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Decision framework for ocean thermal energy plant site selection from a sustainability perspective: The case of China

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A B S T R A C T

Site selection is a key factor to the success of ocean thermal energy conversion (OTEC) project. It is a multi-criteria decision making (MCDM) problem with a series of conflicting criteria involved. However, limited studies were found concerning this area and problems existing in classical MCDM methods tended to fail OTEC site selection decisions. Therefore, this paper proposes an extended MCDM method and establishes a new decision-making framework to select the optimal location. First, a comprehensive evaluation criteria system for OTEC site selection from the view of sustainability with 16 criteria involved is established. Second, feasible alternative sites for OTEC project are identified by PEST analysis. Third, an extended PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) under intuitionistic fuzzy environment is proposed to avoid compensation assumptions. During the decision process, seven groups of experts shared the work and cooperated with each other according to their backgrounds. Finally, a real case is studied and sensitive analysis is conducted, demonstrating the robustness and effectiveness of the proposed method. This study can effectively improve OTEC site selection decision making quality and also extends the domains of intuitionistic fuzzy PROMETHEE applications.

1. Introduction

1.1. Background

1.1.1. OTEC attracts more and more attentions in China

Governments all over the world speed up the development of renewable energy under the pressure of sustainable development of human beings. Demands for sustainable development of energy are becoming more and more urgent. As the promotion of the national development strategy of renewable energy and the 21st century maritime silk road, the marine energy attracts more attention than ever. As energy supply is indispensable for economic construction and industrial development of the areas and countries along the maritime silk road, this strategy proposed enhancing the interaction of energy infrastructure and strengthening green and low carbon construction of infrastructure. Thus, concerns are growing about the utilization of marine resource to supply electricity. Ocean thermal energy is considered to have bright prospects due to its huge resource reserve and stable output. Ocean thermal energy conversion (OTEC) produces electrical power by exploiting and utilizing the temperature difference between the warm layer on the surface of the ocean and the cold layer at greater depth of sea water, so as to convert the heat energy into mechanical energy. OTEC not only has great advantages in solving problems such as isolated island development, offshore equipment operation and water supplement, but also help realize sustainable development of marine and region.

1.1.2. Site selection is essential for OTEC

The site selection is the critical basis and the first priority in ocean thermal energy planning. A good location decision is essential for the OTEC in the whole life cycle. Many researchers have already conducted studies mainly on analyzing one or some of the factors towards OTEC site selection decisions. For instance, the energy resources factors are assessed by Park et al. (2010) to decide

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the location for ocean thermal energy plant. Devis-Morales et al. (2014b) made assessment on the temperature gradient and the bathymetric, environmental and socio-economical characteristics, to identify the ideal maritime location for the OTEC. Valente de Souza and Marques (2016) identified a suitable location for OTEC based on analysis of temperature gradient. However, there still lacks of study which considers comprehensive factors associated with OTEC site selection and identify the optimal site through decision-making framework and process.

The OTEC site selection decision problem with a series of comprehensive factors both qualitative and quantitative involved is a typical MCDM (Multi-Criteria Decision-Making) problem. MCDM indicates that in order to select the most appropriate one from all alternatives, the decision makers need to take multiple factors into consideration due to complexity of realistic problems and uncertainty of environment. In the field of energy planning and management, MCDM methods are widely used such as site selection, investment decision, supplier selection and so on, which all require making decisions under multiple irreplaceable criteria. For example, when selecting a scheme from all options, attribute may vary resulted from projects of different nature. Costa et al. (2018) assessed and classified suppliers considering sustainability aspects using ELECTRE TRI-nc method mainly taking the sustainability into consideration. Yuan et al. (2018) applied linguistic hesitant fuzzy set for the selection and prioritization of various renewable energy for Jilin Province. As for site selection, the criteria such as high economy and environmental friendliness occupy very high positions. Abudeif et al. (2015) studied on selecting the optimal nuclear power plants site by applying multi-Criteria Decision Analysis and GIS software.

1.1.3. Sustainable assessment plays an important role in the energy field

Sustainability assessment of energy system is one of the important issues in the energy field. Whilst sustainability remains an elusive and contested concept, it can be stated as an approach that attempts to consider social, environmental and economic factors when planning and managing the use of resources (Blackstock et al., 2007). Sustainability involves the sustainability of natural resource use and impact on the environment due to emissions/wastes and land use (Singh et al., 2012). It is misleading to believe that a resource such as OTEC is sustainable only because it is renewable. Hence, it can be stated that sustainability is possible only when it follows natural laws of mass and energy balance.

1.2. Problems and certain solutions

1.2.1. Classical MCMD methods may fail OTEC site selection in real-world applications

Though quantities of researches extended the theory of MCDM, there still exist many problems in MCDM process at current stage, which fails OTEC site selection in real-world applications. To begin with, incomplete and uncertain information often exists in the decision making progress. It is often difficult for the evaluation to quantify precisely as the OTEC site selection decision always happens before practical construction and there exist complex environment with varieties of unforeseen situation. However, the assumption of classical MCDM methods defined as the basic information used in decision making is complete and definite, which may be hard to satisfy in many circumstances because real-world decision making information are often vague and incomplete (Wu et al., 2014b). In addition, the decision makers' (DMs) judgments on both satisfactory degree and non-satisfactory degree are fuzzy (Wu et al., 2016). It is hard for the DMs to estimate their preferences precisely with exact numerical values as their preference degree among the alternatives are influenced by their vague knowledge. What is more, compensation problem exists in many canonical decision methods. That is to say, for some alternatives, it may occur that the good performance in some criteria may make up for the bad performance in other criteria, which may exert bad influence on the result. For example, one alternative may perform poor in some criteria such as energy sustainability. But it may still rank top lying in that in other criteria such as society sustainability, it is of great superiority. (Wu et al., 2014a).

As a MCDM problem, the common solution is based on the utility theory, such as Simple Linearity Weighted Method, Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS). However, utility theory assumes the attributes are fully compensated by each other. Therefore, in many cases, it is not functional (Wu et al., 2016). Comparatively, Outranking Methods (OM), as partial or non-compensatory evaluation technique, requires fewer assumptions and has a relatively larger application scope. As a main kind of OM, ELECTRE (Elimination et Choix Traduisant la Realité) decreases compensation among criteria by building weaker binary relations (outranking relation, OR) (Ghoseiri and Lessan, 2014). Similar as ELECTRE, PROMETHEE method is also bases on OR, however, it is a valued outranking method (Wu et al., 2018a). It introduced the concept of preference function to replace the concordance test in ELECTRE, thus overcoming the problem of attribute value gap information ignorance and tedious in setting many subjective parameters (Vincke, 1986). Due to the simplicity and convenience of PROMETHEE, it is widely applied in energy planning area.

Canonical MCDM often faces the problem of vague and ambiguous ((Wu et al., 2018b). To deal with vague information, Zadeh proposed theories of fuzzy set, which had been proved to be an effective solution for decision making under vagueness (Erol et al., 2014). However, when it comes to circumstances of two or more sources of vagueness, limitations of Zadeh's fuzzy sets appear (Tan et al., 2015). To deal with the limitations, Atanassov's intuitionistic fuzzy sets, as a generalization of the ordinary fuzzy sets, have been used to handle more complicated situations where both membership and non-membership are fuzzy (Atanassov, 1986), as a simulation of uncertain human decision behaviors. Atanassov and Gargov (1989) introduced the concepts of interval-valued intuitionistic fuzzy numbers (IVIFN), as an extension of intuitionistic fuzzy sets. The membership function and a non-membership function of IVIFN are defined by interval fuzzy numbers rather than exact numbers, thus allowing more uncertainty to be expressed. Therefore interval-valued intuitionistic fuzzy set, as a powerful and flexible tool in dealing with vague and ambiguous, has aroused more and more concern in MCDM applications (Cavallaro et al., 2018; Onar et al., 2015).

1.2.2. Site selection considering sustainability is absent in the field of OTEC

A number of attempts have been performed to assess sustainability in the field of energy. Singh et al. (2012) performed an overview of sustainability assessment methodologies. Blackstock et al. (2007) shown that sustainability included environmental, economic and social analysis. Cartelle Barros et al. (2015) assessed the global sustainability of power plants throughout its life cycles, taking economic, social and environmental data into account. Cobuloglu and Büyüktahtakın (2015) selected the most sustainable biomass crop type for biofuel production problem involving three main sustainability criteria defined as economic, environmental, and social aspects. Chang and Wang (2017) pointed out that administrative management system should be optimized and financial laws should be strengthened in order to promote the development of marine renewable energy. Prete et al. (2012)

included energy-based and reliability indices when evaluating the role of micro-grids in regional power systems. The results suggested that a power network in which fossil-fueled micro-grids and a price on CO2 emissions were included had the highest composite sustainability index. Matteson (2014) defined energy indicators used in the assessment of energy systems which met the sustainability demands.

In this study, the evaluation criteria system of OTEC site selection for sustainability is established based above all. The comprehensive evaluation system is formed by two modules: internal sustainability and external sustainability. In the module of internal sustainability, the energy factor, construction and maintenance factor, the auxiliary condition factor, and economical factor are considered, to measure the potential development of OTEC project itself at the location in the long run. In the module of external sustainability, the environmental factor and society factor are involved to assess the potential positive or negative influences of OTEC project on the external environment at different locations. In this way, both the internal and external sustainability are analyzed, in order to reconcile the demands of energy development and environmental and social friendly considerations.

