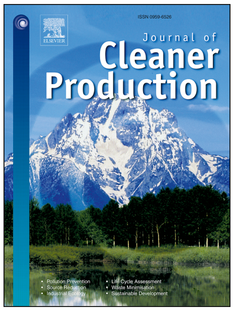

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Risk assessment on offshore photovoltaic power generation projects in China based on a fuzzy analysis framework

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Abstract

China has begun to promote offshore photovoltaic in coastal areas taking its advantages of saving land resources and proximity to load centers. However, the projects are bound to face a series of risk factors as the industry is in its infancy. This paper conducts a risk assessment on offshore photovoltaic power generation projects in China based on a fuzzy framework. Firstly, 16 risk factors affecting offshore photovoltaic power generation projects in China are identified and classified into 4 groups. Secondly, a risk assessment model is constructed involving Hesitant Fuzzy Linguistic Term Sets, Triangular Fuzzy Number and Fuzzy Synthetic Evaluation. Thirdly, this paper conduct an empirical study of China, and the result shows that the risk level of offshore photovoltaic power generation projects in China is medium high. Finally, some response measures are proposed. The risk index system and corresponding countermeasures can provide a reference for project managers to allocate resources to prevent risk events. Besides, the risk assessment model can help project investors to avoid too risky projects. In addition, the risk assessment on offshore photovoltaic power generation projects in China has not been discussed by scholars yet. Thus, this paper contributes to the literature and expand the knowledge.

Key words: Risk assessment, Offshore PV, Hesitant fuzzy linguistic term sets, Triangular fuzzy number, Fuzzy synthetic evaluation.

Nomenclature

$S=\{s_0,\ldots,s_g\}$	linguistic term set	H_S	HFLTS
s_i	i-th linguistic term	$G_H=(V_N,V_T,I,P)$	context-free grammar
V_N	element set	V_T	relation rule
I	element in V_N	P	generated function
ll	linguistic expression	E_{G_H}	transformation function
$\tilde{a}=(a^L,a^M,a^U)$	triangle fuzzy number	a^L	lower bound of a triangle fuzzy number
a^U	upper bound of a triangle fuzzy number	a^M	middle value of a triangular fuzzy number
m	number of linguistic terms in a H_S	h_{cij}	aggregated value of a criterion in terms of H_S by

			an expert
c_i	i-th criterion	u_i	order induced vector
R_c	second-level evaluation vector	$\overset{\circ}{g}_j$	second vector of the largest element in u_i
R_{ci}	first-level evaluation vector	w_{ci}	weight of the i-th risk group
w_{cij}	weight of the j-th criterion in a risk group	Sd	similarity degree between two triangle fuzzy numbers

1. Introduction

As the third renewable energy source in terms of global capacity, solar energy now is a highly appealing source of electricity by means of photovoltaic (PV) systems that cover the conversion of light into electricity using semiconducting materials that exhibit the PV effect [1]. Solar PV power generation, without pollution and greenhouse gas emissions once installed, is growing rapidly and has become a leading player in energy industry in China [2]. Wherein, the most typical form is the large-scale centralized ground-based PV power plant, mainly located in the northwest region including Xinjiang, Qinghai, Gansu, etc. However, more and more problems have emerged in ground PV. For example, installation of PV panels on the ground leads to large land occupancy, thereby bringing some pressure on agricultural production [3]. At the same time, severe solar curtailment occurs because of weak power consumption capacity in regions with adequate solar resources [4]. In contrast, the development of offshore PV power generation (an example is shown in Fig. 1) in China has great advantages in overcoming such problems. On one hand, China has nearly 18,000 kilometers of continental coastline [5], and the installation of large-scale centralized offshore PV generation facilities along the sea can greatly conserve increasingly precious onshore land resources. On the other hand, China’s eastern coastal regions are economically developed with a high population density, and the development of offshore PV power generation provides an ideal solution for the growing power demand of these load centers, without the need for long-distance power transmission from northwestern regions. In addition, installation of PV panels at sea can reduce the temperature of PV modules, reduce the dust adhesion of components, and increase the energy conversion efficiency, resulting in more power output than land PV [6]. Moreover, seawater contains Magnesium Chloride, which could replace the highly toxic and pricy Cadmium Chloride that is one of the key components in PV panels [7].

At present, only several offshore PV power generation projects have been completed and put into operation in the southeast coastal areas of China, and some other projects are at the preparatory or construction stage. Table 1 shows part of their information. It can be said that China’s offshore PV power generation is still in its infancy. Corresponding core technologies are relatively immature such as the central inverter featuring the integration of the inverter, the transformer and the switchgear. Also, the market environment is not standardized enough, and very little reference information is available for new projects. On account of these challenges, investors and owners are bound to face a series of risks in the process of project construction and operation. Thus, reasonable risk assessment and well-founded responses become especially important in project life cycle including the feasibility study, construction, operation and maintenance phase. Nevertheless, this issue has not drawn a widely attention by researchers. When studying offshore PV power generation, almost all of them are concerned about the technical aspect. Trapani et al. [8] put forward an alternative based on flexible thin film PV that floats and then concentrate on the techno-economic appraisal of offshore PV systems directly on the waterline. Trapani and Millar [9] assess the feasibility of offshore PV that is integrated with the existing fossil plant of the Maltese islands. Although Sahu et al. [10] mention some disadvantages and challenges of offshore PV when reviewing the floating photovoltaic power plant, the corresponding analysis is very limited and not deep enough.

Table 1

Some offshore PV power generation projects in China. (Source: Chinese National Energy Administration: http://www.nea.gov.cn/)

NO.	Project Name	Capacity	Stage
1	Fujian Zhangpu Zhuyu Offshore Photovoltaic Power Generation Project	1×5MW	Formal operation
2	Zhejiang Shepantu Mariculture Photovoltaic Power Generation Project	1×99MW	Formal operation
3	Anhui Huainan Offshore Photovoltaic Power Generation Project	1×40MW	Formal operation
4	Fujian Yunxiao Dongsha Offshore Photovoltaic Power Generation Project	1x12MW	Trial operation
5	Jiangsu Donghai Quyang Offshore Photovoltaic Power Generation Project	1×15MW+1×20MW	Construction
6	Jiangsu Nantong Rudong Mariculture Photovoltaic Power Generation Project	1x10MW	Preparation
7	Jiangsu Huaian Xiangshui Mariculture Photovoltaic Power Generation Project	1×10MW+1×40MW	Preparation

As for risk assessment on general PV power generation projects, this issue has been widely discussed by many scholars from different aspects, including the financial, environmental, technical and management risk. For example, Luo et al. [11] conduct an analysis of financing risks involved in distributed PV power generation in China and put forward effective countermeasures. Manzini et al. [12] focus on the safety risk in the process of photovoltaic installations and carry out an assessment on PV systems fire events. Prusty and Jena [13] accomplished risk assessment of a PV integrated power system by means of computing the over-limit probabilities and the severities of events from a technical point of view. Liu et al. [14] put forward an improved framework to conduct uncertainty assessment on grid-connected PV system with taking weather variability and component availability into consideration. Mateo et al. [15] attach an importance to the influence of policy towards PV industry and then perform a quantitative assessment on this kind of risks. It can be seen that these researches are mainly conducted from a certain perspective and thus lack a comprehensive insight into risk assessment of PV projects. In addition to this, most of them only assess individual risks and rank them simply, without discussing the overall risk level of a project. At the same time, offshore PV power generation projects have their own unique characteristics, so it is essential to establish a risk assessment framework with pertinence. That is to say, the situation that there is a lack of literature about overall risk assessment on offshore PV power generation projects as well as a targeted comprehensive index system provides an valuable opportunity for the research of this paper.

This paper aims to: i) identify and analyze the risk factors that have an impact on offshore PV power projects in China and ii) assesse the overall risk level of offshore PV power generation projects in China. The originality of this paper comes from the following three aspects: i) an index system, for risk assessment on offshore PV projects in China, is established through a deep analysis of previous studies, actual projects and expert opinions; ii) a risk assessment model is proposed for offshore PV power generation projects based on Hesitant Fuzzy Linguistic Term Sets (HFLTS) and Triangular Fuzzy Number (TFN), which could well handle the fuzziness and enhance the reliability; iii) risk response measures incorporating management ideas are put forward for each risk factor aiming at improving management efficiency and quality. The contribution of this study are multifaceted: i) through the above work, this paper can contribute to the literature of renewable energy generation and expand the knowledge of risk management; ii) the established index system for offshore PV power generation projects can help risk managers understand each risk factor better and thus ensure smooth implement of projects; iii) with awareness of the overall risk level, project decision makers is able to make appropriate decisions and avoid too risky projects; iv) the countermeasures for each risk factor can provide a reference and management inspiration for policy makers and corresponding practitioners.

Fig. 1. An example of offshore PV power generation. (Source: Solar Tribune: https://solartribune.com/offshore-solar-new-energy-opportunity-coastal-communities/)

The remainder of this study is structured as follows. Section 2 reviews the research status of HFLTS, TFN and ANP in existing literatures. Section 3 analyzes the risk factors that have an impact on offshore PV power generation projects in China and constructs a corresponding criteria system. Section 4 establishes a risk assessment model for offshore PV power generation projects. Section 5 conducts an empirical study of China. Section 6 gives coping strategies for each risk. Finally, Section 7 concludes this paper and proposes limitations.

