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

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<b>Abstract:</b>	<p>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 (MERECC) 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.</p>

**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.

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## 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.

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

3

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14

15 **Abstract:**

16 Carbon Capture, Utilization and Storage (CCUS) is an indispensable technology for  
17 achieving a net-zero emission society. The offshore CCUS project is still in its infancy.  
18 To promote its sustainable development, developing a comprehensive framework for  
19 investment decision-making is very crucial. First, a comprehensive evaluation criteria  
20 system is established. Second, in order to characterize the ambiguity and uncertainty of  
21 information in the process of making decisions, the interval-valued fermatean fuzzy set  
22 (IVFFS) is introduced, and the extended variance method of IVFFS is proposed to  
23 systematically calculate the weights of experts. Then, the power weighted average  
24 (PWA) operator based similarity measure of IVFFSs is developed to aggregate different  
25 expert information. Meanwhile, the fuzzy-weighted zero-inconsistency (FWZIC)  
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27 determine the criteria weights. In addition, considering the interactions between the  
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29 ranking according to compromise solution (MARCOS) method to select the optimal  
30 alternative in the interval-valued fermatean fuzzy (IVFF) environment. The suggested  
31 framework is then used to analyze a case study. After that, sensitivity and comparative  
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33 practical investment framework for offshore CCUS projects, identifies a number of  
34 investment-sensitive criteria and provides management insights. The proposed  
35 framework expands the methods and applications in the field of decision-making and  
36 provides a scientific approach for investment decision-making in offshore CCUS

37 projects, which can be a useful reference for managers.

38

39 **Keywords:** offshore CCUS project; Interval-valued fermatean fuzzy set; Investment

40 decision; Hamacher operator; MARCOS method

41

42 **1. Introduction**

43 **1.1. Background**

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

61

62 **1.2. Motivation**

63 Currently, there are numerous offshore CCUS demonstration projects [7]. Scholars

64 have studied offshore CCUS projects. Tamburini et al.[10] developed an integrated  
65 approach to calculate the consequences of an offshore CO<sub>2</sub> blowout, which could affect  
66 the safety and environmental impacts of CCUS projects. Based on the possibility of  
67 storing CO<sub>2</sub> in China's offshore sedimentary basins, Sun et al.[11] conducted an  
68 offshore source-sink matching and cost study of China's CCUS under various  
69 limitations. Jung et al. [12] developed a source-to-sink CO<sub>2</sub> transportation strategy for  
70 a demonstration project of Carbon Capture and Storage (CCS) in South Korea and  
71 performed a cost estimation based on the CO<sub>2</sub> transportation strategy. An approach to  
72 mixed-integer linear modeling that is spatially explicit was presented by D'Amore et al.  
73 [13] for the purpose of economically optimizing CCS supply chains throughout Europe.  
74 However, most studies have focus on storage capacity assessment, economic analysis,  
75 and technology optimization [9, 14-15], few scholars have studied the investment  
76 decisions of the project.

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

86 (MCDM) problem. Consequently, before building, a thorough and methodical analysis  
87 of the offshore CCUS projects' investment appraisal is required. Although the decision  
88 to invest in offshore CCUS projects has not been extensively studied, for this project,  
89 several references may be found in the research of onshore CCUS projects. As an  
90 illustration, Sun et al. [16] proposed an option game approach to explore incentives to  
91 promote the CCUS project. Fan et al. [17] built a model depending on real options and  
92 source-sink matching to make investment decisions for CCUS transformation of coal-  
93 fired power plants in China. Guo et al. [18] developed an extended TODIM (an acronym  
94 in Portuguese for Interactive Multi-criteria Decision Making) method that uses  
95 assessment information given by decision makers to select CO<sub>2</sub> storage locations.  
96 Based on previous researches, this paper aims to investigate the investment evaluation  
97 of offshore CCUS projects and develop a novel perspective on investment decision-  
98 making by building the MCDM framework.

99

### 100 1.3. Contribution

101 The objective of this study is to offer an exhaustive and reliable framework for  
102 investment decisions in offshore CCUS projects, and to give a few references for  
103 relevant managers. The study's contributions and the innovative aspects of the  
104 suggested framework are then summed up as follows: (1) This research builds a  
105 comprehensive system of criteria for investment in offshore CCUS projects through  
106 three stages: data collection, screening criteria and expert consultation, including five  
107 aspects: resources, economy, environment, society and risk. (2) Expert assessment data

108 is represented by the interval-valued fermatean fuzzy set (IVFFS), which takes into  
109 account the ambiguity and uncertainty of decision-making information. Then, the  
110 power weighted average (PWA) operator based on the similarity measure of IVFFSs is  
111 established to combined the assessment data of different experts to reduce the error due  
112 to ignoring the information bias, while considering experts' relative importance. Among  
113 them, the extended variance method of IVFFSs is proposed to systematically calculate  
114 the weights of experts to make the decision-making information more objective. A  
115 comprehensive weighting model in IVFF environment is proposed to obtain criterion  
116 weights. The fuzzy-weighted zero-inconsistency (FWZIC) method is extended to the  
117 IVFF environment to calculate the criteria's subjective weights. Additionally, the  
118 objective weights of the criteria are determined using the method based on the removal  
119 effects of criteria (MERECC). (4) The Extended IVFF measurement of alternatives and  
120 ranking according to compromise solution (MARCOS) approach is proposed to rank  
121 the alternatives. Hamacher operator is introduced in the MARCOS method to define  
122 the weighted sequence. It is able to better assemble the information and deal with the  
123 interconnection and influence between the criteria.

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

129

130 **2. Literature review**

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

132

133 **2.1 Interval-valued fermatean fuzzy set**

134 As mentioned earlier, the investment decision problem for offshore CCUS projects

135 is an MCDM problem. It can occasionally be impossible to convey the decision-maker's

136 preference information in precise numbers during the real procedure for making

137 decisions due to the ambiguity and unpredictability of human thought as well as the

138 complexity of the situation. To provide better handling of this situation, Zadeh [19] first

139 suggested the fuzzy set (FS) theory. FS's primary feature is that its Membership function

140 (MF) ranges from 0 to 1. As a result of FS lacking an independent Non-membership

141 function (NMF), Atanassov [20] proposed an intuitionistic fuzzy set (IFS) with NMF

142 as an independent factor. In addition, Yager [21] proposed Pythagorean fuzzy set (PFS)

143 to moderate the constraints of IFS (the PFS's MF and NMF square sums are less than

144 1). Recently, fermatean fuzzy set (FFS), proposed by Senapati and Yager [22] as an

145 important enhancement to PFS, has become a valuable concept for describing

146 uncertainty in MCDM environments. In FFS, an object is described by membership

147 degree (MD) and non-membership degree (ND) and their cubic sum  $\leq 1$ . It is difficult

148 to describe MD and ND precisely in terms of clear values because of the limits of human

149 understanding and the complexity of actual occurrences. Nonetheless, they can be

150 disclosed by interval values. Jeevaraj [23] generalized the concept of FFS to IVFFS,

151 where MD and ND can be represented as subsets of the interval  $[0,1]$  instead of clear

152 values. Decision-makers can communicate their opinions across a wider domain with  
153 IVFFS. As a result, complex decision-making problems can be more effectively solved  
154 and modeled by IVFFS [24]. IVFFS has been used in a number of applications. Mijanur  
155 Rahaman Seikh and Utpal Mandal [24] developed the IVFF Dombi weighted average  
156 (geometric) operator combined with Preference Ranking Organization METhod for  
157 Enrichment Evaluation II (PROMETHEE II) and Stepwise Weight Assessment Ratio  
158 Analysis (SWARA) methods, proposed an integrated MCDM approach to select the  
159 organization most capable of managing biomedical waste. Based on IVFFS, M. Hezam  
160 et al. [25] developed a hybrid combined compromise solution (CoCoSo) approach  
161 based on Dombi operator and similarity measure, to select the company that makes  
162 wheelchairs with smart autonomy for patients with disabilities. Biswas et al. [26]  
163 applied IVFF based Multi-Attributive Border Approximation Area Comparison  
164 (MABAC) technique to identify the key characteristics of product family and assist in  
165 making decisions in the face of uncertainty. The new two-phase IVFF dominance  
166 approach, which Jeevaraj et al [27] devised, was used to rate the benefits of different  
167 options for lowering greenhouse gas emissions from activities connected to  
168 transportation. Bouraima et al. [28] integrated Analytic hierarchy process (AHP)  
169 method and Technique for Order Preference by Similarity to an Ideal Solution  
170 (TOPSIS) in an IVFF environment to assess the susceptibility of different countries to  
171 accidents occurring on construction sites. Kirişci, M [29] proposed a new integrated  
172 MCDM approach for IVFF combining AHP, TOPSIS and MABAC methods to propose  
173 a new safety model to assess the risk of self-driving cars. However, few have applied

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

183

184 2.2 Group aggregation methods

185 The process of information aggregation for selection decisions that does not take  
186 into account the bias of expert assessment information can give rise to a degree of  
187 cognitive uncertainty. Therefore, aggregating evaluation data from many experts is  
188 especially well suited for aggregation techniques that can manage information bias [30].