1.3. Objectives

This paper aims at establishing a scientific decision-making framework and dealing with the above problems reasonably. (1) A comprehensive OTEC site selection index system is constructed from perspective of sustainability involving internal and external aspects on the basis of literature study, expert interview and investigation of laws and regulations. As former studies provide some criteria for selection of OTEC site, they are still limited. (2) A new intuitionistic fuzzy PROMETHEE method is proposed to handle the existing problems and a decision-making framework is constructed for rational OTEC site selection. Literature have been found in application of location selection of nuclear power station, solar power station, wind power station and offshore wind power station. However, it has not been used in area of OTEC site selection decision making. Also, problems existing in current MCDM methods are likely to fail OTEC site selection. (3) A sensitive analysis is conducted for further exploration of the obtained results. This is the first paper that studies how the ranking results vary in different circumstances of OTEC site selection by altering the weights of criteria and attitudes of experts.

2. Evaluation criteria system of OTEC site selection for sustainability

Through literature study, expert interview and investigation of laws and regulations, the evaluation criteria system for OTEC site selection from the sustainability perspective is established. The comprehensive criteria system is formed by two aspects: internal sustainability and external sustainability. The criteria and sub-criteria are as follows.

2.1. Energy sustainability (C_1)

Energy sustainability in this study means to have sustained, reliable and valid energy resources for the planned OTEC plants. To achieve this goal, the amount, the quality and the efficiency of the energy resources is to be assessed. For the factor of sustained energy resources supply, the annual effective hours is the sub-criteria. For the reliable quality of the ocean thermal resources, the temperature difference from ocean surface to 1000 m in depth is evaluated (Devis-Morales et al., 2014b) and sub-criteria of the steadiness of the temperature change is adopted for the effects on generation stability (Syamsuddin et al., 2015). For the factor of the valid of energy resources, the potential OTEC efficiency value is applied.

(1) Annual effective hours (C_{11}). It measures the available hours for OTEC in whole year to figure whether there are constant energy supply at the location.
(2) Temperature change (C_{12}). It measures the temperature change of ocean surface and 1000 m in depth. The index indicates the steadiness of OTEC power generation.
(3) OTEC efficiency (C_{13}). Whether the energy resource can be used or not largely depends on OTEC efficiency, which can be obtained by the ideal Rankine cycle as eq. (1).

$$\eta = \frac{T_W - T_C}{2(T_W + 273)}. \tag{1}$$

where:

$\eta =$ Rankine efficiency
$T_W =$ Sea surface temperature (warm water at 20 m depth).
$T_C =$ Deep water temperature (cold water)

Small losses in the generation steps are considered to cause the reduction of the electrical power output, called the gross OTEC efficiency (∂, in %) as eq. (2) (Devis-Morales et al., 2014b):

$$\partial \approx \rho_{tg} \frac{\Delta T}{2T_W}. \tag{2}$$

where:

$$\Delta T = T_W - T_C.$$

ρ_{tg} means the turbo generator efficiency, has a value of 75%.

2.2. Construction and maintenance sustainability (C_2)

Construction and maintenance sustainability means to assess the suitability of the construction and maintenance conditions for the planned OTEC plant to achieve the continuous operation in the whole life cycle. Good fundamental condition such as smooth seafloor is needed for laying pipes, etc. (Devis-Morales et al., 2014b). Oceanographic conditions such as currents, waves and storms should be considered for the stable operation of the OTEC plants (VanZwieten et al., 2017). To reduce the possibility of maintenance frequency, there need to be relatively low likelihood of earthquakes, tropical storms and other natural hazards (Devis-Morales et al., 2014b).

(1) Construction conditions beneath sea (C_{21}). It measures whether the location is suitable for platform construction, cold water pipe laying, etc.
(2) Oceanographic conditions (C_{22}). It indicates the quality level of marine environment for OTEC plants.
(3) Maritime climate (C_{23}). It measures whether there existing extreme weather at the location frequently that have serious influences on OTEC plants.

2.3. Auxiliary condition sustainability (C_3)

Auxiliary condition is important in supporting the construction and operation in full life cycle of OTEC projects. The sustainability of auxiliary condition is a criterion to assess whether the auxiliary condition is benefit for the continuous and sustainable development of OTEC plants.

(1) Traffic conditions (C_{31}). It measures the convenience degree of the local traffic facilities to support the construction and operation of OTEC plants.
(2) Demand for load and water (C_{32}). It measures whether there are sufficient and constant power and water demand at the location. When electricity demand reach 50–150 MW in the site and water demand is more than 3 mgd, a10 MW OTEC plant can become competitive (Hamedi and Sadeghzadeh, 2017).

2.4. Economical sustainability (C_4)

The economic sustainability assessment is critical not only for the economic viability of the plant site, but also for the sustainable operation potential of the plant. The indices including the expected capital investment, the operating costs, the expected electrical and water sales revenue (Kim et al., 2013). In addition, the carbon trading can bring about great revenue potential for OTEC plants (Jagusztyn, 2012).

(1) Expected capital investment (C_{41}). It measures the general initial investment in OTEC plant.
(2) Operating costs (C_{42}). It measures the running cost during the operation of the plant annually.
(3) Expected electrical and water sales revenue (C_{43}). It measures the potential benefits from sales of power and water annually.
(4) Carbon trading (C_{44}). It measures revenue from carbon trading. There are different carbon trading accounting methods in different places.

2.5. Environmental sustainability (C_5)

The environment sustainability assessments are required to evaluate the ecological and carbon impact on the environment before the decision of the OTEC plan selection. In the process of OTEC operation, the pumping and discharging nutrient-rich deep ocean water to near surface depths will have biological and ecological effects on the ocean (Devis-Morales et al., 2014b).

(1) Possible environmental effect (C_{51}). It refers to the biological and environmental impacts of seawater intake and heat exchange on the environment (e.g. seawater, animal behavior, fishing and biomass, etc.) during the operation of OTEC plants (Devis-Morales et al., 2014a; Fetanat and Khorasaninejad, 2015).
(2) Coordination with marine planning (C_{52}). It measures whether the planned project is coordinate with the marine planning near the locations (e.g. nature reserves, scenic spots, historical sites, as well as important political and cultural facilities) and other special provisions from the National Energy Administration (NEA) and the State Oceanic Administration (SOA).

2.6. Society sustainability (C_6)

The OTEC plants can benefit the society in many ways by improving the life quality of the inhabitant, and OTEC plan decision should take those possibilities into consideration. These benefits including water cooling, fresh water production, water treatment, cold water agriculture and mariculture and the seawater health centers (Jagusztyn, 2012). The cool water produced in the OTEC generation process can be consumed by many industries which use a great deal of electricity in the process of cooling, lowering the carbon foot print. Also, a sustainable OTEC plan can benefit the inhabitants by providing abundant supply of healthy drinking water. As a byproduct, oxygen gas can be utilized to clean waste water for reuse. In addition, the agriculture and mariculture and health centers can benefit from the cold water and mineral rich seawater. And the sustainable development also need to take account the support from the local government and people (Wu et al., 2014a).

(1) Inhabitant life quality improvement (C_{61}). It refers to the possible benefit the local people can obtained from the OTEC project.
(2) Support from government and people (C_{62}). It measures the supporting degree from the local government and people.

3. Basic theory of IVIF MCDM problems

Based on the evaluation characters of the discussed object, the MCDM problem under the interval-number intuitionistic fuzzy environment is described in this section and some basic concepts and operations that are used in the following sections are presented as below.

Definition 1. Let X be a finite universe. The IVIF set $\tilde{A}_i$ denoting the evaluation of the ith alternative has the following form

$$\tilde{A}_i = \{\langle x_j, (\tilde{u}_{ij}, \tilde{v}_{ij})\rangle | x_j \in X\} \tag{3}$$

where $\tilde{u}_{ij}$ and .$\tilde{v}_{ij}$.are two closed subintervals representing the membership and non-membership degrees for the evaluation of the ith alternative with respect to criterion x_j, respectively, satisfying $\tilde{u}_{ij}(=[u_{ij}^-, u_{ij}^+]) : X \to [0,1]$, $\tilde{v}_{ij}(=[v_{ij}^-, v_{ij}^+]) : X \to [0,1]$ and $u_{ij}^+ + v_{ij}^+ \le 1$. The IVIF sets can be described in the notion form as follows.

Definition 2. (Chen, 2014a). Let $\tilde{A}_{ij}$ be the IVIF evaluation value of ith alternative with respect to criterion $x_j \in X$, then $\tilde{A}_{ij}$ can be described as

$$\tilde{A}_{ij} = (\tilde{u}_{ij}, \tilde{v}_{ij}) = \left(\left[u_{ij}^-, u_{ij}^+\right], \left[v_{ij}^-, v_{ij}^+\right]\right) \tag{4}$$

The importance of the criterion in the MDCM problems can be described in the IVIF format in the following.

Definition 3. Let X be a finite universe. Let $\tilde{W}$ be the IVIF set denotes evaluation rating of the importance of the criteria. $\tilde{W}$ can be described in the following manner.

$$\tilde{W} = \{\langle x_j, (\tilde{w}_{u_i}, \tilde{w}_{v_i})\rangle\} \tag{5}$$

where $\tilde{w}_{u_i}$ and $\tilde{w}_{v_i}$ are closed subintervals representing the importance and unimportance degree of the criteria $x_j \in X$, satisfying$\tilde{w}_{u_i}(= [\tilde{w}^-, \tilde{w}^+]) : X \to [0,1]$, $\tilde{w}_{v_i}(= [\tilde{w}^-, \tilde{w}^+]) : X \to [0,1]$ and $\tilde{w}^+ + \tilde{w}^+ \le 1$.