2. Literature review

Multiple-criteria decision-making (MCDM) problem, as a sub-discipline of operations research, concerns structuring and solving decision and planning problems involving multiple criteria. The issue of risk assessment have been identified as a typical MCDM problem with uncertainty by many scholars [16-18]. There are two main reasons for the uncertainty of decision-making information. Firstly, risk assessment of a project is usually conducted in the planning and feasibility study stage, which can only be based primarily on pre-estimation of future circumstances. Therefore, uncertainty emerges in the process of risk assessment. Secondly, the judgement of some decision-making information in risk assessment relies on experience and knowledge of experts, with ambiguity existing in such a thinking mode. Hence, the MCDM methods to handle imperfect, vague and imprecise information play a key role in the rationality and accuracy of risk assessment. Several tools, such as fuzzy logic [19] and fuzzy sets theory [20] have been successfully applied to address this issue. Nevertheless, there is great defect in these methods when two or more sources of vagueness appear simultaneously. For this reason, some other generalizations and extensions of fuzzy sets have been introduced including type-2 fuzzy sets, intuitionistic fuzzy sets and interval fuzzy sets [21-24]. However, the experts who are involved in the MCDM problem defined under uncertainty cannot easily provide a single term as an expression of their opinions sometimes because they may think of several terms at the same time. As a result, the theory of hesitant fuzzy is introduced. Hesitant fuzzy sets (HFS) was first put forward by Torra [25] to manage situations where experts hesitate between several values to assess an indicator, alternative or variable, providing a very interesting extension of fuzzy sets. Nevertheless, similar situations may occur in qualitative settings so that experts think of several possible linguistic values or richer expressions than a single term. To solve this weakness, Rodriguez et.al [26] put forward the HFLTS method to provide a linguistic and computational basis to increase the richness of linguistic elicitation and the use of context-free grammars by using comparative terms. To illustrate the advantaged and superiority of the HFLTS method, a comparison has been made among basic fuzzy set theories, extended fuzzy set theories, the HFS and the HFLTS, as shown in Table 2. The HFLTS method has been studied and applied by many scholars. Chen et al. [27] propose proportional HFLTSs and a probability theory-based outranking method for MCDM problem. Liao et al. [28] research correlation coefficients of HFLTSs in the process of qualitative decision making and illustrate it applicability and validation. Wang et al. [29] employ linguistic scale functions to conduct the transformation between qualitative information and quantitative data when the HFLTS is used in multi-criteria decision-making. Proved to be an effective tool for complex and vague MCDM environment, the HFLTS method is employed in this paper to assign evaluation information by experts to each risk factor that has an impact on offshore PV power generation projects, thereby meeting the linguistic expression flexibility requirement of experts.

Table 2

Comparison between different fuzzy methods.

Method	Description
basic fuzzy sets （fuzzy logic, fuzzy sets）	✧ Accords with the human cognitive habits ✧ Depict the fuzziness
extended fuzzy sets （type-2 fuzzy sets, intuitionistic fuzzy sets, interval fuzzy sets）	✧ Accords with the human cognitive habits ✧ Depict the fuzziness ✧ Handle several vagueness resource simultaneously
hesitant fuzzy sets	✧ Accords with the human cognitive habits ✧ Depict the fuzziness ✧ Handle hesitant fuzzy information
hesitant fuzzy linguistic term sets	✧ Accords with the human cognitive habits ✧ Depict the fuzziness ✧ Handle several vagueness resource simultaneously ✧ Handle hesitant fuzzy term ✧ Handle multi-hesitant fuzzy terms

After assigning evaluation information to indexes, how to transfer the linguistic assessment terms into the computational form becomes a question. Fortunately, fuzzy numbers provide a solution. The fuzzy number, a generalization of a regular and real number, does not refer to one single value but rather to a connected set of possible values, and each possible value has its own weight between 0 and 1, called the membership function. After years of development, there have been many different branches of fuzzy numbers. The TFN, firstly proposed by Zadeh [30] in 1965, is one of them. The TFN consists of lower bound, upper bound and most possible value, with the advantage of containing more information in situation expression than the traditional fuzzy number. In recent years, the TFN has been applied to MCDM problems by many researchers on the purpose of making decisions more in line with real-life situations. Samantra et al. [31] employ the TFN to conduct risk assessment on metropolitan construction projects associated with uncertain characteristics. In order to evaluate the benefits of investing in safety measures for pipelines, Urbina and Aoyama [32] use the TFN as a tool to deal with uncertainty. Gul et al. propose a new Fine-Kinney-based risk assessment framework using the TFN, enabling group decision-making to be well solved under uncertain environment. When studying groundwater resources management, Ren et al. [33] develop an inexact interval-valued triangular fuzzy based multi-attribute preference model, which takes vagueness in parameter values into consideration. Zhao et al. [34] develop some hesitant triangular fuzzy aggregation operators and investigate their application to MCDM problems, with an illustrative example to show the validity of these operators. It can be seen that the TFN is able to handle the MCDM problem with vague information well. Therefore, introducing the TFN to risk assessment on offshore PV power generation projects has theoretical reliability and practical significance.

The weight reflects the relative importance of an indicator in the evaluation process. Selecting an appropriate method to determine the weight is important for obtaining a reasonable result in risk assessment. Analytic hierarchy process (AHP) is a commonly used method of weight calculation, with each element in the hierarchy considered to be independent of all the others. However, in real-world cases, there is interdependence among the items and the alternatives. Therefore, it is almost impossible for indicators to be completely independent, and correlations between indicators must be taken into consideration when determining their weight value. The analytic network process (ANP) method, put forward by Saaty [35], has provided an effective approach to addressing this issue. It is able to well handle interdependence between indicators by obtaining the composite weights through the development of super matrix. The ANP method has been widely applied to solving the MCDM problems by many scholars, especially the risk management problem [36-39]. Thus, the ANP method is utilized to calculate the weights of indicators in this paper.

Based on the review above, the applicability and superiority of the risk assessment model proposed in this paper can be explicitly stated. The established framework, including HFLTS and TFN considering correlations between the risk factors under the fuzzy environment, possesses the following advantages: i) HFLTS can allow experts to evaluate a risk factor more flexibly when they are hesitant between several linguistic terms; ii) TFN is a powerful tool to express various kinds of uncertainties involved in the offshore PV projects due to their complicated and changeable environment; iii) the ANP method can take into account the non-negligible fact that indicators associated with risk assessment have correlations. At present, there is no literature that makes such a combination of HFLTS, TFN and ANP in the risk assessment field. Thus, the introduction of these three methods simultaneously plus the idea of group decision making can significantly broaden and deepen the research on the fuzzy theory and the MCDM theory.

3. Criteria system of risk assessment on offshore PV projects in China

Identification of risk factors is an essential prerequisite to implement risk management and achieve project success[40]. Aiming at identifying the risks that have an impact on offshore PV projects, a three-step method is adopted in this paper. In the first step, a thorough analysis of previous studies is conducted, and the literature search is carried out according to the following boundaries. First, the Web of Science, Elsevier-Science Direct, Taylor & Francis and CNKI are chosen as the academic databases to be used for literature search and selection because they included articles in a broad scope. Then, considering the fact that almost no research on offshore PV power generation has been carried out, ‘PV/offshore wind power generation’ is determined as the search keywords to expand the searching scope. Following this, we select journal papers published over the period between January, 2005 and June, 2018 when PV/offshore wind power generation went through a boom. Finally, 38 qualified papers are identified. In the second step, this paper conduct an analysis of some offshore PV projects that are completed or still under construction, to identify and understand possible risk factors. All chosen projects are conducted in China because the aim of this paper is to assess the risk level of China’s offshore PV power generation projects. In the third step, two professors from the field of PV power generation and project management respectively are invited to give opinions on the risk factor list obtained by the first two steps as well as the factor grouping. They point that the meanings of ‘high equipment purchase cost’ and ‘interest rate increase risk’ are both included in risk ‘high initial investment’ so it would be better to delete the two risk factors. At the same time, they hold the viewpoint that feelings of the public should be taken into consideration dew to the concept of human-centered. As a result, the risk ‘Visual effect risk (C34)’ is added. After the three steps, the criteria system of risk assessment on offshore PV projects in China is finally established and classified into four categories, as shown in Fig. 2.

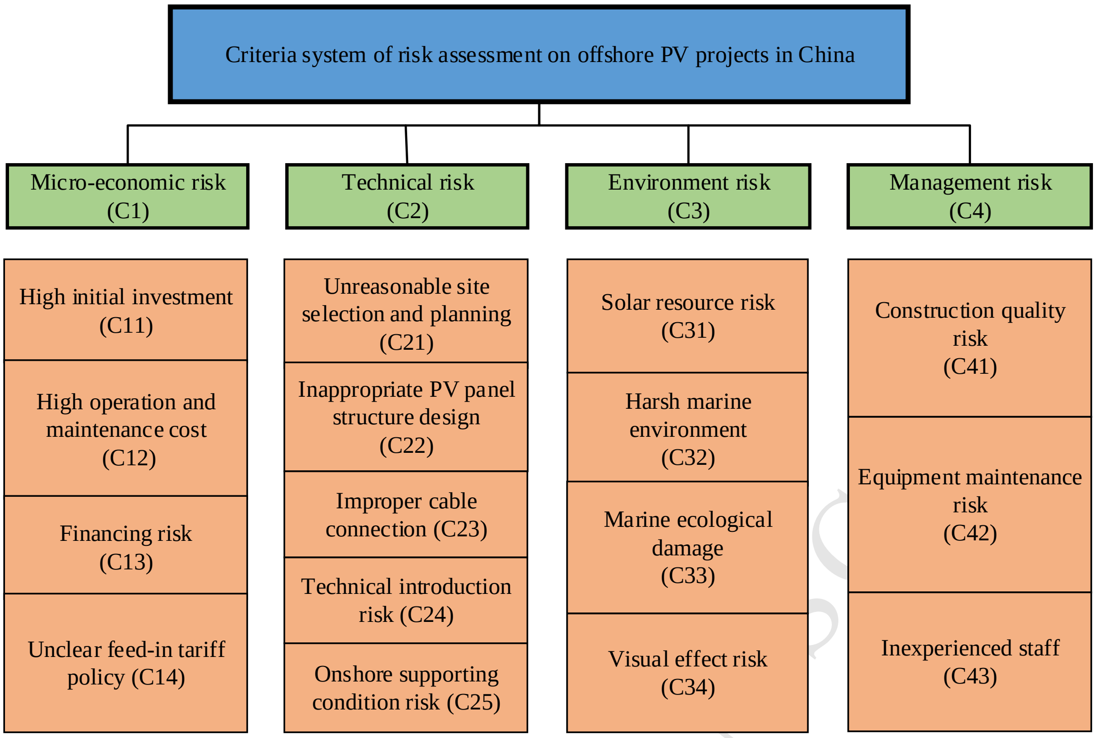

Fig. 2. Index system of risk assessment on offshore PV projects in China

3.1 Micro-economic risk (C1)

i) High initial investment (C11)

Considering the complexity of the design and manufacturing process due to higher performance requirements, the offshore PV power generation project would be faced with higher costs of solar panels compared with the ground one. Moreover, underwater cables have high requirements on construction technology and professional equipment, increasing the capital pressure of initial investment of the project as a result [41].

ii) High operation and maintenance cost (C12)

The operation cost of offshore PV power generation is approximately ten times more than that of other conventional fossil-fuel-based power generation projects during the first ten years of its operational phase [10]. As time goes on, the equipment tends to suffer from deformation, metal corrosion and material aging deterioration easily for various reasons in the marine environment, which virtually leads to maintenance cost increase.

iii) Financing risk (C13)

As mentioned above, the offshore PV power generation requires a relative large scale of funding. Therefore, the financing process is particularly essential for the smooth development of the project. The financing risk refers to the uncertainties arising from financing activities such as financing guarantees, financing structure design and financing channel selection [42]. As the offshore PV power generation technology in China is still in the infant stage, there could exist great obstructions and risks in the financing process considering the great uncertainties in future benefits.

iv) Unclear feed-in tariff policy (C14)

As the most direct manifestation of whether a project is profitable, the feed-in tariff is directly related to the income of offshore PV power generation projects. However, there is no specific tariff policy for offshore PV power generation in China at present, which would lays uncertainty in the revenue of the project.