189 The PWA operator [31] effectively reduces the effect of bias compared to the  
190 Bonferroni mean operator and the Choquet integral [30]. PWA operators have been  
191 applied to aggregate expert information in different fuzzy environments such as interval  
192 2-tuple languages [30], complex spherical fuzzy sets [32]. Individual variances, on the  
193 other hand, raise concerns about the level of consensus. Important elements in the  
194 aggregation process are the relative relevance of various specialists and the coherence  
195 of their opinions [33]. The weighting of experts must be systematically assessed to

196 reduce subjective randomness. In the existing literature [30, 34-36], expert weights are  
197 generally equal or given directly based on the expert's knowledge, position, and other  
198 conditions, often ignoring the objectivity of the expert weights. Therefore, this work  
199 adapts the PWA operator to the IVFF environment by extending it depending on the  
200 distance measure and reduces the error due to ignoring the effect of information bias  
201 while considering the relative importance of experts. In this paper, the IVFF variance  
202 normalization approach is used to determine the expert weights.

203

204 2.3 Criteria weights determination methods

205 Determining the weights of the evaluation criteria is a crucial and considerable stage  
206 in the evaluation process of offshore CCUS projects. Many MCDM techniques have  
207 been used recently, including the AHP method [37], the analytic network process (ANP)  
208 method [38] and the best-worst method (BWM) method [39], have been utilized to  
209 ascertain the subjective weights assigned to the criteria. But the issue of inconsistent in  
210 weighing methods has not been resolved. Recently, the FWZIC approach have been  
211 used to calculate the weighting coefficients for variables with zero inconsistency [40].  
212 It identifies the importance of criteria with the support of experts. The FWZIC method  
213 has been extended to various fuzzy sets such as PFS, FFS, and probabilistic hesitant  
214 fuzzy sets [41-42]. This paper extends the FWZIC approach to the more flexible IVFFS.  
215 In addition, numerous objective weighting techniques are employed to establish the  
216 criteria weights, such as entropy method [43], the criteria importance through  
217 intercriteria correlation (CRITIC) method [44] and integrated determination of

218 objective criteria weights (IDOCRIW) method [45]. Keshavarz et al. [46] proposed the  
219 MEREC objective weight determination method. In unlike previous approaches, this  
220 one determines the weight of the criteria by evaluating the effect of the criteria that have  
221 been eliminated on the total utility; the more the impact, the higher the weight. MEREC  
222 is more stable than the other methods in the presence of anomalous disturbances even  
223 though the outcomes it produces are comparable to those of the other approaches [47].  
224 As a result, the MEREC approach is widely applied. Simic et al. [48] came up with  
225 CoCoSo-MEREC model for transportation planning in Fermatean fuzzy environment.  
226 In order to investigate the selection of agricultural technology, Banik et al. [49]  
227 expanded the MEREC and gray correlation approaches based on the pentagonal  
228 neutrosophic environment. The rank sum-MEREC- model was created by Deveci et al.  
229 [50] to choose different transportation networks. The hybrid method is more  
230 scientifically sound without over-reliance on subjective or objective information  
231 relative to a single subjective or objective approach. Therefore, this paper adopts the  
232 combined weighting method of FWZIC and MEREC to determine the criterion weights  
233 for the offshore CCUS projects.

234

235 2.4 MARCOS method

236 Many tools are typical for dealing with MCDM problems. Examples include  
237 TOPSIS[51], CoCoSo[30] and PROMETHEE II [52]. One of the most recent MCDM  
238 techniques released by Stevi' c et al.[53] is MARCOS. This approach uses reference  
239 point ordering and ratios. Through the defining of ideal/anti-ideal values, the

240 relationship between alternatives and reference points, and the degree of utility, the  
241 MARCOS technique yields a reliable ranking of alternatives. It provides more accurate  
242 and reliable results with less effort and shorter operation time than other methods,  
243 making it a more flexible and effective decision-making method[54]. In order to assess  
244 wastewater reuse applications in thermal power plants, Ocampo et al. [55] presented a  
245 three-way decision extension of the MARCOS technique. A spherical fuzzy MARCOS  
246 was presented by Bonab et al.[56] to rank and assess blockchain platforms. Pamucar et  
247 al. [57] proposed the MARCOS based fuzzy Full Consistency Method and neutrosophic  
248 fuzzy to evaluate alternate fuel automobiles for US road transportation that is  
249 sustainable. In Pythagorean fuzzy environment, Wang et al. [58] proposed an extended  
250 MARCOS method to calculate the criteria importance through CRITIC to determine  
251 the order of importance of each sustainable food supplier. The utilization of the  
252 MARCOS methodology improves the correctness of the decision-making system and  
253 provides useful ranking results for decision makers [59]. In addition, the Hamacher  
254 aggregation operator is able to fully take into account the correlation between attributes,  
255 and thus has been used for the aggregation of a variety of fuzzy information expressions  
256 [60]. Therefore, in this paper, the IVFF-Hamacher aggregation operator is introduced  
257 in the MARCOS method to normalize the weighting sequences in the weighting matrix,  
258 so that it can be better applied to the IVFF environment.

259 A summary of some of the MCDM techniques previously created to deal with  
260 investment assessment problems can be found in Table 1. The following is a summary  
261 of the research gaps according to Table 1 and the review of literature: (1) Few research

262 has been carried out on offshore CCUS projects using MCDM techniques. (2) There  
 263 are few studies that take into the effects of expert weights and individual evaluation  
 264 information bias in the aggregation process. (3) The FWZIC approach has not been well  
 265 explored in IVFFS and most of the literature does not take into account both objective  
 266 and subjective data. (4) The MARCOS approach has limited application in the IVFFS  
 267 environment. Therefore, this paper proposes a comprehensive MCDM model for  
 268 offshore CCUS project for investment decision making.

269

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

Auth or (s)	Methodolog y	Applica tion	Group aggregation		Criteria' weight	Mutual relations	
			Expe rts' rts'	Individ ual	Subject ives	Object ives	hips
			weig hts	deviati on			between the criteria
Yuan et al. [61]	Crisp&ANP	CFPP			✓	✓	✓
	-Entropy-						
	TODIM						
Karatop et al. [62]	TFN &AHP-	Renewa ble			✓		
	EDAS	energy					

Wu et al. [63]	TIFN& DEMATEL -TODIM	PVPCH S		✓		✓
Wu et al. [64]	HFLTS&A NP- entropy	ICR- DPV		✓	✓	✓
Zhou et al. [65]	IT2F& DANP-	Renewa ble		✓		✓
Zhen g et al. [66]	Cloud model & IDOCRIW- TODIM	AVCES	✓	✓	✓	
Mao et al. [52]	IVPFS& DEMATEL - GOWUA-	Offshor e wind- PV-SPS	✓	✓		✓
	HARA- PROMETH	project				
	EE II					
Peng et al.	Z- numbers&	New energy		✓		✓

---

[67] DEMATEL resource

- ELECTRE s

III

This IVFFS&F Offshor √ √ √ √ √

study WZIC- e CCUS

MEREC- project

Hamacher-

MARCOS

---

271

272 **3. The investment decision criteria system**

273 Identifying impact factors and constructing a system of evaluation criteria is the  
274 fundamental task of project investment evaluation. This article will identify impact  
275 indicators for investment appraisal of offshore CCUS projects using a three-phase  
276 process that includes data collection, selection criteria, and consulting experts. First,  
277 using the literature review method, the relevant documentalists will gather relevant  
278 information on offshore CCUS projects, such as published academic articles and  
279 feasibility study results, they will then gather and arrange potential obstacles or factors  
280 that could influence these projects. Next, appropriate staff will be asked to conduct  
281 frequency counts and initial screening of the collected impact indicators. Ultimately, a  
282 working group composed of specialists with in-depth understanding of offshore CCUS  
283 projects will be invited. The experts talked about the impact factors' initial screening  
284 mentioned above, eliminated any redundant or unimportant indicators, integrated those

285 with high significance, and ultimately created a set of criteria for resources, economy,  
286 environment, society, and risk, which includes a total of 18 impact criteria, as shown in  
287 Figure 1. Of these, the cost criteria are C21, C22, C23, C31, C32, C51, C52, and C53,  
288 while the benefit criteria are the remaining ones.

289

290 3.1 Resource (C1)

291 ·Emission source (C11) [68-69]

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

295 ·Storage capacity (C12) [18, 70-71]

296 Before implementing CCUS, an analysis of the CO<sub>2</sub> storage capacity is required. The  
297 cost of geological storage per unit of CO<sub>2</sub> should decrease with increasing storage  
298 capacity, according to theory. Therefore, sites with large storage capacity will be  
299 suitable for CO<sub>2</sub> storage, taking into account investment costs and efficiency.

