.

Finally, the IT2F-PROMETHEE II is applied to calculate the net flow of each site based on the information collected above in order to improve accuracy, and the IT2FNs are not transformed to exact value in calculation. Outgoing flow, incoming flow, and net flow of each site are shown in Table 12. For easy sorting, net flows are defuzzified at last, and the ranking result can be obtained as S8 > S9 > S1 > S2 > S6 > S5 > S7 > S4 > S3, as shown in Table 13. Thus, S8 is selected as the optimal site.

| Sites | C11 (°C) | C12 (m/s) | C25 (km) | C31 (yuan) | C43 (t) |
|-------|----------|-----------|----------|------------|--------|
| S1    | 15.6     | 4.74      | 20       | 735        | 5.39   |
| S2    | 15.6     | 4.74      | 25       | 740        | 5.39   |
| S3    | 16.4     | 4.06      | 15       | 745        | 5.313  |
| S4    | 16.5     | 5.14      | 15       | 730        | 5.2745 |
| S5    | 18.1     | 5.64      | 10       | 735        | 5.467  |
| S6    | 18.1     | 5.2       | 15       | 750        | 5.467  |
| S7    | 18.1     | 5.2       | 10       | 740        | 5.467  |
| S8    | 19.1     | 5.34      | 15       | 725        | 5.4285 |
| S9    | 19.1     | 5.34      | 10       | 725        | 5.4285 |

| Sites | C13 | C21 | C22 | C23 | C24 | C32 | C33 | C34 | C41 | C42 |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| S1    | ML  | H   | M   | L   | H   | H   | MH  | M   | ML  | M   |
| S2    | ML  | H   | M   | ML  | MH  | MH  | H   | M   | L   | M   |
| S3    | ML  | MH  | M   | MH  | MH  | MH  | H   | MH  | M   | L   |
| S4    | ML  | M   | MH  | M   | H   | H   | MH  | M   | M   | ML  |
| S5    | VL  | ML  | MH  | MH  | MH  | MH  | H   | H   | L   | ML  |
| S6    | L   | M   | M   | M   | MH  | MH  | H   | M   | L   | L   |
| S7    | L   | MH  | M   | M   | MH  | H   | MH  | L   | M   |
| S8    | L   | ML  | H   | ML  | MH  | H   | M   | ML  | L   |
| S9    | L   | ML  | H   | ML  | H   | H   | MH  | MH  | ML  | ML  |

Table 8 Numerical value of quantitative criteria

Table 9 Linguistic value of qualitative criteria
5.3 Sensitivity analysis

In order to test the robustness of decision-making, a sensitivity analysis, with respect to criteria weights change, is implemented. The fluctuations of weights from $-30\%$ to $+30\%$ and corresponding influence on the INPP site selection are shown in the Figure 7.

Figure 7A shows the weight changes of C1. It is observed that as the importance of C1 increases, the INPP sites S5, S6, S7, S8, and S9 perform better, while S1, S2, S3, and S4 perform worse. However, the overall ranking of alternatives remains the same. Further, no matter how the weight of natural factors (C1) changes, S8 is always the optimal INPP site.

Figure 7B shows the weight changes of C2 where the superiority fluctuates significantly. When the weight decreases, S8 maintains its ranking as No. 1 although the performance gets not so great. With the weight increases, the superiority of S8 gets stronger. Therefore, no matter how the weight of social factors (C2) changes, S8 is also the optimal INPP site.

Figure 7C shows the weight changes of C3. It can be seen that as the importance of C3 fluctuates, the performances of nine alternatives remain relatively stable and the overall ranking is the same as it was in the beginning. As a consequence, no matter how the weight of economic factors (C3) changes, S8 is still the optimal INPP site.

Figure 7D shows the weight changes of C4. In this case, S8 still performs best, while the ranking of S1, S2, S5, and S6 may change with the weight changes. Just as natural, social, and economic factors, S8 is still the optimal INPP site no matter how the weight of environmental factors (C4) changes.