3.2 Technical risk (C2)

i) Unreasonable site selection and planning (C21)

Site selection and planning is a critical step toward the successful development of offshore PV systems. However, the selection process involves many aspects such as solar resources, distance to load center and geological conditions [43], and thus it becomes risky. The improper offshore PV plant site may not only be unable to meet electricity demand and have a negative impact on project benefits but also give rise to failure to start construction as scheduled.

ii) Inappropriate PV panel structure design (C22)

The content of PV panel structure design contains distance between the PV panels, dimensions and tilt angle of PV panels, the number of units to be installed and so on [44]. Inappropriate PV panel structure design will lead to inadequate utilization of solar radiation and sunshine duration. That is to say, if there is no scientific PV panel layout design for offshore PV systems, the maximum production efficiency cannot be guaranteed consequently.

iii) Improper cable connection (C23)

Under the gravitational effect of celestial bodies, there is a periodic fluctuation in the seawater in coastal areas, which is called ocean tide [45]. This phenomenon brings the offshore PV projects another risk, that is, when the seawater falls back, the pulling force of its downward movement makes the cable to move with it. If the cable connection between the shore inverter and PV panels as well as the connection mode of the nodes are designed in an improper manner, the influence of tides on the cable lines cannot be coped with well.

iv) Technical introduction risk (C24)

At present, the development of offshore PV power generation projects in China is not mature enough. The research on core technology is insufficient and relies heavily on imports. When the foreign technology does not match China’s actual situation due to different geographic conditions and staff capability, the introduction of technology will become one of the risks for the offshore PV project.

v) Onshore supporting condition risk (C25)

Onshore supporting conditions refers to the favorable factors conducive to the construction, operation and maintenance of the projects including the traffic condition, electrical transmission and distribution system. Thus, the traffic condition should be considered because of its influence on the large equipment transportation along the coast. Moreover, there is also a need to analyze whether the onshore power grid or its future planning can meet supporting requirements.

3.3 Environment risk (C3)

i) Solar resource risk (C31)

When conducting the planning and design for an offshore PV power generation project, the amount of generated power is usually estimated based on the local daily radiation and monthly radiation. However, in actual operation, the radiation in the area cannot meet the requirements of the power generation voltage if there are adverse weather conditions such as continuous rain or cloud. At the same time, haze, dust and other obstructions in the atmosphere also diminish the power output [46]. Besides, climate change may pose a risk to the prediction of the solar resource in the long-term. Thus, the power system maybe cannot achieve expected generation volume, thereby affecting project profits.

ii) Harsh marine environment (C32)

Since the coastal areas of China are often attacked by typhoons in summer, the farm construction may be very difficult, and components may suffer serious damage in the operation. In addition, the coastal area of southeast China features a subtropical monsoon climate. The salt brought by prevailing land-sea breeze will cause serious salt spray corrosion and affect the durability of PV modules. Moreover, stress and vibration usually occurs in offshore PV plants owing to wind, waves and other external forces, which will cause micro-cracks in PV modules. It is worth noting that the shifting of climate change may result in aggravation of extreme ocean weather such as the increasing frequency of typhoons in China caused by the La Nina phenomenon [47], bringing a great challenge to the offshore PV projects.

iii) Marine ecological damage (C33)

Owing to the large scale of offshore PV farms, the development and construction process will inevitably have a certain impact on the marine ecological environment. For example, the laying of submarine transmission cables will make seabed sediments float and thus influence the reproduction of plankton. Additionally, the projects will directly occupy the coastal habitat of birds and affect their nesting and breeding. These damages to the marine ecosystem may incur opposition from environmental protection agencies or environmentalists.

iv) Visual effect risk (C34)

Although the light transmittance of tempered glass for PV modules is high, the reflection phenomenon still cannot be completely avoided, which may cause a visual impact on coastal residents. In Japan, a PV power station was sued for compensation by nearby residents because of its light reflection, resulting in considerable economic losses. Besides, large-scale PV power farms also generate visual impacts on the coastal landscape.

3.4 Management risk (C4)

i) Construction quality risk (C41)

PV cell modules will reach a very high direct-current voltage through series connection, which is much higher than the safe voltage [48]. Due to the large number of lines, open-circuit and short-circuit may occur during construction. Therefore, quality problems may be caused in the construction stage if there is a lack of good management.

ii) Equipment maintenance risk (C42)

As equipment used for PV power generation projects including solar panels, inverters and transformers are all large high-tech equipment, mistakes often occur in daily maintenance, resulting in equipment failure and economic loss. Besides, the special marine environment will also bring difficulties and risks to maintenance.

iii) Inexperienced staff (C43)

Most of the employees involved in the offshore PV projects are from the ground mounted PV industry. As the work environment changes from onshore to offshore, they ordinarily have the limited professional knowledge and work experience towards the marine environment, which would be risky to some extent.

4. A risk assessment model for offshore PV power generation projects

Step 1. Determining the correlation and weight of criteria

Obviously, there are differences in the importance of each criterion in risk assessment. Thus, the relative criticality of criteria needs to be reflected by the weight. At the same time, some correlations exist between the criteria. For example, harsh marine environment i.e. risk C32 would cause corrosion of PV panels and thus increase maintenance costs i.e. risk C12. Taking such situation into consideration, the ANP method is adopted to determine the weight of criteria in this paper. Firstly, the internal dependency relationship is analyzed and determined. Then, the pairwise criticality comparison is performed among criteria with the 1-9 scale method, and the judgement matrix can be obtained. Finally, the Super Decision software is employed as the tool to achieve the weight calculation.

Step 2. Defining the linguistic term set and obtaining the HFLTS

The risk assessment on offshore PV power generation projects is so complicated an issue involving quite a lot factors that experts cannot easily provide a single evaluation term as expression of their knowledge and may hesitant between several ones towards a criterion. Fortunately, as mentioned above, the HFLTS method is capable of handling this situation. Thus, the HFLTS method is employed in this paper to give criterion evaluation information so as to reduce information loss and improve decision-making accuracy. The basic definitions and operations of HFLTS are shown as follows [26].

Let $S=\{s_0,\ldots,s_g\}$ be a linguistic term set. Then, an HFLTS, H_S, is an ordered finite subset of the continuous linguistic terms of S. Let G_H be a context-free grammar that generates linguistic expressions represented by HFLTS. The elements of $G_H=(V_N,V_T,I,P)$ are defined as follows:

$$\begin{aligned} &V_N=\left\{\begin{array}{l}\langle\text{primary term}\rangle,\langle\text{composite term}\rangle,\\ \langle\text{unary relation}\rangle,\langle\text{binary relation}\rangle,\langle\text{conjunction}\rangle\end{array}\right\}\\ &V_T=\{\text{lower than, greater than, between, and, } s_0,\ldots s_g\}\\ &I\in V_N\end{aligned} \quad (1)$$

Then, the linguistic expressions ll produced by G_H are transformed into HFLTS by means of the transformation function E_{G_H}. Let E_{G_H} be a function that transforms linguistic expressions ll obtained by G_H into HFLTS H_S, where S is the linguistic term set used by G_H:

$$E_{G_H} : ll \longrightarrow H_S$$

The linguistic expressions that are generated by using the production rules will be transformed into HFLTS in different ways according to their meaning:

a) $E_{G_H}\left(s_i\right) = \left\{s_i / s_i \in S\right\}$ (2)

b) $E_{G_H}\left(\text{less than } s_i\right) = \left\{s_j / s_j \in S \text{ and } s_j \le s_i\right\}$ (3)

c) $E_{G_H}\left(\text{greater than } s_i\right) = \left\{s_j / s_j \in S \text{ and } s_j \ge s_i\right\}$ (4)

d) $E_{G_H}\left(\text{between } s_i \text{ and } s_j\right) = \left\{s_k / s_k \in S \text{ and } s_i \le s_k \le s_j\right\}$ (5)

Step 3. Transforming the HFLTS into triangular fuzzy numbers

In order to expressing expert imperfect knowledge in decision-making utilization more effectively, the triangular fuzzy number is applied in this risk assessment model.

$\tilde{a} = \left(a^L, a^M, a^U\right)$ represents a triangle fuzzy number if its membership degree function is expressed mathematically as follows [49]:

$$\mu_{\tilde{a}}(x) = \begin{cases} 0 & x < a^L \\ (x - a^L)/(a^M - a^L) & a^L \le x \le a^M \\ (a^U - x)/(a^U - a^M) & a^M \le x \le a^U \\ 0 & x > a^U \end{cases} \tag{6}$$

where $a^L \le a^M \le a^U$. a^L and a^U are the lower bound and upper bound, respectively.

Let H_S be a HFLTS provided by an expert group towards a risk factor. Suppose that there are m linguistic terms within it. Then, the HFLTS can be transformed into triangular fuzzy numbers as:

$$h_{cij} = \left(\frac{1}{m}\sum si\right) = \left(\frac{1}{m}\sum a^L, \frac{1}{m}\sum a^M, \frac{1}{m}\sum a^U\right) \tag{7}$$

where h_{cij} represents the aggregated value of a criterion in terms of HFLTS by an expert.

Then, the HFLTS can be aggregated as:

$$h_{cij} = \left(\sum cig si\right) = \left(\sum cig a^L, \sum cig a^M, \sum cig a^U\right) \tag{8}$$

where h_{cij} represents the aggregated value of a criterion in terms of HFLTS by an expert.

Step 4. Aggregating triangular fuzzy numbers of experts based on FIOWHA operator

The risk assessment on offshore PV power generation projects studied in this paper is a group decision making problem in which a group of experts provide their evaluation terms for a risk factor. To achieve the aggregation of experts' opinion, this paper adopts the fuzzy induced ordered weighted harmonic averaging (FIOWHA) operator based on triangular fuzzy number. The following contents give the basic concepts and steps.