Definition 4. (Chen, 2014a). Let $\tilde{W}_j$ be the IVIF evaluation value of the importance of criterion x_j. $\tilde{W}_j$ can be represented as

$$\tilde{W}_j = (\tilde{w}_{u_i}, \tilde{w}_{v_i}) = \left(\left[\tilde{w}^-, \tilde{w}^+\right], \left[\tilde{w}^-, \tilde{w}^+\right]\right) \tag{6}$$

Definition 5. (Chen, 2014b). Let $\tilde{A}_{ij}$ and $\tilde{A}_{i'j}$ be two IVIF sets over the same finite universe. The basic operations between $\tilde{A}_{ij}$ and $\tilde{A}_{i'j}$ can be defined as follows

$$(1)\tilde{A}_{ij}\oplus\tilde{A}_{i'j}=\left(\left[u_{ij}^{-}+u_{i'j}^{-}-u_{ij}^{-}\bullet u_{i'j}^{-},u_{ij}^{+}+u_{i'j}^{+}-u_{ij}^{+}\bullet u_{i'j}^{+}\right],\left[v_{ij}^{-}\bullet v_{i'j}^{-},v_{ij}^{+}\bullet v_{i'j}^{+}\right]\right) \tag{7}$$

$$(2)\tilde{A}_{ij}\otimes\tilde{A}_{i'j}=\left(\left[u_{ij}^{-}\bullet u_{i'j}^{-},u_{ij}^{+}\bullet u_{i'j}^{+}\right],\left[v_{ij}^{-}+v_{i'j}^{-}-v_{ij}^{-}\bullet v_{i'j}^{-},v_{ij}^{+}+v_{i'j}^{+}-v_{ij}^{+}\bullet v_{i'j}^{+}\right]\right) \tag{8}$$

$$(3)\lambda\bullet\tilde{A}_{ij}=\left(\left[1-\left(1-u_{ij}^{-}\right)^{\lambda},1-\left(1-u_{ij}^{+}\right)^{\lambda}\right],\left[\left(v_{ij}^{-}\right)^{\lambda},\left(v_{ij}^{+}\right)^{\lambda}\right]\right) \tag{9}$$

In addition, $0\bullet\tilde{A}_{ij}=([0,0],[1,1])$ and $(\tilde{A}_{ij})^{0}=([1,1],[0,0])$

Definition 6. (Dymova et al., 2013). Denote IVIFNs $\tilde{A}_{ij}=([u_{ij}^{-},u_{ij}^{+}],[v_{ij}^{-},v_{ij}^{+}])$ to be evaluation ratings of ith alternative with respect to criterion $x_j\in X$. The interval-valued score function and accuracy function can be obtained as follows:

$$[S]_{\tilde{A}_{ij}}=\left[u_{ij}^{-}-v_{ij}^{+},u_{ij}^{+}-v_{ij}^{-}\right]. \tag{10}$$

$$[H]_{\tilde{A}_{ij}}=\left[u_{ij}^{-}+v_{ij}^{-},u_{ij}^{+}+v_{ij}^{+}\right]. \tag{11}$$

Definition 7. (Dymova et al., 2013). Denote IVIFNs $\tilde{A}_{ij}=([u_{ij}^{-},u_{ij}^{+}],[v_{ij}^{-},v_{ij}^{+}])$ and $\tilde{A}_{i'j}=([u_{ij}^{-},u_{ij}^{+}],[v_{ij}^{-},v_{ij}^{+}])$ to be evaluation ratings of ith and i'th alternative, respectively, with respect to criterion $x_j\in X$. The interval comparison possibility and center of intervals is defined as

$$\left[P\left(\tilde{A}_{ij}>\tilde{A}_{i'j}\right)\right]=\alpha\mu_{\Delta s}\left([S]_{\tilde{A}_{ij}}-[S]_{\tilde{A}_{i'j}}\right)+(1-\alpha)\mu_{\Delta H}\left([H]_{\tilde{A}_{ij}}-[H]_{\tilde{A}_{i'j}}\right). \tag{12}$$

$$CT_{\tilde{A}_{ij}>\tilde{A}_{i'j}}=\frac{1}{2}\left(P\left(\tilde{A}_{ij}>\tilde{A}_{i'j}\right)^{L}+P\left(\tilde{A}_{ij}>\tilde{A}_{i'j}\right)^{U}\right). \tag{13}$$

where:

$$\mu_{\Delta s}\left([S]_{\tilde{A}_{ij}}-[S]_{\tilde{A}_{i'j}}\right)=\frac{\left([S]_{\tilde{A}_{ij}}-[S]_{\tilde{A}_{i'j}}\right)+2}{4}, \tag{14}$$

$$\mu_{\Delta H}\left([H]_{\tilde{A}_{ij}}-[H]_{\tilde{A}_{i'j}}\right)=\frac{\left([H]_{\tilde{A}_{ij}}-[H]_{\tilde{A}_{i'j}}\right)+2}{4}, \tag{15}$$

4. Decision framework of OTEC plan selection

In this paper, a five-phase OTEC plan selection for sustainability is established under the IVIF environment (see Fig. 1). An extended PROMETHEE method combining traditional outranking relation analysis with intuitionistic fuzzy theory is employed in this paper, which is more effective and valid to select the most satisfactory plan in view of sustainability due to the incomplete or imperfect knowledge. The framework is shown in Fig. 2 and the five phases of the decision process is presented in the following sections.

4.1. Phase I- identification of the alternative plans using PEST method

In this phase, the feasible plans of OTEC projects are identified based on political, economic, social, technological (PEST) analysis (Zalengera et al., 2014). The decision-making committee is formed by invited experts regarding to the above fields in this phase. The committee collects policy documents, power grid maps, GIS information, oceanic planning and other materials needed for decision-making. Firstly, plans that are against political and legal factors (the veto factors) are wiped out from the decision lists for the potential approval denying problems from the State and Central Government Departments. Secondly, the committee makes assessments of the competitive plans according to energy resources and economic factor with the collected data. The committee drops several unfavorable plans by considering single factors and comprehensive feasibility. Thirdly, the committee meets the left places for further investigation. The local government and related departments are visited and socio-political information is considered in case any possible delay happens in getting the final approval of the chosen optimal plans. Afterwards, several feasible alternative plans are identified.

4.2. Phase II- integration of group decision matrix with the IVIFPA operator

In this phase, evaluation criteria system is set up by the decision-making committee. Individuals of the committee score on each alternative plan identified in phase I with regard to the chosen criteria. The importance of the experts in the committee is considered not equal. The IVIF linguistic variables are applied to assess the weights of the experts. Then the weighted individual decision matrixes are integrated as the group decision matrix by the applied IVIFPA operator. The reason that the IVIFPA operator is used in this phase is its effectiveness and validity in the utilization of IVIF data and the reduction of information loss in the data processing procedure (Chen, 2014b). The group decision matrix can be aggregated by the IVIFPA operator is shown in Appendix. Based on the IVIFPA operator, the group decision opinion of the committee can be formed by the individual decision matrix.

4.3. Phase III- determination of preference relation by ICP-based preference function

To evaluate the satisfactory and unsatisfactory degree between each pair of competing alternatives, the comparison of pairwise alternatives with respect to each criterion need to be processed. The concept of interval comparison possibilities (ICP) and interval-valued center is applied in the comparison with respect to criteria, based on which the preference function is introduced for the construction of pairwise preference relations between competing alternative pairs.

The parameter $\alpha\in[0,1]$ indicates the risk aversion of the decision-makers. L and U represent for the lower and upper bound of the interval number, respectively.

Based on the interval comparison possibility, the preference function (Vinodh and Girubha, 2012) is proposed in this paper to express the importance degree of the relative difference between competing alternatives with respect to a certain criterion.

Definition 8. (Chen, 2014a).The ICP-based preference function can be defined as follows.

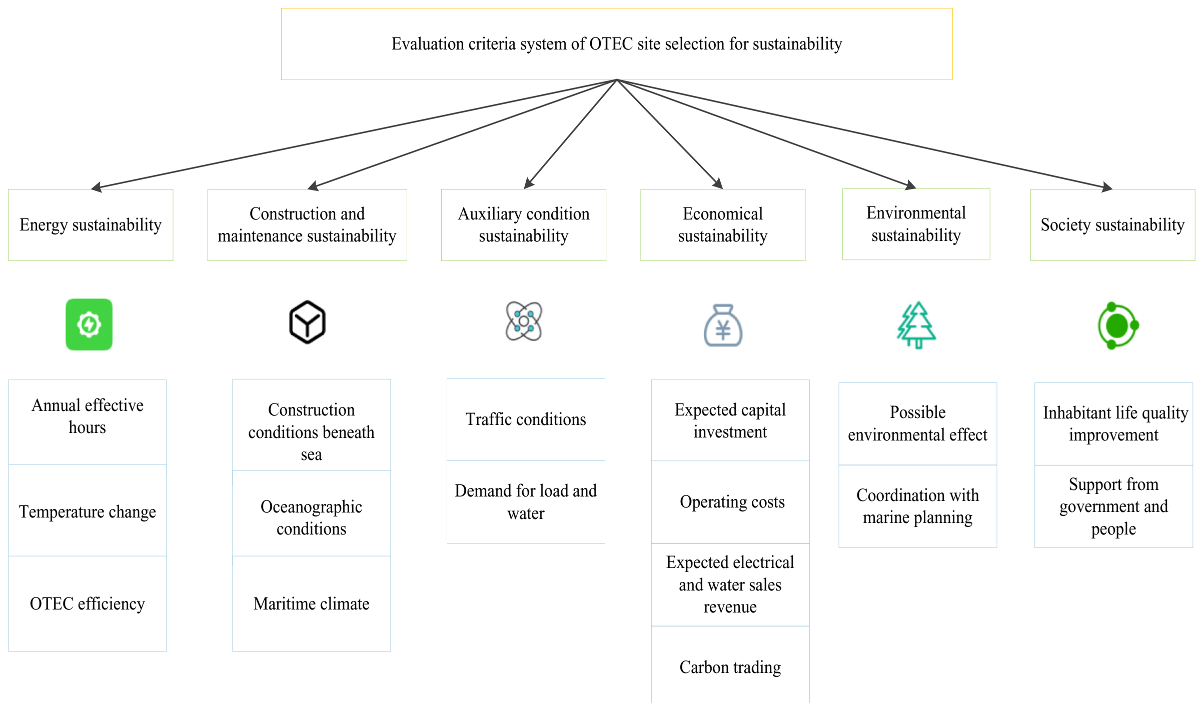

Fig. 1. OTEC site selection evaluation index system.