300 ·Injection rate (C13) [72-73]

301 The effects of reservoir uncertainty and reservoir flow variability on infrastructure  
302 availability and costs must be taken into consideration while planning CCUS  
303 infrastructure. Important geologic storage parameters (temperature, pressure, depth,  
304 and permeability) influence injection rates and cause fluctuations in the flow rates of  
305 CO<sub>2</sub>, which are then redirected into the pipeline system for transportation.

306 ·Infrastructures (C14) [69, 74-75]

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

309

310 3.2 Economy (C2)

311 ·Initial costs (C21) [52, 76]

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

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

315 The long-term management of the project is heavily dependent on O&M costs.

316 Expenses for employee pay and basic equipment configuration, and by extension,  
317 transportation costs are included in O&M costs.

318 ·payback period (C23) [78-79]

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

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

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

327

328 3.3 Environment (C3)

329 ·Marine environmental impacts (C31) [77, 81]  
330 It is important to minimize negative environmental risks and impacts and to ensure that  
331 there is no harm to the oceanic surroundings. The risk of CO<sub>2</sub> seepage may lead to  
332 decline in the quality of the water, acidification of the ocean and harmful impacts on  
333 marine ecosystems. In addition, there may be environmental constraints to placement  
334 close by environmentally protected areas.

335 ·Marine Biological Coordination (C32) [82]  
336 Seafloor organisms, including some associated with commercial fisheries, may die  
337 under extreme acidification conditions near the spill site.

338 ·Reduce carbon emissions (C33) [83-84]  
339 The CCUS project has huge environmental benefits, both the atmosphere and the  
340 greenhouse effect can be greatly diminished.

341  
342 3.4 Social (C4)  
343 ·Policy support (C41) [85-87]  
344 The CCUS project investment is a capital-intensive investment. Therefore, economic  
345 and regulatory support from governments is needed for its further development and  
346 deployment.

347 ·Public acceptance (C42) [70, 88-89]  
348 The degree of public approval is crucial in the deployment of CCUS, both locally and  
349 globally. Public perceptions of CCUS are influenced by more variables than merely  
350 danger or security issues.

351 ·Employment (C43) [85]  
352 Process and industrial engineering knowledge is necessary for CCUS and can be a  
353 source of excellent local jobs. A lot of local jobs in infrastructure deployment are  
354 created by the design-heavy CCUS project. In order to facilitate a fair transition, CCUS  
355 can lower the unemployment rate in the fossil fuel sector.

356 ·Technological innovation promotion (C44) [74, 87]  
357 CCUS projects can be effective in contributing to carbon emission reductions, but the  
358 economic cost poses a significant challenge for commercial-scale deployment of  
359 offshore CCUS. This project's development will save costs and progress associated  
360 technological advancements.

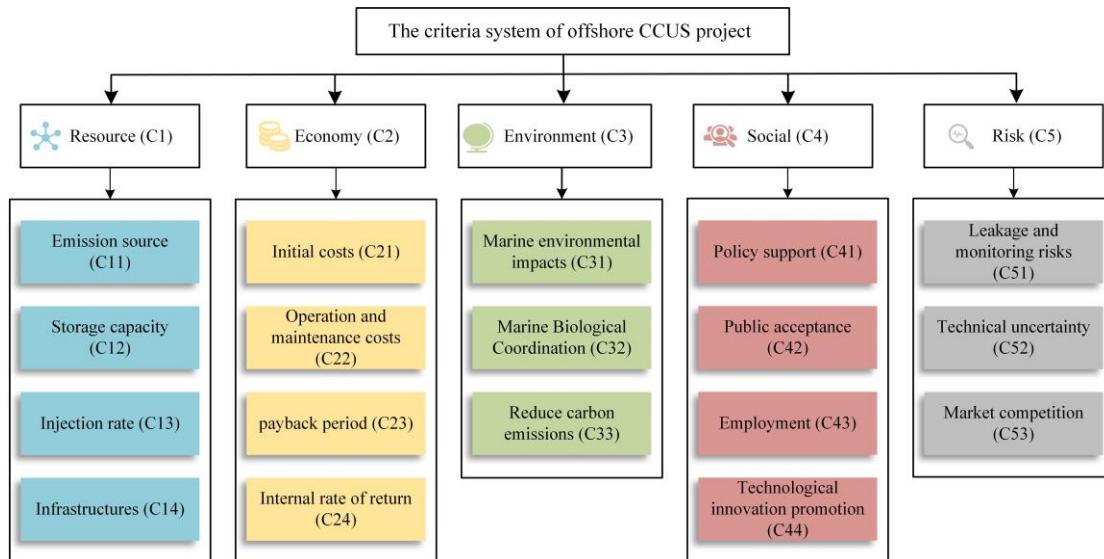
361  
362 3.5 Risk (C5)  
363 ·Leakage and monitoring risks (C51) [81, 90-91]  
364 Carbon leakage can not only harm the marine ecosystem, but can also significantly  
365 reduce the competitiveness of a project, requiring accurate assessment of the risk of  
366 leakage and proper monitoring.

367 ·Technical uncertainty (C52) [74, 92]  
368 The project of offshore CCUS is currently in its early stages, and capture,  
369 transportation, and storage technologies all face different challenges, and technological  
370 uncertainty can lead to increased costs.

371 ·Market competition (C53) [76, 85]  
372 Other low-carbon technologies like energy efficiency and renewable energy compete

373 with offshore CCUS projects for investment. With the ongoing decline in the cost of  
 374 renewable energy technologies, offshore CCUS projects may find it more difficult to  
 375 attract investment.

376



377

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

379

#### 380 4. The evaluation framework for investment decisions

##### 381 4.1. Information gathering

382 Within this part, we perform information gathering. For a given investment  
 383 decision problem for an offshore CCUS project, suppose there are  $m$  different  
 384 alternatives  $A_i (i=1,2,\dots,m)$ ,  $n$  criteria  $C_j (j=1,2,\dots,n)$ , and the weights of the criteria are  $\omega_j$ ,

385  $\omega_j \in [0,1], \sum_{j=1}^n \omega_j = 1$ . Group of experts  $E_k (k=1,2,\dots,s)$ , and the weights of the experts are  $\varpi_k$ ,

386  $\varpi_k \in [0,1], \sum_{k=1}^s \varpi_k = 1$ . During the investment decision-making process for offshore CCUS

387 projects, experts tend to use linguistic terms to express their judgments. In order to

388 better deal with uncertainty in the assessment process, in this paper, IVFFS is used to

389 convey the expert's opinion, and the following describes the concept of IVFFS and its  
 390 basic properties, which serve as the study's foundation.

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

$$393 \quad \tilde{F} = \left\{ \left\langle x_i, \left[ \mu_{\tilde{F}}^L(x_i), \mu_{\tilde{F}}^U(x_i) \right], \left[ v_{\tilde{F}}^L(x_i), v_{\tilde{F}}^U(x_i) \right] \right\rangle : x_i \in X \right\} \quad (1)$$

394 where  $0 \leq \mu_{\tilde{F}}^L(x_i) \leq \mu_{\tilde{F}}^U(x_i) \leq 1$ ,  $0 \leq v_{\tilde{F}}^L(x_i) \leq v_{\tilde{F}}^U(x_i) \leq 1$  and  $(\mu_{\tilde{F}}^U(x_i))^3 + (v_{\tilde{F}}^U(x_i))^3 \leq 1$ . Here,

395  $\mu_{\tilde{F}}(x_i) = [\mu_{\tilde{F}}^L(x_i), \mu_{\tilde{F}}^U(x_i)]$  and  $v_{\tilde{F}}(x_i) = [v_{\tilde{F}}^L(x_i), v_{\tilde{F}}^U(x_i)]$  denote the interval MD and ND of  $x_i \in X$ ,

396 respectively. The hesitancy degree of  $x_i \in X$  to  $\tilde{F}$  is defined as  $\pi_{\tilde{F}}(x_i) = [\pi_{\tilde{F}}^L(x_i), \pi_{\tilde{F}}^U(x_i)]$ ,

397 where  $\pi_{\tilde{F}}^L(x_i) = \sqrt[3]{1 - (\mu_{\tilde{F}}^U(x_i))^3 - (v_{\tilde{F}}^U(x_i))^3}$  and  $\pi_{\tilde{F}}^U(x_i) = \sqrt[3]{1 - (\mu_{\tilde{F}}^L(x_i))^3 - (v_{\tilde{F}}^L(x_i))^3}$ . For simplicity,

398 Jeevaraj[23] defined the idea of interval-valued fermatean fuzzy number (IVFFN),

399 presented as  $\alpha = ([\mu_{\alpha}^L, \mu_{\alpha}^U], [v_{\alpha}^L, v_{\alpha}^U])$  and fulfill  $(\mu_{\alpha}^U)^3 + (v_{\alpha}^U)^3 \leq 1$ .