Let $\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n$ be a set of triangular fuzzy numbers that need to be aggregated. Then the FIOWHA operator is defined as [50]:

$$\mathrm{FIOWHA}_w\left(\langle u_1, \tilde{r}_1\rangle, \langle u_2, \tilde{r}_2\rangle, \ldots, \langle u_n, \tilde{r}_n\rangle\right) = \frac{1}{\sum_{j=1}^{n} \frac{w_j}{\overset{\circ}{g}_j}} \tag{9}$$

where $\tilde{r}_j = \left[r_j^L, r_j^M, r_j^U\right]$, and $w = \left(w_1, w_2, \ldots, w_n\right)^T$ is a weight vector associated with the FIOWHA operator that satisfies $w_j \in [0,1]$ and $\sum_{j=1}^{n} w_j = 1$. $\overset{\circ}{g}_j$ is the second vector $\tilde{r}_i$ in $\langle u_i, \tilde{r}_i\rangle$ of the i^{th} largest element in $u_i\left(i = 1, 2, \ldots n\right)$ that ranks from the largest to the smallest. The first vector u_i in $\langle u_i, \tilde{r}_i\rangle$ is called the order induced vector.

Step 5. Aggregating triangular fuzzy numbers of criteria based on FSE method

In order to handle the risk assessment on offshore PV power generation projects, a multi-criteria uncertainty ambiguity problem that involves subjective judgment of experts, the fuzzy synthetic evaluation (FSE) mothed is adopted in this paper to aggregate triangular fuzzy numbers of each criterion to obtain the overall risk level of the project. The fuzzy synthetic evaluation process is divided into three phases. Firstly, the first-level evaluation vector R_{ci} consisting of triangular fuzzy numbers of criteria within each group is established as:

$$R_{ci} = \begin{pmatrix} h_{ci1} \\ \vdots \\ h_{cij} \end{pmatrix} \tag{10}$$

Secondly, the second-level evaluation vector R_c including triangular fuzzy numbers of every group is obtained by fuzzy synthesis operation, as shown below:

$$h_{ci} = W_{ci} \circ R_{ci} = \begin{pmatrix} w_{ci1} & \cdots & w_{cij} \end{pmatrix} \circ \begin{pmatrix} h_{ci1} \\ \vdots \\ h_{cij} \end{pmatrix} \tag{11}$$

$$R_c = \begin{pmatrix} h_{c1} \\ \vdots \\ h_{ci} \end{pmatrix} \tag{12}$$

where w_{cij} is the weight of each risk factor within every group .

Thirdly, the overall risk level of the project represented by TNFs is calculated as:

$$R = W_i \circ R_c = \begin{pmatrix} w_{c1} & \cdots & w_{ci} \end{pmatrix} \circ \begin{pmatrix} h_{c1} \\ \vdots \\ h_{ci} \end{pmatrix} = \left(r^L, r^M, r^U \right) \tag{13}$$

where w_{ci} denotes the weight of each risk factor group.

Step 6. Defuzzification of the triangular fuzzy number

Through the above steps, the risk level of offshore PV power generation projects is expressed in the form of triangular fuzzy number. In order to get a more intuitive and easy-to-understand result, the similarity degree is introduced for defuzzification treatment in this paper. The similarity degree between two triangular fuzzy numbers can be calculated as [51]:

$$Sd(\alpha, \beta) = 1 - \frac{\left|\alpha^L - \beta^L\right| + \left|\alpha^M - \beta^M\right| + \left|\alpha^U - \beta^U\right|}{3} \tag{14}$$

where $\alpha = \left(\alpha^L, \alpha^M, \alpha^U\right)$ and $\beta = \left(\beta^L, \beta^M, \beta^U\right)$ are two triangular fuzzy numbers, and $Sd(\alpha, \beta)$ represents the similarity degree between α and β. Thus, which risk level the evaluation result is closer to can be determined by the principle of maximum similarity.

5. Empirical study

In this section, the risk assessment on offshore PV power generation projects in China is carried out through the model proposed in Section 4. First of all, a questionnaire survey is performed to obtain the required basic data for achieving the objectives of this study. The questionnaire consisted of three parts. In the first part, the definition of each risk factor is given as a reference in case that experts cannot understand the meaning of a certain risk well. In the second and third parts, experts are requested to give weights and evaluation terms respectively towards each risk factor, which will be described in detail later. Risk assessment on offshore PV power generation projects in China requires first-hand information, extensive project experience and rich knowledge of corresponding fields. Thus, the standard for selection of target respondents included two aspects: i) Having in-depth knowledge in PV power projects as well as a good understanding about risk management of this field; ii) Having been involved in at least one offshore power generation project with rich experience of risk management in such projects. According to above standards, 18 qualified experts are invited, and their general information is summarized in Table 3.

Table 3

General information of the experts.

Organization of experts				
	Power generation company	Power construction company		Academic sector
Percentage	44.4%	33.3%		22.2%
Number of PV power projects that experts have participated in				
	1-2	3-4		5 or above
Percentage	38.9%	44.4%		16.7%
Number of offshore power projects that experts have participated in				
	1-2	3-4		5 or above
Percentage	50.0%	38.9%		11.1%
Project risk management experience of experts				
	5 years or below	6-10 years	11-15 years	16 years or above
Percentage	16.7%	38.9%	27.8%	5.6%

5.1 Weight determination

As mentioned above, the second part of the questionnaire is to invite experts to determine weights of criteria. Brainstorming is firstly held within the invited experts to analyze correlations and conduct pair-wise comparisons between risk factors and risk factor groups. The risky degree of each criterion is determined by the 1-9 scale method in the light of experts' experience and judgment. After pairwise comparison matrixes are obtained, the weight of each criterion can finally be obtained by the Super Decision software when meeting the consistency requirement. The correlations between criteria and weights of criteria are shown in Table 4 and Table 5 respectively.

It can be seen from Table 4 that each risk factor group has a correlation with the others. Among them, C3 has the most influence on other risk groups, followed by the C2, C4 and the C1. Accordingly, the risk factors within the C1 are affected mostly by other risk factors, which means that it is dominant in the risk assessment process. This has been fully reflected in the weight values shown in Table 5, i.e. C1 take up the largest weight. To be more specific, high operation and maintenance cost is attached the most importance to within C1, with the weight as 0.3484. As for C2, C3 and C4, the risk that accounts for the largest proportion is onshore supporting condition risk, solar resource risk and equipment maintenance risk, respectively. Their common feature is that they will directly affect project profits.

Table 4

The correlations between criterion.

		Micro-economic risk (C1)				Technical risk (C2)					Environment risk (C3)				Management risk (C4)		
		C11	C12	C13	C14	C21	C22	C23	C24	C25	C31	C32	C33	C34	C41	C42	C43
C1	C11		√		√	√	√	√	√	√		√	√		√		√
	C12			√						√		√	√				√
	C13					√	√	√	√	√					√	√	√
	C14																
C2	C21	√	√	√	√					√	√	√		√	√		
	C22	√	√	√				√	√		√	√			√	√	
	C23	√	√	√								√	√		√	√	
	C24	√	√	√	√	√	√	√			√	√		√		√	√
	C25	√	√		√		√									√	
C3	C31	√	√	√	√	√	√							√	√	√	
	C32		√	√	√				√	√	√		√		√	√	√
	C33		√	√												√	√
	C34		√	√												√	
C4	C41	√	√			√	√	√	√		√		√			√	
	C42		√	√	√						√		√				
	C43					√	√	√	√			√		√	√	√	

Table 5

Weights of criterion.

C1 (0.404)	C11	0.09367
	C12	0.34084
	C13	0.25382
	C14	0.31167
C2 (0.165)	C21	0.20808
	C22	0.23436
	C23	0.07628
	C24	0.17972
	C25	0.30155
C3 (0.154)	C31	0.49852
	C32	0.28521
	C33	0.0648
	C34	0.15147
C4 (0.278)	C41	0.26367
	C42	0.51473
	C43	0.2216

5.2 Data collection

The third part of questionnaire survey aims at collecting evaluation information to be used in subsequent calculations. The 18 experts are divided into three groups, and every expert group are requested to give their judgement about the risky level towards each factor by way of linguistic expressions. Firstly, the linguistic term set that is used by the context-free grammar G_H is set as {s0 = Very Low (VL), s1 = Low (L), s2 = Medium Low (ML), s3 = Moderate (M), s4 = Medium High (MH), s5 = High (H), s6 = Very High (VH)} in this paper. Then, corresponding HFLTSs are generated from the linguistic term set according to E_{G_H} described in Section 4. Table 6 shows the linguistic expressions and corresponding HFLTSs by the three expert groups.

5.3 Transformation of HFLTS into triangular fuzzy number

Here the triangular fuzzy number is adopted according to seven linguistic terms with their semantics. Fig. 3 shows the lower value, middle value and upper value of the seven terms [52]. Wherein, the y-axis represents the membership degree of each triangular fuzzy number, and the x-axis represents the value of a set of triangular fuzzy numbers in accordance with semantics of the seven linguistic terms.

Thus, the terms can be converted as follows:

$$S=\left\{\begin{array}{l} s_0:(0,0,0.17),s_1:(0,0.17,0.33), \\ s_2:(0.17,0.33,0.5),s_3:(0.33,0.5,0.67), \\ s_4:(0.5,0.67,0.83),s_5:(0.67,0.83,1),s_6:(0.83,1,1) \end{array}\right\}$$

Based on Eq. (7), the transformation of HFLTS into triangular fuzzy number is conducted. Here we take the HFLTS of C14 by Group 1 as the example. Its corresponding triangular fuzzy number is calculated as:

$$h_{c14} = \begin{pmatrix} \frac{1}{3}(0.5+0.67+0.83), \\ \frac{1}{3}(0.67+0.83+1), \\ \frac{1}{3}(0.83+1+1) \end{pmatrix} = (0.67, 0.83, 0.94)$$

Similarly, the triangular fuzzy number of other criteria by each expert group can also be calculated. The results are shown in Table 7.