$$ip\left(\tilde{A}_{ij},\tilde{A}_{i'j}\right)=\begin{cases}1 & ,if\ CT_{\tilde{A}_{i'j}>\tilde{A}_{ij}}-0.5>p\\ \dfrac{\left|CT_{\tilde{A}_{i'j}>\tilde{A}_{ij}}-0.5\right|-q}{p-q} & ,if\ q<CT_{\tilde{A}_{i'j}>\tilde{A}_{ij}}-0.5\le p\\ 0 & ,otherwise\end{cases} \tag{16}$$

p represents for the significant difference parameter and $q$refers to the indifference parameter. The ICP-based preference function $ip(\tilde{A}_{ij},\tilde{A}_{i'j})$ has the essential meanings as follows: (1) indicates a strong preference relation of $\tilde{A}_{ij}$ over $\tilde{A}_{i'j}$; (2) indicates a weak preference relation of $\tilde{A}_{ij}$over $\tilde{A}_{i'j}$; (3) $ip(\tilde{A}_{ij},\tilde{A}_{i'j})\sim 0$indicates that the relation between $\tilde{A}_{ij}$ and$\tilde{A}_{i'j}$ is indifference. The value of p and $q$is determined by the decision-makers.

The aim of this Definition is to consider the subjective preference of decision-makers in the process of OTEC site selection. For instance, for some criteria, small performance differences between alternatives can be ignored if criteria values reach a certain level, while for other criteria, alternatives are considered to be strictly priority as long as their criteria values are different.

4.4. Phase IV- construction of comprehensive preference indices

In this phase, the comprehensive preference indices are established on the basis of ICP-based preference function, in order to obtain the outranking relations with inflow and outflow calculation, for the determination of partial ranking orders of the alternatives.

Definition 9. Denote IVIFNs $\tilde{A}_{ij}$ and $\tilde{A}_{i'j}$ to be evaluation ratings of ith and i'th alternative, respectively, with respect to criterion $x_j \in X$. Let $\tilde{W}_j$denote the relative importance of criterion x_j. The comprehensive preference index can be defined as follows

$$\begin{aligned}\tilde{p}_{ii'} &= IVIFPA_{\tilde{W}_j}\left(ip\left(\tilde{A}_{i1},\tilde{A}_{i'1}\right),ip\left(\tilde{A}_{i2},\tilde{A}_{i'2}\right),\ldots ip\left(\tilde{A}_{in},\tilde{A}_{i'n}\right)\right)\\ &= \mathop{\oplus}_{j=1}^{n}\left(ip\left(\tilde{A}_{ij},\tilde{A}_{i'j}\right)\right)\cdot\tilde{W}_j=\left(\left[\rho_{ii'}^{-},\rho_{ii'}^{+}\right],\left[\beta_{ii'}^{-},\beta_{ii'}^{+}\right]\right).\end{aligned} \tag{17}$$

The aim of this Definition is to aggregate all assessment criteria values, which involves in OTEC site selection, by combining the importance of these criteria.

Theorem 1. (Chen, 2014a) *Let IVIFNs $\tilde{W}_j=([\varpi_j^-,\varpi_j^+],[\xi_j^-,\xi_j^+])$ be the weight of criterion x_j. The calculation of the comprehensive preference index $\tilde{p}_{ii'}$is as follows.*

$$\begin{aligned}\tilde{p}_{ii'} &= \left(\left[\rho_{ii'}^{-},\rho_{ii'}^{+}\right],\left[\beta_{ii'}^{-},\beta_{ii'}^{+}\right]\right)\\ &\left(\left[1-\prod_{k}^{l}\left(1-\varpi_j^-\right)^{ip(\tilde{A}_{ij},\tilde{A}_{i'j})},1-\prod_{k}^{l}\left(1-\varpi_j^+\right)^{ip(\tilde{A}_{ij},\tilde{A}_{i'j})}\right],\left[\prod_{k}^{l}\left(\varpi_j^-\right)^{ip(\tilde{A}_{ij},\tilde{A}_{i'j})},\prod_{k}^{l}\left(\varpi_j^+\right)^{ip(\tilde{A}_{ij},\tilde{A}_{i'j})}\right]\right)\end{aligned} \tag{18}$$

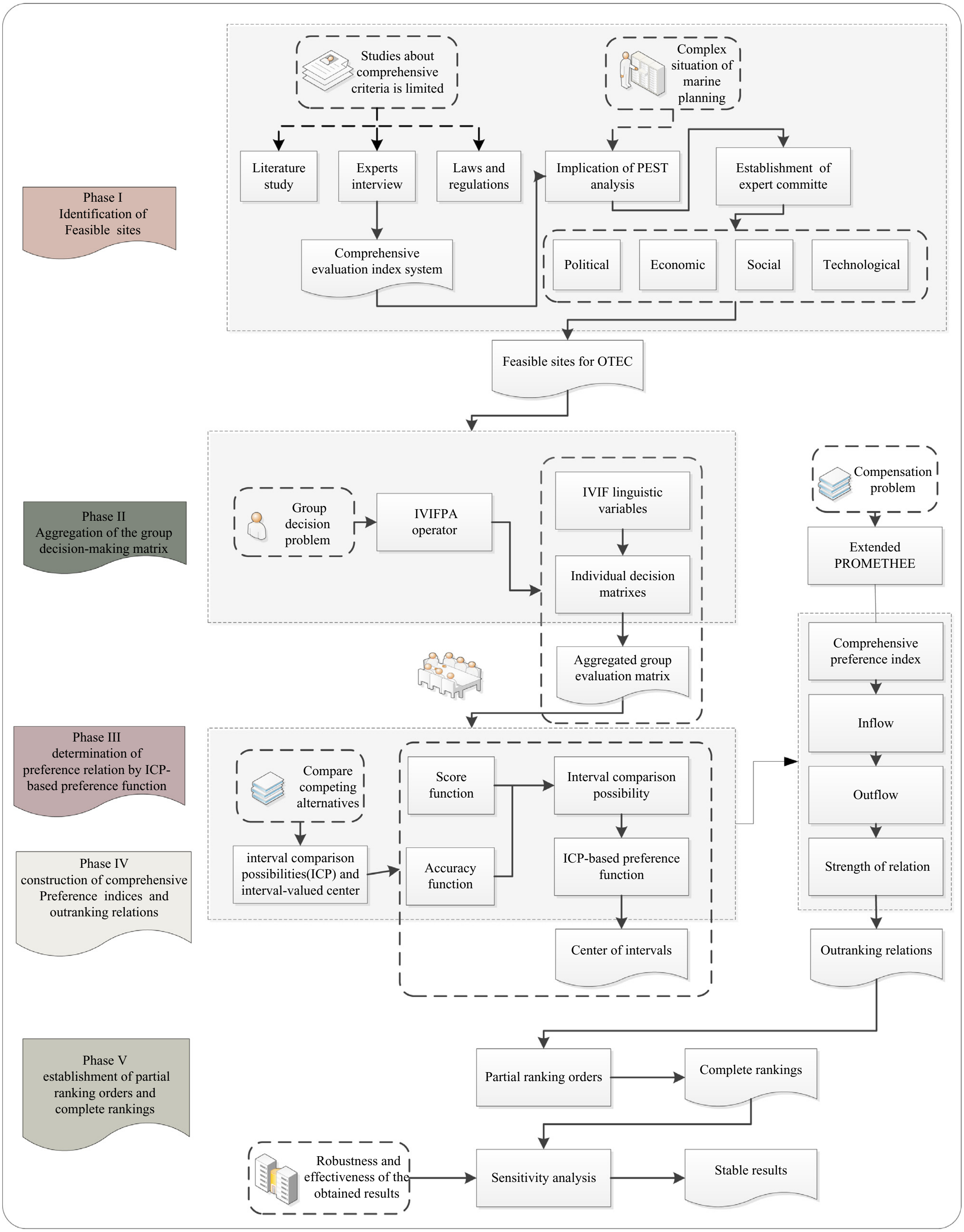

Fig. 2. Decision framework for OTEC site selection decision from sustainability perspective.

4.5. *Phase V- establishment of partial ranking orders and complete rankings*

The process of PROMETHEE can be referred to Appendix B(Georgiou et al., 2015; Kabir and Sumi, 2014; Moiz et al., 2018).

The partial ranking orders ($O^{(1)}$,$I^{(1)}$,R) of alternatives can be defined on the basis of outranking relations (O^+,I_r^+,O^-,I_r^-) based on the following rules.

(1) $A_i$dominates over $A_{i'}$, i.e. $A_iO^{(1)}A_{i'}$, if $A_iO^+A_{i'}$ and $A_iO^-A_{i'}$; or $A_iO^+A_{i'}$ and $A_iI_r^-A_{i'}$; or $A_iI_r^+A_{i'}$and $A_iO^-A_{i'}$,
(2) $A_i$is indifferent over $A_{i'}$, i.e. $A_iR^{(1)}A_{i'}$, if $A_iI_r^-A_{i'}$and $A_iI_r^+A_{i'}$,
(3) $A_i$and $A_{i'}$ are incomparable, i.e. $A_iRA_{i'}$, otherwise.