400 **Definition 2**[93]. Let  $\alpha_1 = ([\mu_{\alpha_1}^L, \mu_{\alpha_1}^U], [v_{\alpha_1}^L, v_{\alpha_1}^U])$  and  $\alpha_2 = ([\mu_{\alpha_2}^L, \mu_{\alpha_2}^U], [v_{\alpha_2}^L, v_{\alpha_2}^U])$  be two IVFFNs.

401 Then, the relations between  $\alpha_1$  and  $\alpha_2$  are presented as

402 (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  $v_{\alpha_1}^U = v_{\alpha_2}^U$ ,

403 (ii)  $\alpha_1 \prec \alpha_2$  iff  $\mu_{\alpha_1}^L \leq \mu_{\alpha_2}^L, \mu_{\alpha_1}^U \leq \mu_{\alpha_2}^U, v_{\alpha_1}^L \geq v_{\alpha_2}^L$  and  $v_{\alpha_1}^U \geq v_{\alpha_2}^U$ .

404 **Definition 3**[93]. For any IVFFN  $\alpha = ([\mu_{\alpha}^L, \mu_{\alpha}^U], [v_{\alpha}^L, v_{\alpha}^U])$ , the score and accuracy functions

405 are provided by

$$406 \quad S(\alpha) = \frac{1}{2} \left( (\mu_{\alpha}^L)^3 + (\mu_{\alpha}^U)^3 - (v_{\alpha}^L)^3 - (v_{\alpha}^U)^3 \right) \quad (2)$$

$$407 \quad H(\alpha) = \frac{1}{2} \left( (\mu_{\alpha}^L)^3 + (\mu_{\alpha}^U)^3 + (v_{\alpha}^L)^3 + (v_{\alpha}^U)^3 \right) \quad (3)$$

408 For any two IVFFNs  $\alpha_1$  and  $\alpha_2$ , the following are the comparison rules:

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

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

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

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

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

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

415 **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  $\alpha_2 = \left( \left[ \mu_{\alpha_2}^L, \mu_{\alpha_2}^U \right], \left[ v_{\alpha_2}^L, v_{\alpha_2}^U \right] \right)$

416 be three IVFFNs and  $\beta > 0$ . Then, the operations in IVFFNs are given as

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

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

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

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

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

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

423 **Definition 5**[93]. Let  $\alpha_1 = \left( \left[ \mu_{\alpha_1}^L, \mu_{\alpha_1}^U \right], \left[ v_{\alpha_1}^L, v_{\alpha_1}^U \right] \right)$ ,  $\alpha_2 = \left( \left[ \mu_{\alpha_2}^L, \mu_{\alpha_2}^U \right], \left[ v_{\alpha_2}^L, v_{\alpha_2}^U \right] \right), \dots$ ,

424  $\alpha_n = \left( \left[ \mu_{\alpha_n}^L, \mu_{\alpha_n}^U \right], \left[ v_{\alpha_n}^L, v_{\alpha_n}^U \right] \right)$  be any IVFFNs. The following equation displays the IVFFSs

425 aggregation operator.

$$426 IVFFA(a_1, a_2, \dots, a_n) = \left( \left[ \sqrt[3]{1 - \prod_{h=1}^n \left( 1 - \left( \mu_{ah}^L \right)^3 \right)}, \sqrt[3]{1 - \prod_{h=1}^n \left( 1 - \left( \mu_{ah}^U \right)^3 \right)} \right], \left[ \prod_{h=1}^n v_{ah}^L, \prod_{h=1}^n v_{ah}^U \right] \right) \quad (4)$$

427 **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

428 IVFFNs. Then the generalized Euclidean distance between  $\alpha_1$  and  $\alpha_2$  as follows.

$$429 d(\alpha_1, \alpha_2) = \sqrt{\frac{\left( \left( \mu_{\alpha_1}^L \right)^3 - \left( \mu_{\alpha_2}^L \right)^3 \right)^2 + \left( \left( \mu_{\alpha_1}^U \right)^3 - \left( \mu_{\alpha_2}^U \right)^3 \right)^2 + \left( \left( v_{\alpha_1}^L \right)^3 - \left( v_{\alpha_2}^L \right)^3 \right)^2 + \left( \left( v_{\alpha_1}^U \right)^3 - \left( v_{\alpha_2}^U \right)^3 \right)^2 + \left( \left( 1 - \left( \mu_{\alpha_1}^L \right)^3 - \left( v_{\alpha_1}^L \right)^3 \right) - \left( 1 - \left( \mu_{\alpha_2}^L \right)^3 - \left( v_{\alpha_2}^L \right)^3 \right) \right)^2 + \left( \left( 1 - \left( \mu_{\alpha_1}^U \right)^3 - \left( v_{\alpha_1}^U \right)^3 \right) - \left( 1 - \left( \mu_{\alpha_2}^U \right)^3 - \left( v_{\alpha_2}^U \right)^3 \right) \right)^2}{6}} \quad (5)$$

430

431 4.2. Group aggregation

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

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

439 Step 2. Translating expert assessments into crisp values  $\varepsilon_{ij}^k$  using Eq. (3).

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

$$442 \varepsilon_k^2 = \sum_{i=1}^m \sum_{j=1}^n \frac{\left( \varepsilon_{ij}^k - \bar{\varepsilon}_i^k \right)^2}{n-1} \quad (6)$$

443 where  $\bar{\varepsilon}_i^k$  and  $\varepsilon_k^2$  represent the mean and variance of the  $k$ th expert, respectively.

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

$$448 (C.F)_k = 1 - \tilde{\varepsilon}_k \quad (7)$$

$$449 \varpi_k = \frac{(C.F)_k}{\sum_{k=1}^s (C.F)_k} \quad (8)$$

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

452 Step 5. Summarize the evaluation data provided by experts.  
 453 Considering the individual importance of the experts, an overall evaluation matrix  
 454  $P = (p_{ij})_{m \times n}$  is created by combining the assessments provided by DMs. using the PWA  
 455 operator based on the similarity measure, where  $p_{ij}$  is described in terms of IVFFNs.

456 Assume that  $p_{ij}^k = (\mu_{ij}^{kL}, \mu_{ij}^{kU}], [v_{ij}^{kL}, v_{ij}^{kU}])$  and  $p_{ij}^g = (\mu_{ij}^{gL}, \mu_{ij}^{gU}], [v_{ij}^{gL}, v_{ij}^{gU}])$  are the  
 457 corresponding IVFFNs from Alternative  $A_i$  under Criterion  $C_j$  of Experts  $E_k$  and  $E_g$ .

458 Next, the PWA operator of IVFFN is described in this way.

$$459 p_{ij} = PWA(p_{ij}^1, p_{ij}^2, \dots, p_{ij}^s) = \sum_{k=1}^s \frac{\varpi_k (1 + T(p_{ij}^k))}{\sum_{k=1}^s \varpi_k (1 + T(p_{ij}^k))} \cdot p_{ij}^k \quad (9)$$

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

$$462 T(p_{ij}^k) = \sum_{g=1, g \neq k}^s S(p_{ij}^k, p_{ij}^g) \quad (10)$$

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

$$465 S(p_{ij}^k, p_{ij}^g) = 1 - d(p_{ij}^k, p_{ij}^g) \quad (11)$$

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

467  
 468 4.3. Determination of the criteria weights

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

472 Step 1. Determine the subjective weight using the FWZIC.

473 In the IVFF environment, to determine the criteria's subjective weights, FWZIC is

474 extended in the following steps:

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

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

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

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

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

494 (5.1) Use Eq. (12) to calculate the ratio of the data.

495 
$$\tilde{E} : \tilde{C} = \frac{\text{Imp}(E_k / C_j)}{\sum_{j=1}^n \text{Imp}(E_k / C_j)} \quad (12)$$

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

498 (5.2) Calculate the mean value to obtain the fuzzy value weights of the  
499 evaluation criteria.

500 
$$\tilde{w}_j^s = \left( \frac{\sum_{k=1}^l \text{Imp}(E_{kj} / C_{kj})}{\sum_{j=1}^n \text{Imp}(E_{kj} / C_{kj})} \right) / m, \text{ for } k = 1, 2, 3, \dots, l \text{ and } j = 1, 2, 3, \dots, n. \quad (13)$$

501 (5.3) Using the score value provided by [93], The standard weights are  
502 defuzzified using Eq. (14). The weights are then rescaled using Eq. (15) to find the  
503 final weights.

