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An investment decision framework for offshore CCUS project under interval-valued Fermatean fuzzy environment

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Corresponding Author:	neha dash sharma Yanshan University INDIA
First Author:	neha dash sharma
Order of Authors:	neha dash sharma
Abstract:	Carbon Capture, Utilization and Storage (CCUS) is an indispensable technology for achieving a net-zero emission society. The offshore CCUS project is still in its infancy. To promote its sustainable development, developing a comprehensive framework for investment decision-making is very crucial. First, a comprehensive evaluation criteria system is established. Second, in order to characterize the ambiguity and uncertainty of information in the process of making decisions, the interval-valued fermatean fuzzy set (IVFFS) is introduced, and the extended variance method of IVFFS is proposed to systematically calculate the weights of experts. Then, the power weighted average (PWA) operator based similarity measure of IVFFSs is developed to aggregate different expert information. Meanwhile, the fuzzy-weighted zero-inconsistency (FWZIC) method and the method based on the removal effects of criteria (MEREC) are used to determine the criteria weights. In addition, considering the interactions between the criteria, we introduce the Hamacher operator into the measurement of alternatives and ranking according to compromise solution (MARCOS) method to select the optimal alternative in the interval-valued fermatean fuzzy (IVFF) environment. The suggested framework is then used to analyze a case study. After that, sensitivity and comparative analyses are conducted to confirm its robustness and viability. This study creates a practical investment framework for offshore CCUS projects, identifies a number of investment-sensitive criteria and provides management insights. The proposed framework expands the methods and applications in the field of decision-making and provides a scientific approach for investment decision-making in offshore CCUS projects, which can be a useful reference for managers.

To,
The Editor-in-Chief
Environmental study

Subject: Submission of Manuscript – *An Investment Decision Framework for Offshore CCUS Project under Interval-Valued Fermatean Fuzzy Environment*

Dear Editor,

I am pleased to submit our manuscript entitled *"An Investment Decision Framework for Offshore CCUS Project under Interval-Valued Fermatean Fuzzy Environment"* for your kind consideration for publication in [Journal Name].

In this paper, we present a novel decision-making approach to evaluate offshore Carbon Capture, Utilization, and Storage (CCUS) projects under uncertainty by employing the interval-valued Fermatean fuzzy environment framework. This research aims to address investment challenges in large-scale CCUS initiatives, providing a robust tool for policymakers and stakeholders to make informed decisions.

We believe that our work will be of interest to the readership of [Journal Name], given its relevance to sustainable energy strategies, environmental protection, and advanced fuzzy decision-making methods. We confirm that the manuscript is original, has not been published elsewhere, and is not under consideration by any other journal.

We respectfully request you to consider our manuscript for publication in [Journal Name]. Please find the manuscript and supplementary files attached herewith.

Corresponding Author:

Yaqing Gao

School of Economics and Management, Yanshan University, Qinhuangdao 066004, China

gaoyq0307@163.com

Highlights

- Proposes a novel decision-making framework for offshore Carbon Capture, Utilization, and Storage (CCUS) projects.
- Incorporates the *interval-valued Fermatean fuzzy environment* to handle high uncertainty in project evaluation.
- Integrates economic, environmental, and technical factors into a unified assessment model.
- Demonstrates applicability through a case study on offshore CCUS deployment.
- Offers valuable insights for policymakers and investors in the energy transition sector.

An investment decision framework for offshore CCUS project under interval-valued Fermatean fuzzy environment

Qinghua Mao[1]·Yaqing Gao[1]·Jiacheng Fan[1]

[1]School of Economics and Management, Yanshan University, Qinhuangdao 066004, China

Corresponding Author:

Yaqing Gao

School of Economics and Management, Yanshan University, Qinhuangdao 066004, China

Email address: gaoyq0307@163.com

Abstract:

Carbon Capture, Utilization and Storage (CCUS) is an indispensable technology for achieving a net-zero emission society. The offshore CCUS project is still in its infancy. To promote its sustainable development, developing a comprehensive framework for investment decision-making is very crucial. First, a comprehensive evaluation criteria system is established. Second, in order to characterize the ambiguity and uncertainty of information in the process of making decisions, the interval-valued fermatean fuzzy set (IVFFS) is introduced, and the extended variance method of IVFFS is proposed to systematically calculate the weights of experts. Then, the power weighted average (PWA) operator based similarity measure of IVFFSs is developed to aggregate different expert information. Meanwhile, the fuzzy-weighted zero-inconsistency (FWZIC) method and the method based on the removal effects of criteria (MEREC) are used to determine the criteria weights. In addition, considering the interactions between the criteria, we introduce the Hamacher operator into the measurement of alternatives and ranking according to compromise solution (MARCOS) method to select the optimal alternative in the interval-valued fermatean fuzzy (IVFF) environment. The suggested framework is then used to analyze a case study. After that, sensitivity and comparative analyses are conducted to confirm its robustness and viability. This study creates a practical investment framework for offshore CCUS projects, identifies a number of investment-sensitive criteria and provides management insights. The proposed framework expands the methods and applications in the field of decision-making and provides a scientific approach for investment decision-making in offshore CCUS projects, which can be a useful reference for managers.

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1. Introduction

1.1. Background

The burning of fossil fuels releases a large amount of carbon dioxide, which could lead to increasingly severe climate change. The International Energy Agency (IEA) has developed a global consensus to achieve a net-zero emissions society by 2050 in order to mitigate climate change [1]. While renewable energy plays an important role in decarbonizing the power sector, technologies for Carbon Capture, Utilization and Storage (CCUS) are essential for lowering carbon emissions from the burning of fossil fuels in the production of electricity and provide a financially viable way to overhaul the energy system [2-3]. CCUS reduces atmospheric deposition of emission sources through large-scale capture of carbon dioxide followed by geological storage and utilization [4]. CCUS has been used in the power, steel, cement and chemical sectors to reduce CO_2 emissions [5]. While geological storage on land has been extensively studied, the potential benefits of offshore storage have drawn a lot of attention. Offshore carbon storage not only increases the amount of storage capacity on land, but it also keeps subsurface drinking water clean and does not potentially harm agricultural and industrial operations, as there are few sources of drinking water at sea [6-7]. In addition, offshore carbon storage is important for sources of CO_2 emissions in coastal areas far from salty aquifers and onshore oil and gas fields [8-9].

1.2. Motivation

Currently, there are numerous offshore CCUS demonstration projects [7]. Scholars have studied offshore CCUS projects. Tamburini et al.[10] developed an integrated approach to calculate the consequences of an offshore CO_2 blowout, which could affect the safety and environmental impacts of CCUS projects. Based on the possibility of storing CO_2 in China's offshore sedimentary basins, Sun et al.[11] conducted an offshore source-sink matching and cost study of China's CCUS under various limitations. Jung et al. [12] developed a source-to-sink CO_2 transportation strategy for a demonstration project of Carbon Capture and Storage (CCS) in South Korea and performed a cost estimation based on the CO_2 transportation strategy. An approach to mixed-integer linear modeling that is spatially explicit was presented by D'Amore et al. [13] for the purpose of economically optimizing CCS supply chains throughout Europe. However, most studies have focus on storage capacity assessment, economic analysis, and technology optimization [9, 14-15], few scholars have studied the investment decisions of the project.

The growth of offshore CCUS projects is a key strategy for burning fossil fuels to achieve large-scale decarbonization, where investment decisions are fundamental to offshore CCUS project development. The investment assessment of the project determines, to a certain extent, the challenge of construction throughout the building period and the performance following operation, both of which are essential to the project's performance and steady operation. This project's investment assessment process will be influenced by a number of elements, including the substantial invested sum, the high levels of technicality, and the erratic state of the market, which makes the investment decision of offshore CCUS project a multi-criteria decision-making

(MCDM) problem. Consequently, before building, a thorough and methodical analysis of the offshore CCUS projects' investment appraisal is required. Although the decision to invest in offshore CCUS projects has not been extensively studied, for this project, several references may be found in the research of onshore CCUS projects. As an illustration, Sun et al. [16] proposed an option game approach to explore incentives to promote the CCUS project. Fan et al. [17] built a model depending on real options and source-sink matching to make investment decisions for CCUS transformation of coal-fired power plants in China. Guo et al. [18] developed an extended TODIM (an acronym in Portuguese for Interactive Multi-criteria Decision Making) method that uses assessment information given by decision makers to select CO_2 storage locations. Based on previous researches, this paper aims to investigate the investment evaluation of offshore CCUS projects and develop a novel perspective on investment decision-making by building the MCDM framework.

1.3. Contribution

The objective of this study is to offer an exhaustive and reliable framework for investment decisions in offshore CCUS projects, and to give a few references for relevant managers. The study's contributions and the innovative aspects of the suggested framework are then summed up as follows: (1) This research builds a comprehensive system of criteria for investment in offshore CCUS projects through three stages: data collection, screening criteria and expert consultation, including five aspects: resources, economy, environment, society and risk. (2) Expert assessment data is represented by the interval-valued fermatean fuzzy set (IVFFS), which takes into account the ambiguity and uncertainty of decision-making information. Then, the power weighted average (PWA) operator based on the similarity measure of IVFFSs is established to combined the assessment data of different experts to reduce the error due to ignoring the information bias, while considering experts' relative importance. Among them, the extended variance method of IVFFSs is proposed to systematically calculate the weights of experts to make the decision-making information more objective. A comprehensive weighting model in IVFF environment is proposed to obtain criterion weights. The fuzzy-weighted zero-inconsistency (FWZIC) method is extended to the IVFF environment to calculate the criteria's subjective weights. Additionally, the objective weights of the criteria are determined using the method based on the removal effects of criteria (MEREC). (4) The Extended IVFF measurement of alternatives and ranking according to compromise solution (MARCOS) approach is proposed to rank the alternatives. Hamacher operator is introduced in the MARCOS method to define the weighted sequence. It is able to better assemble the information and deal with the interconnection and influence between the criteria.

Following is the remainder of the paper. Section 2 reviews the approaches taken in this work. Section 3 constructs a system of investment criteria for offshore CCUS projects. Section 4 presents a comprehensive framework for investment appraisal of offshore CCUS projects. Section 5 presents a case study. Section 6 performs a sensitivity analysis and a comparative analysis. Section 7 provides conclusions.

2. Literature review

In this section, the methodology used in this paper is briefly reviewed.