The graphic representation of the outranking relations and binary relations of the partial ranking are connected with Fig. 3. Based on partial ranking orders, the complete rankings can be obtained. From the partial ranking orders, the value of the difference between the arrows pointed out from one alternative R_i and pointed to one alternative Q_i can be obtained which is denoted as D_i. And the complete rankings are obtained on the basis of the values D_i. That is to say, for example, if D_i of alternative A_i is greater than others, alternative A_i is the optimal selection among all alternatives.

5. A real case study

A 10 MW OTEC power plant is planned to construct in areas of Guangdong and Guangxi provinces. The owner sends a team of qualified experts to imply site selection work, whose backgrounds concerning energy, engineering, economics environtology and sociology. And the correspondence with Section 4 is demonstrated in Appendix C.

In the first phase, preparations for feasible location identification are made by the experts before the site reconnaissance work. First, the expert team communicates with the owner to understand his demands and opinions. Then, an indoor macro location selection is conducted on the basis of GIS. In this process, the initial information of local energy resources for OTEC is obtained from the National Meterological Administration and the National Marine Environmental Forecasting Center, and a short list is formed. Further, approximate project benefits are calculated according to energy resources and general investment. Sites with irrational performance in economy compared with other alternatives are eliminated from the short list and enter the standby list. After the indoor preparations, the site reconnaissance work is conducted by the experts according to the lists. The sea floor topography and marine geological data are studied to see whether it is technically feasible to build platform for OTEC and lay pipes for cold water. Following this, information about the environmentally sensitive area are collected, and the potential influence of plant on the environment is assessed. After that, the experts visit the local government to know if there are any local policies for ocean thermal energy such as subsidies, the planning around the alternative sites and the attitude of the local government. Considering the complex condition about OTEC, the experts are also visited to avoid choosing infeasible sites which have conflicts with sea planning. After this, the initial site scope is delimited by using GPS and the size of the area is calculated. Some sites do not meet the demand of the required generating capacity are wiped off from the list. Then, a group meeting is conducted by the experts. The experts vote on the standby sites according to the newly collected information. Those sites have good performance on other aspects besides economic are reconsidered. Finally, a list of feasible sites are identified for OTEC according to the above process, which is Xieyang Island, Weizhou Island, Dan'gan Island, Dong'ao Island and Wanshan Island, namely, A_1, A_2, A_3, A_4 and A_5 which is shown in Fig. 4.

In the second phase, the initial evaluation matrix is obtained based on group decision of the experts. The expert team is divided into seven groups, i.e. the energy group, the technology group, the oceanography group, the economic group, the environment group, the society group and the comprehensive group according to the experts' backgrounds. First, the former six groups make assessment on the alternative sites with respect to criteria and form the individual evaluation matrix. In this process, double blind method which involves no communications between experts is applied to keep the independence of individuals. After four rounds of evaluation and feedbacks, the opinions of the experts tend to be stable. Then, the individual opinions are aggregated based on the IVIFPA operator. The linguistic values and their corresponding IVIFNs for alternative ratings are shown in Table 1.

Table 2 shows the evaluation rating matrixes of alternatives on alternatives with respect to each criteria. The importance of the experts in each group is determined according to their professional titles. The importance levels of senior title, intermediate title and primary title are considered as very important, quite important and

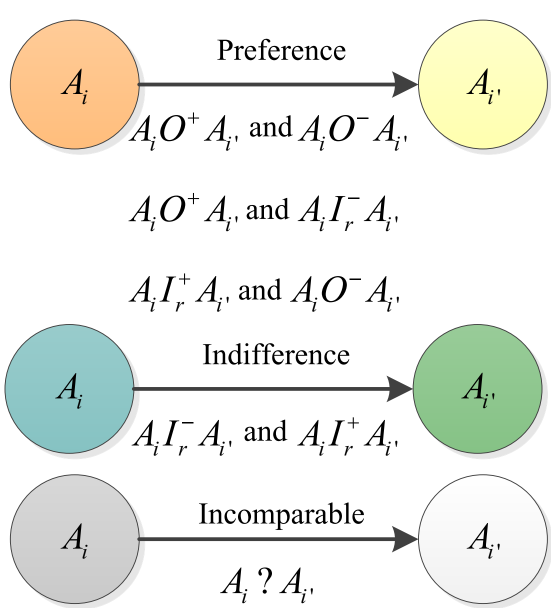

Fig. 3. Graphic representation of binary relations.

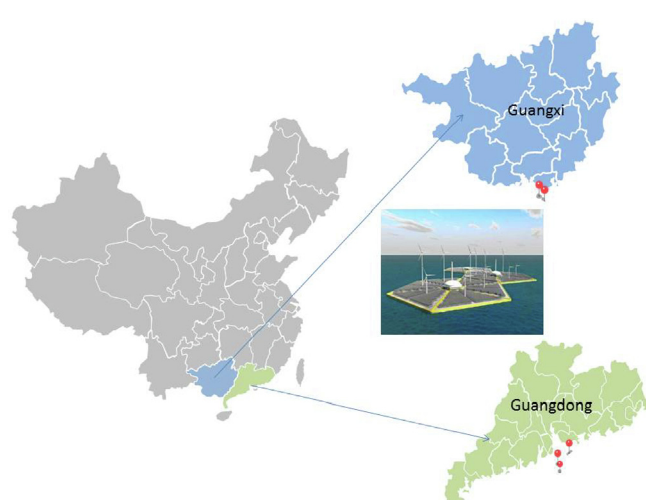

Fig. 4. Site selection of the OTEC.

Table 1
The linguistic values and their corresponding IVIFNs for alternative ratings.

Linguistic values	Abbreviation	IVIFNs
Very low	VL	([0.0,0.1], [0.8,0.9])
Low	L	([0.1,0.2], [0.6,0.8])
Fairly low	FL	([0.2,0.3], [0.4,0.6])
Fair	F	([0.4,0.5], [0.3,0.4])
Fairly high	FH	([0.6,0.7], [0.2,0.3])
High	H	([0.8,0.9], [0.1,0.2])
Very high	VH	([1.0,1.0], [0.0,0.0])

important, respectively. The linguistic terms are shown in Table 3 correspondingly. With the individual evaluation matrix and experts weights, the integrated group decision matrix is shown in Table 4.

In the third phase, the preference relation between each competing alternative pair is built on the basis of the group decision matrix. Firstly, based on interval-valued score function and accuracy function, the interval comparison possibility between pairwise alternatives is calculated according to eq. (12). Then the center of intervals is obtained in accordance with eq. (13). Following this, an expert meeting is held to discuss the value of indifference parameter p and significant difference parameter q, which is $p = 0.005$and $q = 0.35$. After this, the ICP-based preference relations of alternative pairs with respect to each criterion can be calculated according to eq. (16).

In the fourth phase, the outranking relations are constructed based on the comprehensive preference indices. During this period, the comprehensive group gives remarks on the importance of criteria. The evaluation on the criteria weights is similar as alternative assessment. Each member in the comprehensive group grades on the importance of the criteria independently and the individual opinions are aggregated as shown in Table 5.

Using the comprehensive criteria weights and the result of ICP-based preference relation with respect to each criterion obtained from the previous phase, the comprehensive preference can be calculated in accordance with eq. (18), as shown in Table 6.

Then IVIFNs inflow $\tilde{\phi}^-(\tilde{A}_i)$ and outflow $\tilde{\phi}^+(\tilde{A}_i)$ are calculated according to eq. (B.1) and eq. (B.2), as shown in Table 7.

After that, the strength of relation between inflow and outflow can be calculated based on eq. (B.7), as shown in Table 8.

Table 2
Evaluation rating matrixes of alternatives on the sub-criteria.

	DM1	DM2	DM3	DM4	DM5
C_{11}	H FH H F F	FH H FH F FH	H H F FL FH	FH H FH F FL	H FH H FH H
C_{12}	FH FH F H F	H H H FH H	FH FH F F FH	H H H F FH	FH H F F FH
C_{13}	FH H H H FL	H H H F FL	FH H F F F	FH FH F H FL	H H F FL F
C_{21}	FL FH FL FH FH	FH FH FH FL FH	FL FH F F FH	FH FH FH H FH	FH FH F VH F
C_{22}	L FH FL FH H	L VH F FL FH	L H FL F FL	FL H F FH L	FL H FH FL FH
C_{23}	FL F F FH L	F F F FL FL	FL FL H H F	FL F H FH L	F F H FH FL
C_{31}	H VH FH F F	H H FH FH L	FH H H F FL	FH VH FH FH L	H VH VH F F
C_{32}	F H FL FH FH	F VH F FH FH	FL VH L H FH	L H FL FH FH	FL H F FH FH
C_{41}	H H H H FL	H H H H FL	H VH VH H FL	FH VH VH H FL	FH H VH FH FL
C_{42}	L H H FL F	F VH F F FH	FL VH H FL F	FL H H FH F	F VH H FH F
C_{43}	FL H F H F	L H FH FH F	F H VH H L	F FH H H L	FL H FH FH F
C_{44}	F F F FH FL	FH FH FH F FL	F FH FH FL FL	F F F FL FH	FH F FH F FL
C_{51}	H H H FL VH	H FH H F VH	H H H H H	H FH H FL VH	H F H FL VH
C_{52}	F FL FL H L	FH FH L FH FL	F FL L H FL	H FH FL FH F	FH F F F FL
C_{61}	F H H FL F	F H H H FL	F H H H FL	F H VH F FL	F VH FH F F
C_{62}	F H FH FH L	FL FH H FH FL	F FH H F FL	FL VH VH FL L	FL VH VH F FL

Table 3
Relative importance of the DMs.

	DM_k	DM_k	DM_k
Professional title	Junior	Intermediate	Senior
Linguistic terms	Important	Medium	Very important
IVIF numbers	[0.15,0.35][0.6,0.8]	[0.5,0.7], [0.25,0.45],	[0.65,0.85], [0.1,0.3]

Table 4
Aggregate evaluation ratings of the experts group.