504 
$$S'(\alpha) = \frac{1}{2} \left( \frac{1}{2} \left( (\mu_\alpha^L)^3 + (\mu_\alpha^U)^3 - (v_\alpha^L)^3 - (v_\alpha^U)^3 \right) + 1 \right) \quad (14)$$

505 
$$w_j^s = \frac{\tilde{w}_j^s}{\sum_{j=1}^n \tilde{w}_j^s} \quad (15)$$

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

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

508 
$$\tilde{p}_{ij} = \left( \left[ \tilde{\mu}_{ij}^L, \tilde{\mu}_{ij}^U \right], \left[ \tilde{v}_{ij}^L, \tilde{v}_{ij}^U \right] \right) = \begin{cases} v_{ij} = \left( \left[ \mu_{ij}^L, \mu_{ij}^U \right], \left[ v_{ij}^L, v_{ij}^U \right] \right), & j \in B \\ \left( v_{ij} \right)^c = \left( \left[ v_{ij}^L, v_{ij}^U \right], \left[ \mu_{ij}^L, \mu_{ij}^U \right] \right), & j \in C \end{cases} \quad (16)$$

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

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

512 (3) Calculate overall performance  $Q_i$ .

513 
$$Q_i = \ln \left( 1 + \left( \frac{1}{n} \sum_j |\ln(\eta_{ij})| \right) \right) \quad (17)$$

514 (4) Calculate performance by excluding each criterion.

515 
$$Q'_{ij} = \ln \left( 1 + \left( \frac{1}{n} \sum_{b,b \neq j} |\ln(\eta_{ib})| \right) \right) \quad (18)$$

516 where  $Q'_{ij}$  indicates how well the  $i$ th alternative performed once the  $j$ th criterion is  
517 dropped.

518 (5) Sum the absolute deviations.

519 
$$M_j = \sum_i |Q'_{ij} - Q_i| \quad (19)$$

520 (6) Calculation of the weights of the criteria.

521 
$$\omega_j^o = \frac{M_j}{\sum_{j=1}^n M_j} \quad (20)$$

522 Step 3. Combined weights for determining criteria.

523 
$$\omega_j = \phi \omega_j^s + (1 - \phi) \omega_j^o \quad (21)$$

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

525

526 4.4. Expanded MARCOS to determine the optimal investment alternative.

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

535 Step 1. Determine the ideal and anti-ideal solutions to obtain the extended

536 decision matrix  $\bar{P}$ .

$$537 \quad \begin{aligned} A^- &= \begin{cases} \left[ \left[ \min_i \mu_{ij}^L, \min_i \mu_{ij}^U \right], \left[ \max_i \nu_{ij}^L, \max_i \nu_{ij}^U \right] \right] & \text{if } j \in B \\ \left[ \left[ \max_i \mu_{ij}^L, \max_i \mu_{ij}^U \right], \left[ \min_i \nu_{ij}^L, \min_i \nu_{ij}^U \right] \right] & \text{if } j \in C \end{cases} \\ A^+ &= \begin{cases} \left[ \left[ \max_i \mu_{ij}^L, \max_i \mu_{ij}^U \right], \left[ \min_i \nu_{ij}^L, \min_i \nu_{ij}^U \right] \right] & \text{if } j \in B \\ \left[ \left[ \min_i \mu_{ij}^L, \min_i \mu_{ij}^U \right], \left[ \max_i \nu_{ij}^L, \max_i \nu_{ij}^U \right] \right] & \text{if } j \in C \end{cases} \end{aligned} \quad (22)$$

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

$$539 \quad \bar{P} = A_1 \begin{pmatrix} C_1 & C_2 & \dots & C_n \\ p_1^- & p_2^- & \dots & p_n^- \\ p_{11} & p_{12} & \dots & p_{1n} \\ p_{21} & p_{22} & \dots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \dots & p_{mn} \\ p_1^+ & p_2^+ & \dots & p_n^+ \end{pmatrix}_{(m+2) \times n}$$

540 Step 2. Normalized decision matrix construction. The same normalization process

541 as in the MEREC method (Eq. (16)) yields the normalized matrix  $\tilde{P} = (\tilde{p}_{ij})_{(m+2) \times n}$ .

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

$$543 \quad K_i^- = \frac{S_i}{S^-} \quad (23)$$

$$544 \quad K_i^+ = \frac{S_i}{S^+} \quad (24)$$

545 where  $S^-$ ,  $S^+$ , and  $S_i$  ( $i = 1, 2, \dots, m$ ) represent the weighted sequence obtained by using

546 the IVFFHWA operator (Eq (25)).

547 **Definition 7[51].** Suppose  $I_j = \left[ \left[ \mu_{I_j}^L, \mu_{I_j}^U \right], \left[ \nu_{I_j}^L, \nu_{I_j}^U \right] \right]$ , ( $j = 1, 2, \dots, n$ ) be the collection of

548 IVFFNs, Then, the aggregated result utilizing the IVFFHWA is an IVFFN, and

$$\begin{aligned}
549 \quad & \text{IVFFHWA}_w(I_1, I_2, \dots, I_n) = \bigoplus_{j=1}^n (\omega_j I_j) \\
& = \left[ \sqrt[3]{\frac{\prod_{j=1}^n (1 + (\zeta - 1) (\mu_{I_j}^L)^3)^{\omega_j} - \prod_{j=1}^n (1 - (\mu_{I_j}^L)^3)^{\omega_j}}{\prod_{j=1}^n (1 + (\zeta - 1) (\mu_{I_j}^L)^3)^{\omega_j} + (\zeta - 1) \prod_{j=1}^n (1 - (\mu_{I_j}^L)^3)^{\omega_j}}}, \sqrt[3]{\frac{\prod_{j=1}^n (1 + (\zeta - 1) (\mu_{I_j}^U)^3)^{\omega_j} - \prod_{j=1}^n (1 - (\mu_{I_j}^U)^3)^{\omega_j}}{\prod_{j=1}^n (1 + (\zeta - 1) (\mu_{I_j}^U)^3)^{\omega_j} + (\zeta - 1) \prod_{j=1}^n (1 - (\mu_{I_j}^U)^3)^{\omega_j}}}, \right. \\
& \quad \left. \left[ \sqrt[3]{\frac{\zeta \prod_{j=1}^n (v_{I_j}^L)^{\omega_j}}{\prod_{j=1}^n (1 + (\zeta - 1) (1 - (v_{I_j}^L)^3))^{\omega_j} + (\zeta - 1) \prod_{j=1}^n (v_{I_j}^L)^{3\omega_j}}}, \sqrt[3]{\frac{\zeta \prod_{j=1}^n (v_{I_j}^U)^{\omega_j}}{\prod_{j=1}^n (1 + (\zeta - 1) (1 - (v_{I_j}^U)^3))^{\omega_j} + (\zeta - 1) \prod_{j=1}^n (v_{I_j}^U)^{3\omega_j}}}} \right] \right]
\end{aligned}$$

550 (25)

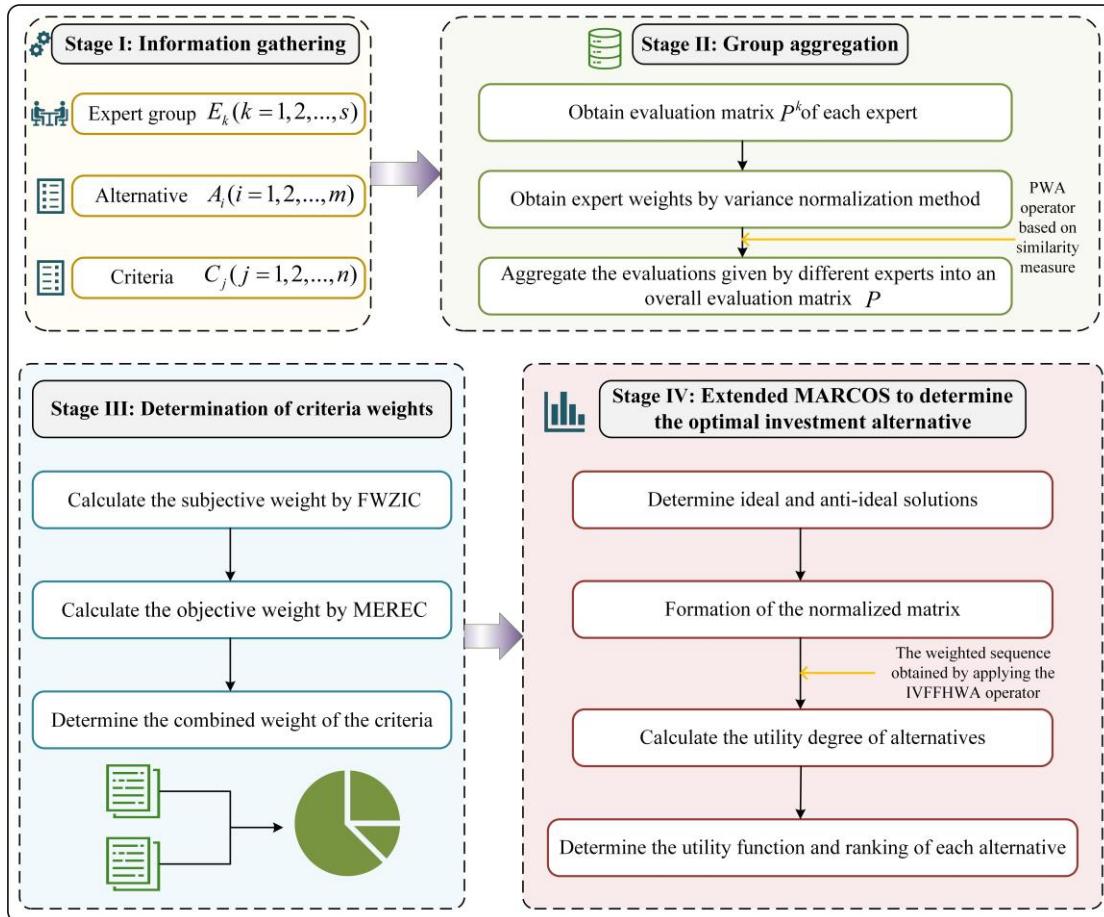
551 Step 4. Determine the utility function and ranking of each alternative.