As can be seen from the above analysis, the overall ranking remains relatively stable although part of results fluctuates a little bit. Furthermore, no matter how the weights change, S8 always secures its top ranking. Therefore, the INPP site selection decision-making, employing IT2FPROMETHEE II, is robust and effective. In addition, for the social and environmental factors, changes of the

| TABLE 10 | The weights of suitability criteria |
|-----------|----------------------------------|
| Criteria  | Weights                          | Subcriteria | Weights |
| C1        | (0.16,0.20,0.29,0.37,0.9,0.9,0.9), (0.15,0.19,0.30,0.39,1,1) | C11         | (0.03,0.05,0.09,0.14,0.09,0.9,0.9), (0.03,0.04,0.10,0.16,1,1) |
|           |                                  | C12         | (0.03,0.05,0.09,0.14,0.09,0.9,0.9), (0.03,0.04,0.10,0.16,1,1) |
|           |                                  | C13         | (0.05,0.08,0.16,0.25,0.9,0.9,0.9), (0.04,0.07,0.17,0.27,1,1) |
| C2        | (0.20,0.28,0.44,0.57,0.9,0.9,0.9), (0.19,0.26,0.46,0.60,1,1) | C21         | (0.02,0.04,0.09,0.16,0.09,0.9,0.9), (0.02,0.04,0.10,0.18,1,1) |
|           |                                  | C22         | (0.03,0.05,0.11,0.19,0.09,0.9,0.9), (0.02,0.04,0.13,0.21,1,1) |
|           |                                  | C23         | (0.03,0.06,0.16,0.27,0.9,0.9,0.9), (0.03,0.06,0.18,0.30,1,1) |
|           |                                  | C24         | (0.02,0.03,0.07,0.13,0.9,0.9,0.9), (0.01,0.03,0.08,0.15,1,1) |
|           |                                  | C25         | (0.03,0.05,0.10,0.16,0.09,0.9,0.9), (0.02,0.04,0.11,0.18,1,1) |
| C3        | (0.10,0.13,0.21,0.29,0.9,0.9,0.9), (0.10,0.13,0.22,0.32,1,1) | C31         | (0.02,0.03,0.05,0.08,0.9,0.9,0.9), (0.02,0.02,0.05,0.09,1,1) |
|           |                                  | C32         | (0.02,0.04,0.07,0.13,0.9,0.9,0.9), (0.02,0.03,0.08,0.14,1,1) |
|           |                                  | C33         | (0.02,0.03,0.06,0.10,0.9,0.9,0.9), (0.02,0.03,0.07,0.11,1,1) |
|           |                                  | C34         | (0.01,0.02,0.05,0.08,0.9,0.9,0.9), (0.01,0.02,0.05,0.09,1,1) |
| C4        | (0.16,0.20,0.29,0.37,0.9,0.9,0.9), (0.15,0.19,0.30,0.39,1,1) | C41         | (0.05,0.07,0.12,0.19,0.9,0.9,0.9), (0.04,0.06,0.14,0.20,1,1) |
|           |                                  | C42         | (0.05,0.07,0.12,0.19,0.9,0.9,0.9), (0.04,0.06,0.14,0.20,1,1) |
|           |                                  | C43         | (0.03,0.04,0.08,0.14,0.9,0.9,0.9), (0.02,0.04,0.09,0.15,1,1) |

| TABLE 11 | Preference function and thresholds |
|-----------|-----------------------------------|
| Criteria  | Preference function               | Thresholds |
| C11       | V-shape with indifference Criterion | q            |
| C12       | V-shape with indifference Criterion | p            |
| C13       | V-shape Criterion                 | s            |
| C21       | U-shape Criterion                 | q            |
| C22       | U-shape Criterion                 | p            |
| C23       | Usual Criterion                   | s            |
| C24       | V-shape Criterion                 | q            |
| C25       | V-shape Criterion                 | p            |
| C31       | V-shape with indifference Criterion | q            |
| C32       | V-shape Criterion                 | p            |
| C33       | V-shape Criterion                 | s            |
| C34       | V-shape Criterion                 | q            |
| C35       | V-shape Criterion                 | p            |

Figure 7A shows the weight changes of C1. It is observed that as the importance of C1 increases, the INPP sites S5, S6, S7, S8, and S9 perform better, while S1, S2, S3, and S4 perform worse. However, the overall ranking of alternatives remains the same. Further, no matter how the weight of natural factors (C1) changes, S8 is always the optimal INPP site.

Figure 7B shows the weight changes of C2 where the superiority fluctuates significantly. When the weight decreases, S8 maintains its ranking as No. 1 although the performance gets not so great. With the weight increases, the superiority of S8 gets stronger. Therefore, no matter how the weight of social factors (C2) changes, S8 is also the optimal INPP site.

Figure 7C shows the weight changes of C3. It can be seen that as the importance of C3 fluctuates, the performances of nine alternatives remain relatively stable and the overall ranking is the same as it was in the beginning. As a consequence, no matter how the weight of economic factors (C3) changes, S8 is still the optimal INPP site.

Figure 7D shows the weight changes of C4. In this case, S8 still performs best, while the ranking of S1, S2, S5, and S6 may change with the weight changes. Just as natural, social, and economic factors, S8 is still the optimal INPP site no matter how the weight of environmental factors (C4) changes.