	A_1	A_2	A_3	A_4	A_5
C_{11}	([0.904,0.990], [0.004,0.061])	([0.892,0.988], [0.004,0.065])	([0.872,0.983], [0.006,0.072])	([0.695,0.901], [0.020,0.136])	([0.841,0.972], [0.008,0.085])
C_{12}	([0.8737,0.983], [0.005,0.071])	([0.901,0.990], [0.004,0.062])	([0.800,0.961], [0.010,0.096])	([0.796,0.954], [0.012,0.098])	([0.851,0.976], [0.0079,0.079])
C_{13}	([0.897,0.989], [0.004,0.063])	([0.925,0.994], [0.003,0.052])	([0.840,0.973], [0.008,0.084])	([0.728,0.929], [0.017,0.132])	([0.550,0.803], [0.034,0.201])
C_{21}	([0.726,0.923], [0.016,0.136])	([0.834,0.968], [0.009,0.085])	([0.704,0.910], [0.018,0.133])	([0.850,0.975], [0.006,0.075])	([0.799,0.954], [0.011,0.096])
C_{22}	([0.288,0.591], [0.120,0.451])	([0.938,0.995], [0.002,0.039])	([0.656,0.880], [0.023,0.158])	([0.614,0.861], [0.027,0.184])	([0.802,0.955], [0.012,0.109])
C_{23}	([0.570,0.815], [0.032,0.188])	([0.629,0.860], [0.026,0.155])	([0.850,0.978], [0.007,0.080])	([0.797,0.957], [0.0114,0.1088])	([0.433,0.712], [0.059,0.297])
C_{31}	([0.912,0.992], [0.003,0.057])	([0.957,0.998], [0.001,0.027)	([0.918,0.991], [0.002,0.045])	([0.737,0.926], [0.016,0.114])	([0.509,0.772], [0.052,0.250])
C_{32}	([0.543,0.795], [0.037,0.210])	([0.956,0.997], [0.001,0.028])	([0.546,0.800], [0.040,0.215])	([0.858,0.977], [0.007,0.077])	([0.834,0.968], [0.008,0.085])
C_{41}	([0.901,0.990], [0.004,0.061])	([0.941,0.996], [0.002,0.039])	([0.957,0.998], [0.001,0.027])	([0.907,0.991], [0.004,0.059])	([0.405,0.690], [0.049,0.290])
C_{42}	([0.546,0.799], [0.040,0.215])	([0.968,0.998], [0.001,0.019])	([0.888,0.987], [0.005,0.067])	([0.667,0.890], [0.021,0.155])	([0.728,0.919], [0.017,0.117])
C_{43}	([0.450,0.738], [0.055,0.285])	([0.925,0.994], [0.003,0.052])	([0.869,0.978], [0.006,0.066])	([0.882,0.985], [0.005,0.069])	([0.590,0.828], [0.038,0.193])
C_{44}	([0.776,0.943], [0.013,0.103])	([0.762,0.936], [0.014,0.107])	([0.804,0.955], [0.011,0.094])	([0.665,0.881], [0.023,0.149])	([0.442,0.739], [0.044,0.271])
C_{51}	([0.927,0.995], [0.002,0.051])	([0.852,0.976], [0.007,0.080])	([0.927,0.995], [0.002,0.051])	([0.663,0.888], [0.023,0.168])	([0.969,0.998], [0.001,0.018])
C_{52}	([0.790,0.953], [0.011,0.098])	([0.667,0.890], [0.021,0.155])	([0.426,0.710], [0.069,0.319])	([0.852,0.976], [0.007,0.080])	([0.392,0.689], [0.059,0.317])
C_{61}	([0.671,0.885], [0.022,0.133])	([0.947,0.997], [0.001,0.035])	([0.910,0.992], [0.003,0.056])	([0.820,0.967], [0.009,0.098])	([0.550,0.803], [0.034,0.201])
C_{62}	([0.530,0.790], [0.036,0.214])	([0.924,0.992], [0.002,0.042])	([0.940,0.996], [0.001,0.036])	([0.755,0.931], [0.015,0.112])	([0.363,0.649], [0.068,0.346])

Table 5
Aggregated criteria and sub-criteria weights.

Criteria	Criteria weight	Sub-criteria	Sub-criteria weight
C_1	([0.865, 0.967], [0.007, 0.085])	C_{11}	([0.749,0.936], [0.014,0.163])
		C_{12}	([0.608,0.888], [0.0515,0.238])
		C_{13}	([0.763,0.956], [0.0108,0.140])
C_2	[0.735, 0.952], [0.051, 0.195]	C_{21}	([0.611,0.917], [0.063,0.314])
		C_{22}	([0.619,0.931], [0.060,0.285])
		C_{23}	([0.572,0.911], [0.0674,0.290])
C_3	[0.617,0.897], [0.078, 0.242]	C_{31}	([0.433,0.824], [0.120,0.461])
		C_{32}	([0.539,0.879], [0.083,0.307])
C_4	([0.874,0.980], [0.005, 0.072])	C_{41}	([0.777,0.973], [0.008,0.119])
		C_{42}	([0.652,0.920], [0.0374,0.351])
		C_{43}	([0.736,0.958], [0.015,0.176])
		C_{44}	([0.482,0.847], [0.114,0.340])
C_5	([0.831,0.963], [0.013, 0.112])	C_{51}	([0.700,0.941], [0.023,0.212])
		C_{52}	([0.700,0.941], [0.023,0.183])
C_6	([0.371,0.737], [0.188, 0.446])	C_{61}	([0.297,0.719], [0.205,0.490])
		C_{62}	([0.292,0.706], [0.210,0.554])

Following this, the outranking relations are constructed by using the strength function value, as illustrated in Fig. 5.

From Fig. 5, the value of each alternative can be obtained as is shown in Table 9. In the fifth phase, the partial ranking orders and complete rankings are obtained based on the rules. And from Table 9, it is easy to see A_1 is superior to others with the value of four.. The complete ranking result is formed, which is $A_2 \succ A_3 \succ A_4 \succ A_1 \succ A_5$. From the ranking result, it can be seen that alternative A_2, namely Weizhou Island, is the optimal site for OTEC project construction. From Table 4, A_2 has distinct advantages over the other alternatives in aspects of energy, construction and maintenance, auxiliary condition, economic and society. However, in terms of the other criteria, alternative A_2doesn't seem to be as good as alternatives of $A_1$and A_4. A_3 has advantage in energy, economic and society, but the advantage in energy and environment are also obvious. A_4 has advantage in environment and disadvantage in economic. A_1 and A_5 have good energy resources, however, the other criteria perform inferior to the other alternatives.

6. Sensitive analysis

In this section, a comprehensive sensitive analysis is conducted to study further the application of the proposed method in various conditions. Through this part, we analyze how the ranking order change in different circumstances by altering influencing decision variables. Impacts of expert attitude and criteria weights on the final evaluation are analyzed as follow.

First, the influences of criteria weights on the obtained ranking result are studied. We alter the significant proportion of criteria weights (Table 5) from −100% to 100% and analyze the influences on the ranking results. First, we change the criteria weights by a small proportion, i.e. from −30%, to 30%. The sensitive results shows the ranking orders are rather stable, as shown in Fig. 6. And to make the results clearer, we apply color gradation table to show the final results which is shown in Table 10.

As fluctuation of criteria weights become larger, small changes appear between alternatives. When criteria weight of C_2 doubles, differences between alternative A_1 and A_5 are rather small. As criteria weight of C_3 increases by 100%, alternative $A_3$and A_4.are getting more and more close. When the weight of C_1 decreases by

Table 8
Strength of relation between inflow and outflow.

	A_1	A_2	A_3	A_4	A_5
A_1	-	0.208	0.106	0.077	−0.071
A_2	−0.208	-	−0.102	−0.131	−0.279
A_3	−0.106	0.102	-	−0.029	−0.177
A_4	−0.077	0.131	0.029	-	−0.148
A_5	0.071	0.279	0.177	0.148	-

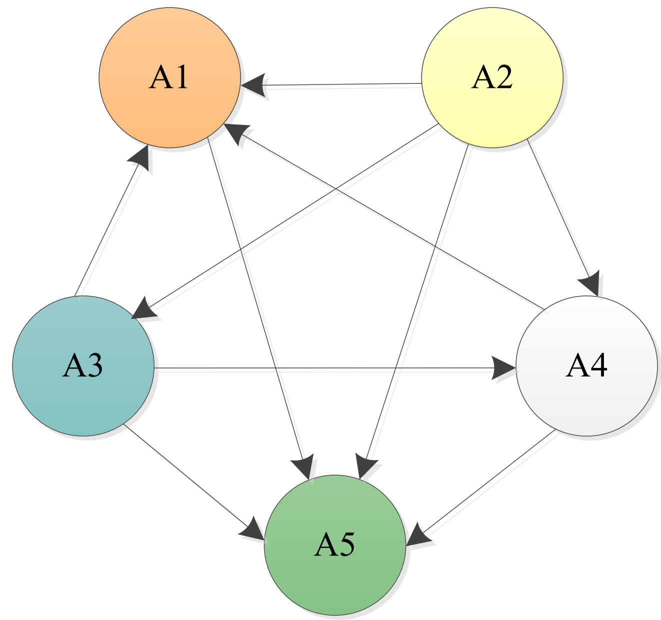

Fig. 5. The binary relations between alternatives.

Table 6
ICP-based comprehensive preference indices.