$$552 \quad f(K_i) = \frac{K_i^+ + K_i^-}{1 + \frac{1 - f(K_i^+)}{f(K_i^+)} + \frac{1 - f(K_i^-)}{f(K_i^-)}} \quad (26)$$

$$553 \quad f(K_i^-) = \frac{K_i^+}{(K_i^+ + K_i^-)} \quad (27)$$

$$554 \quad f(K_i^+) = \frac{K_i^-}{(K_i^+ + K_i^-)} \quad (28)$$

555



556

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

558

559 **5. Case study**

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

562

563 **5.1. Information gathering**

564 In recent years, many countries have started to pay increasing attention to the  
 565 problem of CO<sub>2</sub> emissions. Developing and fully utilizing CCUS technology is the  
 566 future trend of industry. Therefore, a business in Guangdong Province intends to invest  
 567 in an offshore CCUS project. The board of directors examined four options while

568 assessing the project investment decision. The alternative set is  $A = (A1, A2, A3, A4)$ .

569 Section 3 identifies 18 criteria, with the set of criteria being  $C = (C_1, C_2, \dots, C_n)$ , and the

570 criteria weights are denoted as  $\omega = (\omega_1, \omega_2, \dots, \omega_n)$ , where

571  $\omega_i \in [0,1]$ , ( $i = 1, 2, \dots, n$ ),  $\sum_{i=1}^n \omega_i = 1$ . To serve as decision managers, three specialists with in-

572 depth understanding of offshore CCUS projects are invited. They need to have worked

573 in engineering design and CCUS project operations for at least five years. They also

574 need to be authorities in management, environmental sustainability, and market

575 analysis. The accuracy, dependability, and professionalism of the evaluation data can

576 only be ensured by experts who fulfill the above indicated conditions. First, they need

577 to assess the relative importance of the criteria and determine the weights of the criteria

578 using the FWZIC-MEREC methodology. Second, they will use IVFFS to evaluate each

579 alternative associated with each criterion and then use the MARCOS method to choose

580 the best possible option. The group of experts was assembled as  $E = (E1, E2, E3)$ , and

581 the expert weights are expressed as  $\varpi = (\varpi_1, \varpi_2, \varpi_3)$ , where

582  $\varpi_k \in [0,1]$ , ( $k = 1, 2, 3$ ),  $\sum_{k=1}^3 \varpi_k = 1$ .

583

584 5.2. Group aggregation

585 Using the seven scaled linguistic variables shown in Table A2, the experts in the

586 expert group evaluate the alternatives according to criteria  $C = (C_1, C_2, \dots, C_n)$ . The

587 weights of the experts are calculated according to the variance method, and then their

588 distinct viewpoints are combined in accordance with the PWA operator based on the

589 similarity measure. The corresponding steps are as follows.

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

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

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

599 Step 4. The weights of the experts are computed using Eqs. (7)-(8), Among them  
 600  $(C.F)_1 = 0.6544$ ,  $(C.F)_2 = 0.6842$ ,  $(C.F)_3 = 0.6614$ . The final weights of the experts are  $\varpi_1 = 0.3272$ ,  
 601  $\varpi_2 = 0.3421$ ,  $\varpi_3 = 0.3307$ .

602 Step 5. The evaluation of the experts is aggregated using the PWA operator based  
 603 on the similarity measure. The group evaluation matrix  $P = (p_{ij})_{m \times n}$  is derived by Eqs.  
 604 (9)-(11), as shown in Table A5. Taking the evaluation of A1 under criterion C11 as an  
 605 example, the distance between the evaluations of each expert is first calculated using

606 Eq. (5):  $d(p_{11}^1, p_{11}^2) = 0.48$ ,  $d(p_{11}^1, p_{11}^3) = 0.37$ ,  $d(p_{11}^2, p_{11}^3) = 0.47$ . Then,  
 607  $S(p_{11}^1, p_{11}^2) = 1 - d(p_{11}^1, p_{11}^2) = 1 - 0.48 = 0.52$ , similarly,  $S(p_{11}^1, p_{11}^3) = 0.63$ ,  $S(p_{11}^2, p_{11}^3) = 0.53$ . Next,  
 608 support function  $T(p_{11}^1) = 0.52 + 0.63 = 1.15$ ,  $T(p_{11}^2) = 0.52 + 0.53 = 1.05$ ,  $T(p_{11}^3) = 0.63 + 0.53 = 1.16$ .

609 Finally, According to Eq. (9) the result after aggregation can be obtained as  
 610  $([0.823, 0.881], [0.182, 0.236])$ .

611

612 5.3. Determination of the criteria weights

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

615 Step 1. Calculate the subjective weight by FWZIC.

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

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

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

$$\begin{aligned} 627 \text{ Next, } \tilde{w}_{11}^s &= \frac{[(0.80003, 0.90), (0.10, 0.20)] \oplus [(0.80003, 0.90), (0.10, 0.20)] \oplus [(0.80003, 0.90), (0.10, 0.20)]}{3} \\ &= [(0.7728, 0.8752), [0.1260, 0.2714]] \end{aligned}$$

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

631 Step 2. Determine the objective weight using MEREC.

632 According to the constructed group evaluation matrix  $P = (p_{ij})_{m \times n}$ , Eqs. (16)-(20) is

633 used to calculate the objective weights of each criterion. The calculation outcomes are  
634 displayed in Table A9.

635 Firstly, normalize the original evaluation matrix is normalized according to Eq.  
636 (16) and then use Eq. (14) to obtain the score matrix. The overall performance is then  
637 calculated according to Eq. (17). Here is an example of A1:

$$638 Q_1 = \ln \left( 1 + \left( \frac{1}{n} \sum_j |\ln(\eta_{ij})| \right) \right) = \ln \left( 1 + \left( \frac{|\ln(\eta_{11})| + |\ln(\eta_{12})| + \dots + |\ln(\eta_{53})|}{18} \right) \right) = \ln \left( 1 + \left( \frac{0.22 + 0.29 + \dots + 0.38}{18} \right) \right) = 0.38$$

639 . Similarly,  $Q_2 = 0.59$ ,  $Q_3 = 0.45$ ,  $Q_4 = 0.59$ . Next, the performance after excluding each  
640 criterion is calculated according to Eq. (18). For example, the performance of A1 after

641 the exclusion of criterion C11 is

$$642 Q'_{11} = \ln \left( 1 + \left( \frac{1}{n} \sum_{b,b \neq j} |\ln(\eta_{ib})| \right) \right) = \ln \left( 1 + \left( \frac{|\ln(\eta_{12})| + \dots + |\ln(\eta_{53})|}{18} \right) \right) = 0.37 . \text{After, according to Eq. (19),}$$

$$643 M_{11} = \sum_i |Q'_{ij} - Q_i| = |0.37 - 0.38| + \dots + |0.56 - 0.58| = 0.07 . \text{Finally, objective weights are calculated}$$

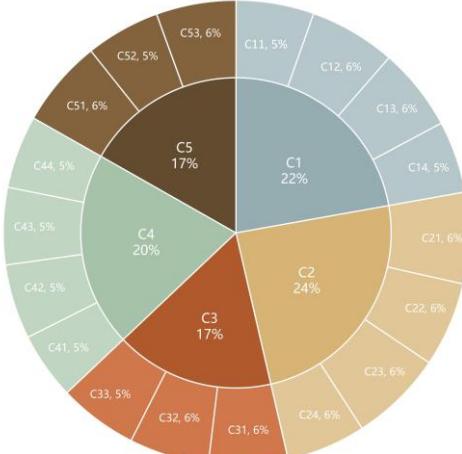
644 for each criterion according to Eq. (20),  $\omega_{11}^o = \frac{M_{11}}{M_{11} + M_{12} + \dots + M_{53}} = \frac{0.07}{1.59} = 0.04$ . Other criteria

645 are calculated in the same way.