2.1 Interval-valued fermatean fuzzy set

As mentioned earlier, the investment decision problem for offshore CCUS projects is an MCDM problem. It can occasionally be impossible to convey the decision-maker's preference information in precise numbers during the real procedure for making decisions due to the ambiguity and unpredictability of human thought as well as the complexity of the situation. To provide better handling of this situation, Zadeh [19] first suggested the fuzzy set (FS) theory. FS's primary feature is that its Membership function (MF) ranges from 0 to 1. As a result of FS lacking an independent Non-membership function (NMF), Atanassov [20] proposed an intuitionistic fuzzy set (IFS) with NMF as an independent factor. In addition, Yager [21] proposed Pythagorean fuzzy set (PFS) to moderate the constraints of IFS (the PFS's MF and NMF square sums are less than 1). Recently, fermatean fuzzy set (FFS), proposed by Senapati and Yager [22] as an important enhancement to PFS, has become a valuable concept for describing uncertainty in MCDM environments. In FFS, an object is described by membership degree (MD) and non-membership degree (ND) and their cubic sum ≤ 1. It is difficult to describe MD and ND precisely in terms of clear values because of the limits of human understanding and the complexity of actual occurrences. Nonetheless, they can be disclosed by interval values. Jeevaraj [23] generalized the concept of FFS to IVFFS, where MD and ND can be represented as subsets of the interval [0,1] instead of clear values. Decision-makers can communicate their opinions across a wider domain with IVFFS. As a result, complex decision-making problems can be more effectively solved and modeled by IVFFS [24]. IVFFS has been used in a number of applications. Mijanur Rahaman Seikh and Utpal Mandal [24] developed the IVFF Dombi weighted average (geometric) operator combined with Preference Ranking Organization METhod for Enrichment Evaluation II (PROMETHEE II) and Stepwise Weight Assessment Ratio Analysis (SWARA) methods, proposed an integrated MCDM approach to select the organization most capable of managing biomedical waste. Based on IVFFS, M. Hezam et al. [25] developed a hybrid combined compromise solution (CoCoSo) approach based on Dombi operator and similarity measure, to select the company that makes wheelchairs with smart autonomy for patients with disabilities. Biswas et al. [26] applied IVFF based Multi-Attributive Border Approximation Area Comparison (MABAC) technique to identify the key characteristics of product family and assist in making decisions in the face of uncertainty. The new two-phase IVFF dominance approach, which Jeevaraj et al [27] devised, was used to rate the benefits of different options for lowering greenhouse gas emissions from activities connected to transportation. Bouraima et al. [28] integrated Analytic hierarchy process (AHP) method and Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) in an IVFF environment to assess the susceptibility of different countries to accidents occurring on construction sites. Kirişci, M [29] proposed a new integrated MCDM approach for IVFF combining AHP, TOPSIS and MABAC methods to propose a new safety model to assess the risk of self-driving cars. However, few have applied

IVFFS to investment issues in offshore CCUS projects. The theory of IVFFS is one of the effective and appropriate tools to manage the uncertainty and imprecision that occurs in several real-life decision problems. From the above literature, it can be seen that IVFFS has been applied to different real-life problems and the specific semantics of IVFFS changes with the evaluation problem. Some real-life problems may not be able to involve precise data, then IVFFS is well suited to model problems involving incomplete and imprecise information. In order to improve the flexibility and effectiveness of IVFFS, this paper aims to propose a hybrid framework for evaluating MCDM problems from an IVFF perspective.

2.2 Group aggregation methods

The process of information aggregation for selection decisions that does not take into account the bias of expert assessment information can give rise to a degree of cognitive uncertainty. Therefore, aggregating evaluation data from many experts is especially well suited for aggregation techniques that can manage information bias [30]. The PWA operator [31] effectively reduces the effect of bias compared to the Bonferroni mean operator and the Choquet integral [30]. PWA operators have been applied to aggregate expert information in different fuzzy environments such as interval 2-tuple languages [30], complex spherical fuzzy sets [32]. Individual variances, on the other hand, raise concerns about the level of consensus. Important elements in the aggregation process are the relative relevance of various specialists and the coherence of their opinions [33]. The weighting of experts must be systematically assessed to reduce subjective randomness. In the existing literature [30, 34-36], expert weights are generally equal or given directly based on the expert's knowledge, position, and other conditions, often ignoring the objectivity of the expert weights. Therefore, this work adapts the PWA operator to the IVFF environment by extending it depending on the distance measure and reduces the error due to ignoring the effect of information bias while considering the relative importance of experts. In this paper, the IVFF variance normalization approach is used to determine the expert weights.

2.3 Criteria weights determination methods

Determining the weights of the evaluation criteria is a crucial and considerable stage in the evaluation process of offshore CCUS projects. Many MCDM techniques have been used recently, including the AHP method [37], the analytic network process (ANP) method [38] and the best-worst method (BWM) method [39], have been utilized to ascertain the subjective weights assigned to the criteria. But the issue of inconsistent in weighing methods has not been resolved. Recently, the FWZIC approach have been used to calculate the weighting coefficients for variables with zero inconsistency [40]. It identifies the importance of criteria with the support of experts. The FWZIC method has been extended to various fuzzy sets such as PFS, FFS, and probabilistic hesitant fuzzy sets [41-42]. This paper extends the FWZIC approach to the more flexible IVFFS. In addition, numerous objective weighting techniques are employed to establish the criteria weights, such as entropy method [43], the criteria importance through intercriteria correlation (CRITIC) method [44] and integrated determination of objective criteria weights (IDOCRIW) method [45]. Keshavarz et al. [46] proposed the MEREC objective weight determination method. In unlike previous approaches, this one determines the weight of the criteria by evaluating the effect of the criteria that have been eliminated on the total utility; the more the impact, the higher the weight. MEREC is more stable than the other methods in the presence of anomalous disturbances even though the outcomes it produces are comparable to those of the other approaches [47]. As a result, the MEREC approach is widely applied. Simic et al. [48] came up with CoCoSo-MEREC model for transportation planning in Fermatean fuzzy environment. In order to investigate the selection of agricultural technology, Banik et al. [49] expanded the MEREC and gray correlation approaches based on the pentagonal neutrosophic environment. The rank sum-MEREC- model was created by Deveci et al. [50] to choose different transportation networks. The hybrid method is more scientifically sound without over-reliance on subjective or objective information relative to a single subjective or objective approach. Therefore, this paper adopts the combined weighting method of FWZIC and MEREC to determine the criterion weights for the offshore CCUS projects.

2.4 MARCOS method

Many tools are typical for dealing with MCDM problems. Examples include TOPSIS[51], CoCoSo[30] and PROMETHEE II [52]. One of the most recent MCDM techniques released by Stevi´ c et al.[53] is MARCOS. This approach uses reference point ordering and ratios. Through the defining of ideal/anti-ideal values, the relationship between alternatives and reference points, and the degree of utility, the MARCOS technique yields a reliable ranking of alternatives. It provides more accurate and reliable results with less effort and shorter operation time than other methods, making it a more flexible and effective decision-making method[54]. In order to assess wastewater reuse applications in thermal power plants, Ocampo et al. [55] presented a three-way decision extension of the MARCOS technique. A spherical fuzzy MARCOS was presented by Bonab et al.[56] to rank and assess blockchain platforms. Pamucar et al. [57] proposed the MARCOS based fuzzy Full Consistency Method and neutrosophic fuzzy to evaluate alternate fuel automobiles for US road transportation that is sustainable. In Pythagorean fuzzy environment, Wang et al. [58] proposed an extended MARCOS method to calculate the criteria importance through CRITIC to determine the order of importance of each sustainable food supplier. The utilization of the MARCOS methodology improves the correctness of the decision-making system and provides useful ranking results for decision makers [59]. In addition, the Hamacher aggregation operator is able to fully take into account the correlation between attributes, and thus has been used for the aggregation of a variety of fuzzy information expressions [60]. Therefore, in this paper, the IVFF-Hamacher aggregation operator is introduced in the MARCOS method to normalize the weighting sequences in the weighting matrix, so that it can be better applied to the IVFF environment.

A summary of some of the MCDM techniques previously created to deal with investment assessment problems can be found in Table 1. The following is a summary of the research gaps according to Table 1 and the review of literature: (1) Few research has been carried out on offshore CCUS projects using MCDM techniques. (2) There are few studies that take into the effects of expert weights and individual evaluation information bias in the aggregation process. (3) The FWZIC approach has not been well explored in IVFFS and most of the literature does not take into account both objective and subjective data. (4) The MARCOS approach has limited application in the IVFFS environment. Therefore, this paper proposes a comprehensive MCDM model for offshore CCUS project for investment decision making.

Table 1. An overview of a few earlier studies on the evaluation of investments.

Author (s)	Methodology	Application	Group aggregation		Criteria' weight		Mutual relationships between the criteria
			Experts' weights	Individual deviation	Subjective	Objective	
Yuan et al. [61]	Crisp&ANP-Entropy-TODIM	CFPP			√	√	√
Karatop et al. [62]	TFN &AHP-EDAS	Renewable energy			√		

Wu et al. [63]	TIFN& DEMATEL -TODIM	PVPCHS		√		√
Wu et al. [64]	HFLTS&ANP- entropy -TODIM	ICR-DPV		√	√	√
Zhou et al. [65]	IT2F& DANP-QUALIFLEX	Renewable energy		√		√
Zheng et al. [66]	Cloud model & IDOCRIW-TODIM	AVCES	√	√	√	
Mao et al. [52]	IVPFS& DEMATEL - GOWUA-HARA-PROMETHEE II	Offshore wind-PV-SPS project	√	√		√
Peng et al.	Z-numbers&	New energy		√		√

[67]	DEMATEL - ELECTRE III	resources					
This study	IVFFS&F WZIC-MEREC-Hamacher-MARCOS	Offshore CCUS project	√	√	√	√	√

3. The investment decision criteria system

Identifying impact factors and constructing a system of evaluation criteria is the fundamental task of project investment evaluation. This article will identify impact indicators for investment appraisal of offshore CCUS projects using a three-phase process that includes data collection, selection criteria, and consulting experts. First, using the literature review method, the relevant documentalists will gather relevant information on offshore CCUS projects, such as published academic articles and feasibility study results, they will then gather and arrange potential obstacles or factors that could influence these projects. Next, appropriate staff will be asked to conduct frequency counts and initial screening of the collected impact indicators. Ultimately, a working group composed of specialists with in-depth understanding of offshore CCUS projects will be invited. The experts talked about the impact factors' initial screening mentioned above, eliminated any redundant or unimportant indicators, integrated those with high significance, and ultimately created a set of criteria for resources, economy, environment, society, and risk, which includes a total of 18 impact criteria, as shown in Figure 1. Of these, the cost criteria are C21, C22, C23, C31, C32, C51, C52, and C53, while the benefit criteria are the remaining ones.

3.1 Resource (C1)

·Emission source (C11) [68-69]

Considering distance, technology, cost, and public perception, Certain requirements must be met for the deployment of offshore CCUS, including the locations of major emission sources and the societal circumstances that each facility faces.

·Storage capacity (C12) [18, 70-71]

Before implementing CCUS, an analysis of the CO_2 storage capacity is required. The cost of geological storage per unit of CO_2 should decrease with increasing storage capacity, according to theory. Therefore, sites with large storage capacity will be suitable for CO_2 storage, taking into account investment costs and efficiency.