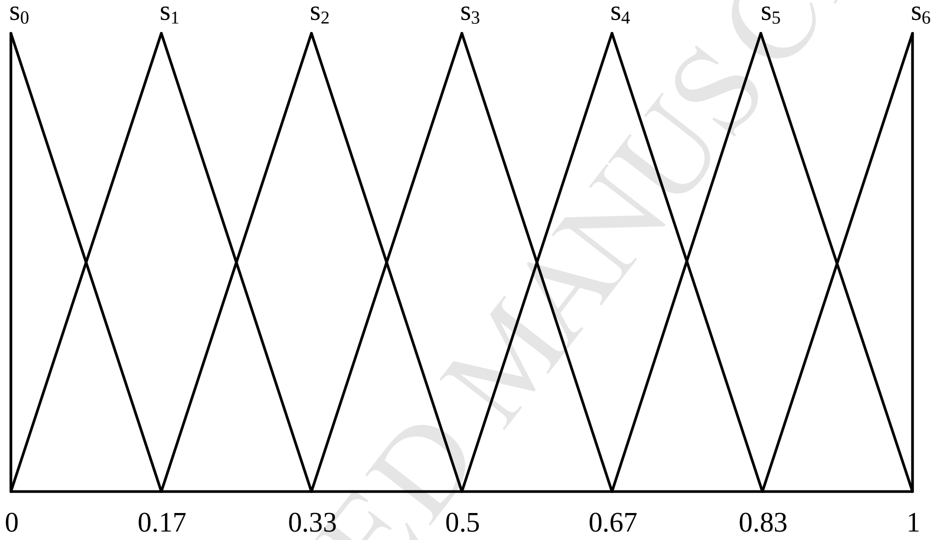

Fig. 3. Set of seven terms with its semantics

5.4 Aggregation of expert opinions

Before conducting the aggregation of expert groups' opinion, the weighting vector associated with the FIOWHA operator is determined as (0.25, 0.5, 0.25) firstly. Then, according to the calculation method described in Section 4, the aggregated results can be obtained, as show in Table 7.

5.5 Fuzzy synthetic operation of risk assessment

In this step, triangular fuzzy numbers of each criterion is aggregated based on the FSE method. Here the risk group 'Micro-economic risk' is taken as the example. Its risk fuzzy composition operation is performed by Eq. (11):

$$h_{c1} = W_{c1} \circ R_{c1} = (0.094, 0.341, 0.254, 0.312) \circ \begin{pmatrix} (0.5, 0.667, 0.833) \\ (0.583, 0.749, 0.868) \\ (0.25, 0.416, 0.584) \\ (0.543, 0.708, 0.86) \end{pmatrix} = (0.478, 0.644, 0.79)$$

Evaluation vector of other risk groups can also be calculated and the results are:

$h_{c2} = (0.415, 0.581, 0.725)$, $h_{c3} = (0.333, 0.485, 0.627)$, $h_{c4} = (0.511, 0.677, 0.830)$

Then, the overall risk evaluation result of offshore PV power generation projects in China can be calculated according to Eq. (13):

$$R = W_i \circ R_c = (0.404, 0.165, 0.154, 0.278) \circ \begin{pmatrix} (0.478, 0.644, 0.79) \\ (0.415, 0.581, 0.725) \\ (0.333, 0.485, 0.627) \\ (0.511, 0.677, 0.830) \end{pmatrix} = (0.455, 0.619, 0.765)$$

5.6 Defuzzification process

Through the comparison between the overall risk evaluation result and the evaluation term as shown in Fig. 4, it can be seen that the result is between ‘Moderate’ and ‘Medium high’. To determine the certain overall risk level, the similarity degrees between the evaluation result and the two terms can be calculated through Eq. (14):

$$\begin{aligned} Sd(R, s_3) &= 1 - \frac{\left|R^L - s_3{}^L\right| + \left|R^M - s_3{}^M\right| + \left|R^U - s_3{}^U\right|}{3} \\ &= 1 - \frac{|0.455 - 0.33| + |0.619 - 0.5| + |0.765 - 0.67|}{3} \\ &= 0.887 \end{aligned}$$

$$\begin{aligned} Sd(R, s_4) &= 1 - \frac{\left|R^L - s_4{}^L\right| + \left|R^M - s_4{}^M\right| + \left|R^U - s_4{}^U\right|}{3} \\ &= 1 - \frac{|0.455 - 0.5| + |0.619 - 0.67| + |0.765 - 0.83|}{3} \\ &= 0.946 \end{aligned}$$

The similarity degree between R and S_3 is 0.887, lower than that between R and S_4. Thus, the overall risk level is closer to S_4 according to the principle of maximum similarity. That is to say, the risk level of offshore PV power generation projects in China is medium high.

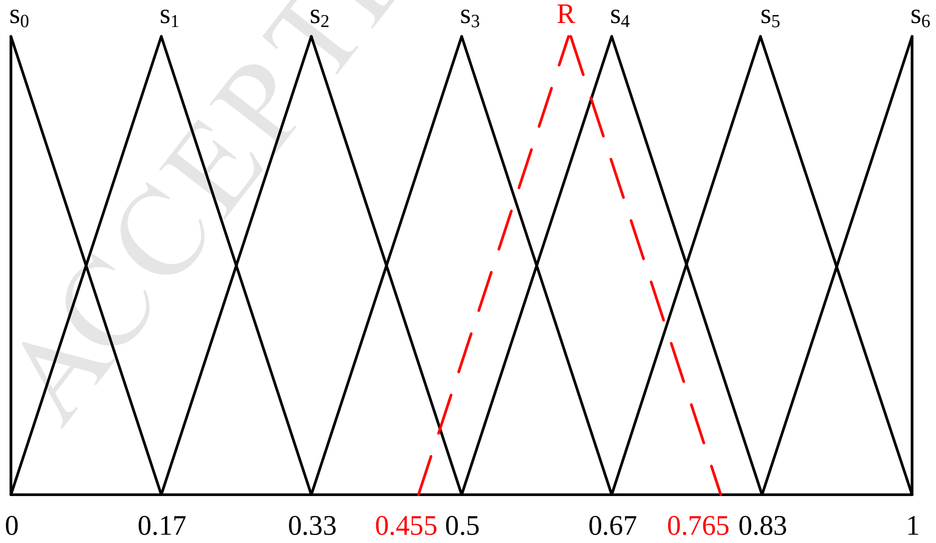

Fig. 4. The overall risk evaluation term

5.7 Discussion

According to the risk assessment result in Section 5.6, the risk level of offshore PV power generation projects in China is medium high, with the degree of membership standing between 0.455 and 0.765. Specifically, the management risk appears to own the highest risk level compared with the other three risk groups., which is consistent with the view of Gatzert and Kosub that management must be taken seriously in the project implement process for those industries that are at the infant stage because relevant experience is usually insufficient in such situations [53]. The micro-economical risk group ranked second, indicating that the capital and profits of targeted projects are faced with great threats and challenges. As for the technical and environmental risk groups, their risk level are also standing between medium and medium high, with a requirement of enough attention and relevant control. In the next section, this paper will give corresponding response strategies towards single risk factor based on the assessment results.

Table 6

Linguistic expression and HFLTS towards each criterion.

	Group 1		Group 2		Group 3	
	Linguistic expression	HFLTS	Linguistic expression	HFLTS	Linguistic expression	HFLTS
C11	between MH and H	{s4, s5}	between M and H	{s3, s4, s5}	between M and MH	{s3, s4}
C12	greater than H	{s5, s6}	greater than MH	{s4, s5, s6}	between ML and M	{s2, s3}
C13	between ML and M	{s2, s3}	between M and MH	{s3, s4}	between L and ML	{s1, s2}
C14	greater than MH	{s4, s5, s6}	between ML and MH	{s2, s3, s4}	between MH and H	{s4, s5}
C21	greater than H	{s5, s6}	between L and M	{s1, s2, s3}	between L and ML	{s1, s2}
C22	between M and MH	{s3, s4}	between ML and M	{s2, s3}	between L and ML	{s1, s2}
C23	between L and ML	{s1, s2}	between M and H	{s3, s4, s5}	between L and M	{s1, s2, s3}
C24	between MH and H	{s4, s5}	between ML and M	{s2, s3}	greater than H	{s5, s6}
C25	between ML and MH	{s2, s3, s4}	greater than MH	{s4, s5, s6}	greater than H	{s5, s6}
C31	greater than MH	{s4, s5, s6}	less than ML	{s0, s1, s2}	between L and ML	{s1, s2}
C32	greater than H	{s5, s6}	between MH and VH	{s4, s5, s6}	less than L	{s0, s1}
C33	less than ML	{s0, s1, s2}	between ML and M	{s2, s3}	greater than MH	{s4, s5, s6}
C34	between L and M	{s1, s2, s3}	greater than H	{s5, s6}	between ML and M	{s2, s3}
C41	between L and ML	{s1, s2}	between M and H	{s3, s4, s5}	between M and MH	{s3, s4}
C42	greater than H	{s5, s6}	between MH and H	{s4, s5}	between M and H	{s3, s4, s5}
C43	between ML and M	{s2, s3}	between M and H	{s3, s4, s5}	greater than MH	{s4, s5, s6}

Table 7

Triangular numbers of each criterion.

	Group 1	Group 2	Group 3	Aggregated results
C11	(0.585,0.75,0.915)	(0.5,0.667,0.833)	(0.415,0.585,0.75)	(0.5,0.667,0.833)
C12	(0.75,0.915,1)	(0.667,0.833,0.943)	(0.25,0.415,0.585)	(0.583,0.749,0.868)
C13	(0.25,0.415,0.585)	(0.415,0.585,0.75)	(0.085,0.25,0.415)	(0.250,0.416,0.584)
C14	(0.667,0.833,0.943)	(0.333,0.5,0.667)	(0.585,0.75,0.922)	(0.543,0.708,0.86)
C21	(0.75,0.915,1)	(0.167,0.333,0.5)	(0.085,0.25,0.415)	(0.292,0.458,0.604)
C22	(0.415,0.585,0.75)	(0.25,0.415,0.585)	(0.085,0.25,0.415)	(0.25,0.416,0.584)
C23	(0.085,0.25,0.415)	(0.5,0.667,0.833)	(0.167,0.333,0.5)	(0.209,0.375,0.541)
C24	(0.585,0.75,0.922)	(0.25,0.415,0.585)	(0.75,0.915,1)	(0.543,0.708,0.854)
C25	(0.333,0.5,0.667)	(0.667,0.833,0.943)	(0.75,0.915,1)	(0.604,0.77,0.888)
C31	(0.667,0.833,0.943)	(0.057,0.167,0.333)	(0.085,0.25,0.415)	(0.223,0.375,0.527)
C32	(0.75,0.915,1)	(0.667,0.833,0.943)	(0,0.085,0.25)	(0.521,0.667,0.784)
C33	(0.057,0.167,0.333)	(0.25,0.415,0.596)	(0.667,0.833,0.943)	(0.306,0.458,0.612)
C34	(0.167,0.333,0.5)	(0.75,0.915,1)	(0.25,0.415,0.585)	(0.354,0.52,0.668)
C41	(0.085,0.25,0.415)	(0.5,0.667,0.833)	(0.415,0.585,0.75)	(0.354,0.522,0.687)
C42	(0.75,0.915,1)	(0.585,0.75,0.922)	(0.5,0.667,0.833)	(0.605,0.77,0.916)
C43	(0.25,0.415,0.585)	(0.5,0.667,0.833)	(0.667,0.833,0.943)	(0.479,0.645,0.799)

6. Management inspiration

As it can be seen from the result that the risk level of offshore PV power generation projects in China is medium high, it is necessary to take effective risk management measures to ensure the smooth implementation and reasonable profits of the risky project. Although risk response measures have already been discussed widely, offshore PV power generation projects have their own uniqueness and general measures are not entirely applicable. Therefore, this paper puts forward the response strategy toward each risk factor based on the review of literature that focus on general risk management plus the analysis of the characteristics of offshore PV projects, thereby achieving pertinence through such combination. The targeted countermeasures and suggestions for risk factors are given below, which could provide a reference and management inspiration for policy makers and corresponding practitioners.