646 Step 3. Determine the overall weight of the criteria.

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

649



650

651 Fig. 3. Visual proportions of criteria.

652

653

654 5.4. Expanded MARCOS to determine the optimal investment alternative.

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

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

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

662 Step 3. The degree of utility of alternatives related to  $A^+$  and  $A^-$  is defined by Eqs.  
 663 (23)-(25). First, Eq. (25) is applied to get the total of the normalized matrix's weighted  
 664 entries ( $\varsigma = 1$ ), i.e.,

$$665 S^- = ([0.394, 0.442], [0.588, 0.640]), S_1 = ([0.675, 0.732], [0.322, 0.374]), S_2 = ([0.448, 0.497], [0.530, 0.581]),$$

$$666 S_3 = ([0.577, 0.629], [0.396, 0.446]), S_4 = ([0.459, 0.508], [0.529, 0.581]), S^+ = ([0.686, 0.743], [0.313, 0.365]).$$

667 Then, through Eq. (14), the obtained weighted sequence is transformed into crisp value.

668 Then, through Eqs. (23)-(24), the utility degree of alternatives is obtained (Table A13).

669 Step 4. The utility functions  $f(K_i)$  of the alternatives are obtained according to Eqs.

670 (26)-(28). The alternatives are then ranked in descending order according to the

671 obtained  $f(K_i)$ . The final result is A1>A3>A4>A2, as shown in Table A13.

672

## 673 **6. Sensitivity and comparative analyses**

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

675 comparative analysis.

676

### 677 6.1. Sensitivity analysis

678 Since there are subjectively defined parameters in the IVFFHWA operator,

679 analyzing how the parameters affect the final result is essential. Furthermore, we will

680 examine how the alteration of the criteria weights affects the ultimate ranking

681 outcomes.

#### 682 6.1.1. Effect of the parameter $\varsigma$ on the outcomes of the model

683 In the initial results, the value of parameter  $\varsigma=1$  is used. Since parameter affects

684 the transformation of the IVFFHWA operator, in this subsection, the effect of the change

685 of parameter  $\varsigma$  ( $1 \leq \varsigma \leq 200$ ) on the initial results will be analyzed, where 1 is the

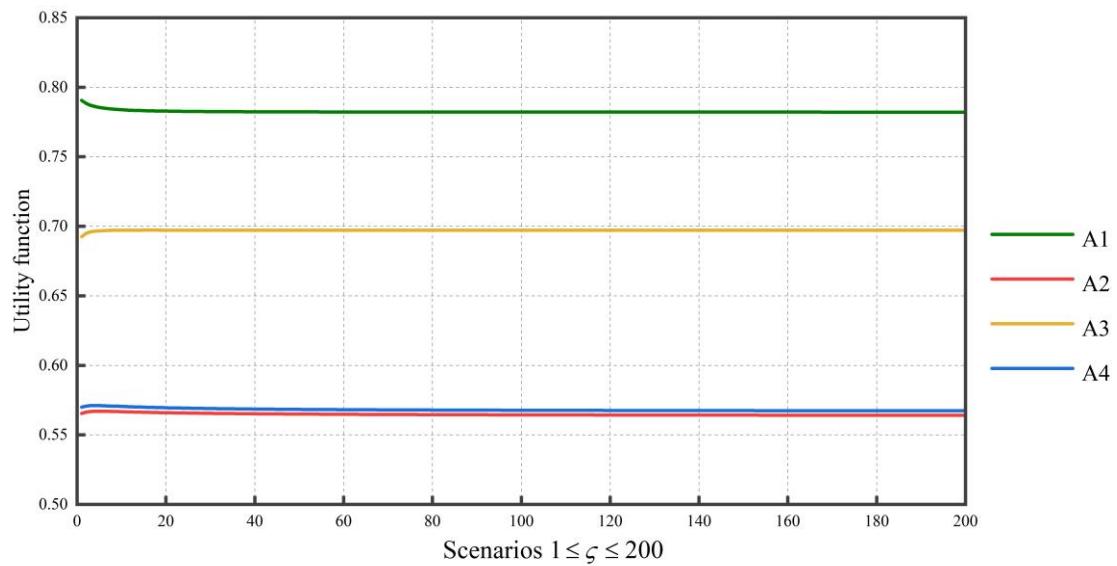
686 incremental step value. Figure 4 displays the outcomes of the experiment. In 200

687 scenarios, the change of  $\varsigma$  has a small impact on the utility value of the alternatives,

688 but in general, the utility value and the ranking of the alternatives are relatively stable,

689 and A1 maintains its dominant position over the rest of the alternatives. According to  
690 the outcomes of the experiment, we can conclude that A1 is the best option and that the  
691 initial solution is tenable. Keep in mind that this only pertains to the case that this study  
692 examines. In the case of inputting other evaluation data, the change of parameter  $\varsigma$   
693 may have a substantial effect on the final result. Thus, this analysis is a necessary stage  
694 prior to reaching a decision.

695



696

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

698

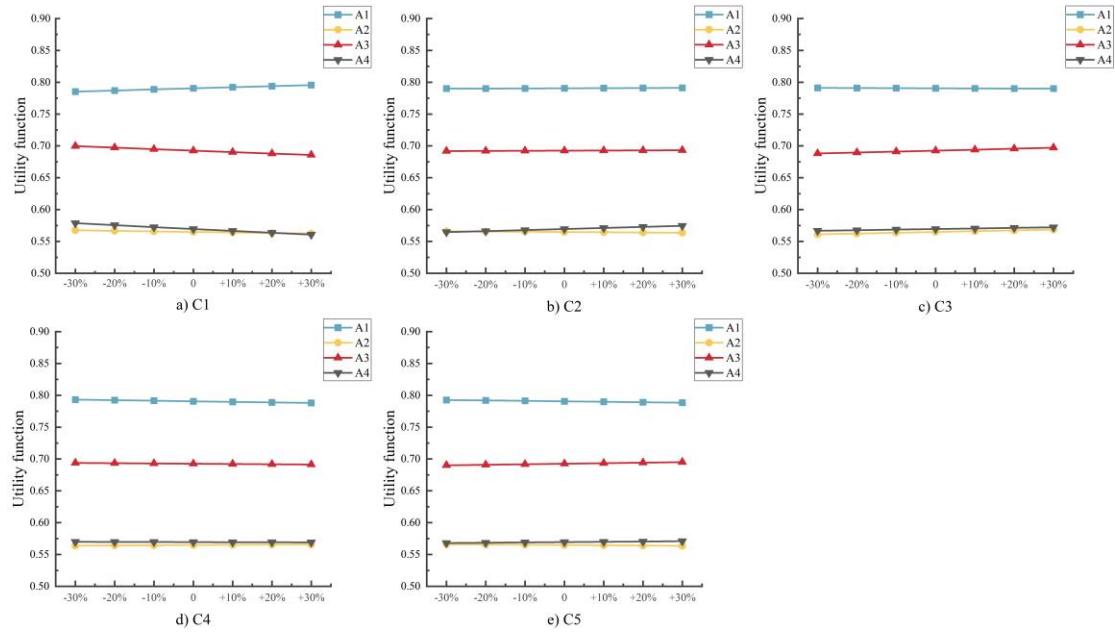
#### 699 6.1.2. Influence of the criteria weights on the model results

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

704 As can be shown, option A1 is consistently the best option to take for investments,

705 A3 is always the second-best investment solution, and the alternative ranking results  
706 are basically stable with respect to the shifts in the criteria's weights. However, when  
707 the weights of criteria C1 and C2 fluctuate up and down, the rankings of alternative  
708 programs A2 and A4 change slightly (change to A1>A3>A2>A4). When the weight of  
709 C1 gradually increases, the score of A1 increases, the score of other alternatives  
710 gradually decreases, and the ranking of A2 finally exceeds that of A4. when the weight  
711 of C2 goes from small to large, A1 and A3 are basically stable, and the score of  
712 alternative A4 increases with the increase of the weight of C2, and the final ranking  
713 exceeds that of A2. when the weight of C3 fluctuates, the scores of A2, A3, and A4  
714 increase with the increase of the weight, and the A1 decreases. When C4 weights  
715 gradually increase, the scores of A1, A3 and A4 gradually decrease, and the score of A2  
716 gradually increases and tends to exceed A4. When C5 weights fluctuate, A1 and A2  
717 scores decrease with the increase of C5 weights, A3 and A4 increase with the increase  
718 of C5 weights, and with the decrease of C5 weights, it is possible for A2 to be ranked  
719 more than A4. In addition, according to the relative fluctuation amplitude, the sensitive  
720 criterion of scheme A1 and A3 can be recognized as C1. With the decrease of C1,  
721 scheme A3 may exceed A1 to be the optimal scheme. The sensitive criterion for scheme  
722 A2 is C3. The sensitive criteria for scheme A4 are C1 and C2.