·Injection rate (C13) [72-73]

The effects of reservoir uncertainty and reservoir flow variability on infrastructure availability and costs must be taken into consideration while planning CCUS infrastructure. Important geologic storage parameters (temperature, pressure, depth, and permeability) influence injection rates and cause fluctuations in the flow rates of CO_2, which are then redirected into the pipeline system for transportation.

·Infrastructures (C14) [69, 74-75]

Effective use of existing infrastructure such as pipelines, platforms, good transportation conditions, etc. can reduce investment costs.

3.2 Economy (C2)

·Initial costs (C21) [52, 76]

The upfront cost includes the cost of purchasing the facility, construction costs, human resource costs and interest.

·Operation and maintenance (O&M) costs (C22) [74, 77]

The long-term management of the project is heavily dependent on O&M costs. Expenses for employee pay and basic equipment configuration, and by extension, transportation costs are included in O&M costs.

·payback period (C23) [78-79]

The time after an investment project has been operationalized until its entire economic benefits match the initial investment is known as the payback period. Furthermore, the payback period can accurately depict the project's financial gains and rate of capital turnover.

·Internal rate of return (IRR)（C24）[80]

In cases where there is no net present value, the IRR is determined. A project's profitability and ability to withstand risk can be seen in the IRR. Furthermore, it can assist investors in evaluating and comparing projects of various sizes.

3.3 Environment (C3)

·Marine environmental impacts (C31) [77, 81]

It is important to minimize negative environmental risks and impacts and to ensure that there is no harm to the oceanic surroundings. The risk of CO_2 seepage may lead to decline in the quality of the water, acidification of the ocean and harmful impacts on marine ecosystems. In addition, there may be environmental constraints to placement close by environmentally protected areas.

·Marine Biological Coordination (C32) [82]

Seafloor organisms, including some associated with commercial fisheries, may die under extreme acidification conditions near the spill site.

·Reduce carbon emissions (C33) [83-84]

The CCUS project has huge environmental benefits, both the atmosphere and the greenhouse effect can be greatly diminished.

3.4 Social (C4)

·Policy support (C41) [85-87]

The CCUS project investment is a capital-intensive investment. Therefore, economic and regulatory support from governments is needed for its further development and deployment.

·Public acceptance (C42) [70, 88-89]

The degree of public approval is crucial in the deployment of CCUS, both locally and globally. Public perceptions of CCUS are influenced by more variables than merely danger or security issues.

·Employment (C43) [85]

Process and industrial engineering knowledge is necessary for CCUS and can be a source of excellent local jobs. A lot of local jobs in infrastructure deployment are created by the design-heavy CCUS project. In order to facilitate a fair transition, CCUS can lower the unemployment rate in the fossil fuel sector.

·Technological innovation promotion (C44) [74, 87]

CCUS projects can be effective in contributing to carbon emission reductions, but the economic cost poses a significant challenge for commercial-scale deployment of offshore CCUS. This project's development will save costs and progress associated technological advancements.

3.5 Risk（C5）

·Leakage and monitoring risks (C51) [81, 90-91]

Carbon leakage can not only harm the marine ecosystem, but can also significantly reduce the competitiveness of a project, requiring accurate assessment of the risk of leakage and proper monitoring.

·Technical uncertainty (C52) [74, 92]

The project of offshore CCUS is currently in its early stages, and capture, transportation, and storage technologies all face different challenges, and technological uncertainty can lead to increased costs.

·Market competition (C53) [76, 85]

Other low-carbon technologies like energy efficiency and renewable energy compete with offshore CCUS projects for investment. With the ongoing decline in the cost of renewable energy technologies, offshore CCUS projects may find it more difficult to attract investment.

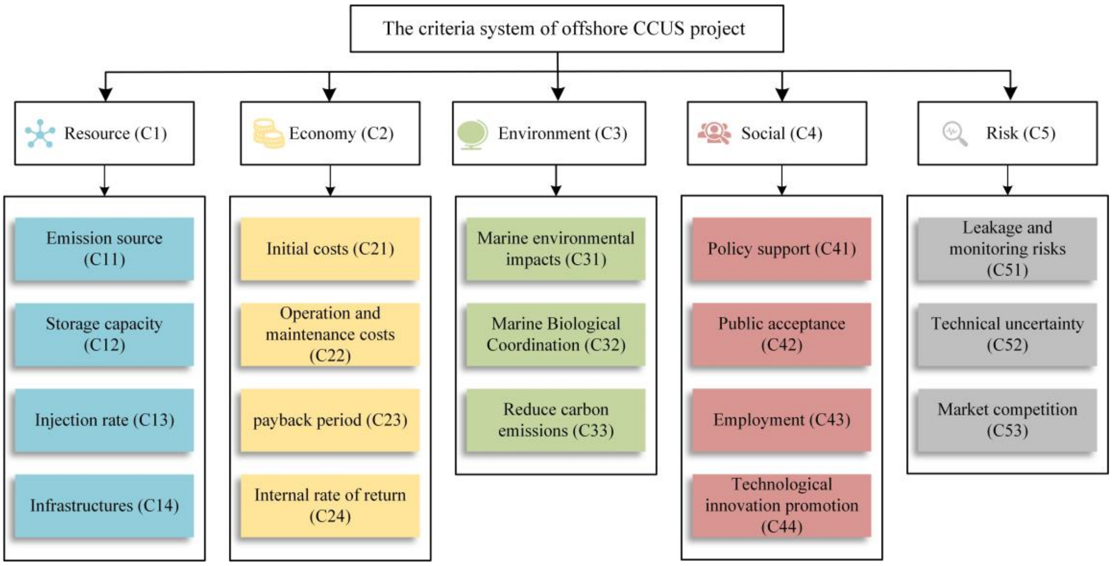

Fig. 1. The offshore CCUS project's investment decision criteria system.

4. The evaluation framework for investment decisions

4.1. Information gathering

Within this part, we perform information gathering. For a given investment decision problem for an offshore CCUS project, suppose there are m different alternatives $A_i\,(i=1,2,...,m)$, n criteria $C_j\,(j=1,2,...,n)$, and the weights of the criteria are ω_j, $\omega_j \in [0,1]$, $\sum_{j=1}^{n}\omega_j = 1$. Group of experts $E_k\,(k=1,2,...,s)$, and the weights of the experts are ϖ_k, $\varpi_k \in [0,1]$, $\sum_{k=1}^{s}\varpi_k = 1$. During the investment decision-making process for offshore CCUS projects, experts tend to use linguistic terms to express their judgments. In order to better deal with uncertainty in the assessment process, in this paper, IVFFS is used to convey the expert's opinion, and the following describes the concept of IVFFS and its basic properties, which serve as the study's foundation.

Definition 1[23, 93]**.** Let X be a finite universe of discourse, and $\tilde{F}$ is a set of IVFFS expressed in mathematical form as

$$\tilde{F} = \left\{ \left\langle x_i, \left[\mu_{\tilde{F}}^L(x_i), \mu_{\tilde{F}}^U(x_i)\right], \left[v_{\tilde{F}}^L(x_i), v_{\tilde{F}}^U(x_i)\right] \right\rangle : x_i \in X \right\} \tag{1}$$

where $0 \le \mu_{\tilde{F}}^L(x_i) \le \mu_{\tilde{F}}^U(x_i) \le 1,\ \ 0 \le v_{\tilde{F}}^L(x_i) \le v_{\tilde{F}}^U(x_i) \le 1$ and $\left(\mu_{\tilde{F}}^U(x_i)\right)^3 + \left(v_{\tilde{F}}^U(x_i)\right)^3 \le 1$ Here, $\mu_{\tilde{F}}(x_i) = \left[\mu_{\tilde{F}}^L(x_i), \mu_{\tilde{F}}^U(x_i)\right]$ and $v_{\tilde{F}}(x_i) = \left[v_{\tilde{F}}^L(x_i), v_{\tilde{F}}^U(x_i)\right]$ denote the interval MD and ND of $x_i \in X$, respectively. The hesitancy degree of $x_i \in X$ to $\tilde{F}$ is defined as $\pi_{\tilde{F}}(x_i) = \left[\pi_{\tilde{F}}^L(x_i), \pi_{\tilde{F}}^U(x_i)\right]$, where $\pi_{\tilde{F}}^L(x_i) = \sqrt[3]{1 - \left(\mu_{\tilde{F}}^U(x_i)\right)^3 - \left(v_{\tilde{F}}^U(x_i)\right)^3}$ and $\pi_{\tilde{F}}^U(x_i) = \sqrt[3]{1 - \left(\mu_{\tilde{F}}^L(x_i)\right)^3 - \left(v_{\tilde{F}}^L(x_i)\right)^3}$. For simplicity, Jeevaraj[23] defined the idea of interval-valued fermatean fuzzy number (IVFFN) , presented as $\alpha = \left(\left[\mu_\alpha^L, \mu_\alpha^U\right], \left[v_\alpha^L, v_\alpha^U\right]\right)$ and fulfill $\left(\mu_\alpha^U\right)^3 + \left(v_\alpha^U\right)^3 \le 1$.

Definition 2[93]. Let $\alpha_1 = \left(\left[\mu_{\alpha_1}^L, \mu_{\alpha_1}^U\right], \left[v_{\alpha_1}^L, v_{\alpha_1}^U\right]\right)$ and $\alpha_2 = \left(\left[\mu_{\alpha_2}^L, \mu_{\alpha_2}^U\right], \left[v_{\alpha_2}^L, v_{\alpha_2}^U\right]\right)$ be two IVFFNs. Then, the relations between α_1 and α_2 are presented as

(i) $\alpha_1 = \alpha_2$ iff $\mu_{\alpha_1}^L = \mu_{\alpha_2}^L, \mu_{\alpha_1}^U = \mu_{\alpha_2}^U, v_{\alpha_1}^L = v_{\alpha_2}^L$ and $v_{\alpha_1}^U = v_{\alpha_2}^U$,

(ii) $\alpha_1 \prec \alpha_2$ iff $\mu_{\alpha_1}^L \le \mu_{\alpha_2}^L, \mu_{\alpha_1}^U \le \mu_{\alpha_2}^U, v_{\alpha_1}^L \ge v_{\alpha_2}^L$ and $v_{\alpha_1}^U \ge v_{\alpha_2}^U$.

Definition 3[93]**.** For any IVFFN $\alpha = \left(\left[\mu_\alpha^L, \mu_\alpha^U\right], \left[v_\alpha^L, v_\alpha^U\right]\right)$, the score and accuracy functions are provided by

$$S(\alpha) = \frac{1}{2}\left(\left(\mu_\alpha^L\right)^3 + \left(\mu_\alpha^U\right)^3 - \left(v_\alpha^L\right)^3 - \left(v_\alpha^U\right)^3\right) \tag{2}$$

$$H(\alpha) = \frac{1}{2}\left(\left(\mu_\alpha^L\right)^3 + \left(\mu_\alpha^U\right)^3 + \left(v_\alpha^L\right)^3 + \left(v_\alpha^U\right)^3\right) \tag{3}$$

For any two IVFFNs α_1 and α_2, the following are the comparison rules:

(i) If $S(\alpha_1) > S(\alpha_2)$, then $\alpha_1 > \alpha_2$,

(ii) If $S(\alpha_1) < S(\alpha_2)$, then $\alpha_1 \prec \alpha_2$,

(iii) If $S(\alpha_1)=S(\alpha_2)$, then

(a) If $H(\alpha_1)>H(\alpha_2)$, then $\alpha_1>\alpha_2$,

(b) If $H(\alpha_1)<H(\alpha_2)$, then $\alpha_1\prec\alpha_2$,

(c) If $H(\alpha_1)=H(\alpha_2)$, then $\alpha_1=\alpha_2$.