6.1 Micro-economic risk

i) High initial investment: Using a combination of economic sense and technical knowledge to locate and eliminate unnecessary project costs, Value engineering (VE) can effectively reduce costs. It is estimated that the application of VE can cut back the initial investment of a construction project by 5% to 10% [54]. Thus, taking advantage of VE provides an idea for coping with this risk.

ii) High operation and maintenance cost: Firstly, predictive technology can be applied to improve the performance of PV modules [55]. Then, electronic components can be upgraded to improve the reliability of PV parts. Additionally, application-based support system can simplify the maintenance process. All the three methods are able to effectively reduce the cost of operation and maintenance.

iii) Financing risk: Reasonable financing structure design is a key step to reduce the financing risk [56]. Another core link of the project financing risk management is the corresponding relationship between the project financing risk and the parties involved in the project, so that a risk constraint system can be formed to ensure the overall stability of project financing.

iv) Unclear feed-in tariff policy: From the perspective of government, management departments and policy makers need to formulate the long-term price policy as a guideline of price regulation so as to promote the development of the offshore PV industry. From the perspective of project owners, they should pay close attention to policy trends and refer to tariffs in similar industries.

6.2 Technical risk

i) Unreasonable site selection and planning: As mentioned above, offshore PV farm site selection is a multiple attribute decision problem involving resource factor, economic factor, environment factor and some others. The combination of GIS technology and MCDM methods, proved to be an effective tool to improve site selection and planning reliability [57, 58], can be utilized in offshore PV projects to avoid this risk.

ii) Inappropriate PV panel structure design: PV panel structure planning is a basic but important work in the design stage, experienced professionals should be invited to take part in this process. Before production, the simulation algorithm can be adopted to find design defects and thus improvement can be made correspondingly. Moreover, panel structure design of land-based PV projects is also worth referring.

iii) Improper cable connection: Since even small cracks caused by improper connection can destroy the cable after many years, project developers should pay attention to the design of the cable connection. Taking the ocean tide effect into consideration, cables should be connected in a stronger and more endurable form compared with land-based PV power generation projects.

iv) Technical introduction risk: On one hand, the collection of intelligence information should be strengthened for better introduction screening. On the other hand, it is better for the project owner to import technologies that are in the development or growth stage of their life cycle. Such technologies can be more capable of adapting to different environments. If possible, the root technology is the best choice.

v) Onshore supporting condition risk: In the site selection process, terrain and transportation conditions should be studied in case that unfavorable supporting conditions impede the implementation of the project. When necessary, accommodation roads must be built for large equipment. Also, the project developer should actively communicate with grid companies to ensure the supporting of onshore power grid.

6.3 Environment risk

i) Solar resource risk: There is a saying in the industry that PV projects live at the mercy of the weather, which means that solar energy conditions directly determine project benefits. As a result, preliminary research on radiation data is particularly important. Through climate speculation, the change within a year and the long-term trend of solar energy resources can be calculated [59]. Besides, field observation is also indispensable for the sake of conducting a comparison with calculated data and ensuring a solid resource analysis.

ii) Harsh marine environment: To deal with the corrosion caused by the marine environment, the protection of surface materials should be strengthened, such as the formation of a protective film by electroplating, and the use of stainless steel anti-corrosion materials. From the macro perspective, it is necessary for Chinese government to detect and record the weather in the southeastern sea area and establish its own database in preparation for large-scale development of offshore PV power projects.

iii) Marine ecological damage: First of all, the planning and site selection of offshore PV farms should be as far away as possible from the habitats, breeding grounds, and migratory routes of marine life and birds. During the construction period, marine environmental protection warning mechanism should be established to ensure that problems can be solved in the bud. After the project is completed, the responsible party must apply for the environmental quality inspection and acceptance to the environmental protection department. The above measures can reduce the resistance from environmental protection agencies or environmentalists.

iv) Visual effect risk: In response to this risk factor, site selection would better try to avoid the marine wetland ecology area so as not to affect the natural beauty. At the same time, light reflections should be tested in advance in order to make possible adjustments.

6.4 Management risk

i) Construction quality risk: A quality management plan should be formulated firstly with clear accountability according to the characteristics of offshore PV. During the construction stage, each step should be in strict accordance with the scientific construction process so that the construction quality can be strictly controlled. The quality inspection after project completion cannot be ignored, either.

ii) Equipment maintenance risk: The smart energy management platform is a new concept that relies on the internet of things, artificial intelligence and big data analytics to achieve digital operations. PV offshore power generation projects can utilize this concept to realize intelligent operation and maintenance and thus avoid equipment maintenance risk to some extent. In addition, the knowledge of maintenance management under special marine environment should also be studied.

iii) Inexperienced staff: Multiple measures should be taken to cultivate a skilled team. Firstly, it is necessary to conduct employee training courses with respect to theoretical knowledge of offshore PV power by means of physical explanation and practical operation. Secondly, the personnel who have participated in offshore wind projects can be absorbed into the team. Finally, in the long run, cooperation between companies and academics ought to be strengthened to cultivate excellent engineers and project managers.

7. Conclusions

This paper carries out a risk assessment on offshore PV power generation projects in China, and the main conclusions are as follows: i) An evaluation index system is constructed in the foundation of previous studies, actual projects and expert opinions. 16 risk factors influencing offshore PV power generation projects in China are included, and they are divided into four categories, namely the micro-economic risk, the technical risk, the environment risk and the management risk. ii) The risk assessment model is established. In this model: the ANP method is employed to determine index weights considering the interrelationship; the HFLTS method is introduced to assign assessment information to risk factors; the TNF method is utilized to transform the linguistic terms into a computable form; the FIOWHA operator is adopted to aggregate the TNFs of each expert towards a risk factor; the FSE method and the principle of maximum similarity are used to calculate the overall risk level. iii) The established model is applied to the empirical study, namely to calculate the risk level of offshore PV power generation projects in China, which is medium high as the result shows. The empirical study illustrates the applicability of the model. iv) Countermeasures and suggestions for each risk factor are put forward to guarantee the smooth implementation and reasonable profits of the risky projects.

However, there are still some limitations and shortcomings in this paper. For one thing, the identification of risk factors cannot be perfect, and inevitably, there will be some omissions because of limited available information. We will continue to collect more information for the improvement of the indicator system. For another thing, different decision makers hold different attitudes towards risks, and this difference may lead to absolute opposite decision results sometimes. Therefore, we will take the risk preference of decision makers into consideration in future research.

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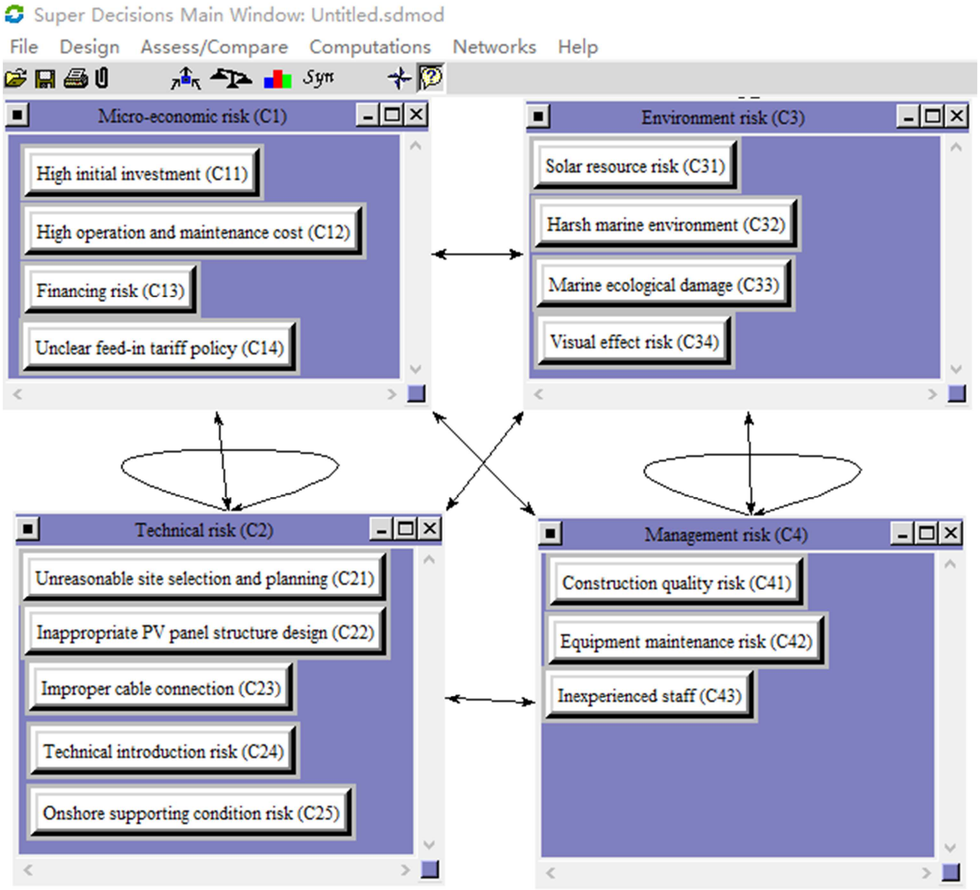
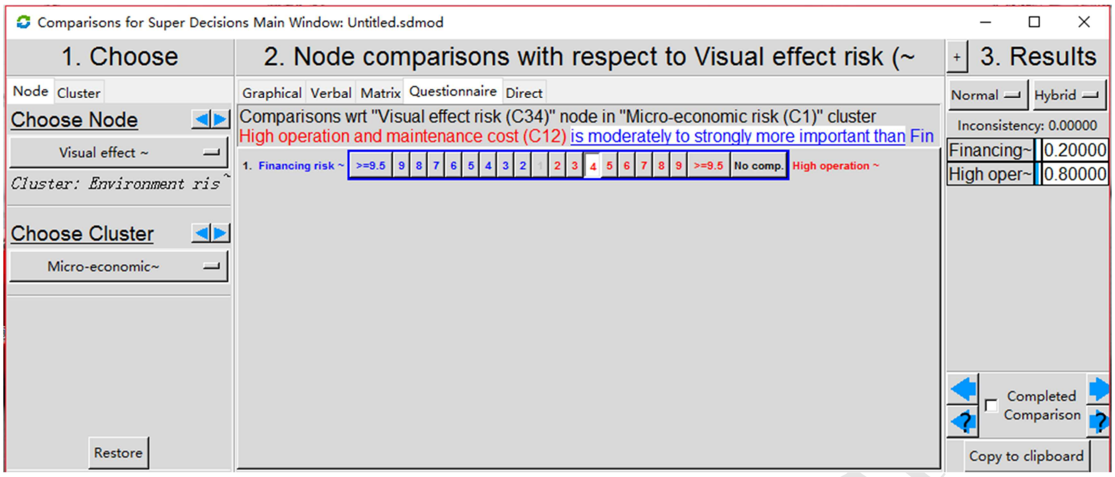
Appendix