	A_1	A_2	A_3	A_4	A_5
A_1	-	([0.083,0.185], [0.763,0.887])	([0.247,0.486], [0.412,0.669])	([0.374,0.66], [0.225,0.531])	([0.732,0.964], [0.013,0.150])
A_2	([0.713,0.964], [0.019,0.191])	-	([0.4522,0.786], [0.156,0.433])	([0.554,0.865], [0.075,0.347])	([0.843,0.992], [0.002,0.072])
A_3	([0.613,0.921], [0.046,0.285])	([0.113,0.282], [0.683,0.842])	-	([0.433,0.751], [0.157,0.475])	([0.789,0.984], [0.005,0.106])
A_4	([0.605,0.916], [0.052,0.282])	([0.156,0.352], [0.587,0.784])	([0.374,0.689], [0.232,0.514])	-	([0.782,0.980], [0.007,0.111])
A_5	([0.467,0.810], [0.149,0.444])	([0.042,0.097], [0.874,0.946])	([0.202,0.457], [0.499,0.727])	([0.308,0.582], [0.322,0.621])	-

Table 7
IVIFNs inflow and outflow.

	A_1	A_2	A_3	A_4	A_5
Inflow	([0.609,0.918], [0.051,0.287])	([0.100,0.235], [0.719,0.863])	([0.326,0.631], [0.294,0.574])	([0.425,0.737], [0.171,0.483])	([0.790,0.982], [0.006,0.106])
Outflow	[0.417,0.732], [0.175,0.467])	([0.676,0.946], [0.026,0.213])	([0.549,0.877], [0.071,0.332])	([0.538,0.865], [0.082,0.335])	([0.271,0.556], [0.380,0.660])

Table 9
The difference of the arrows of alternatives.

	R_i	Q_i	D_i	Rank
A1	1	3	−2	4
A2	4	0	4	1
A3	3	1	2	2
A4	2	2	0	3
A5	0	−4	−4	5

Table 10
Results of sensitive analysis - status 1.

	C1	C2	C3	C4	C5	C6	Rank
A1	−2	−2	−2	−2	−2	−2	4
A2	4	4	4	4	4	4	1
A3	2	2	2	2	2	2	2
A4	0	0	0	0	0	0	3
A5	−4	−4	−4	−4	−4	−4	5

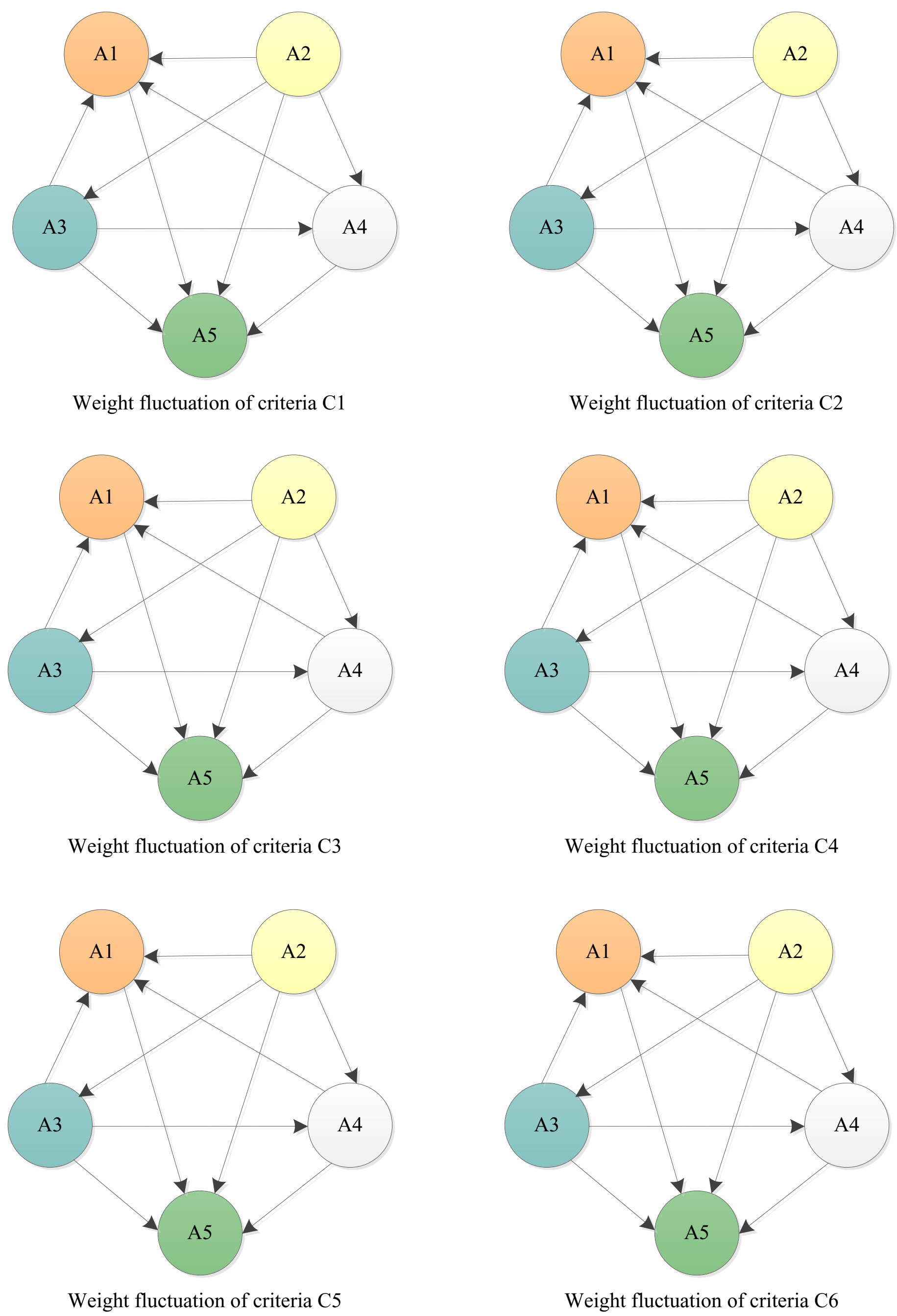

Fig. 6. Sensitive analysis - status 1.

90%, positions of alternatives of $A_3$and A_4.change. When the weight of C_1 is cut by 90%, alternative $A_3$and A_4.are getting very close. In a word, the ranking orders have not altered as criteria weights changes from −80% to100% (status1). When criteria weights reach to −90% (status2), orders of an alternative pair change, as is shown in Fig. 7 and Table 11.

Then, the effects of the experts' attitudes on the ranking orders are analyzed. We change the risk aversion parameter $\alpha$from 0.1 to 0.9, and observe changes of alternative relations. It is found that when the experts are conservative or risk aversion, there is no change in the ranking results and relation between alternatives keep stable. As the decision makers become more and more optimistic or risky, A_3 and A_4, A_1 and A_5 are getting very close.

To conclude, from the sensitive analysis, it can be seen that the rankings are rather stable in general, demonstrating the robustness and effectiveness of the obtained results.

7. Conclusion

Optimal site selection decision is a fundamental issue for ocean thermal energy development. In this paper, how to select the best performed location for OTEC project is studied in consideration of conflicting criteria though comprehensive decision making framework.

This paper firstly established a comprehensive evaluation criteria system from the view of sustainability involving internal and external aspects with a total of 16 criteria. Then, considering complex conditions of maritime planning, feasible alternative sites for OTEC project were identified by PEST analysis to avoid possible delays. After that, an extend PROMETHEE method was proposed by

Table 11
Results of sensitive analysis - status 2.

	C1	C2	C3	C4	C5	C6	Rank
A1	−2	−2	−2	−2	−2	−2	4
A2	4	4	4	4	4	4	1
A3	0	2	2	2	2	2	2, 3(C1)
A4	2	0	0	0	0	0	3, 2(C1)
A5	−4	−4	−4	−4	−4	−4	5