Definition 4[93]**.** Let $\alpha=\left(\left[\mu_\alpha^L,\mu_\alpha^U\right],\left[v_\alpha^L,v_\alpha^U\right]\right)$, $\alpha_1=\left(\left[\mu_{\alpha_1}^L,\mu_{\alpha_1}^U\right],\left[v_{\alpha_1}^L,v_{\alpha_1}^U\right]\right)$ and $\alpha_2=\left(\left[\mu_{\alpha_2}^L,\mu_{\alpha_2}^U\right],\left[v_{\alpha_2}^L,v_{\alpha_2}^U\right]\right)$ be three IVFFNs and $\beta>0$. Then, the operations in IVFFNs are given as

(i) $\alpha_1\cup\alpha_2=\left(\left[\max\left\{\mu_{\alpha_1}^L,\mu_{\alpha_2}^L\right\},\max\left\{\mu_{\alpha_1}^U,\mu_{\alpha_2}^U\right\}\right],\left[\min\left\{v_{\alpha_1}^L,v_{\alpha_2}^L\right\},\min\left\{v_{\alpha_1}^U,v_{\alpha_2}^U\right\}\right]\right)$,

(ii) $\alpha_1\cap\alpha_2=\left(\left[\min\left\{\mu_{\alpha_1}^L,\mu_{\alpha_2}^L\right\},\min\left\{\mu_{\alpha_1}^U,\mu_{\alpha_2}^U\right\}\right],\left[\max\left\{v_{\alpha_1}^L,v_{\alpha_2}^L\right\},\max\left\{v_{\alpha_1}^U,v_{\alpha_2}^U\right\}\right]\right)$,

(iii) $\alpha_1\oplus\alpha_2=\left(\left[\sqrt[3]{\left(\mu_{\alpha_1}^L\right)^3+\left(\mu_{\alpha_2}^L\right)^3-\left(\mu_{\alpha_1}^L\right)^3\left(\mu_{\alpha_2}^L\right)^3},\sqrt[3]{\left(\mu_{\alpha_1}^U\right)^3+\left(\mu_{\alpha_2}^U\right)^3-\left(\mu_{\alpha_1}^U\right)^3\left(\mu_{\alpha_2}^U\right)^3}\right],\left[v_{\alpha_1}^L v_{\alpha_2}^L,v_{\alpha_1}^U v_{\alpha_2}^U\right]\right)$,

(iv) $\alpha_1\otimes\alpha_2=\left(\left[\mu_{\alpha_1}^L\mu_{\alpha_2}^L,\mu_{\alpha_1}^U\mu_{\alpha_2}^U\right],\left[\sqrt[3]{\left(v_{\alpha_1}^L\right)^3+\left(v_{\alpha_2}^L\right)^3-\left(v_{\alpha_1}^L\right)^3\left(v_{\alpha_2}^L\right)^3},\sqrt[3]{\left(v_{\alpha_1}^U\right)^3+\left(v_{\alpha_2}^U\right)^3-\left(v_{\alpha_1}^U\right)^3\left(v_{\alpha_2}^U\right)^3}\right]\right)$,

(v) $\beta\alpha=\left(\left[\sqrt[3]{1-\left(1-\left(\mu_\alpha^L\right)^3\right)^\beta},\sqrt[3]{1-\left(1-\left(\mu_\alpha^U\right)^3\right)^\beta}\right],\left[\left(v_\alpha^L\right)^\beta,\left(v_\alpha^U\right)^\beta\right]\right)$,

(vi) $\alpha^\beta=\left(\left[\left(\mu_\alpha^L\right)^\beta,\left(\mu_\alpha^U\right)^\beta\right],\left[\sqrt[3]{1-\left(1-\left(v_\alpha^L\right)^3\right)^\beta},\sqrt[3]{1-\left(1-\left(v_\alpha^U\right)^3\right)^\beta}\right]\right)$.

Definition 5[93]**.** Let $\alpha_1=\left(\left[\mu_{\alpha_1}^L,\mu_{\alpha_1}^U\right],\left[v_{\alpha_1}^L,v_{\alpha_1}^U\right]\right)$, $\alpha_2=\left(\left[\mu_{\alpha_2}^L,\mu_{\alpha_2}^U\right],\left[v_{\alpha_2}^L,v_{\alpha_2}^U\right]\right),\ldots,$ $\alpha_n=\left(\left[\mu_{\alpha_n}^L,\mu_{\alpha_n}^U\right],\left[v_{\alpha_n}^L,v_{\alpha_n}^U\right]\right)$ be any IVFFNs. The following equation displays the IVFFSs aggregation operator.

$$IVFFA\left(a_1,a_2,\ldots,a_n\right)=\left(\left[\sqrt[3]{1-\prod_{h=1}^{n}\left(1-(\mu_{ah}^L)^3\right)},\sqrt[3]{1-\prod_{h=1}^{n}\left(1-(\mu_{ah}^L)^3\right)}\right],\left[\prod_{h=1}^{n}v_{ah}^L,\prod_{h=1}^{n}v_{ah}^U\right]\right) \quad (4)$$

Definition 6[23]**.** Let $\alpha_1=\left(\left[\mu_{\alpha_1}^L,\mu_{\alpha_1}^U\right],\left[v_{\alpha_1}^L,v_{\alpha_1}^U\right]\right)$ and $\alpha_2=\left(\left[\mu_{\alpha_2}^L,\mu_{\alpha_2}^U\right],\left[v_{\alpha_2}^L,v_{\alpha_2}^U\right]\right)$ be any two IVFFNs. Then the generalized Euclidean distance between α_1 and α_2 as follows.

$$d(\alpha_1,\alpha_2)=\sqrt{\frac{\begin{array}{l}\left((\mu_{\alpha_1}^L)^3-(\mu_{\alpha_2}^L)^3\right)^2+\left((\mu_{\alpha_1}^U)^3-(\mu_{\alpha_2}^U)^3\right)^2+\left((v_{\alpha_1}^L)^3-(v_{\alpha_2}^L)^3\right)^2+\left((v_{\alpha_1}^U)^3-(v_{\alpha_2}^U)^3\right)^2+\\ \left(\left(1-(\mu_{\alpha_1}^U)^3-(v_{\alpha_1}^U)^3\right)-\left(1-(\mu_{\alpha_2}^U)^3-(v_{\alpha_2}^U)^3\right)\right)^2+\left(\left(1-(\mu_{\alpha_1}^L)^3-(v_{\alpha_1}^L)^3\right)-\left(1-(\mu_{\alpha_2}^L)^3-(v_{\alpha_2}^L)^3\right)\right)^2\end{array}}{6}} \quad (5)$$

4.2. Group aggregation

Given the intricacy of the structure involved in collective decision-making, subjectively giving various experts varying weights may result in information loss. Therefore, in this work, the extended variance method of IVFFNs is applied to systematically calculate the weights of decision-making experts. Then, in order to aggregate the opinions of different experts, a PWA operator based on IVFFNs distance similarity measure is established.

Step 1. Obtain an assessment matrix for each expert $P^k = (p_{ij}^k) = \left(\left[\mu_{ij}^{kL}, \mu_{ij}^{kU}\right], \left[\nu_{ij}^{kL}, \nu_{ij}^{kU}\right]\right)_{m\times n}$

Step 2. Translating expert assessments into crisp values ε_{ij}^k using Eq. (3).

Step 3. Calculate the variance associated with the above conversion values as follows.

$$\varepsilon_k^2 = \sum_{i=1}^{m}\sum_{j=1}^{n}\frac{\left(\varepsilon_{ij}^k - \overline{\varepsilon_i^k}\right)^2}{n-1} \tag{6}$$

where $\overline{\varepsilon_i^k}$ and ε_k^2 represent the mean and variance of the kth expert, respectively.

Step 4. The confidence factor for each expert is calculated by taking the complement of the normalized variance value. In fact, the expert's hesitation is inversely proportional to the confidence level. Here, the experts' weights are determined using this concept. The formula is calculated as follows.

$$(C.F)_k = 1 - \tilde{\varepsilon}_k \tag{7}$$

$$\varpi_k = \frac{(C.F)_k}{\sum_{k=1}^{s}(C.F)_k} \tag{8}$$

where $\tilde{\varepsilon}_k$ represents normalized variance for E_k and $\tilde{\varepsilon}_k = \varepsilon_k \Big/ \sum_{k=1}^{l}\varepsilon_k$, $(C.F)_k$ represents confidence factor for E_k.

Step 5. Summarize the evaluation data provided by experts.

Considering the individual importance of the experts, an overall evaluation matrix $P=\left(p_{ij}\right)_{m\times n}$ is created by combining the assessments provided by DMs. using the PWA operator based on the similarity measure, where p_{ij} is described in terms of IVFFNs.

Assume that $p_{ij}^{k}=\left(\left[\mu_{ij}^{kL},\mu_{ij}^{kU}\right],\left[v_{ij}^{kL},v_{ij}^{kU}\right]\right)$ and $p_{ij}^{g}=\left(\left[\mu_{ij}^{gL},\mu_{ij}^{gU}\right],\left[v_{ij}^{gL},v_{ij}^{gU}\right]\right)$ are the corresponding IVFFNs from Alternative A_i under Criterion C_j of Experts E_k and E_g. Next, the PWA operator of IVFFN is described in this way.

$$p_{ij}=PWA\left(p_{ij}^{1},p_{ij}^{2},\cdots,p_{ij}^{s}\right)=\sum_{k=1}^{s}\frac{\varpi_k\left(1+T\left(p_{ij}^{k}\right)\right)}{\sum_{k=1}^{s}\varpi_k\left(1+T\left(p_{ij}^{k}\right)\right)}\cdot p_{ij}^{k} \tag{9}$$

where ϖ_k is the weight of expert E_k, derived from Eq. (6). The support function $T\left(p_{ij}^{k}\right)$ is calculated in the manner described below.

$$T\left(p_{ij}^{k}\right)=\sum_{g=1,k\neq g}^{s}S\left(p_{ij}^{k},p_{ij}^{g}\right) \tag{10}$$

where $S\left(p_{ij}^{k},p_{ij}^{g}\right)$ is the support function for p_{ij}^{k} from $p_{ij}^{g}\left(p_{ij}^{k},p_{ij}^{g}\right)\in[0,1]$. The similarity measure of IVFFNs determines the support function and is defined as:

$$S\left(p_{ij}^{k},p_{ij}^{g}\right)=1-d\left(p_{ij}^{k},p_{ij}^{g}\right) \tag{11}$$

where $d\left(p_{ij}^{k},p_{ij}^{g}\right)$ is the Euclidean distance between the two IVFFNs.