The calculation process of the weight of each indicator through the Super Decision software can be summarized as follows:

i) According to the constraint relations among indicators in Table 4, the ANP model diagram of risk assessment of offshore PV power generation projects can be established.



ii) The pair-wise comparison is conducted based on expert opinions, and the first-level indicators are taken as the example.



Comparisons for Super Decisions Main Window: Untitled.sdmod

2. Node comparisons with respect to Visual effect risk (~

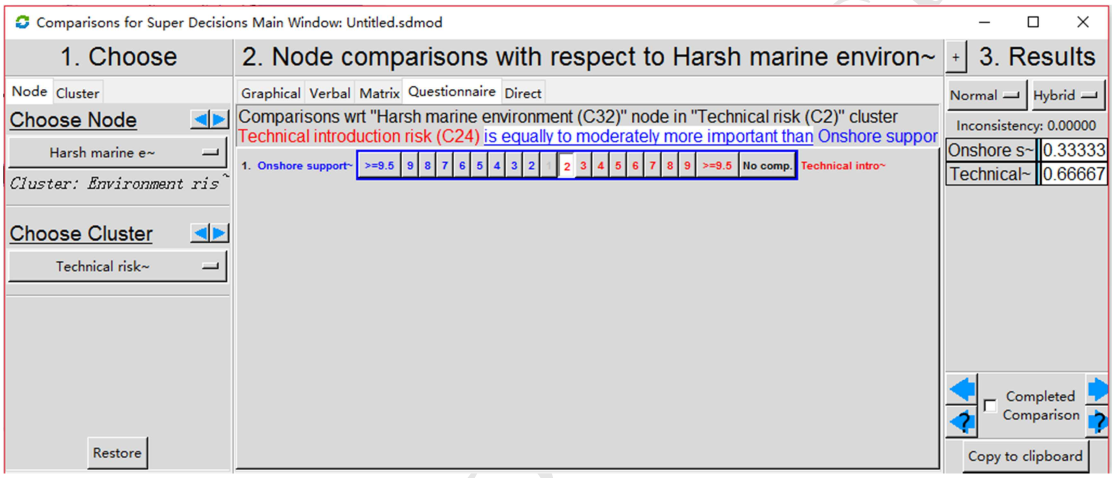
Choose Node: Visual effect ~
Cluster: Environment ris~
Choose Cluster: Micro-economic~

Comparisons wrt "Visual effect risk (C34)" node in "Micro-economic risk (C1)" cluster
High operation and maintenance cost (C12) is moderately to strongly more important than Fin

1. Financing risk ~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. High operation ~

Inconsistency: 0.00000

Financing~	0.20000
High oper~	0.80000



Comparisons for Super Decisions Main Window: Untitled.sdmod

2. Node comparisons with respect to Harsh marine environ~

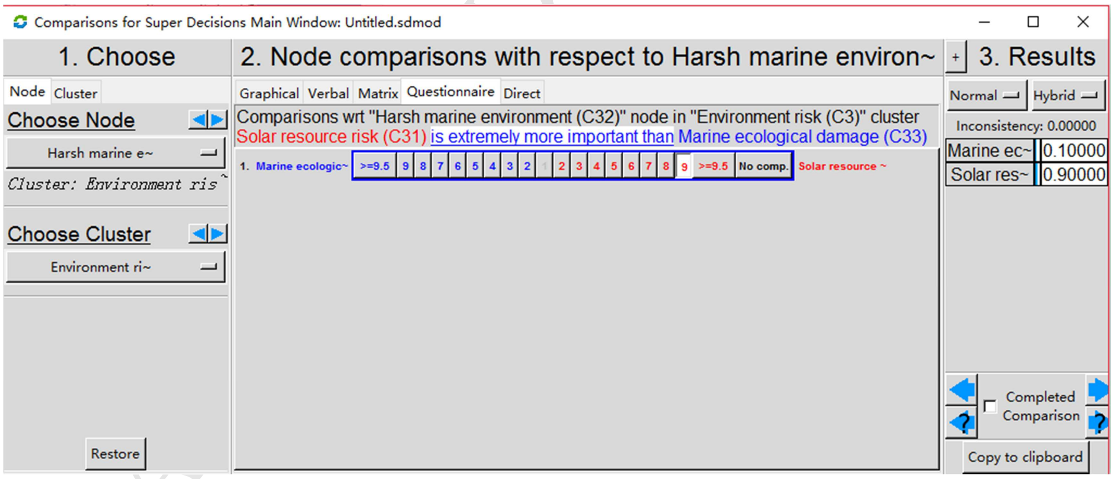
Choose Node: Harsh marine e~
Cluster: Environment ris~
Choose Cluster: Technical risk~

Comparisons wrt "Harsh marine environment (C32)" node in "Technical risk (C2)" cluster
Technical introduction risk (C24) is equally to moderately more important than Onshore suppor

1. Onshore support~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Technical intro~

Inconsistency: 0.00000

Onshore s~	0.33333
Technical~	0.66667



Comparisons for Super Decisions Main Window: Untitled.sdmod

2. Node comparisons with respect to Harsh marine environ~

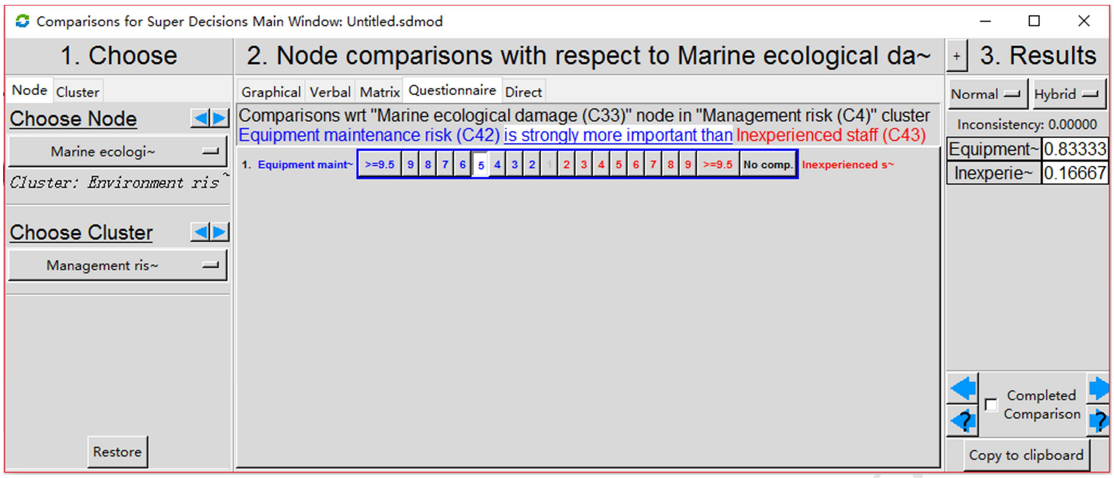
Choose Node: Harsh marine e~
Cluster: Environment ris~
Choose Cluster: Environment ri~

Comparisons wrt "Harsh marine environment (C32)" node in "Environment risk (C3)" cluster
Solar resource risk (C31) is extremely more important than Marine ecological damage (C33)

1. Marine ecologic~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Solar resource ~

Inconsistency: 0.00000

Marine ec~	0.10000
Solar res~	0.90000



Comparisons for Super Decisions Main Window: Untitled.sdmod

1. Choose

2. Node comparisons with respect to Marine ecological da~

3. Results

Choose Node: Marine ecologi~

Cluster: Environment ris~

Choose Cluster: Management ris~

Comparisons wrt "Marine ecological damage (C33)" node in "Management risk (C4)" cluster
Equipment maintenance risk (C42) is strongly more important than Inexperienced staff (C43)

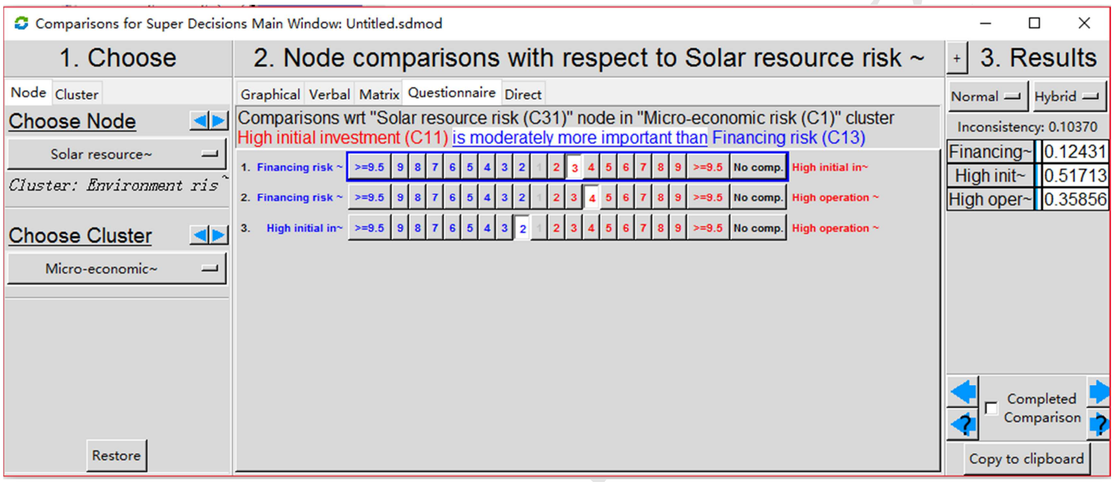
1. Equipment maint~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Inexperienced s~