As can be seen from the above analysis, the overall ranking remains relatively stable although part of results fluctuates a little bit. Furthermore, no matter how the weights change, S8 always secures its top ranking. Therefore, the INPP site selection decision-making, employing IT2FPROMETHEE II, is robust and effective. In addition, for the social and environmental factors, changes of the
weights lead to significant fluctuations in performance. It indicates these two factors are more sensitive that need to be paid special attention to in the construction of nuclear power.

### TABLE 12

| Sites | Outgoing flow | Incoming flow | Net flow |
|-------|---------------|---------------|----------|
| S1    | (0.083, 0.150, 0.356, 0.683; 0.8, 0.8), (0.069, 0.134, 0.398, 1.012; 1, 1) | (0.078, 0.122, 0.260, 0.517; 0.8, 0.8), (0.063, 0.110, 0.286, 0.778; 1, 1) | (0.005, 0.029, 0.097, 0.166; 0.8, 0.8), (0.005, 0.023, 0.112, 0.234; 1, 1) |
| S2    | (0.088, 0.150, 0.343, 0.653; 0.8, 0.8), (0.072, 0.134, 0.380, 0.948; 1, 1) | (0.073, 0.118, 0.258, 0.514; 0.8, 0.8), (0.060, 0.106, 0.285, 0.811; 1, 1) | (0.015, 0.032, 0.085, 0.139; 0.8, 0.8), (0.012, 0.028, 0.095, 0.137; 1, 1) |
| S3    | (0.060, 0.093, 0.188, 0.345; 0.8, 0.8), (0.052, 0.084, 0.207, 0.449; 1, 1) | (0.106, 0.182, 0.422, 0.861; 0.8, 0.8), (0.084, 0.163, 0.467, 1.569; 1, 1) | (−0.046, −0.089, −0.233, −0.516; 0.8, 0.8), (−0.032, −0.078, −0.260, −1.120; 1, 1) |
| S4    | (0.088, 0.145, 0.300, 0.576; 0.8, 0.8), (0.043, 0.081, 0.234, 0.628; 1, 1) | (0.103, 0.170, 0.382, 0.788; 0.8, 0.8), (0.082, 0.153, 0.422, 1.480; 1, 1) | (−0.051, −0.079, −0.172, −0.375; 0.8, 0.8), (−0.039, −0.072, −0.188, −0.852; 1, 1) |
| S5    | (0.075, 0.115, 0.251, 0.519; 0.8, 0.8), (0.059, 0.105, 0.276, 0.886; 1, 1) | (0.097, 0.131, 0.331, 0.924; 1, 1) | (0.016, 0.011, 0.009, 0.062; 0.8, 0.8), (0.010, 0.012, 0.005, 0.215; 1, 1) |
| S6    | (0.057, 0.091, 0.207, 0.430; 0.8, 0.8), (0.045, 0.082, 0.228, 0.754; 1, 1) | (0.085, 0.146, 0.325, 0.602; 0.8, 0.8), (0.071, 0.131, 0.361, 0.847; 1, 1) | (−0.027, −0.055, −0.119, −0.172; 0.8, 0.8), (−0.026, −0.049, −0.132, −0.093; 1, 1) |
| S7    | (0.106, 0.177, 0.403, 0.786; 0.8, 0.8), (0.087, 0.159, 0.447, 1.206; 1, 1) | (0.053, 0.085, 0.185, 0.359; 0.8, 0.8), (0.043, 0.077, 0.205, 0.497; 1, 1) | (0.053, 0.092, 0.218, 0.427; 0.8, 0.8), (0.044, 0.082, 0.242, 0.709; 1, 1) |
| S8    | (0.085, 0.148, 0.350, 0.701; 0.8, 0.8), (0.068, 0.133, 0.389, 1.160; 1, 1) | (0.061, 0.095, 0.209, 0.409; 0.8, 0.8), (0.049, 0.086, 0.231, 0.565; 1, 1) | (0.025, 0.053, 0.140, 0.292; 0.8, 0.8), (0.019, 0.046, 0.158, 0.595; 1, 1) |

### TABLE 13

| Sites | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|-------|----|----|----|----|----|----|----|----|----|
| Defuzzification | 0.081 | 0.065 | −0.289 | −0.222 | 0.016 | 0.042 | −0.080 | 0.226 | 0.161 |
| Rank | 3 | 4 | 9 | 8 | 6 | 5 | 7 | 1 | 2 |

### FIGURE 7
Sensitivity analysis result of changing the weight of criteria (A-D)

(A) Weight changes of C1.
(B) Weight changes of C2.
(C) Weight changes of C3.
(D) Weight changes of C4.