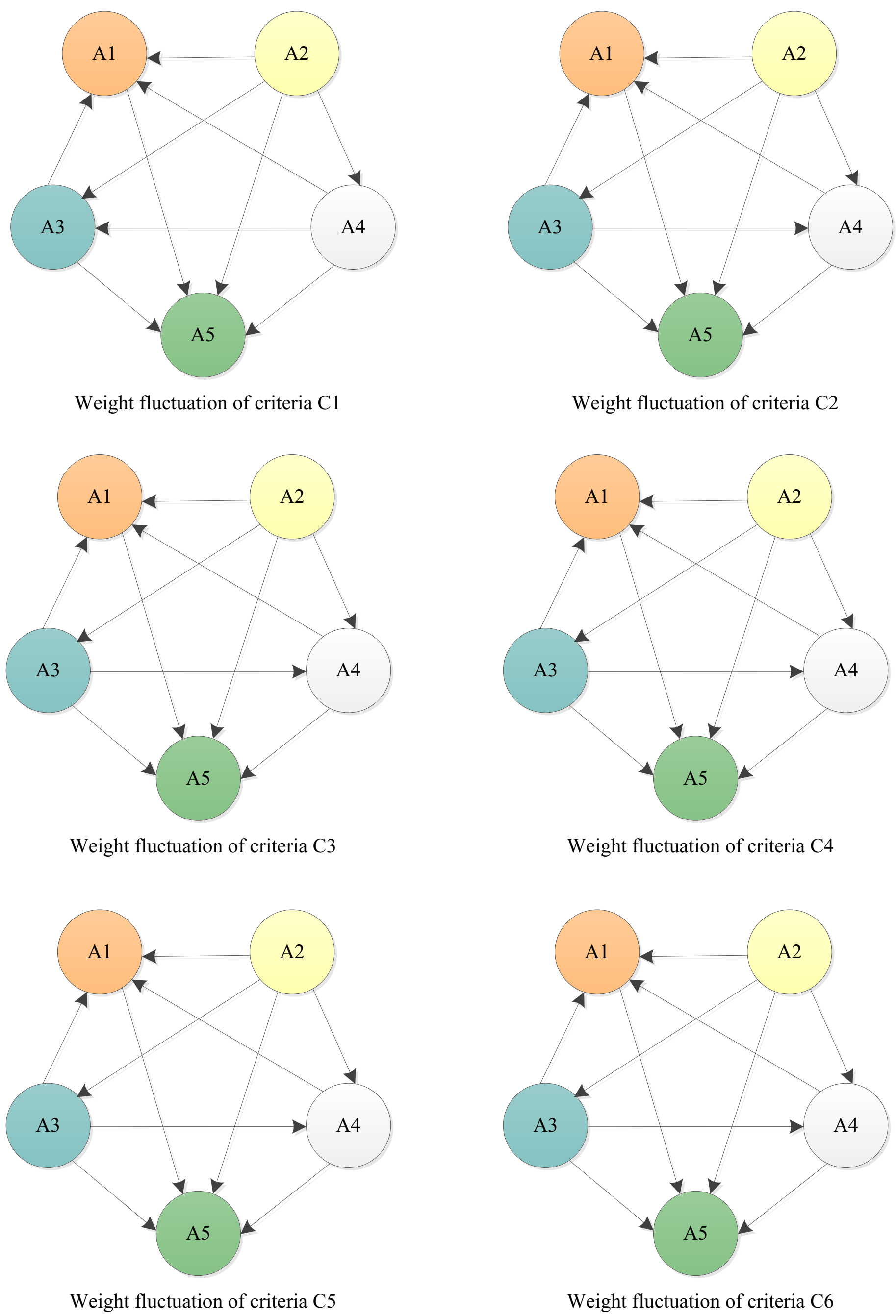

Fig. 7. Sensitive analysis - status 2.

this study to solve compensation problem and intuitionistic fuzzy numbers were used in this process to deal with vague and ambiguous information. To improve decision rationality, experts were divided into seven groups with different decision making tasks in accordance with their backgrounds, including energy, construction and maintenance, auxiliary condition, economic, environment and society. Last, the complete ranking orders were obtained and the result shown that alternative site A_2 located at Weizhou Island in Guangxi Province had the most satisfactory performance and should be chosen as the optimal site. To testify the robustness and effectiveness of the obtained results, a sensitive analysis was performed. The results indicated that the ranking orders were stable no matter how variables changed. Therefore, the proposed method was proved to be practical, effective and robustness. This study helps improve the decision making quality and facilitates energy decision making applications.

Competing interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Appendix A

Definition 10. (Chen, 2014b). Let $\tilde{W}_k = ([\tilde{w}_k^-, \tilde{w}_k^+], [\tilde{w}_k^-, \tilde{w}_k^+])$o be the importance value of the kth decision-maker. Denote the IVIF value $\tilde{A}_{ij}^k = ([u_{ij}^{k-}, u_{ij}^{k+}], [v_{ij}^{k-}, v_{ij}^{k+}])$ scored by the kth decision-maker to be the evaluation rating of the ith alternative with respect to criterion $x_j \in X$, where $i = 1,2,\dots,m, j = 1,2,\dots,n$ and $k = 1,2,\dots,l$.

$$IVIFPA_{W_k}\left(\tilde{A}_{ij}^1, \tilde{A}_{ij}^2, \dots, \tilde{A}_{ij}^l\right) = \mathop{\oplus}_{k=1}^{l}\left(\tilde{W}_k \otimes \tilde{A}_{ij}^k\right) = \left(\left[1-\prod_k^l\left(1-\omega_k^- \cdot u_{ij}^{k-}\right), 1-\prod_k^l\left(1-\omega_k^+ \cdot u_{ij}^{k+}\right)\right]\right), \times \left[\prod_k^l\left(\omega_k^- + v_{ij}^{k-} - \omega_k^- \cdot v_{ij}^{k-}\right), \prod_k^l\left(\omega_k^+ + v_{ij}^{k+} - \omega_k^+ \cdot v_{ij}^{k+}\right)\right] \tag{A.1}$$

Appendix B

Definition 11. For the ith alternative, the IVIFNs inflow $\tilde{\phi}^{\upsilon}(\tilde{A}_i)$and outflow $\tilde{\phi}^{\gamma}(\tilde{A}_i)$ are defined as follows

$$\tilde{\phi}^{\gamma}\left(\tilde{A}_i\right) = \frac{1}{m-1} \mathop{\oplus}_{i'=1, i\neq i'}^{m} \tilde{p}_{ii'} \tag{B.1}$$

$$\tilde{\phi}^{\upsilon}\left(\tilde{A}_i\right) = \frac{1}{m-1} \mathop{\oplus}_{i'=1, i\neq i'}^{m} \tilde{p}_{i'i} \tag{B.2}$$

Apparently, high value of outflow $\tilde{\phi}^{\gamma}(\tilde{A}_i)$ indicates a high possibility that the ith alternative outranks other competing alternatives. Similarly, a low level of inflow $\tilde{\phi}^{\upsilon}(\tilde{A}_i)$indicates a relatively high ranking of the ith alternative compared with other alternatives or a relatively low possibility that other alternatives outranks the ith alternative. Define the outranking relations (O^+, I_r^+, O^-, I_r^-) in terms of inflow and outflows in the following manner.

$$(1) \quad A_i O^+ A_{i'} \text{ if } , \tilde{\phi}^{\gamma}\left(\tilde{A}_i\right) > \tilde{\phi}^{\gamma}\left(\tilde{A}_{i'}\right) \tag{B.3}$$

$$(2)\ A_i I_r^+ A_{i'}, \text{ if } \tilde{\phi}^{\gamma}\left(\tilde{A}_i\right) = \tilde{\phi}^{\gamma}\left(\tilde{A}_{i'}\right) \tag{B.4}$$

$$(3)\ A_i O^- A_{i'}, \text{ if } \tilde{\phi}^{\upsilon}\left(\tilde{A}_i\right) < \tilde{\phi}^{\upsilon}\left(\tilde{A}_{i'}\right) \tag{B.5}$$

$$(4)\ A_i I_r^- A_{i'} \text{ if } \tilde{\phi}^{\upsilon}\left(\tilde{A}_i\right) = \tilde{\phi}^{\upsilon}\left(\tilde{A}_{i'}\right) \tag{B.6}$$

However, due to the characteristic of IVIFNs, we still cannot make comparisons between inflow and outflow immediately or calculate the net flow directly. In order to solve this problem, we estimate the inequalities relation between the IVIFNs inflow and outflow using the strength function value (Dymova et al., 2013) as follows.

Definition 12. The strength of relation between inflow/outflow $\tilde{\phi}^{\upsilon}/\tilde{\phi}^{\gamma}$ is defined as follows

$$\begin{aligned} ST_{\tilde{\phi}^{\gamma}(\tilde{A}_i)-\tilde{\phi}^{\upsilon}(\tilde{A}_{i'})} = \frac{1}{2}\Bigg(& P\left(\tilde{\phi}^{\gamma}\left(\tilde{A}_i\right) > \tilde{\phi}^{\upsilon}\left(\tilde{A}_{i'}\right)\right)^L \\ & - P\left(\tilde{\phi}^{\upsilon}\left(\tilde{A}_{i'}\right) > \tilde{\phi}^{\gamma}\left(\tilde{A}_i\right)\right)^U \Bigg) \\ & + \left(P\left(\tilde{\phi}^{\gamma}\left(\tilde{A}_i\right) > \tilde{\phi}^{\upsilon}\left(\tilde{A}_{i'}\right)\right)^U \right. \\ & \left. - P\left(\tilde{\phi}^{\upsilon}\left(\tilde{A}_{i'}\right) > \tilde{\phi}^{\gamma}\left(\tilde{A}_i\right)\right)^L \right) \end{aligned} \tag{B.7}$$

For the convenience of application, the procedure of the construction of comprehensive preference indices and binary outranking relations can be summarized in the following steps.

STEP 1. Integrate the pairwise preference relations with respect to a certain criterion and criteria importance on the basis of IVIFPA operator to form the comprehensive preference indices via eq. (17). The importance of the criteria is evaluated by the entropy method.

STEP 2. Calculate the interval-valued intuitionistic fuzzy outflow $\tilde{\phi}^{\gamma}$ and inflow $\tilde{\phi}^{\upsilon}$for the ith alternative by eq. (B.1) and eq. (B.2), respectively.

STEP 3. Process the comparison between the inflow and outflow of alternatives using the strength function value via eq. (B.7). Construct the outranking relations (O^+, I_r^+, O^-, I_r^-) between pairwise alternatives in terms of inflow and outflows via eq. (B.3), eq. (B.4), eq. (B.5) and eq. (B.6).

Appendix C

The correspondence between the definitions in section 4 and the OTEC plan site selection is shown in the following Table C1.

Table C.1
Correspondence between the definitions in section 5 and the OTEC plan site

Process	Purpose	Methodology	Definition	Case study
Identification of the alternative plans	Select the alternatives and obtain evaluation rating matrixes of alternatives on alternatives with respect to each criteria	IVIF linguistic variables		Fig. 4, Table 1, Table 2, Table 3
Integration of group decision matrix	Form the group decision opinion into the individual decision matrix.	IVIFPA operator	Definition 10 (Appendix A) is used for describing IVIFPA, and Definition 5 (Section 3) is the basis of it.	Table 4
Determination of preference relation	Evaluate the satisfactory and unsatisfactory degree between each pair of competing alternatives	ICP, IVIFNS	Definition 8 is used for expressing the importance degree. Definition 6 and 7(Section 3) are basis for Definition 8.	Table 5
Construction of comprehensive preference indices	Obtain the outranking relations and weights	ICP-based preference function	Definition 9 is used for aggregating all assessment criteria values	Table 6, Table 7, Table 8
Establishment of ranking orders	Obtain the final rankings of alternatives	PROMETHEE	Definition 11 and 12 are used to describing the PROMETHEE method.	Fig. 5, Table 9

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