4.3. Determination of the criteria weights

A new comprehensive weighting technique is proposed, MEREC is an objective weighing approach [46]whereas FWZIC is a subjective one [40]. Both the opinion of experts and objective information are taken into account.

Step 1. Determine the subjective weight using the FWZIC.

In the IVFF environment, to determine the criteria's subjective weights, FWZIC is extended in the following steps:

(1) Determine and categorize the evaluation criteria for the project, as shown in Section 3.

(2) Structured Expert Judgment (SEJ): Data collection forms are developed by a committee of experts and approved for assessment by designated experts. The experts expressed their views on each criterion using the linguistic terms in Table A1 (Appendix A).

(3) Expert Decision Matrix (EDM): The assessment criteria and the experts collide to produce the EDM. Next, a numerical scale is created using the language terms that are gathered from the assessment form in the prior step.

(4) Utilizing the membership function of IVFFS. This step involves the application of IVFFSs-based affiliation function and the associated fuzzification process to the EDM data. The conversion of EDM data to IVFFS-EDM using IVFFSs affiliation function and fuzzification process increases precision and ease of use of the data for subsequent analysis. The relevant definitions are given in Definition 1. According to Table A1, for each criterion that each expert evaluates, all language variables and numerical scores must be transformed to IVFFNs as variables.

(5) To ascertain the evaluation criteria's weights, there are three sub-steps in this step.

(5.1) Use Eq. (12) to calculate the ratio of the data.

$$\tilde{E}:\tilde{C} = \frac{\widetilde{\text{Imp}(E_k / C_j)}}{\sum_{j=1}^{n} \widetilde{\text{Imp}(E_k / C_j)}} \tag{12}$$

where $\widetilde{\text{Imp}(E_k / C_j)}$ is the degree of importance given by the kth expert to the jth criterion represented by an IVFFN. and $\sum_{j=1}^{n} \widetilde{\text{Imp}(E_k / C_j)}$ is obtained by Eq. (4).

(5.2) Calculate the mean value to obtain the fuzzy value weights of the evaluation criteria.

$$\tilde{w}_j^s = \left(\sum_{k=1}^{l} \frac{\text{Imp}\left(E_{kj} / C_{kj}\right)}{\sum_{j=1}^{n} \text{Imp}\left(E_{kj} / C_{kj}\right)} / m \right), \text{ for } k = 1,2,3,\ldots,l \text{ and } j = 1,2,3,\ldots,n. \tag{13}$$

(5.3) Using the score value provided by [93], The standard weights are defuzzified using Eq. (14). The weights are then rescaled using Eq. (15) to find the final weights.

$$S'(\alpha) = \frac{1}{2}\left(\frac{1}{2}\left(\left(\mu_\alpha^L\right)^3 + \left(\mu_\alpha^U\right)^3 - \left(v_\alpha^L\right)^3 - \left(v_\alpha^U\right)^3 \right) + 1 \right) \tag{14}$$

$$w_j^s = \frac{\tilde{w}_j^s}{\sum_{j=1}^{n} \tilde{w}_j^s} \tag{15}$$

Step 2. Determine the objective's weight using MEREC.

(1) Normalization of the evaluation matrix $\tilde{P} = \left(\tilde{p}_{ij}\right)_{m \times n}$.

$$\tilde{p}_{ij} = \left(\left[\tilde{\mu}_{ij}^L, \tilde{\mu}_{ij}^U\right], \left[\tilde{v}_{ij}^L, \tilde{v}_{ij}^U\right]\right) = \begin{cases} v_{ij} = \left(\left[\mu_{ij}^L, \mu_{ij}^U\right], \left[v_{ij}^L, v_{ij}^U\right]\right), & \text{j} \in \text{B} \\ \left(v_{ij}\right)^c = \left(\left[v_{ij}^L, v_{ij}^U\right], \left[\mu_{ij}^L, \mu_{ij}^U\right]\right), & \text{j} \in C \end{cases} \tag{16}$$

where $\tilde{p}_{ij}$ denotes the normalized IVFFN, B stands for benefit criteria, and C for cost criteria.

(2) Computation of the score matrix $\Omega = \left(\eta_{ij}\right)_{m \times n}$ of each IVFFN $\tilde{I}_{ij}$ by Eq. (14).

(3) Calculate overall performance Q_i.

$$Q_i = \ln\left(1 + \left(\frac{1}{n}\sum_j \left|\ln\left(\eta_{ij}\right)\right|\right)\right) \tag{17}$$

(4) Calculate performance by excluding each criterion.

$$Q'_{ij} = \ln\left(1 + \left(\frac{1}{n}\sum_{b,b\neq j}\left|\ln\left(\eta_{ib}\right)\right|\right)\right) \tag{18}$$

where Q'_{ij} indicates how well the ith alternative performed once the jth criterion is dropped.

(5) Sum the absolute deviations.

$$M_j = \sum_i \left|Q'_{ij} - Q_i\right| \tag{19}$$

(6) Calculation of the weights of the criteria.

$$\omega_j^o = \frac{M_j}{\sum_{j=1}^{n} M_j} \tag{20}$$

Step 3. Combined weights for determining criteria.

$$\omega_j = \phi\omega_j^s + (1-\phi)\omega_j^o \tag{21}$$

where $\phi \in [0,1]$ is a combined weighting factor. In this paper, $\phi = 0.5$.

4.4. Expanded MARCOS to determine the optimal investment alternative.

The MARCOS method has several advantages over other MCDM techniques, including increased efficiency, simpler decision-making process construction and optimization, more precise reference point desirability determination, increased stability and robustness of the results, and the absence of ranking reversals [94]. The IVFF Hamacher weighted average (IVFFHWA) operator is introduced in the MARCOS method to define the weighting sequence in the normalized weighting matrix. The IVFFHWA operator is introduced because of its ability to perceive the interrelationships between the assessment criteria.

Step 1. Determine the ideal and anti-ideal solutions to obtain the extended decision matrix $\bar{P}$.

$$A^- = \begin{cases} \left(\left[\min_i \mu_{ij}^L, \min_i \mu_{ij}^U\right], \left[\max_i \nu_{ij}^L, \max_i \nu_{ij}^U\right]\right) & if\ j \in \mathrm{B} \\ \left(\left[\max_i \mu_{ij}^L, \max_i \mu_{ij}^U\right], \left[\min_i \nu_{ij}^L, \min_i \nu_{ij}^U\right]\right) & if\ j \in C \end{cases}$$

$$A^+ = \begin{cases} \left(\left[\max_i \mu_{ij}^L, \max_i \mu_{ij}^U\right], \left[\min_i \nu_{ij}^L, \min_i \nu_{ij}^U\right]\right) & if\ j \in \mathrm{B} \\ \left(\left[\min_i \mu_{ij}^L, \min_i \mu_{ij}^U\right], \left[\max_i \nu_{ij}^L, \max_i \nu_{ij}^U\right]\right) & if\ j \in C \end{cases} \quad (22)$$

Therefore, the extended decision matrix $\bar{P}$ is:

$$\bar{P} = \begin{matrix} \\ A^- \\ A_1 \\ A_2 \\ \vdots \\ A_m \\ A^+ \end{matrix} \begin{matrix} \begin{matrix} C_1 & C_2 & \cdots & C_n \end{matrix} \\ \begin{pmatrix} p_1^- & p_2^- & \cdots & p_n^- \\ p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mn} \\ p_1^+ & p_2^+ & \cdots & p_n^+ \end{pmatrix}_{(m+2)\times n} \end{matrix}$$

Step 2. Normalized decision matrix construction. The same normalization process as in the MEREC method (Eq. (16)) yields the normalized matrix $\tilde{P} = \left(\tilde{p}_{ij}\right)_{(m+2)\times n}$.

Step 3. Determine the degree of utility of the alternative.

$$K_i^- = \frac{S_i}{S^-} \quad (23)$$

$$K_i^+ = \frac{S_i}{S^+} \quad (24)$$

where S^-, S^+, and $S_i\,(i = 1,2,...,m)$ represent the weighted sequence obtained by using the IVFFHWA operator (Eq (25)).

Definition 7[51]**.** Suppose $I_j = \left(\left[\mu_{I_j}^L, \mu_{I_j}^U\right], \left[v_{I_j}^L, v_{I_j}^U\right]\right), (j = 1,2,\ldots,n)$ be the collection of IVFFNs, Then, the aggregated result utilizing the IVFFHWA is an IVFFN, and

$$\text{IVFFHWA}_{w}\left(I_1, I_2, \ldots, I_n\right) = \bigoplus_{j=1}^{n}\left(\omega_j I_j\right)$$

$$= \left(\left[\sqrt[3]{\frac{\prod_{j=1}^{n}\left(1+(\varsigma-1)\left(\mu_{I_j}^{L}\right)^3\right)^{\omega_j} - \prod_{j=1}^{n}\left(1-\left(\mu_{I_j}^{L}\right)^3\right)^{\omega_j}}{\prod_{j=1}^{n}\left(1+(\varsigma-1)\left(\mu_{I_j}^{L}\right)^3\right)^{\omega_j} + (\varsigma-1)\prod_{j=1}^{n}\left(1-\left(\mu_{I_j}^{L}\right)^3\right)^{\omega_j}}}, \sqrt[3]{\frac{\prod_{j=1}^{n}\left(1+(\varsigma-1)\left(\mu_{I_j}^{U}\right)^3\right)^{\omega_j} - \prod_{j=1}^{n}\left(1-\left(\mu_{I_j}^{U}\right)^3\right)^{\omega_j}}{\prod_{j=1}^{n}\left(1+(\varsigma-1)\left(\mu_{I_j}^{U}\right)^3\right)^{\omega_j} + (\varsigma-1)\prod_{j=1}^{n}\left(1-\left(\mu_{I_j}^{U}\right)^3\right)^{\omega_j}}} \right], \left[\frac{\sqrt[3]{\varsigma}\prod_{j=1}^{n}\left(\nu_{I_j}^{L}\right)^{\omega_j}}{\sqrt[3]{\prod_{j=1}^{n}\left(1+(\varsigma-1)\left(1-\left(\nu_{I_j}^{L}\right)^3\right)\right)^{\omega_j} + (\varsigma-1)\prod_{j=1}^{n}\left(\nu_{I_j}^{L}\right)^{3\omega_j}}}, \frac{\sqrt[3]{\varsigma}\prod_{j=1}^{n}\left(\nu_{I_j}^{U}\right)^{\omega_j}}{\sqrt[3]{\prod_{j=1}^{n}\left(1+(\varsigma-1)\left(1-\left(\nu_{I_j}^{U}\right)^3\right)\right)^{\omega_j} + (\varsigma-1)\prod_{j=1}^{n}\left(\nu_{I_j}^{U}\right)^{3\omega_j}}} \right] \right) \tag{25}$$