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**CONCLUSION**

Site selection is a critical strategic decision for inland nuclear power projects. Some studies focused on this area have
been done, which have several deficiencies to some extent. First of all, the decision frameworks for INPP site selection only focus on one stage, which is obviously incomplete. Second, the properties of criteria are treated indiscriminately. Moreover, the uncertainty and vagueness in the ranking calculation are not taken seriously.

To deal with the above problems, a two-stage decision framework is proposed to handle the INPP site selection problems in this study. Firstly, the GIS and preselection criteria are utilized to identify suitable alternative sites, and a MCDM method and suitability criteria are applied to select the optimal site. Secondly, the specific preference functions of PROMETHEE II are determined for the property of each criterion. Thirdly, the IT2FNs are carried out to describe the uncertainty and vagueness in calculation, without being transformed to exact value, to improve accuracy. Finally, a sensitivity analysis, is processed, testifying the rationality and robustness of the proposed two-stage decision framework. As results show, S8 performs the best with relative high scores in Support from the local government (C22), Availability of the land (C32), and Convenience of nuclear fuel supply (C34). And while, due to poor performance in Negative impact on aquatic environment (C42) and Extreme weather risk (C13), S3 does the worst.

In the following study, the cloud model is planned to improve IT2FNs. Cloud model, including expectation, entropy, and superentropy, belongs to the field of uncertainty artificial intelligence, mainly dealing with uncertain transformations of qualitative concepts and quantitative descriptions. Moreover, how to combine expert decision-making with artificial intelligence will be an interesting research direction in the future. On the one hand, the decision-making efforts of experts can be relieved and even the expense for experts will be saved. On the other hand, the objective randomness can be reduced as much as possible, which can more precisely express expert knowledge and improve the accuracy of the results.

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NOMENCLATURE
Acronyms

| Acronyms          | Definitions                                          |
|-------------------|------------------------------------------------------|
| EC                | an expert committee                                  |
| GIS               | geographic information system                        |
| INPPs             | inland nuclear power plants                          |
| IT2FNs            | interval type-2 fuzzy numbers                        |
| LMF               | the lower membership function                        |
| MCDM              | multiple criteria decision-making                    |
| NPPs              | nuclear power plants                                 |
| P                 | preselection criteria                                |
| RI                | the random consistency index                         |
| UMF               | the upper membership function                        |

Parameters

| Parameters          | Definitions                                          |
|---------------------|------------------------------------------------------|
| $H$                 | generating equipment availability hour (h)           |
| $C$                 | installed capacity of inland nuclear power plant (kW) |
| $\tilde{A}$         | a type-2 fuzzy set                                  |
| $\mu$               | independent variable                                 |
| $X$                 | the universe of discourse                           |
| $\Pi$               | the primary membership of $x$                       |
| $\bar{A}$, $\bar{U}$| the lower/upper trapezoidal fuzzy numbers            |
| $h_i(\bar{A}_i), h_i(\bar{U}_i)$ | the lower/upper membership values |
| $\tilde{A}_i$       | interval type-2 trapezoidal fuzzy numbers            |
| $\tilde{h}_i$       | the interval type-2 fuzzy evaluation matrix          |
| $\tilde{B}_i$       | the normalized interval type-2 fuzzy matrix          |
| $\Pi(\tilde{z}_i,\tilde{z}_k)$ | the comprehensive priority function |
| $\Phi(\tilde{z}_i)$ | the net/outgoing/incoming flow function             |

Functions

| Functions          | Definitions                                          |
|---------------------|------------------------------------------------------|
| $S_{PM2.5}$         | the amount of particulate matter 2.5                 |
| $J_x$               | the primary membership function of $x$              |
| $f_i$               | geometric mean of each row in a judgment matrix      |
| $\tilde{w}_i$       | fuzzy weights of suitability criteria                 |
| $\tilde{d}(\tilde{z}_i,\tilde{z}_k)$ | performance difference between the $\tilde{z}_i$ over $\tilde{z}_k$ |
| $\Phi(\tilde{z}_i)$ | the net/outgoing/incoming flow function             |

Constants

| Constants          | Definitions                                          |
|---------------------|------------------------------------------------------|
| $k$                 | average coal consumption (g/kWh)                     |
| $m$                 | quantity of particulate matter 2.5 produced by burning a ton of standard coal (t) |

Symbols

| Symbols            | Definitions                                          |
|---------------------|------------------------------------------------------|
| $\bigcup$           | the union of the corresponding relation between each element and the membership degree |
| $\oplus$            | addition operation                                   |
| $\ominus$           | subtraction operation                                |
| $\otimes$           | multiplication operation                             |
| $\div$              | division operation                                   |
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