723



724

725

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

726

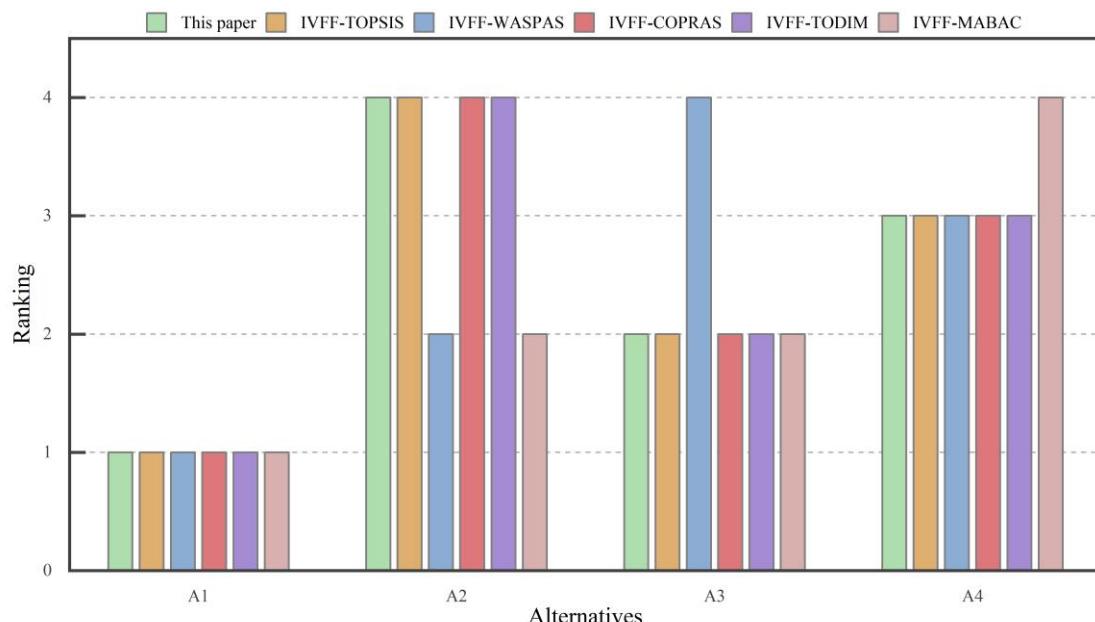
727 6.2. Comparative analysis

728 The purpose of this subsection is to demonstrate the viability and suitability of the  
 729 investment decision framework for offshore CCUS projects. A comparative analysis  
 730 will be conducted. Therefore, IVFF-TOPSIS method [51]、IVFF-WASPAS method  
 731 [95]、IVFF-COPRAS (Complex Proportional Assessment) method [96]、IVFF-  
 732 TODIM method [97] and IVFF-MABAC method [98] will be applied to the  
 733 comparative study. The relevant input data are displayed in Tables A5 and A10, and the  
 734 analysis results are shown in Table A14 and Fig. 5.

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

739 [100]. SRCC are (1, 0.2, 1, 1, 0.8). All of them are greater than or equal to 0.8 except  
 740 for the IVFF-WASPAS model. The WSC is (1, 0.7083, 1, 1, 0.9167), respectively, and  
 741 all of them are greater than 0.7. It is evident that the rankings produced by the various  
 742 techniques do not have much difference and have a high degree of consistency. Thus, it  
 743 can be said that the ranking results are legitimate and the suggested model makes sense.  
 744 Although the results are similar, the extended MARCOS proposed in this paper  
 745 introduces the Hamacher operator, which can better assemble information and deal with  
 746 the interconnection and influence of criteria. And the parameters can be flexibly  
 747 adjusted according to the decision maker's preference to obtain more stable results. It  
 748 increases the scientificity of the decision outcomes.

749



750

751 Fig. 5. Ranking results of different MCDM methods.

752

753

754 **7. Discussion and managerial insights**

755 As can be seen from Table A10 and Figure 3, economy (C2) is important for  
756 investment in offshore CCUS projects. In addition to the economic criteria, storage  
757 capacity (C12), and leakage and monitoring risks (C51) are also given greater weight.  
758 In order to prevent the serious consequences of CO<sub>2</sub> leakage, it is necessary to find a  
759 suitable storage site, and to evaluate and monitor its storage stability and capacity  
760 during the storage process, so these two factors are important factors to be considered  
761 in the investment process [101]. In addition, the social (C4) is also given a high weight.  
762 This result accurately reflects the current status of offshore projects. The deployment  
763 of CCUS projects is influenced by different social dimensions. Policy support,  
764 acceptance by the surrounding population, and the opportunities presented by the  
765 program are all factors that influence the development of CCUS projects [102-103]. On  
766 the other hand, based on the framework proposed in this paper, the alternatives were  
767 evaluated and ranked, and the final ranking was A1>A3>A4>A2. In addition, we can  
768 see from Table A5 that A1 outperforms the other alternatives in terms of resources,  
769 economy, and social. Since the weights of these criteria account for most of the total  
770 weights, A1 achieves the most favorable results. The other alternatives have their own  
771 shortcomings in different aspects of performance. After sensitivity analysis and  
772 comparison with other methods proposed in the related literature, the robustness,  
773 effectiveness and superiority of the methodology of this paper are verified. Firstly,  
774 IVFFS is powerful and ensures the authenticity and effectiveness of the decision-  
775 making process. Secondly, in terms of expert weights, information aggregation, and

776 criterion weights, this paper integrates the scientific nature of information and the  
777 simplicity of calculation, which improves the effectiveness of decision-making. Finally,  
778 the proposed Hamacher-MARCOS method not only considers the interrelationships  
779 among the criteria, but also operates flexibly and has a high degree of stability, which  
780 also proves the efficiency of the method proposed in this paper.

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

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

801

## 802 **8. Conclusion**

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

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

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

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

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

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

835 Offshore CCUS projects are still in their infancy. This research offers an in-depth  
836 analysis and discussion of the investment decision problem of offshore CCUS projects  
837 using complex and applicable decision theories. The results offer points of reference  
838 for future research aimed at promoting the sustainable growth of offshore carbon  
839 capture and storage facilities. Even though this paper's methodology for making  
840 investment decisions offers some theoretical references for evaluating investments in  
841 offshore CCUS projects, there are still some limitations in this study. First, due to the

842 large number of influencing factors involved in the investment decision of offshore  
843 CCUS projects, it is necessary to enhance the system of investment decision criteria.  
844 And with the continuous progress of technology, different criteria can be selected for  
845 evaluation according to different needs. Secondly, the expert weight determination  
846 model needs to be further improved, such as the trust relationship between experts can  
847 be introduced. Finally, more alternatives can be considered for assessment in future  
848 studies, depending on the degree of development of the offshore CCUS project.  
849 Furthermore, we will extend the Hamacher-MARCOS model that has been suggested  
850 to environments with bipolar fuzzy sets, Fermatean hesitant fuzzy sets, and interval-  
851 valued Fermatean hesitant fuzzy sets.

852

### 853 **Disclosure statement**

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

855

### 856 **Data availability statement**

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

860

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864

865 **Author Contributions**

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

867 Qinghua Mao: Conceptualization, Data curation, Funding acquisition. Yaqing Gao:

868 Methodology, Writing - original draft, Writing - review & editing, Formal analysis.

869 Jiacheng Fan: Resources, Formal analysis.

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

871 approved the final manuscript.

872

873 **Ethical approval**

874 Ethics committee approval is not required.

875

876 **Consent to participate**

877 Not applicable.

878

879 **Consent for publication**

880 The authors confirm that the final version of the manuscript has been reviewed

881 approved, and consented for publication.

882

883

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**Declaration Statement**

There are no conflicts of interest.

## Review Checklist

### Title

- Is the title clear and concise, reflecting the brief nature of the study?

### Abstract

- Does the abstract provide a short but complete overview of objectives, methods, results, and conclusions?

### Introduction

- Is background information minimal but sufficient to set context?

### Methods & Results

- Are essential methods described briefly yet reproducibly?
- Are results presented concisely without unnecessary detail?

### Discussion and Conclusion

- Are findings discussed briefly in relation to literature?
- Are conclusions justified despite limited scope?

### Tables and Figures

- Are minimal but effective visual elements used?

### References

- Are references selective but adequate?

## Review Decision & Feedback

 Accept with minor revision

Originality of the work	★★★★☆	(4.0)
Methodological soundness	★★★★☆	(4.0)
Clarity of presentation	★★★★☆	(3.0)
Significance of findings	★★★★☆	(3.0)
Relevance to journal's scope	★★★★☆	(3.0)

### Ethical Considerations

Is there evidence of appropriate ethics approval and/or consent?

Yes

hjj

### Figures and Tables

Are figures/tables clear and necessary?

Yes

Would you like to review a revision of this manuscript?

Yes

### Overall Comments

nj