Step 4. Determine the utility function and ranking of each alternative.

$$f\left(K_i\right) = \frac{K_i^{+} + K_i^{-}}{1 + \frac{1-f\left(K_i^{+}\right)}{f\left(K_i^{+}\right)} + \frac{1-f\left(K_i^{-}\right)}{f\left(K_i^{-}\right)}} \tag{26}$$

$$f\left(K_i^{-}\right) = \frac{K_i^{+}}{\left(K_i^{+} + K_i^{-}\right)} \tag{27}$$

$$f\left(K_i^{+}\right) = \frac{K_i^{-}}{\left(K_i^{+} + K_i^{-}\right)} \tag{28}$$

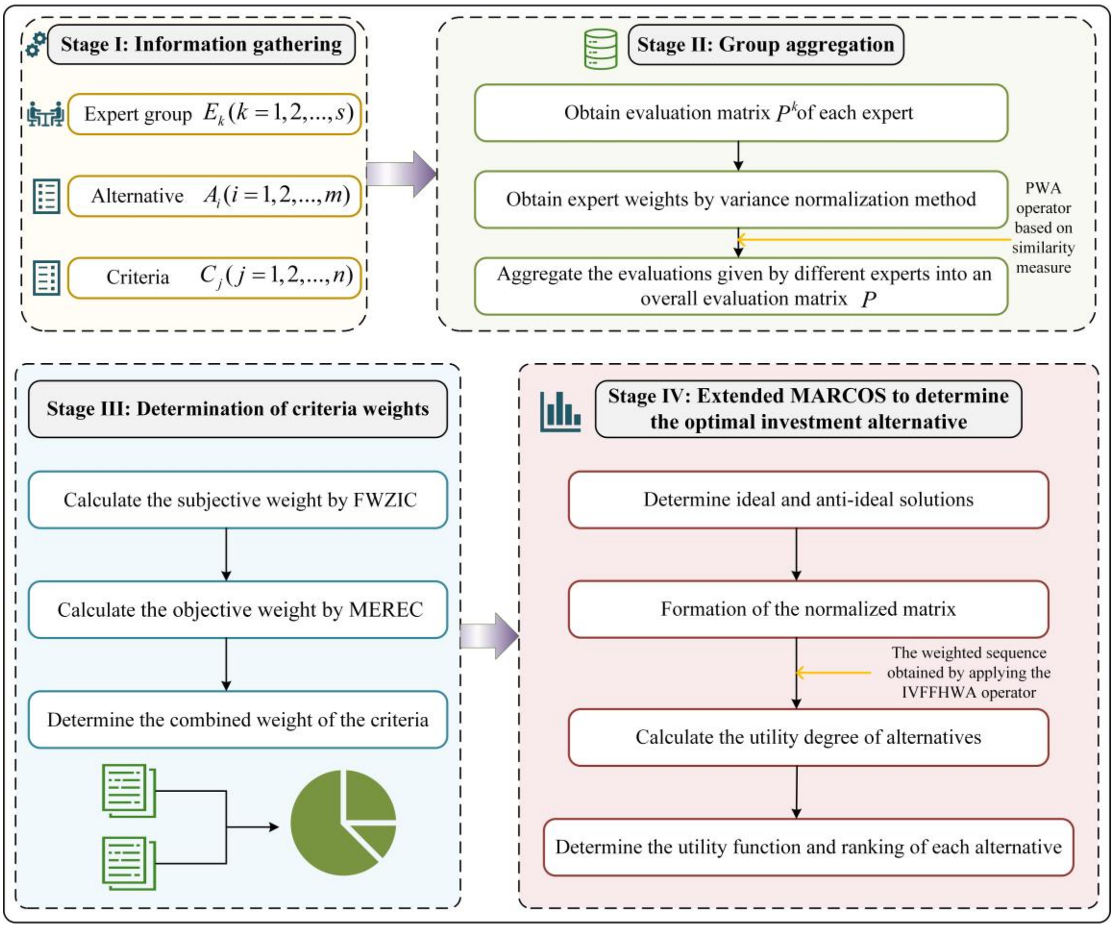

Fig. 2. The proposed investment framework of the offshore CCUS project.

5. Case study

In the paper, a case study is explored to better demonstrate the logic and usefulness of the investment assessment framework for offshore CCUS projects.

5.1. Information gathering

In recent years, many countries have started to pay increasing attention to the problem of CO_2 emissions. Developing and fully utilizing CCUS technology is the future trend of industry. Therefore, a business in Guangdong Province intends to invest in an offshore CCUS project. The board of directors examined four options while assessing the project investment decision. The alternative set is $A=(A1,A2,A3,A4)$. Section 3 identifies 18 criteria, with the set of criteria being $C = (C_1, C_2,\cdots, C_n)$, and the criteria weights are denoted as $\omega = (\omega_1, \omega_2,\cdots, \omega_n)$, where $\omega_i \in [0,1], (i = 1,2,\cdots, n), \sum_{i=1}^{n} \omega_i = 1$. To serve as decision managers, three specialists with in-depth understanding of offshore CCUS projects are invited. They need to have worked in engineering design and CCUS project operations for at least five years. They also need to be authorities in management, environmental sustainability, and market analysis. The accuracy, dependability, and professionalism of the evaluation data can only be ensured by experts who fulfill the above indicated conditions. First, they need to assess the relative importance of the criteria and determine the weights of the criteria using the FWZIC-MEREC methodology. Second, they will use IVFFS to evaluate each alternative associated with each criterion and then use the MARCOS method to choose the best possible option. The group of experts was assembled as $E = (E1, E2, E3)$, and the expert weights are expressed as $\varpi = (\varpi_1, \varpi_2, \varpi_3)$, where $\varpi_k \in [0,1], (k = 1,2,3), \sum_{k=1}^{3} \varpi_k = 1$.

5.2. Group aggregation

Using the seven scaled linguistic variables shown in Table A2, the experts in the expert group evaluate the alternatives according to criteria $C = (C_1, C_2,\cdots, C_n)$. The weights of the experts are calculated according to the variance method, and then their distinct viewpoints are combined in accordance with the PWA operator based on the similarity measure. The corresponding steps are as follows.

Step 1. Each expert constructed a linguistic decision matrix of criteria-related alternatives according to their expertise and experience as shown in Table A3. Then, the linguistic evaluation is transformed into the IVFFS evaluation matrix P^k . In the case of expert, matrix P^1 is shown in Table A4.

Step 2. Translating expert assessments into crisp values ε_{ij}^k using Eq. (3). For example, Expert 1's evaluation of Alternative A1 under Criterion C11 can be calculated as follows: $\varepsilon_{11}^1 = \frac{1}{2}\left((0.90)^3 + (0.95)^3 + (0.10)^3 + (0.15)^3\right) = 0.80$.

Step 3. The variance associated with each expert is calculated using Eq. (6), $\varepsilon_1^2 = 0.0701,\ \varepsilon_2^2 = 0.0640,\ \varepsilon_3^2 = 0.0686$.

Step 4. The weights of the experts are computed using Eqs. (7)-(8), Among them $(C.F)_1 = 0.6544,\ (C.F)_2 = 0.6842,\ (C.F)_3 = 6614.$ The final weights of the experts are $\varpi_1 = 0.3272,$ $\varpi_2 = 0.3421,\ \varpi_3 = 0.3307$.

Step 5. The evaluation of the experts is aggregated using the PWA operator based on the similarity measure. The group evaluation matrix $P = \left(p_{ij}\right)_{m\times n}$ is derived by Eqs. (9)-(11), as shown in Table A5. Taking the evaluation of A1 under criterion C11 as an example, the distance between the evaluations of each expert is first calculated using Eq. (5): $d\left(p_{11}^1, p_{11}^2\right) = 0.48$, $d\left(p_{11}^1, p_{11}^3\right) = 0.37$, $d\left(p_{11}^2, p_{11}^3\right) = 0.47$ .Then, $S\left(p_{11}^1, p_{11}^2\right) = 1 - d\left(p_{11}^1, p_{11}^2\right) = 1 - 0.48 = 0.52$, similarly, $S\left(p_{11}^1, p_{11}^3\right) = 0.63$, $S\left(p_{11}^2, p_{11}^3\right) = 0.53$. Next, support function $T\left(p_{11}^1\right) = 0.52 + 0.63 = 1.15$, $T\left(p_{11}^2\right) = 0.52 + 0.53 = 1.05$, $T\left(p_{11}^3\right) = 0.63 + 0.53 = 1.16$. Finally, According to Eq. (9) the result after aggregation can be obtained as ([0.823,0.881], [0.182,0.236]).

5.3. Determination of the criteria weights

In this part, the FWZIC-MEREC method is used to determine the weights of the criteria. The steps of the proposed comprehensive weighting method are as follows.

Step 1. Calculate the subjective weight by FWZIC.

Using the language variables in Table A1, the expert group evaluated the criteria and established an EDM based on the IVFF-FWZIC concept (Table A6). After then, the EDM is converted from a language term into a numerical scale for use in additional research. Next, the EDM numerical scale is converted to IVFFS-EDM using the IVFFS membership function (Table A7). Finally, Eqs. (12)-(15) are used to calculate data ratio, average value and defuzzification criterion weight, and the calculation results are shown in Table A8.

As an example, Expert 1's assessment of Criterion C11 is given as VI, it can be converted to ([0.80,0.90], [0.10,0.20]) according to the conversion rules provided by Table A1. In the same steps, we can get IVFFS-EDM. Then, based on Eq. (12),

$$\begin{aligned}\tilde{E}:\tilde{C} &= \frac{\text{Imp}(E_k / C_j\tilde{)}}{\sum_{j=1}^{n}\text{Imp}(E_k / C_j\tilde{)}} = \frac{\text{Imp}(E_1 / C_{11}\tilde{)}}{IVFFA\left(\text{Imp}(E1/C_{11}),\ldots,\text{Imp}(E1/C_{53})\right)} = \frac{\left[(0.80,0.90),(0.10,0.20)\right]}{\left[(0.9997,0.9999),(0.0001,0.00001)\right]} \\ &= \left[(0.80003,0.90),(0.10,0.20)\right]\end{aligned}.$$

Next, $\begin{aligned}\tilde{w}_{11}^{s} &= \left(\left[(0.80003,0.90),(0.10,0.20)\right]\oplus\left[(0.80003,0.90),(0.10,0.20)\right]\oplus\left[(0.80003,0.90),(0.10,0.20)\right]\right)/3 \\ &= \left([0.7728,0.8752],\ [0.1260,0.2714]\right)\end{aligned}$.

Finally, defuzzification is performed to obtain the final subjective weights of the criteria, $w_{11}^{s} = 0.0649$. The subjective weights of the other criteria are obtained in the same way (Table A8).

Step 2. Determine the objective weight using MEREC.