Normal — Hybrid —

Inconsistency: 0.00000

Equipment~	0.83333
Inexperie~	0.16667

☐ Completed Comparison



Comparisons for Super Decisions Main Window: Untitled.sdmod

1. Choose

2. Node comparisons with respect to Solar resource risk ~

3. Results

Choose Node: Solar resource~

Cluster: Environment ris~

Choose Cluster: Micro-economic~

Comparisons wrt "Solar resource risk (C31)" node in "Micro-economic risk (C1)" cluster
High initial investment (C11) is moderately more important than Financing risk (C13)

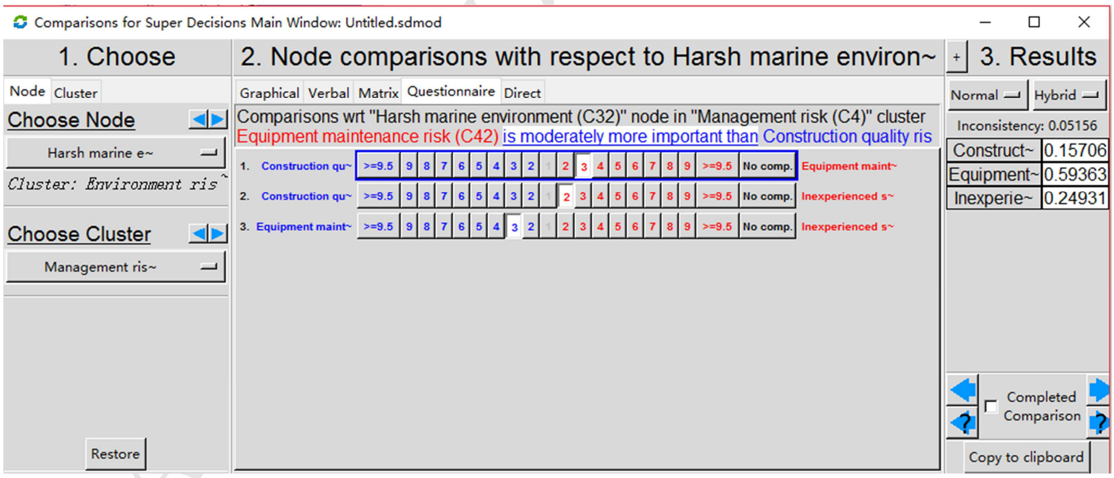
1. Financing risk ~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. High initial in~
2. Financing risk ~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. High operation ~
3. High initial in~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. High operation ~

Normal — Hybrid —

Inconsistency: 0.10370

Financing~	0.12431
High init~	0.51713
High oper~	0.35856

☐ Completed Comparison



Comparisons for Super Decisions Main Window: Untitled.sdmod

1. Choose

2. Node comparisons with respect to Harsh marine environ~

3. Results

Choose Node: Harsh marine e~

Cluster: Environment ris~

Choose Cluster: Management ris~

Comparisons wrt "Harsh marine environment (C32)" node in "Management risk (C4)" cluster
Equipment maintenance risk (C42) is moderately more important than Construction quality ris

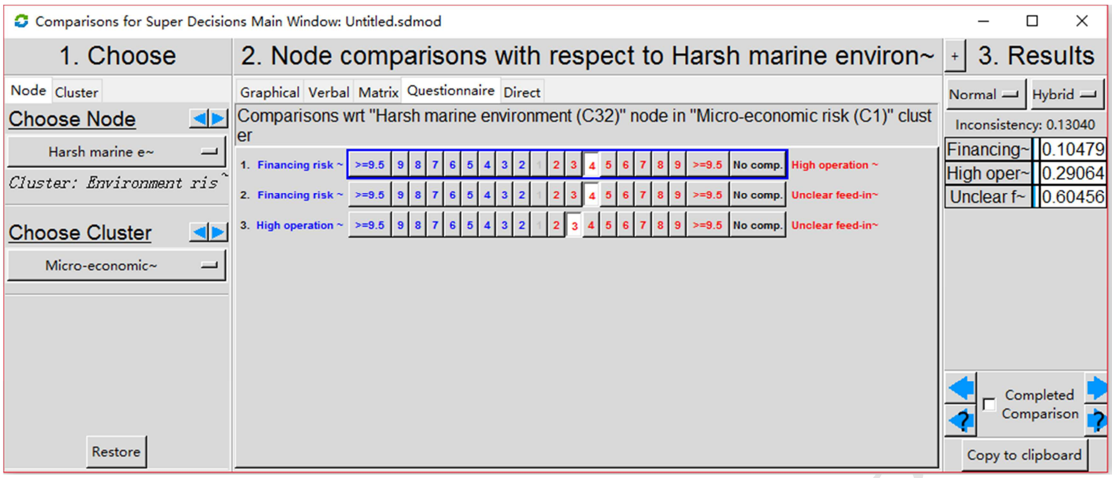
1. Construction qu~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Equipment maint~
2. Construction qu~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Inexperienced s~
3. Equipment maint~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Inexperienced s~

Normal — Hybrid —

Inconsistency: 0.05156

Construct~	0.15706
Equipment~	0.59363
Inexperie~	0.24931

☐ Completed Comparison



Comparisons for Super Decisions Main Window: Untitled.sdmod

1. Choose

Node Cluster

Choose Node

Harsh marine e~

Cluster: Environment ris

Choose Cluster

Micro-economic~

2. Node comparisons with respect to Harsh marine environ~

Graphical Verbal Matrix Questionnaire Direct

Comparisons wrt "Harsh marine environment (C32)" node in "Micro-economic risk (C1)" cluster

1. Financing risk ~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. High operation ~

2. Financing risk ~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Unclear feed-in~

3. High operation ~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 No comp. Unclear feed-in~

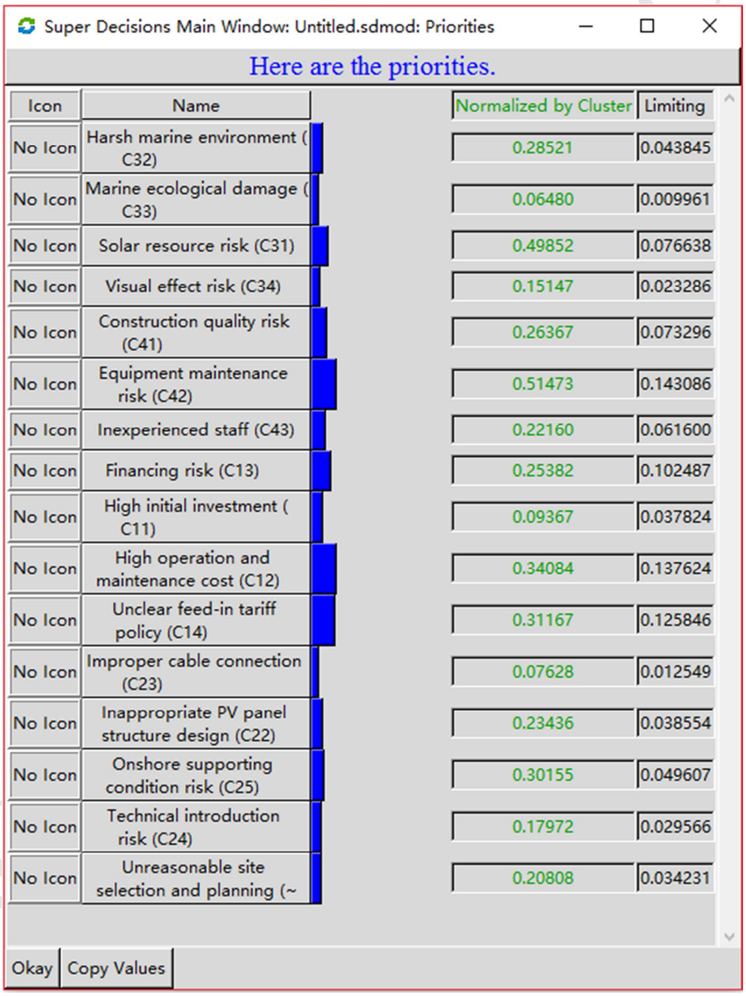
3. Results

Normal Hybrid

Inconsistency: 0.13040

Financing~	0.10479
High oper~	0.29064
Unclear f~	0.60456

iii) The weight of each indicator could be calculated by the software, and the result is shown as follows.



Super Decisions Main Window: Untitled.sdmod: Priorities

Here are the priorities.

Icon	Name	Normalized by Cluster	Limiting
No Icon	Harsh marine environment (C32)	0.28521	0.043845
No Icon	Marine ecological damage (C33)	0.06480	0.009961
No Icon	Solar resource risk (C31)	0.49852	0.076638
No Icon	Visual effect risk (C34)	0.15147	0.023286
No Icon	Construction quality risk (C41)	0.26367	0.073296
No Icon	Equipment maintenance risk (C42)	0.51473	0.143086
No Icon	Inexperienced staff (C43)	0.22160	0.061600
No Icon	Financing risk (C13)	0.25382	0.102487
No Icon	High initial investment (C11)	0.09367	0.037824
No Icon	High operation and maintenance cost (C12)	0.34084	0.137624
No Icon	Unclear feed-in tariff policy (C14)	0.31167	0.125846
No Icon	Improper cable connection (C23)	0.07628	0.012549
No Icon	Inappropriate PV panel structure design (C22)	0.23436	0.038554
No Icon	Onshore supporting condition risk (C25)	0.30155	0.049607
No Icon	Technical introduction risk (C24)	0.17972	0.029566
No Icon	Unreasonable site selection and planning (~	0.20808	0.034231

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1. An index system is established for risk assessment on offshore photovoltaic power generation projects.
2. A risk assessment model is put forward based on hesitant fuzzy linguistic term sets, triangular fuzzy number and fuzzy synthetic evaluation
3. Correlations between criteria are analyzed to construct the analytic network process structure
4. An empirical study of China is conducted.
5. Effective response strategies are proposed towards each risk.