According to the constructed group evaluation matrix $P = \left(p_{ij}\right)_{m\times n}$, Eqs. (16)-(20) is used to calculate the objective weights of each criterion. The calculation outcomes are displayed in Table A9.

Firstly, normalize the original evaluation matrix is normalized according to Eq. (16) and then use Eq. (14) to obtain the score matrix. The overall performance is then calculated according to Eq. (17). Here is an example of A1: $Q_1 = \ln\left(1+\left(\frac{1}{n}\sum_j \left|\ln(\eta_{ij})\right|\right)\right) = \ln\left(1+\left(\frac{\left|\ln(\eta_{11})\right| + \left|\ln(\eta_{12})\right| + ... + \left|\ln(\eta_{53})\right|}{18}\right)\right) = \ln\left(1+\left(\frac{0.22+0.29+...+0.38}{18}\right)\right) = 0.38$. Similarly, $Q_2 = 0.59$, $Q_3 = 0.45$, $Q_4 = 0.59$. Next, the performance after excluding each criterion is calculated according to Eq. (18). For example, the performance of A1 after the exclusion of criterion C11 is $Q'_{11} = \ln\left(1+\left(\frac{1}{n}\sum_{b,b\neq j}\left|\ln(\eta_{ib})\right|\right)\right) = \ln\left(1+\left(\frac{\left|\ln(\eta_{12})\right| + ... + \left|\ln(\eta_{53})\right|}{18}\right)\right) = 0.37$.After, according to Eq. (19), $M_{11} = \sum_i \left|Q'_{ij} - Q_i\right| = \left|0.37-0.38\right| + ... + \left|0.56-0.58\right| = 0.07$. Finally, objective weights are calculated for each criterion according to Eq. (20), $\omega_{11}^o = \frac{M_{11}}{M_{11}+M_{12}+...+M_{53}} = \frac{0.07}{1.59} = 0.04$. Other criteria are calculated in the same way.

Step 3. Determine the overall weight of the criteria.

Finally, the combined weights ω_j are calculated according to Eq. (21), as displayed in Table A10. In addition, Fig. 3 shows the criteria visual scales.

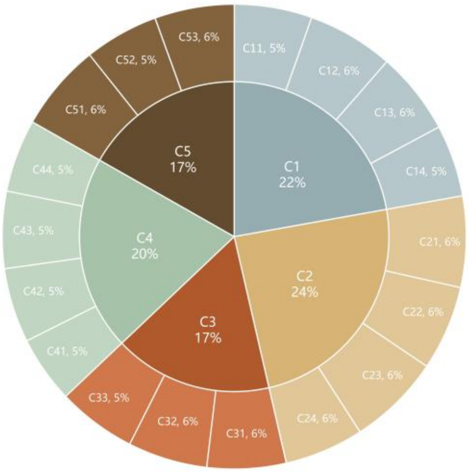

Fig. 3. Visual proportions of criteria.

5.4. Expanded MARCOS to determine the optimal investment alternative.

The alternatives are ranked based on the Hamacher-MARCOS method and the best alternative is selected.

Step 1. Firstly, based on the group evaluation matrix $P=\left(p_{ij}\right)_{m\times n}$, the ideal solution ($A^{+}$) and anti-ideal solution (A^{-}) are determined for each criterion by Eq. (22), as shown in Table A11.

Step 2. Eq. (16) is used to form a normalized decision matrix $\tilde{P}=\left(\tilde{p}_{ij}\right)_{(m+2)\times n}$, as shown in Table A12.

Step 3. The degree of utility of alternatives related to A^{+} and A^{-} is defined by Eqs. (23)-(25). First, Eq. (25) is applied to get the total of the normalized matrix's weighted entries ($\varsigma=1$), i.e.,

$S^{-}=([0.394,0.442],[0.588,0.640])$, $S_1=([0.675,0.732],[0.322,0.374])$, $S_2=([0.448,0.497],[0.530,0.581])$,

$S_3=([0.577,0.629],[0.396,0.446])$, $S_4=([0.459,0.508],[0.529,0.581])$, $S^{+}=([0.686,0.743],[0.313,0.365])$.

Then, through Eq. (14), the obtained weighted sequence is transformed into crisp value. Then, through Eqs. (23)-(24), the utility degree of alternatives is obtained (Table A13).

Step 4. The utility functions $f(K_i)$ of the alternatives are obtained according to Eqs. (26)-(28). The alternatives are then ranked in descending order according to the obtained $f(K_i)$. The final result is A1>A3>A4>A2, as shown in Table A13.

6. Sensitivity and comparative analyses

This section will be carried out from two aspects: sensitivity analysis and comparative analysis.

6.1. Sensitivity analysis

Since there are subjectively defined parameters in the IVFFHWA operator, analyzing how the parameters affect the final result is essential. Furthermore, we will examine how the alteration of the criteria weights affects the ultimate ranking outcomes.

6.1.1. Effect of the parameter ς on the outcomes of the model

In the initial results, the value of parameter $\varsigma = 1$ is used. Since parameter affects the transformation of the IVFFHWA operator, in this subsection, the effect of the change of parameter ς $(1 \le \varsigma \le 200)$ on the initial results will be analyzed, where 1 is the incremental step value. Figure 4 displays the outcomes of the experiment. In 200 scenarios, the change of ς has a small impact on the utility value of the alternatives, but in general, the utility value and the ranking of the alternatives are relatively stable, and A1 maintains its dominant position over the rest of the alternatives. According to the outcomes of the experiment, we can conclude that A1 is the best option and that the initial solution is tenable. Keep in mind that this only pertains to the case that this study examines. In the case of inputting other evaluation data, the change of parameter ς may have a substantial effect on the final result. Thus, this analysis is a necessary stage prior to reaching a decision.

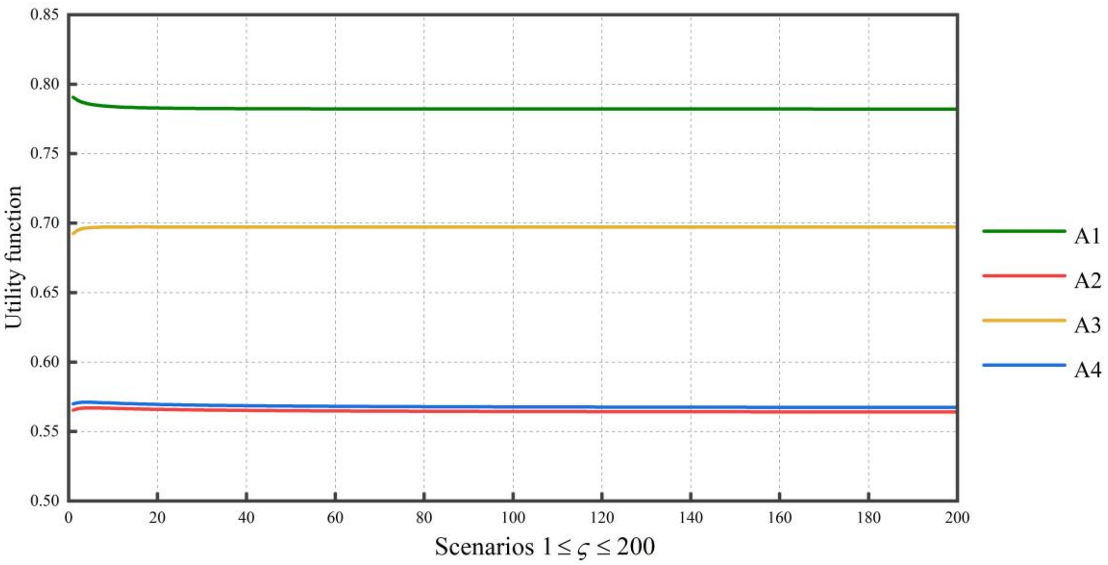

Fig. 4. Influence of parameters $1 \le \varsigma \le 200$ on change of value $f(K_i)$

6.1.2. Influence of the criteria weights on the model results

The weights of all the criteria are assumed to vary by 10%, 20%, and 30% from their initial weights in this paper. The sensitivity of each option under the criteria and the volatility of the results are both readily apparent with this study. The results are shown in Figure 5 (initial ranking is A1>A3>A4>A2).

As can be shown, option A1 is consistently the best option to take for investments, A3 is always the second-best investment solution, and the alternative ranking results are basically stable with respect to the shifts in the criteria's weights. However, when the weights of criteria C1 and C2 fluctuate up and down, the rankings of alternative programs A2 and A4 change slightly (change to A1>A3>A2>A4). When the weight of C1 gradually increases, the score of A1 increases, the score of other alternatives gradually decreases, and the ranking of A2 finally exceeds that of A4. when the weight of C2 goes from small to large, A1 and A3 are basically stable, and the score of alternative A4 increases with the increase of the weight of C2, and the final ranking exceeds that of A2. when the weight of C3 fluctuates, the scores of A2, A3, and A4 increase with the increase of the weight, and the A1 decreases. When C4 weights gradually increase, the scores of A1, A3 and A4 gradually decrease, and the score of A2 gradually increases and tends to exceed A4. When C5 weights fluctuate, A1 and A2 scores decrease with the increase of C5 weights, A3 and A4 increase with the increase of C5 weights, and with the decrease of C5 weights, it is possible for A2 to be ranked more than A4. In addition, according to the relative fluctuation amplitude, the sensitive criterion of scheme A1 and A3 can be recognized as C1. With the decrease of C1, scheme A3 may exceed A1 to be the optimal scheme. The sensitive criterion for scheme A2 is C3. The sensitive criteria for scheme A4 are C1 and C2.

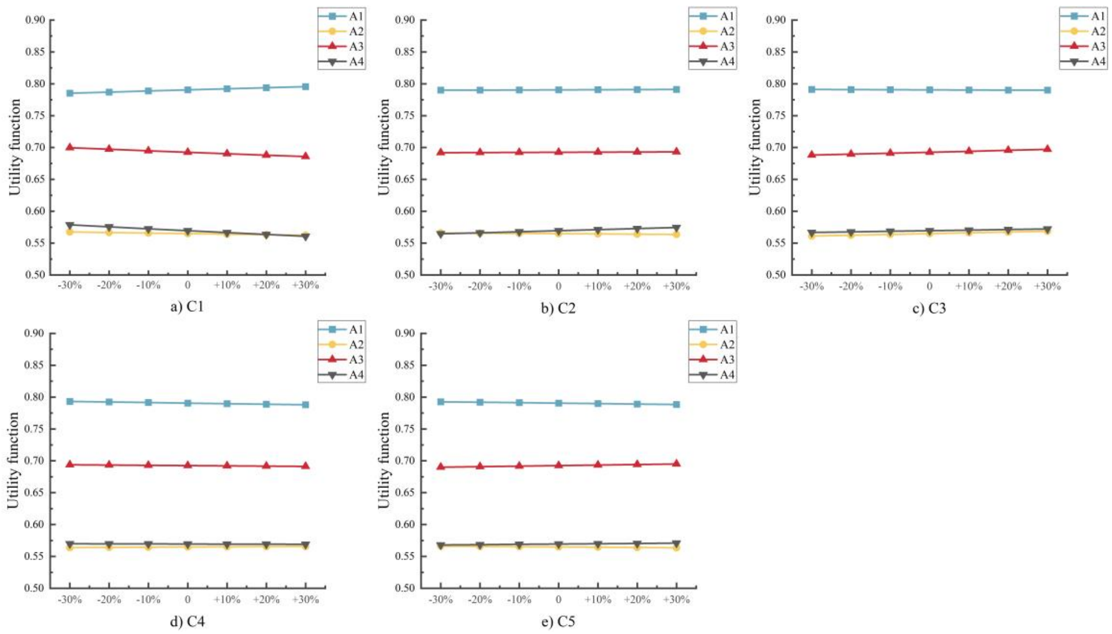

Fig. 5. The sensitivity analysis results of criteria weights.

6.2. Comparative analysis

The purpose of this subsection is to demonstrate the viability and suitability of the investment decision framework for offshore CCUS projects. A comparative analysis will be conducted.. Therefore, IVFF-TOPSIS method [51]、IVFF-WASPAS method [95]、IVFF-COPRAS (Complex Proportional Assessment) method [96]、IVFF-TODIM method [97] and IVFF-MABAC method [98] will be applied to the comparative study. The relevant input data are displayed in Tables A5 and A10, and the analysis results are shown in Table A14 and Fig. 5.

As can be shown, the model's output in this work is consistent with TOPSIS, COPRAS, and TODIM results. In WASPAS and MABAC, there are minor changes in the rankings, but A1 is always the best solution. Further, we verify the consistency of the rankings with the Spearman coefficient (SRCC) [99] and the WS coefficient (WSC)

[100]. SRCC are (1, 0.2, 1, 1, 0.8). All of them are greater than or equal to 0.8 except for the IVFF-WASPAS model. The WSC is (1, 0.7083, 1, 1, 0.9167), respectively, and all of them are greater than 0.7. It is evident that the rankings produced by the various techniques do not have much difference and have a high degree of consistency. Thus, it can be said that the ranking results are legitimate and the suggested model makes sense. Although the results are similar, the extended MARCOS proposed in this paper introduces the Hamacher operator, which can better assemble information and deal with the interconnection and influence of criteria. And the parameters can be flexibly adjusted according to the decision maker's preference to obtain more stable results. It increases the scientificity of the decision outcomes.

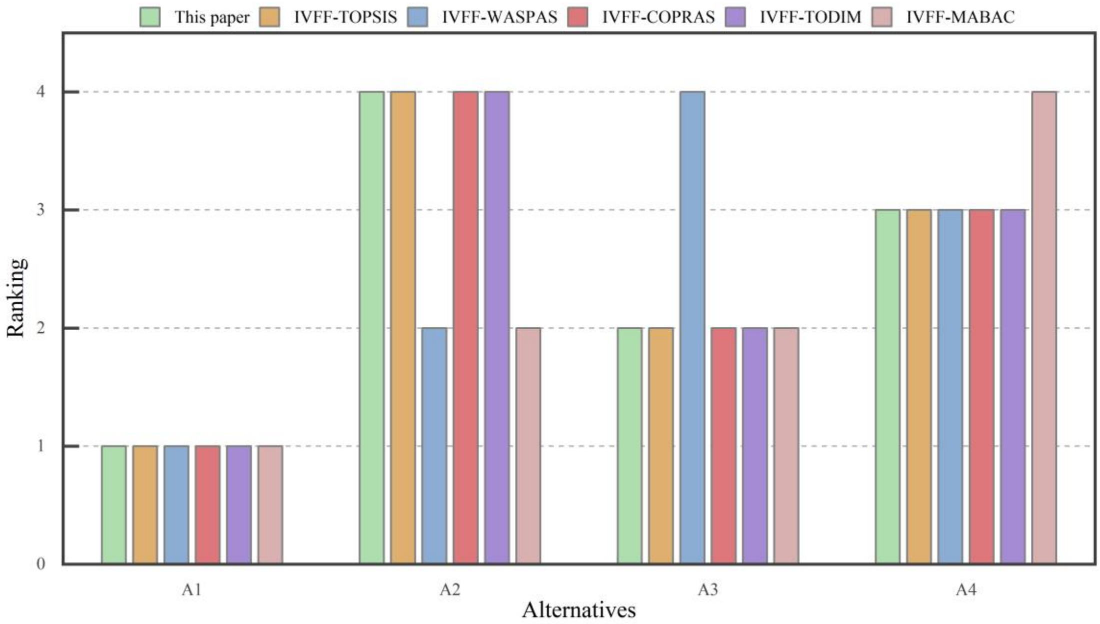

Fig. 5. Ranking results of different MCDM methods.

7. Discussion and managerial insights

As can be seen from Table A10 and Figure 3, economy (C2) is important for investment in offshore CCUS projects. In addition to the economic criteria, storage capacity (C12), and leakage and monitoring risks (C51) are also given greater weight. In order to prevent the serious consequences of CO_2 leakage, it is necessary to find a suitable storage site, and to evaluate and monitor its storage stability and capacity during the storage process, so these two factors are important factors to be considered in the investment process [101]. In addition, the social (C4) is also given a high weight. This result accurately reflects the current status of offshore projects. The deployment of CCUS projects is influenced by different social dimensions. Policy support, acceptance by the surrounding population, and the opportunities presented by the program are all factors that influence the development of CCUS projects [102-103]. On the other hand, based on the framework proposed in this paper, the alternatives were evaluated and ranked, and the final ranking was A1>A3>A4>A2. In addition, we can see from Table A5 that A1 outperforms the other alternatives in terms of resources, economy, and social. Since the weights of these criteria account for most of the total weights, A1 achieves the most favorable results. The other alternatives have their own shortcomings in different aspects of performance. After sensitivity analysis and comparison with other methods proposed in the related literature, the robustness, effectiveness and superiority of the methodology of this paper are verified. Firstly, IVFFS is powerful and ensures the authenticity and effectiveness of the decision-making process. Secondly, in terms of expert weights, information aggregation, and criterion weights, this paper integrates the scientific nature of information and the simplicity of calculation, which improves the effectiveness of decision-making. Finally, the proposed Hamacher-MARCOS method not only considers the interrelationships among the criteria, but also operates flexibly and has a high degree of stability, which also proves the efficiency of the method proposed in this paper.

The results of this study have valuable managerial implications. First, on the theoretical side, this paper expands the methodology and applications in the field of decision-making by providing managers with a scientific decision-making tool for evaluating and selecting offshore CCUS projects for investment. The proposed methodology has some important advantages in that it allows the effective use of expert ideas, experience and judgment in the assessment. Second, in terms of project management, this study can help decision makers to better understand the investment appraisal process of offshore CCUS projects. Using the proposed model, managers can more effectively develop decision-making mechanisms and prioritize investment appraisal criteria with respect to sustainability. Calculations in Section 5 show that economic (C2) is the most critical criterion, followed by resource (C1), social (C4), environmental (C3), and risk (C5). Based on the calculation results of the criterion weights, relevant managers should pay full attention to the economic criterion when making investment decisions for offshore CCUS projects. Value engineering can be introduced to improve and control the investment cost, and intelligent management technology can be fully utilized for real-time monitoring and full management of offshore CCUS projects, etc. Thirdly, this study contributes to the policy aspect.

Participating governments and stakeholders must pay attention to CCUS policy issues in order to formulate effective policies. At the same time, a proper regulatory framework must be established to build cooperation within the industry.

8. Conclusion

In this paper, we construct a criteria system for investment evaluation of offshore CCUS projects and extend some decision-making methods to the IVFF environment to construct a fuzzy MCDM framework for investment decision-making of offshore CCUS projects. The framework combines IVFFS, PWA operator, FWZIC, MEREC, Hamacher operator and MARCOS methods, synthesizes the importance of experts, criteria, reduces information bias, and produces reliable decision results. To demonstrate the logic and application of the proposed method, a case study, sensitivity analysis, and comparative analysis are conducted. The MCDM framework constructed in this paper can be summarized in terms of its practicality and innovation in the following five aspects.

(1) Through a three-step process, a criteria system for investment evaluation of offshore CCUS projects has been established, covering five aspects, resources, economy, environment, social and risk, which is relatively comprehensive and in line with the reality.

(2) To describe the evaluation data of criteria and options, IVFFS is introduced. IVFFS has a higher capacity for modeling and solving complicated choice issues than other fuzzy sets.

(3) An extended IVFFS variance method is proposed to systematically compute the weights of experts to more reasonably reflect the importance of expert assessment information. In addition, an extended PWA operator is developed for aggregating information from different experts based on the similarity measure of IVFFN distance, which reduces the information bias.

(4) The FWZIC method is extended to the IVFF environment and the FWZIC-MEREC method is proposed to calculate the criteria weights. Both subjective and objective information are considered to make the criterion weight determination more credible.

(5) Considering that the offshore CCUS project involves many interacting criteria, in order, this study incorporates the IVFF-Hamacher operator into the MARCOS technique in an IVFF environment to choose the best investment option, which is more scientific. The framework for suggested investment decisions can be used as a reference for relevant investors and as a general reference for investment decisions in related projects.

Offshore CCUS projects are still in their infancy. This research offers an in-depth analysis and discussion of the investment decision problem of offshore CCUS projects using complex and applicable decision theories. The results offer points of reference for future research aimed at promoting the sustainable growth of offshore carbon capture and storage facilities. Even though this paper's methodology for making investment decisions offers some theoretical references for evaluating investments in offshore CCUS projects, there are still some limitations in this study. First, due to the large number of influencing factors involved in the investment decision of offshore CCUS projects, it is necessary to enhance the system of investment decision criteria. And with the continuous progress of technology, different criteria can be selected for evaluation according to different needs. Secondly, the expert weight determination model needs to be further improved, such as the trust relationship between experts can be introduced. Finally, more alternatives can be considered for assessment in future studies, depending on the degree of development of the offshore CCUS project. Furthermore, we will extend the Hamacher-MARCOS model that has been suggested to environments with bipolar fuzzy sets, Fermatean hesitant fuzzy sets, and interval-valued Fermatean hesitant fuzzy sets.

Disclosure statement

No potential conflict of interest was reported by the author(s)

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Access to some data may be restricted due to privacy concerns.

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Author Contributions

All authors contributed to the study conception and design, as below:

Qinghua Mao: Conceptualization, Data curation, Funding acquisition. Yaqing Gao: Methodology, Writing - original draft, Writing - review & editing, Formal analysis. Jiacheng Fan: Resources, Formal analysis.

All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethical approval

Ethics committee approval is not required.

Consent to participate

Not applicable.

Consent for publication

The authors confirm that the final version of the manuscript has been reviewed approved, and consented for publication.

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Declaration Statement

There are no conflicts of interest.